UNIVERSITY OF CAPE TOWN

A FRAMEWORK TOWARDS THE DESIGN OF MORE SUSTAINABLE CONCRETE STRUCTURES

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DECLARATION

I declare that this thesis is essentially my own work and is being submitted for the degree of Doctor of Philosophy at the University of Cape Town. It has not been submitted before for any degree or examination in any other university.

Signature: **Rachel Muigai** **Date:** 21-11-2014

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DEFINITIONS

The definitions for terms used in the study according to a number of references and in the context of this study are given below[1]:

Anthropogenic	Resulting from or produced by human beings (IPCC "Fourth Assessment Report", 2007)
Biosphere	Consists of all life on earth and all the parts of the earth in which life exists, including land, water and atmosphere.
Biodiversity	The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (http://www.iucn.org).
Carbon dioxide equivalent (CO_2-eq)	The amount of CO_2 emission that would cause the same radiative forcing as an emitted amount of a well-mixed greenhouse gas or a mixture of well mixed greenhouse gases, all multiplied with their respective global warming potentials to take into account the differing times they remain in the atmosphere (IPCC "Fourth Assessment Report", 2007)
Carbon footprint	A life-cycle assessment with the analysis limited to emissions that have a global warming potential (GWP). It gives the overall amount of equivalent carbon dioxide emissions (CO_2-eq) that are directly and indirectly caused by anthropogenic activities (Wiedman and Minx, 2008)
Cradle-to-cradle	This refers to the whole life-cycle phases from raw material extraction to end-of-life material recovery strategies that include the recycling/reuse of the demolished materials.
Cradle-to-gate	This comprises all relevant processes from raw materials extraction (cradle), manufacturing and processing of the materials and their transportation: to the processing plant, within the plant, and to the batching plant and/or construction site (gate).
Cradle-to-grave	This refers to the whole life-cycle phases of a product or structure from raw material extraction to final demolition and disposal.
Design	The activity of transforming the functional requirements of a design into a solution concept or concepts for fulfilling requirements Chakrabarti and Bligh (1994).
Ecology	The branch of biology dealing with the relationships and interactions between organisms and the (natural) environment; the set of relationships existing between organisms and their environment (Webster College Dictionary, 1995, Random House). The term ecology as applied in this study thus refers to both the society and the environment.
Embodied energy	Embodied energy is a measure of the gross amount of energy requirements of the analyzed construction material, structural component or structure (Ashley and Lemay, 2008).

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[1] The references for the definitions are given in the reference list of Chapter 1

Environment	The aggregate of surrounding things, conditions or influences, surrounding milieu, the air, water, minerals, organisms and other external factors surrounding and affecting a given organism at any time; the social and cultural forces that shape the life of a person or population (Webster College Dictionary, 1995, Random House). Thus, this is interpreted as the physical environment from which humans derive their resources and includes the immediate environment of a concrete structure.
Exergy:	The maximum amount of work that can be produced by a system or flow of matter or energy as it comes to equilibrium with its environment with respect to a standard temperature of 25ºC (298.15K) and pressure of 1 atmosphere (101.325 kPa), and with respect to the chemical potential of stable chemical species in the environment (Szargut, Morris and Stewart 1988; Çengel and Boles 2011). Thus, exergy is a measure of the potential for carrying out work contained in a material (i.e. its potential to cause changes to the surrounding environment). The exergy metric is used to assess the ‘quantity’ (energy and mass) of a material and its ‘quality’ (environmental impact due to use of energy and matter).
Framework	A set of ideas, principles, agreements, or rules that provides the basis or outline for something intended to be more fully developed at a later stage (Encarta Dictionary, UK). In the context of this study, a framework refers to a set of design parameters and variables that need to be taken into consideration for the design of more sustainable concrete structures.
Functional unit	Quantified performance of a product system for use as a reference unit, which enables comparison of the environmental impacts of different types of products in a life-cycle assessment (ISO 14040:2006).
Gate-to-grave	This phase as used in the context of this study covers the construction of the structure, on-site transportation activities, operational phase, demolition of the structure and the disposal of demolished material to a landfill.
Global warming potential (GWP)	An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation (IPCC 4th Assessment Report, 2007).
Greenhouse gases	These include: Carbon dioxide ($C0_2$); Methane (CH_4); Nitrous oxide (N_20); Hydrofluorocarbons (HFCs); Perfluorocarbons (PFCs) and; Sulphur hexafluoride (SF_6) (United Nations, 1997).
More sustainable	This term is used in this study to depict the fact that design is just one of numerous ways of

moving towards sustainable concrete structures

Performance : In the context of this study 'performance' refers to the quantitative measure of a structure or its components with respect to a design requirement e.g. durability and/or compressive strength value.

Primary energy : Energy embodied in natural resources that have not undergone any form of anthropogenic conversions or transformations (IPCC, 2001).

Serviceability limit state (SLS) : A state that corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met.

Social impact : The consequences to human populations of any public or private action that alters the ways in which people live, work, play, relate to one another, organize to meet their needs and generally cope as members of society. The term also includes cultural impacts involving changes in the norms, values, and beliefs that guide and rationalize their cognition of themselves and their society
(Inter-organizational Committee on Principles and Guidelines for Social Impact Assessment, 2003).

Sustainability : 'Sustainability' belongs originally to the field of ecology, referring to an ecosystem's potential for subsisting over time, with almost no alteration (Jabareen, 2008).

Sustainable development : Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

LIST OF ABBREVIATIONS AND ACRONYMS

AADT	:	Annual Average Daily Traffic
ADP	:	Abiotic Depletion Potential
AP	:	Acidification Potential
ASPASA	:	Aggregate and Sand Producers Association of South Africa
BCMC	:	Building Component and Material Combinations
BOQ	:	Bill of Quantities
BREEAM	:	Building Research Establishment Environmental Assessment Method (in the United Kingdom)
C&CI	:	Cement and Concrete Institute, South Africa
C&DW	:	Construction and Demolition Waste
CAD	:	Computer Aided Design
CASBEE	:	Comprehensive Assessment System for Building Environmental Efficiency (in Japan)
CCS	:	Carbon Capture and Storage
CDM	:	Clean Development Mechanism
CFC	:	Chlorofluorocarbon
CH	:	Abbreviation is used in SimaPro to represent data from Switzerland
CH_4	:	Methane
CKD	:	Cement Kiln Dust
CMA	:	Concrete Manufacturers Association (South Africa)
CO_2	:	Carbon Dioxide
CO_2-eq	:	Carbon Dioxide Equivalent
COP	:	Conference of the Parties
COV	:	Coefficient of Variation
CSH	:	Calcium Silicate Hydrates
DB	:	Dichlorobenzene
DE	:	Abbreviation is used in SimaPro to represent data from Germany
DMR	:	Department of Mineral Resources (South Africa)
DPP	:	Discounted Payback Period
EF	:	Ecological Footprint
ELCD	:	European Life-Cycle Database
EP	:	Eutrophication Potential
EPD	:	Environmental Product Declaration
FA	:	Fly Ash
FRP	:	Fibre Reinforced Polymer
FU	:	Functional Unit
GDP	:	Gross Domestic Product
GGBS	:	Ground Granulated Blast-Furnace Slag
GHG	:	Greenhouse Gas
GJ	:	Giga Joules = 10^6 Joules
GLO	:	Abbreviation is used in SimaPro to represent global data
GNI	:	Gross National Income
GNP	:	Gross National Product
GWP	:	Global Warming Potential
GWP_{100}	:	Global Warming Potential, 100 year baseline
HDI	:	Human Development Index
HDPE	:	High-Density Polyethylene

IPCC : Intergovernmental Panel on Climate Change
IRR : Internal Rate of Return
ISO : International Standards Organization
ITZ : Interfacial Transition Zone
IUCN : International Union for Conservation of Nature
kg : kilogram = 10^3 grams
kN : kilonewton = 10^3 Newtons
LCA : Life-Cycle Assessment
LCC : Life-Cycle Costing
LCI : Life-Cycle Inventory
LCIA : Life-Cycle Impact Assessment
LEED : Leadership in Energy and Environmental Design (in the USA)
LQI : Life Quality Index
MFA : Material Flow Analysis
MJ : Megajoules = 10^6 Joules
mm : Millimetre
MOO : Multi-Objective Optimization
Mt : Mega Tonnes = 10^6 Tonnes
N : Newton
N_2O : Nitrous Oxide
NAC : Natural Aggregate Concrete
NEB : New Engineering Building (at the University of Cape Town, South Africa)
NL : Abbreviation is used in SimaPro to represent data from Netherlands
NPV : Net Present Value
ODP : Ozone Depletion Potential
OECD : Organisation for Economic Co-operation and Development
PC : Post-tensioned Concrete
PPC : Pretoria Portland Cement (South Africa’s cement producing company)
ppm : Parts Per Million
ppp : Purchasing Power Parity
PVC : Polyvinyl Chloride
RAC : Recycled Aggregate Concrete
RC : Reinforced Concrete
RD : Relative Density
RER : Abbreviation is used in SimaPro to represent data from the European region
SA : South Africa
SBAT : Sustainable Building Assessment Tool (in South Africa)
SCM : Supplementary Cementitious Material
SDg : Geometric Standard Deviation
SE : Surplus Energy
SF : Silica Fume
SL : Slag
SO_2 : Sulphur Dioxide
SPAID : Support Programme for Accelerated Infrastructure Development (South Africa)
ton : Tonne = 10^3 kg
UN : United Nations
UNEP : United Nations Environmental Programme

UNFCCC	:	United Nations Framework Convention on Climate Change
USEPA	:	United States Environmental Protection Agency
WBCSD	:	World Business Council on Sustainable Development
WBP	:	Whole Building Process
WCED	:	World Commission on Environment and Development
WRI	:	World Resources Institute
WWF	:	World Wildlife Fund

NOTATIONS

In this study, the following notations have been used in the design calculations for concrete structures.

Symbol	Denotation	Dimension
Roman upper case letters		
A_s	Area of steel reinforcement	mm^2
A_p	Cross-sectional area of prestressing tendon	mm^2
A_c	Area of concrete	mm^2
$CaCO_3$	Calcium carbonate	$CaCO_3$
CaO	Calcium oxide	*CaO*
CO_2	Carbon dioxide	CO_2
CO_2-e	Carbon dioxide-equivalent	CO_2*-eq*
E_a	Unit environmental impacts of aggregates	*kg* CO_2*-eq/kg*
E^b	Unit environmental impacts of cement	*kg* CO_2*-eq/kg*
$E^{concrete}$	Unit environmental impacts of concrete	*kg* CO_2*-eq/*m^3
E^s	Unit environmental impacts of steel	*kg* CO_2*-eq/ton*
E_w	Unit environmental impacts of water	*kg* CO_2*-eq*
E_s	Elastic modulus of steel	*GPa*
E_c	Elastic modulus of concrete	*GPa*
L	Litres	*litres*
P	Prestress force in tendon	*N*
V	Shear stress	kN/m^2
M	Bending moment	*kNm*
M_a	Mass of aggregates	kg/m^3
M_{ult}	Ultimate bending moment capacity	*kNm*
M_t	Applied moment at transfer	*kNm*
M_s	Applied moment in service	*kNm*
NO_2	Nitrogen dioxide	NO_2
$\mathfrak{R}^N$	set of real numbers	-
SO_2	Sulphur dioxide	SO_2
Roman lower case letters		
a/c	Aggregate/cement ratio	-
b	Amount and type of binder	*kg,-*
d	Effective depth of member	*mm*
e	Equivalent units	-
f_{ck}	Characteristic compressive strength of concrete	N/mm^2
f_{yk}	Characteristic yield strength of steel reinforcement	N/mm^2
f_{ys}	Yield strength of steel tendons	N/mm^2
f_{tt}	Allowable tensile stress at transfer	N/mm^2
f_{tc}	Allowable compressive stress at transfer	N/mm^2
f_{st}	Allowable tensile stress in service	N/mm^2
f_{sc}	Allowable compressive stress in service	N/mm^2
k	Cementing efficiency factor	-

l	:	Span of a structural element	*mm*
r	:	Discount rate	*%*
t	:	Time	*seconds*
w/c	:	Water-cement ratio	-
b	:	Width of the structural components cross-section	*mm*
g_k	:	Dead load	*kN/m*
q_k	:	Live load	*kN/m*
m^3	:	Cubic metres	m^3
x_{min}	:	Minimum concrete cover to reinforcing steel	*mm*
tkm	:	Tonne-kilometre	*tkm*
v/v	:	Volume per unit volume	-

Greek lower case letters:

α	:	Elastic modulus ratio (E_s/E_c)	-
σ_p	:	Maximum stress applied to the tendon	N/mm^2
Δx_{dev}	:	Construction error in concrete cover	*mm*
δ	:	displacement	*mm*
δ_{actual}		Short term deflection due to live loading	*mm*
$\delta_{allowable}$		Allowable deflection	*mm*
φ	:	diameter	*mm*
ɣ	:	factor of safety	-
ρ_s	:	density of steel	kg/m^3

ABSTRACT

The main contribution of this study is the development of a novel framework for the design of reinforced concrete (RC) structures which aims at ensuring that future RC structures have the lowest possible carbon footprint, energy use and impact on the environment. The key focus of the study is on structural design where there is a lack of grasp of materials aspects, and environmental aspects of construction. In the proposed framework, a set of quantifiable design parameters and variables (binder type, concrete grade, diffusivity, concrete cover depth, area of steel in the structural component) are selected with respect to a set of performance measures which cover the functionality and availability of the structure to the user during its service life. The outputs generated from the framework are optimised material types and properties which not only meet the design performance requirements but also lead to minimised life-cycle environmental impacts. Two case studies are used to demonstrate the proposed design methodology. These include a reinforced concrete frame building and a post-tensioned box girder. The application of the framework for design in the material specifications showed a reduced volume of materials in construction compared to the current materials and structures design practice.

Key words: Reinforced concrete, Sustainability, Design framework, Materials, Structural design

SUMMARY

The primary objective of this study is to develop a framework for design of reinforced concrete (RC) structures which aims at ensuring that future concrete structures have the lowest possible carbon footprint, energy use and impact on the environment. The framework gives a set of quantifiable design parameters and variables that need to be taken into consideration for the design of more sustainable concrete structures.

Based on the established framework, a RC design optimization tool is developed to be used in selecting alternative binders for concrete based on a set of performance requirements. By applying the tool, the designer should come up with an optimum design that will minimise life-cycle environmental impacts of concrete structures.

The framework for design and design optimization tool are important as they cater for the need to include sustainability design as an integral part of the design process of concrete structures and not just an add-on measure, as is currently the case, if at all. The framework and tool are also applicable to a number of concrete applications such as buildings and infrastructure and this has been demonstrated using two varied case studies: a reinforced concrete frame building and a post-tensioned concrete box girder.

As part of the development of the framework for design and the tool, this study carried out critical literature reviews that form the backbone of the proposed framework. The first part of the literature review is on the concept of ‘sustainable development’ and its application in the concrete construction industry. The review covers the history and philosophy behind the subject of ‘sustainable development’ and gives some critique of the concept. Sustainable development has generally been defined as: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Despite the number of critiques of this definition, this study is able to show the fundamental principles of sustainable development and give their applications in the concrete construction industry. Based on the literature review, a ‘sustainable concrete structure is defined’ as: “*one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling*”.

A second critical literature review is on the ISO 14000 series: life-cycle assessment methodology, that aims at achieving a general understanding of existing measurement methods for sustainability developed using this methodology, and their suitability in measuring the environmental impacts of concrete structures. In particular, two thermodynamic metrics, namely energy and exergy, are compared. Both metrics are consistent in their methodology and produce reliable results as they are based on sound scientific principles. However, this study shows that exergy is a more suitable metric than energy, for concrete structures, as it able to account for both materials and energy resources in the same units. The method avoids the need to establish subjective weighting measures. However, the exergy method is tedious in its computations and requires a consistent database of the exergy of resources, which is not complete at this stage. The selected exergy metric is then applied in the broader framework for design of more sustainable concrete structures.

A third critical and original review is carried out to quantify the extent of resource use and emissions associated with the production of concrete construction materials in South Africa. Six-year average (2005-2010) data are provided for resources consumed and wastes emitted to the air due to quarrying and processing of raw materials for concrete in SA. From the study, it is determined that on average, 9.1×10^9 kg CO_2-eq emissions per year were emitted in SA for the period 2005 to 2010. These CO_2-eq emissions per annum relate to the production activities for cement and aggregates used for concrete production. Cement is the main contributor of CO_2-eq emissions, contributing on average 98 % of the total carbon equivalent emissions by the concrete industry in SA. This shows the need to select an optimum binder system for a concrete mix-design as is later demonstrated in the proposed framework. In addition, this study quantified the average amount of concrete produced per annum in SA for 2005-2010 as 27 million m^3 (65.2 Mt). This amount is only 0.49% of the estimated 8 billion m^3 of concrete produced worldwide. However, it is noted that based on the continued government and private sector investment in new (and replacement) construction to cope with the rapid rate of urbanization and population growth, these values are expected to rise in future. The review identified the design of more sustainable concrete structures as a practicable means to drive the concrete construction industry in reducing its short- and long-term impacts.

Aforementioned, the main contribution of this study is the development of a novel framework for design that leads to the design of more sustainable concrete structures. The key focus of the study is on structural design where there is a lack of grasp of materials aspects, and environmental aspects of construction. In the proposed framework, the design variables (binder type, concrete grade, diffusivity, concrete cover depth, area of steel in the structural component) are selected with respect to a set of performance measures which cover the functionality and availability of the structure to the user during its service life. The outputs generated from the framework are

optimised material types and properties which not only meet the design performance requirements but also lead to minimised life-cycle environmental impacts. Two case studies are used to demonstrate the proposed design methodology. These include a reinforced concrete frame building and a post-tensioned box girder. The application of the framework for design in the material specifications showed a reduced volume of materials in construction compared to the current materials and structures design practice.

In conclusion, the proposed framework is important as it allows the designer to take a life-cycle perspective in design and also contribute towards sustainable development.

Note: The references in the summary are given in the reference list of Chapter one.

Chapter 1

1 INTRODUCTION

1.1 Background

Since the mid-20th Century and beginning of the 21st century, there has been an increased uptake of concrete as a structural material. The worldwide consumption of concrete has been estimated to be increasing gradually from 6.4 billion m^3 in 1997 (Aïtcin, 2000) to about 8 billion m^3 in 2009 (CEMBUREAU, 2009). This volume will continue to increase particularly in the developing countries due to an exponential increase in population growth, urbanisation and economic growth (Scheubel and Nachtwey, 1997; Humphreys and Mahasenan, 2002). Scheubel and Nachtwey (1997) directly correlated cement consumption (a key constituent of concrete[2]) to the level of development of a country. They showed that cement consumption peaks when the gross national income (GNI) per capita is between US $ 10 000 and US $ 13 000. A relatively linear relationship was established between the GNI per capita and the per capita cement consumption for countries with a GNI per capita of less than US $8000 (expressed in 1990 US dollars). Developing economies such as that of South Africa[3] fall within this category. This low consumption in developing countries can be attributable to the focus on developmental needs in these countries i.e. the governments in developing countries first ensure that the people meet their basic needs for survival and development through provision of social housing infrastructure and ignore or give less attention to the construction of more permanent structures. For developed economies with a GNI greater than the peak values (e.g. USA, UK, and Western Europe), a slow increase in cement demand is reported. This is consistent with the fact that in industrialized countries different engineering materials are presently facing a saturated market, and maintenance and replacement are the main driving forces for their use (Aïtcin, 2000). In contrast, developing countries, are expected by 2020, to have increased their demand for cement by 155-180% from 1990 levels as well as register a four-fold increase of the same by 2050 (Damtoft *et al*., 2008). An increase in cement demand signifies a corresponding use of concrete in construction.

While concrete production continues to grow and contribute towards economic development around the world, evidence suggests that this growth is associated with escalating negative and irreversible impact on the environment. Firstly, aggregate extraction and processing may lead to loss of

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[2] Modern concrete consists of a mixture of aggregates (65-80% volume per unit volume (v/v)), cement (10-12% v/v), water (14-21% v/v) and usually includes other constituents such as mineral components (cement extenders/additives) and chemical admixtures (e.g. air-entraining agents, water reducers and accelerators), and occasionally fibres (<1% v/v) (van Oss and Padovani, 2003).

[3] South Africa's population in 2008 was around 48 million people with a GDP of US$ 277 billion (GDP per capita ≈ US$ 5770) (World Development Indicators database, 2009)

arable/forest land coupled with a loss of bio-diversity, waste generation and resource depletions (Uher, 1999; Alexander and Mindess, 2006; Cheng *et al*., 2006). Secondly, quarrying and construction activities may affect the society negatively due to the noise and air pollution that arise during the blasting of aggregates at the quarry/construction sites, transportation of materials and repair activities which also lead to user inconveniences. Thirdly, concrete produces massive inert waste through construction and demolition activities. Lastly, cement, the key constituent in concrete, is energy intensive and accounts for 5-8% of global anthropogenic CO_2 emissions (WBCSD, 2002) as well as significant levels of SO_2 and NO_2, particulate matter and other pollutants (USEPA, 1999). This latter point is a global concern that has been increasingly addressed by current research studies.

The most common approach to reducing the environmental impacts of concrete, due to cement production, is through the use of alternative materials such as uncalcined limestone and/or industrial by-products such as ground granulated blast furnace slag (GGBS) from iron production, silica fume (SF) from the manufacture of silicon, and fly ash (FA) from coal combustion, which are prescribed as partial replacements of cement to form blended cements (Glavind, 2009; Naik *et al*., 2003; Malhotra, 2003). The industrial by-products are also referred to as supplementary cementitious materials (SCMs). Blended cements are produced either by intergrinding SCMs with clinker[4] from cement production, or separate grinding of clinker followed by interblending with SCMs. The use of blended cements reduces the amount of clinker that needs to be produced, also lowers the CO_2 emissions, and diverts wastes from landfills as SCMs are by-products of other industries that would have otherwise been disposed. The approach is adopted by current green building environmental assessment tools[5] that grade design solutions for environmental sustainability using a pre-assigned grading scale. For example, the use of SCMs such as FA, SF and GGBS in concrete qualifies a concrete structure for a higher rating than one constructed using conventional concrete. Prescribing the use of alternative materials and SCMs for concrete is a positive step towards reducing the environmental impacts of concrete as it encourages the designer to think about the impact of material designs on the environment. However, the approach is qualitative and does not allow/encourage the structural engineer to make specific optimum design choices of materials at the design stage. A quantitative prediction of the performance of various concretes made using blended cements is therefore vital from both environmental and structural performance viewpoints.

Hence, there is a need to develop an approach that allows for a means to check actual sustainability performance of constituent materials of concrete. This study proposes a novel framework for the

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[4] Clinker is the main product of Portland cement manufacture and is generated by heating raw materials (limestone, iron ore and alumino-silicates such as clay) together at temperatures of about 1400 – 1500 °C.

[5] Tools for environmental assessment of infrastructure include the Leadership in Energy and Environmental Design (LEED) in the USA, Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan, Sustainable Building Assessment Tool (SBAT) tool in South Africa (S.A.), Green Star Building tool developed in Australia, and Minergie in Switzerland.

design of concrete structures that allows the structural engineer to explicitly address rational, quantitative design of concrete for sustainability. The main elements of the proposed framework, developed in this study, are illustrated in ***Figure 1-1*** .

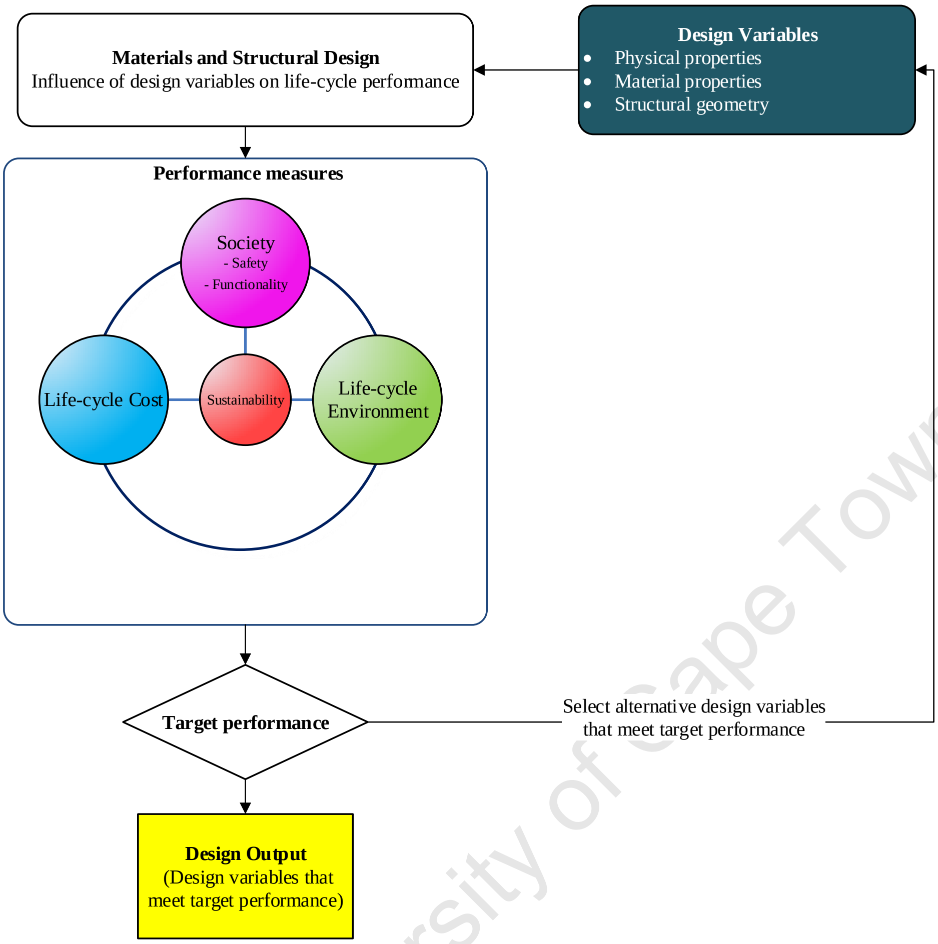

Figure 1-1: *Summary of proposed framework for design*

The key features of the proposed framework for design are:

1. A set of design variables and parameters that influence the sustainability of concrete. The selected variables and parameters are quantifiable and this enables a distinction to be made between different marginal materials such as marginal and site-derived materials in structural concrete.
2. A set of performance measures that quantify the sustainability performance of concrete with respect to defined acceptable levels (targets). These are the: (i) structural performance in terms of strength and durability, (ii) life-cycle financial costs and environmental impacts of concrete.
3. An optimization procedure to be used in selecting optimum material properties and structural dimensions. From ***Figure 1-1***, it is apparent that the design of concrete structures for

sustainability involves integrating a number of aspects such as the environmental impact and cost of a material and selecting optimum design variables based on these combined criteria.

The outputs generated from the framework are optimised material and geometrical properties which not only meet the design requirements but also lead to minimised life-cycle environmental impacts. With this proposed framework, it is demonstrated that material wastage is reduced compared to existing design methods.

The framework is important as it allows the designer to take a life-cycle perspective in design and also contribute towards more sustainable[6] concrete structures.

1.2 Research aims and objectives

This thesis aims to contribute towards the design of 'more sustainable' concrete structures through developing a framework for design of reinforced concrete (RC) structures that encapsulates structural and environmental considerations for these structures over their life-cycle. By applying the framework, the designer of a concrete structure should come up with an optimum design that will help minimise environmental impacts of RC structures. In order to realize this, the following objectives need to be attained:

1) To propose a framework for the design of more sustainable RC structures where considerations regarding the sustainability of the structure over its life-cycle are explicitly considered in the design process.
2) To test the applicability of the proposed framework. The framework should be adaptable to a range of infrastructure applications, and hence there is a need to provide practical examples in the form of case studies explaining the different applications in the methodology. Two existing reinforced concrete structures are analyzed: (i) a highway switch ramp and (ii) a building structure.

As a backbone for these objectives the study will undertake a state-of-the art literature review to establish the following:

- (i) Give a working definition of the term "sustainable concrete structure" and determine a suitable metric(s) for measuring quantitatively the sustainability of concrete structures.
- (ii) Undertake a comprehensive environmental assessment of SA's cement and concrete industry with a view to establishing where SA ranks in the growing trends of resource savings and environmental pressures due to increasing resource consumption and waste generation of the concrete construction industry.

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[6] The term 'more sustainable' is used in this study to depict the fact that design is one among many other ways of moving towards sustainable concrete structures.

1.3 Research methodology

This thesis is a novel research on the design of RC structures for sustainability. Being a new area of research, the concept of a sustainable concrete structure, methods of measuring sustainability, and the area in which the RC designer can contribute are first established through critical reviews. Following this, the study formulates a novel framework for design showing the parameters the designer needs to take into consideration. The functioning of the framework is then demonstrated using two case studies.

1.4 Scope and limitations

The scope and limitations of the study are outlined in the following sections.

(a) *Scope of the study*

The study focuses on materials selection of a RC structure at the detailed design phase. It should be noted that design aspects such as planning of the layout of the structure and determining the structural form and shape of the RC structure contribute importantly towards the design of more sustainable concrete structures. However, these aspects are not explicitly included in the scope of this study. Thus, the integration of all the design parameters contributing to more sustainable concrete structures is beyond the scope of the current study.

(b) *Selected parameters and variables*

The framework is limited to quantifiable material parameters and variables that can be verified using e.g. laboratory tests, i.e. the framework is performance-based. However, there are other qualitative materials related parameters that have an influence on the overall sustainability of concrete e.g. construction site practices such as curing, compaction and good workmanship. These qualitative factors also play a major role in the long-term structural performance of concrete. However they are not included in this study as they cannot be quantified in physical units. Suffice to say that best practice in these aspects is necessary to realize sustainable concrete structures.

(c) *Performance prediction models*

This study adopted prediction models for concrete compressive strength and durability that relate the selected strength and durability performance measures of concrete to measurable variables and parameters. These models are from studies conducted on an international basis and require further verification using local data.

(d) *Uncertainty in design parameters and prediction models*

The models selected for material performance prediction contain uncertainties as precise determination of concrete performance is not practical due to the complexity of concrete microstructure and also the differences in properties of composite materials in concrete. In addition, there is inherent variability in datasets that are used to quantify the life-cycle environmental impact of concrete. This uncertainty and variability in model parameters makes it difficult if not impossible to say that there is a uniquely defined value for each of the performance measures. Rather, there is a certain probability range for the same. Ideally, a probabilistic approach should be used, being a rational approach to dealing with data variability caused by the uncertainty and variability. However, the data available for e.g. quantifying the environmental impact of different concrete types is limited to a small sample size (< 30) and hence it would not be possible to use a probabilistic approach in the current study to measure sustainability performance.

(e) *Inclusion of social impacts*

Civil engineering structures such as bridges are characterized by large investments and a long-service life of over 100 years. They involve public expenditure funds coming directly from the tax-payer, and the day-to-day performance of concrete infrastructure significantly affects the well-being of the society (this includes the users of the structure and the surrounding community). At the detailed design phase of a structure it is necessary to include social impacts considerations such as functionality of the structure and effects of the availability of the structure on its users. With regard to the functionality of the structure, the designer should guarantee the ability of the concrete structure to meet all current and changing requirements of the user of the structure (Nathwani *et al*., 1997).

However, an appropriate method of quantifying social impacts is still under contention and hence the scope of this particular study does not include the social impacts of concrete structures.

This study is limited to considerations of the life-cycle environmental aspects of concrete structures.

1.5 Layout of the thesis

Chapter 1: gives the main objective of the thesis which is to develop a framework towards the design of more sustainable concrete structures and to test its applicability using a number of case studies. To achieve these objectives, this study has been compiled in six additional chapters: Chapter 2, 3 and 4 give critical reviews that support the main contribution of this study. Chapter 5 discusses the proposed design framework, Chapter 6 shows the application of the design framework on a reinforced concrete building and post-tensioned concrete box girder, and finally the summary and conclusions of the study are given in Chapter 7.

The organization of this thesis is indicated in ***Figure 1-2***.

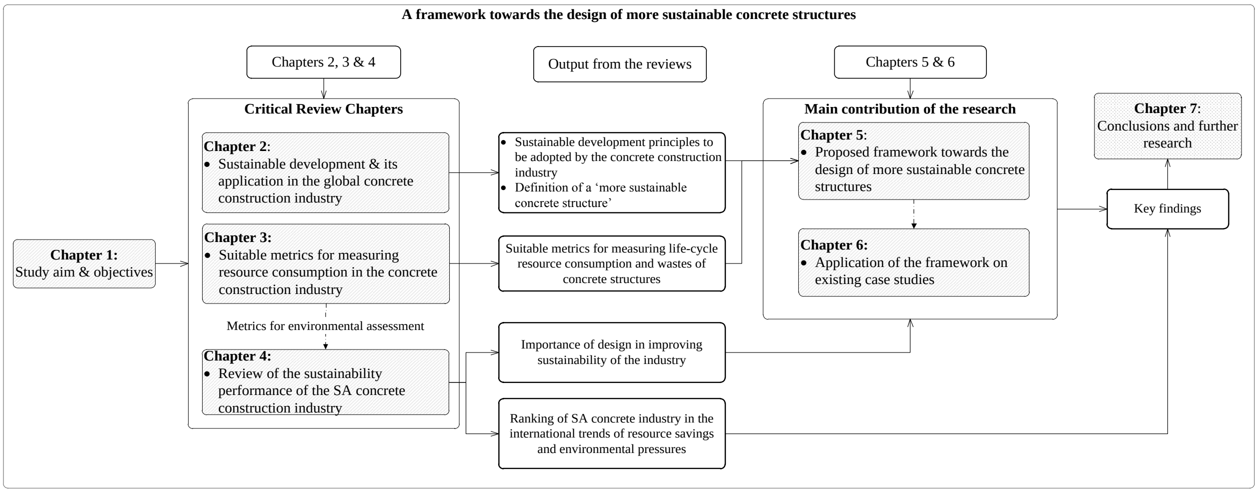

Figure 1-2: *Thesis roadmap.*

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Chapter 2

2 SUSTAINABLE DEVELOPMENT AND ITS APPLICATION IN THE CONCRETE CONSTRUCTION INDUSTRY

2.1 Introduction

Sustainable development is a key concept that is seen as a solution to environmental degradation and economic and social conditions that have an influence on the environment. The concept requires inter-disciplinary efforts to deal with environmental problems such as natural resource exploitation, pollution, and loss of biodiversity caused by economic activities and social conditions such as poverty and affluence. The term 'sustainable development' has a wide range of definitions though it is commonly defined as "…*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, Brundtland Commission, 1987; p.43). This definition has been purposefully put in a general manner to allow the involvement of as many persons, institutions, governments and practitioners including civil engineers, to include the sustainable development concept in decision making. The operational definition of sustainable development in the concrete construction industry is 'sustainable concrete'. There remains a lack of proper definition of the term 'sustainable concrete' to allow for its operationalization. The main contribution of this chapter is to give a working definition of the term 'sustainable concrete structure'.

This chapter begins by giving the history and philosophy behind the term 'sustainable development', its conceptualization into operational models and some critiques of the concept. This is followed by a review of sustainable development principles, such as the 'closed materials cycle', and their application in the context of other industries, and focusing on the concrete construction industry.

2.2 History and philosophical background of sustainable development

2.2.1 Background

Ecological systems (ecosystems) are made up of the earth (physical environment) along with its biosphere[8] and the interactions[9] which take place between them (Jackson *et al.*, 2000; Raven *et al.*, 2008). The physical environment is referred to in economic terms as '*natural capital*' as it provides a

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[8] Biosphere consists of all life on earth and includes autotrophs (e.g. plants) and heterotrophs (animals). The former can synthesize their own food in the presence of sunlight whereas the latter depend on other organisms to obtain their energy for survival (Raven *et al*., 2008).

[9] Interactions of organisms with their physical environment can be either abiotic or biotic (Raven *et al*., 2008).

- *Abiotic interactions* in the biosphere include: carbon-cycle, phosphorus, nitrogen, and water and oxygen-cycle.
- *Biotic interactions* in the biosphere include: migration or predation

number of useful resources that support human well-being[10] and economic development, these include; fossil fuels, minerals, water, land, and living organisms (Daly and Farley, 2004). 'Natural capital' can be classified as renewable or non-renewable (Constanza and Daly, 1992). The former refers to resources that can restock themselves using e.g. solar energy, whereas non-renewable resources exist in finite amounts and cannot be renewed following their depletion. Examples of non-renewable resources include mineral deposits and fossil fuels commonly used in current production processes.

The interconnected and interrelated cyclic pathways (interactions [9]) in the ecosystems, mainly operate off solar energy, and allow for the flow of energy and matter, from the physical environment, and the release of wastes back to the physical environment. As a result of these interactions, the ecosystem has to adjust to changes and attain a state of dynamic equilibrium (Raven *et al*., 2008). Ideally, to sustain a dynamic equilibrium, waste solids and emissions should be kept within the assimilative capacity (*sink capacity*) of the physical environment (Goodland, 1995). In addition, the renewable resources from the ecosystem should be sustained within their regenerative capacity (*yield*) (Goodland, 1995; Huesmann, 2003).

However, since the second half of the 20th Century, many scientists and commentators believe that, anthropogenic (human) activities have changed the earth's climate (IPPC, 2007) and ecosystems (Millennium Ecosystem Assessment, 2005a) more rapidly than at any comparable period of time in human history. In general, human actions that directly and indirectly influence the ecosystems include (Millennium Ecosystem Assessment, 2005b):

(i) Changes in local land use and cover, whereby more land has been converted to cropland in the 30 years after 1950 than in the 160 years between 1700 and 1859. This change in land use is projected to continue increasing up to 2050 due to the expansion of cities and infrastructure;

(ii) Introduction and/or removal of a plant and animal species which leads to loss in biodiversity[11]. A summary of the current threated species is given in the "2012 IUCN Red List" available at: http://www.iucnredlist.org/;

(iii) Technology adaptation which increases resource exploitation but can also lead to increased efficiency in resource production and processing;

(iv) Resource consumption characterized by increased use of e.g. non-renewable resources such as fossil fuels, due to demographic changes and the need for economic development. For example, the global demand for engineering materials (i.e. those used to construct buildings, infrastructure

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[10] Human well-being includes basic material needs, freedom of choice, health, security and good social relations. Together these provide the conditions for physical, social, psychological, and spiritual fulfilment (Millennium Ecosystem Assessment, 2005b).

[11] Biodiversity refers to: "the variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (http://www.iucn.org)

and equipment such as cement, steel, aluminium and thermoplastics) quadrupled between 1960 and 2005 (Allwood *et al*., 2011);

(v) The dependence on non-renewable energy resources (e.g. fossil fuels) in production of goods and services or the processing of e.g. cementitious materials largely contributes to greenhouse gas emissions (GHG)[12]. Increased GHG in the atmosphere can also be attributed to land-use changes whereby the amount of carbon-intake decreases with loss of forest area. As a result, there has been a 39% increase in global greenhouse gas (GHG) emissions from a pre-industrial level (1750) of 280 parts per million (ppm) CO_2, to the 2012 level of 393 ppm CO_2 (Blasing, 2012; http://www.esrl.noaa.gov/gmd/ccgg/trends). Further, by 2100 an increase of atmospheric concentration of CO_2 ranging to between 541 and 970 ppm is projected to occur (IPCC, 2007). This is an increase of 90 – 250% as compared to the year 1750.

These human-induced changes to the environment are expected to continue increasing up to 2050 due to a projected exponential increase in human population. The world's population is currently (2013) estimated at 7 billion, having increased non-linearly in the less developed countries in the past half century (1950 – 2010), but almost linearly in the more developed countries, for the same period, as shown in ***Figure 2-1*** (*http://esa.un.org/wpp/Other-Information/faq.htm*).

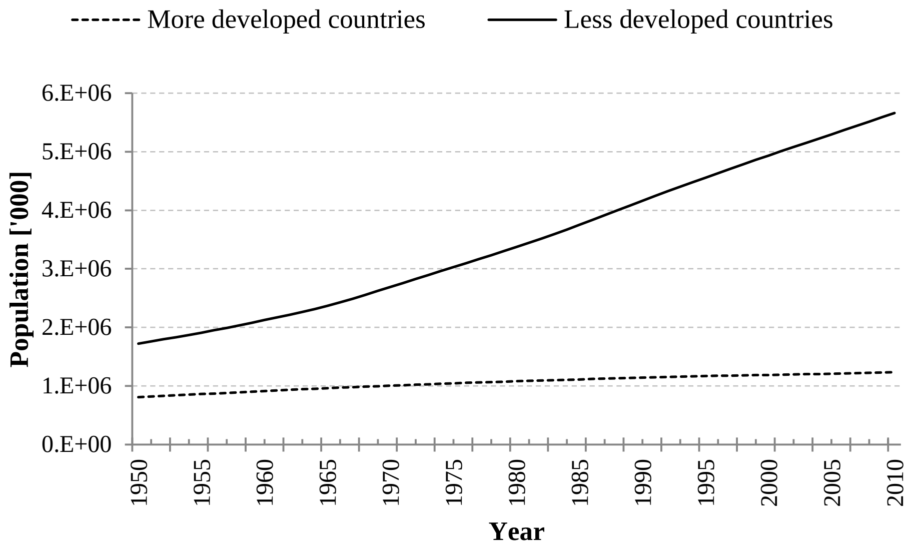

Figure 2-1: *World population (1950-2010) in developed and less developed countries (http://esa.un.org/wpp/Other-Information/faq.htm).*

- (a) More developed regions comprise e.g. Europe, North America, Australia/New Zealand and Japan.
- (b) Less developed regions comprise all regions of Africa, Asia (excluding Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia.

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[12] Greenhouse gases (GHG) include six types of gases, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC's), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (United Nations, 1997)

- In this study, more developed countries are interchangeably referred to as ‘developed’ countries; Northern countries and/or industrialized countries. Similarly, less developed countries are referred to in this study as developing countries or countries in the South.

By 2050, the world’s population is expected to reach 9.2 billion (United Nations World Population Prospects, 2006). Similar to the past, most of this population growth will occur in the developing countries (increasing from 5.4 to 7.9 billion) (De Sherbinin *et al*., 2007).

A high population signifies a high level of resource consumption and associated pollution. Currently, there are inequitable patterns of resource consumption between the more developed countries, with linear population growth, and less developed countries with exponential population growth. Even though there has been a fourfold increase of engineering materials consumption for the period 1960 to 2005 (Allwood *et al*., 2011), which is currently estimated to range between 50 and 60 billion tonnes (Gigatonnes) per year (Krausmann *et al*., 2009; Behrens *et al*., 2007), 75% of this consumption has occurred in the more developed countries (Hart, 1996). Further, the increased use of resources has led to accumulation of pollution gases and solid wastes. Current GHG emissions are estimated at 393 ppm compared to the pre-industrial level (1750) of 280 ppm. Again, approximately 70% of these pollution levels have been generated by developed countries due to their increased production activities and use of fossil fuels in their manufacturing processes (Roseland, 2000; Preston, 1994). The main environmental degradation occurring in developing countries is change in land-use cover from forest land to agricultural and fuel energy use, and is caused by rapid population growth and poverty (De Sherbinin *et al*., 2007). However, developing countries require resources to transition to economies that can provide better livelihoods for their growing populations. It is questionable whether the present levels of consumption in the developed countries, that are generally understood as development, can be generalized to developing countries, much less to future generations, without destroying the ecological resources and sinks on which economic activity depends (Goodland and Daly, 1996).

Evidence that the natural capital is being degraded based on past consumption patterns are illustrated using various concepts. The ‘peak oil’ concept by Hubert (1956) is one such concept that estimates the pressure on oil reserves due to mankind’s dependence on fossil fuels. The peak oil curve is ‘bell-shaped’ and is used to predict the time when the world oil reserves will peak. It is shown that before the peak, production prices for the commodity are low and the reserves are sufficient to meet demands. Subsequent to the peak, increasing energy demand for economic development is expected to bring about diminished oil reserves (recurrent fuel shortages) coupled with a rise in the cost of oil production. The peak oil concept can be extended to show the depletion of other non-renewable resources such as coal and bulk mineral ores and aggregates used in construction.

In response to the environmental pressures (e.g. resource depletion and GHG emissions) due to increased anthropogenic activities, sustainable development has emerged as a guiding paradigm to create a new way of making decisions and doing things globally. Sustainable development requires that relative to their respective demographic bases, each generation bequeaths to its successor a constant stock of resources as great as that which it inherited from its predecessor (Dasgupta, 2007). There are two schools of thoughts that examine the interpretation of sustainable development based on this condition (Roseland, 2000): (i) '*strong sustainability*' and (ii) '*weak sustainability*'.

The first school of thought is by Malthus (1798) which is the earliest written evidence on the influence of population growth on the degradation of the physical environment. He showed that under optimum conditions, any biological population including that of humans has the capacity to increase exponentially, and hence put pressure on the earth's finite resource base and 'sink capacity' (Goodland, 1995). Adherents of Malthus (1798) (or Neo-Malthusians as they are usually referred) include Ehrlich (1968) and 'the Club of Rome'. The latter is an international association, which published "*The limits to growth*" (Meadows *et al.,* 1972) that argued that unchecked consumption of the earth's finite resources and emissions from industry and agriculture would have a significant influence on global economic developments in the 21st century. Ehrlich (1968) published "*The population bomb*" which showed the relationship between population growth, resource availability and environmental deterioration. Neo-Malthusianism recognizes that the earth's resources are finite and that increasing demands are placed on these resources by the growing human population and its expanding economies. They show the need to limit population growth by e.g. formulating public policies that will facilitate a reduction in birth rate in order to control the impact of population growth on the environment. In addition, Neo-Malthusianism advocate for 'steady-state' growth of national economies, a concept introduced by Daly (1992). The steady state growth theorem emphasises the need to maintain critical levels of natural resource stocks for future generations. The main draw-back of Neo-Malthusianism is that it does not show the importance of technological improvement, the role of social and cultural traits (e.g. change in consumer behaviour), and economic systems (e.g. law of supply and demand) as short-term solutions that influence resource conservation and pollution reduction (De Sherbinin *et al*., 2007). Technological innovations facilitate continued resource consumption for economic development through a number of ways. Firstly, they increase resource production and processing efficiency which in turn results in resource conservation as fewer natural resources are utilized in production processes. Secondly, they allow for the exploration of additional reserves of non-renewable resources such as fossil fuels, and the exploitation of alternative sources of natural resources. Lastly, they allow for the development of substitutes for natural resources and increased recycling of wastes.

The Neoclassical economic growth theory by Solow (1974) represents the second school of thought, 'weak sustainability' with regard to the interpretation of sustainable development. It distinguishes between three classes of capital: natural capital (renewable and non-renewable resources); human capital (acquired knowledge and skills that individuals bring to productive activity) (Roseland, 2000) and; manufactured capital (tools and infrastructure). The Neoclassical economic theory argues that scarcity in natural capital due to its increased use will drive technological progress which in turn will lead to increased efficiency in the use of scarce resources. The theory counts upon technological progress to ensure infinite substitution possibilities of natural capital with human or manufactured capital in order to mitigate all 'scarcity/limits' constraints (environmental sources/sinks) (Turner *et al*., 1993). However, substitution has inherent limitations (Pearce *et al*., 1989):

- There are irreversible losses that occur when biodiversity is lost i.e. when a plant or animal species becomes extinct, it cannot be recreated.
- Some forms of natural capital are non-substitutable e.g. the ozone layer cannot be recreated with manufactured or human capital once depleted
- There exists uncertainty on the reliability of future technological advances to allow for the substitution of different types of capital. This is caused by limited understanding of the life-supporting functions of natural capital.
- Economic inequity within human populations causes the less affluent populations to be more vulnerable to degraded environments than the rich.

The two disparate schools of thought: (i) that the earth has ecological limits or, (ii) that technological progress will ensure infinite substitution possibilities capable of mitigating all 'scarcity/limits' constraints, have been referred to as the '*strong sustainability*' and '*weak sustainability*' concepts, respectively. The strong sustainability concept refers to Neo-Malthusianism and avers that human-made capital is not substitutable to natural capital, whereas weak sustainability avers that manmade capital through technological advancements can be used as a substitute for natural capital. In view of both opinions, one cannot limit resource consumption as developing countries are faced with need for resources to raise living standards of their exponentially growing human population. In essence, developing and developed countries should recognize ecological constraints as advocated for by the views of 'strong sustainability' and develop technologies and substitutes that can assist in economic growth within these limits. This as explained later in this Chapter, involves the adoption of ecological principles requiring that waste solids and emissions (e.g. CO_2) be kept within the assimilative capacity (sink capacity) of the physical environment (Goodland, 1995). In addition, the renewable and replenishable resources from the ecosystem should be sustained within their regenerative capacity (yield), and the exploitation of non-renewable resources should be such that their rate of depletion does not exceed the rate of creation of renewable substitutes (Daly, 1990; Goodland, 1995; Huesmann, 2003).

In summary, increased anthropogenic activities have interfered both directly and indirectly with ecosystems. These interferences in some of the ecosystems, that are increasingly driven by population growth, have raised questions regarding the sustenance of the dynamic equilibrium within the ecosystems due to issues such as environmental degradation (resource depletion, deforestation, pollution), economic disparities and social inequality (poverty) (Goodland, 1995). Sustainable development recognizes the need to preserve natural ecosystems that humanity is so dependent on by using natural resources with greater efficiency and controlling GHG emissions. Through sustainable development, the promotion of human well-being does not have to depend on the destruction of nature but is carried out within the ecological capacity of the earth. In order to apply the concept of "sustainable development" in the context of this study, there is a need to first gain a basic understanding of the concept by reviewing its historical and philosophical background.

2.2.2 Brief history of the term 'sustainable development'

The term 'sustainable' belongs originally to the field of ecology, referring to an ecosystem's potential for subsisting over time, with almost no alteration (Jabareen, 2008). The original application of the term 'sustainable' has been defined as '*ecological sustainability*' (Lélé, 1991; Hardoy *et al*., 1992) and has since been expanded to include concepts such as: '*social sustainability*' describing social conditions such as health and adequate housing protected from environmental hazards, that are necessary to support 'ecological sustainability'; '*economic sustainability*', which refers to the sustenance of economic growth whilst maintaining productive assets including natural capital and; '*cultural sustainability*', which refers to the preservation of traditional knowledge of relevance to the sustainable use of natural resources (Hardoy *et al*., 1992).

The addition of the term 'development', defined as 'a gradual unfolding' in the Oxford and Webster dictionaries, shows the dynamic nature of the term that keeps changing with time depending on the global conditions with respect to human needs.

Hence, the term 'sustainable development' is used to refer to the ability of both the ecosystem and human interaction with the physical environment to subsist over time.

The concept of sustainable development was first highlighted by Rachel Carson in 1962 in her book "*The silent spring*" on environmental degradation, which showed the limits of the earth's sink capacity in absorbing chemicals from pesticide use. Similar publications by Ehrlich (1968) on human overpopulation and Meadows *et al*. (1972) expressed views on the ecological crises that would emanate from over-consumption of the earth's resources. However, it was only after the latter publication that the sustainable development concept gained international interest.

Figure 2-2 shows how the ‘sustainable development’ concept has progressed with time in major international conferences and summits organized by intergovernmental and non-governmental organizations.

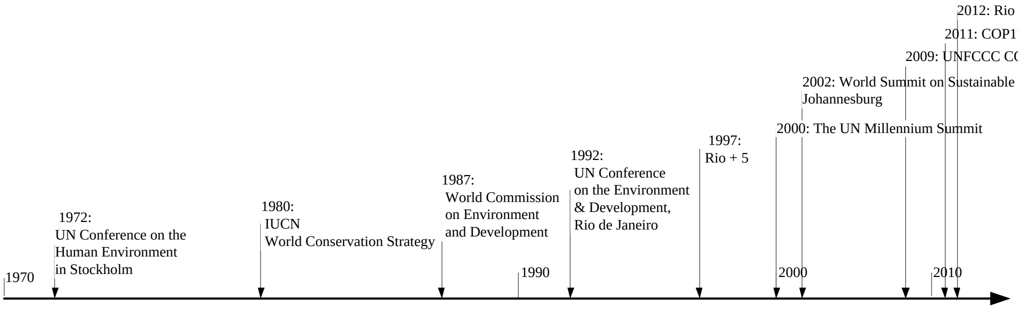

Figure 2-2: *Timeline of international meetings on ‘sustainable development’ (Reference: this study).*

COP – Conference of the Parties; UN – United Nations; CMP – COP serving as Meeting of the Parties;
UNFCCC – United Nations Framework Convention on Climate Change; IUCN – International Union for Conservation of Nature

A comprehensive review of the evolution of the concept of ‘sustainable development’ is given in Mebratu (1998). This review serves as a summary of the chronological development of ‘sustainable development’ since its conception.

One of the earliest attempts to address the relationship between economic development and environmental degradation in a global context took place at the United Nations (U.N) Conference on the Human Environment, held in Stockholm in 1972 (http://www.un.org/geninfo/bp/envirp2.html). However, the first mention of the term ‘sustainable development’ in a publication was made in the *World Conservation Strategy* (IUCN[13] /WWF[14]/UNEP[15], 1980) which stated that sustainable development:

> ‘*… must take account of social and ecological[16] factors, as well as the economic ones; of the living and non-living resource base; and of the long-term as well as the short-term advantages and disadvantages of alternate action”*’ (IUCN/UNEP/WWF, 1980).

The World Conservation Strategy recognized the importance of living resource conservation through application of three of its basic principles: sustainable utilization of species and ecosystems, maintenance of essential ecological processes and life-support systems, and preservation of genetic diversity (Pezzy, 1989; Robinson, 2004). As an environmental conservationist organization, the International Union for Conservation of Nature (IUCN) was accused of being more concerned in

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[13] IUCN – International Union for Conservation of Nature and Natural Resources
[14] WWF –World Wildlife Fund
[15] UNEP – United Nations Environmental Programme
[16] Ecological – is an adjective describing ecology (the relationship between organisms and their environment).

conserving natural resources rather than addressing the developmental needs of the human race, per se (Mitlin, 1992). In addition, the strategy was unable to address social factors relating to international economic and political order, war, population and urbanization (Khosla, 1987 *as cited in* Lélé, 1991). This focus on ecological concerns is still evident in the Northern countries, and is attributable to the large consumption in resources and pollution in these countries, due to industrial societies and urbanization (Redclift, 1990). The 'environmental ('green') agenda' in the Northern countries focuses on how present environmental constraints such as global warming can be overcome while maintaining the standard of living (Mitlin, 1992). The 'brown' agenda i.e. the need for development, of ensuring that all people in the world might obtain the resources they need for survival and development, is ignored or given little attention (Mitlin, 1992). Thus, the IUCN definition of 'sustainable development' recognized the links between economic development and environmental conservation, but did not succeed in integrating them into actual plans for economic development.

Following the IUCN report came the realisation by many governments that sustainable development would not be achieved without certain social and economic changes such as a reduction in poverty levels and greater equity in resource distribution, both within current generations (inter-generation) and between future generations (intra-generation) (UNEP Nairobi Declaration, 1982). For this reason, the World Commission on Environment and Development (WCED) was initiated by the General Assembly of the United Nations in 1983. The WCED had its first conference in 1987 which was chaired by then Prime Minister of Norway, Gro Harlem Brundtland, thus earning the name the Brundtland Commission. In their report, "*Our Common Future*" (WCED, 1987), the Brundtland Commission came up with the most universally quoted definition of sustainable development:

> '*…development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED, Brundtland Commission, 1987; p.43).

This definition has been purposefully put in a general manner to allow the involvement of as many persons, institutions, governments and practitioners, to include the sustainable development concept in decision making.

The WCED (1987) definition of sustainable development identifies multiple goals of sustainable development that can be applied to any economic activity. These goals include: environmental protection, economic growth and social equity, which are also described as the triple-bottom line.

(a) Environmental sustainability

An environmentally sustainable system maintains a stable resource base, avoiding over-exploitation of renewable resource system or environmental sink function, and depleting non-renewable resources only to the extent that investment is made in adequate substitutes. This includes maintenance of biodiversity, atmospheric stability, and other ecosystem functions not ordinarily classed as economic resources (Goodland, 1995; Harris, 2000).

(b) Economic sustainability

An economically sustainable system must be able to produce goods and services on a continuing basis, maintain manageable levels of government and external debt, and avoid extreme sectoral imbalances which damage agricultural or industrial production (Harris, 2000).

(c) Social sustainability

The social sustainable system aims at achieving a fair allocation of resources and opportunities, an adequate provision of social services including health and education, gender equity, and political accountability and participation (Goodland, 1995; Harris, 2000).

The multiple goals represent areas which should be taken into consideration in decision making for sustainable development to occur. The three dimensions are directly related and require to be integrated simultaneously in decision making. Thus, the WCED's definition of 'sustainable development' accentuates the need to sustain the earth's resources, promote human development and alleviate poverty simultaneously.

A variety of models have been developed in an attempt to present and capture the interactions between the dimensions of sustainable development (i.e. the environment, economy and society). These include the inter-locking rings model and the nested rings model as illustrated in ***Figure 2-3***. The models are not only limited to the 3 dimensions included in ***Figure 2-3*** but can be extended to include additional dimensions of sustainable development such as 'culture' and 'politics'.

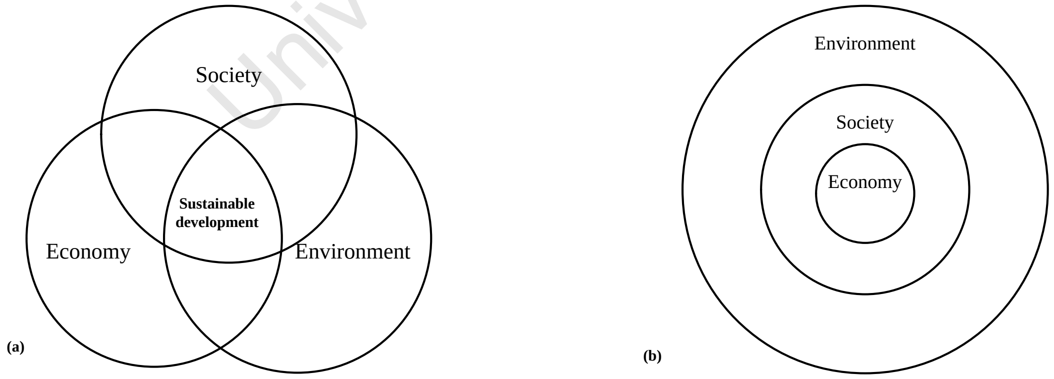

Figure 2-3: *(i) Inter-locking rings model (ii) Nested rings model (Mebratu, 1998).*

(i) *Inter-locking ring models*

The inter-locking rings model shows equal sized rings in a symmetrical interconnection. This shows each of the sustainable development dimensions as independent from each other, although they have some areas that overlap. The interaction of the three different dimensions represents the solution area for sustainable development (Mebratu, 1998).

The interlocking rings model assumes the three key dimensions for sustainable development (*environment*, *economic* and *social sustainability*) to be separate and independent from each other (Mebratu, 1998), and of equal importance. However, the dimensions influence each other e.g. the economy depends on the environment for provision of raw materials and for environmental preservation to occur, poverty needs to be alleviated. Hence, the inter-locking rings model risks approaching and tackling issues of sustainable development in a compartmentalized manner (Mebratu, 1998; Giddings *et al*., 2002).

The inter-locking rings model represents a '*weak sustainability*' approach to sustainable development, in that it advocates for trade-offs between the three spheres that represent: physical capital (infrastructure), human capital (e.g. education) and natural capital (Rees and Wackernagel, 1995; Gutés 1996). The model assumes that a reduction in one of the dimensions e.g. environmental degradation can be compensated for by improvement of another e.g. economic growth.

(ii) *Nested rings models*

In the nested model, the 'economic' and 'social' spheres are portrayed as dependent on the 'environmental' sphere (Rees and Wackernagel, 1995). This implies that social and economic development can only take place upon the availability of environmental resources such as raw materials and energy. Hence, the importance of ensuring that all activities are carried out within the ecosystem's 'source' and 'sink' functions.

The nested-rings model shows that the dimensions making up the earth's economic productive base (i.e. physical, human and natural capital) cannot be substituted with each other hence it advocates for '*strong sustainability'*.

In summary, there are inter-linkages between the different dimensions of sustainable development, presented by the WCED (1987) definition of sustainable development, which can evidently not be ignored when conceptualizing the term. The nested rings model best represents these inter-relationships. However, the model is over-simplified as it does not depict the diversity of the world: rich and poor nations (Giddings *et al*., 2002). Developing countries need to cater for other needs and hence at best can look at substituting natural capital using technology.

In 1992, the United Nations Conference on the Environment and Development (UNCED), also known as the Earth Summit (http://www.un.org/geninfo/bp/envirp2.html), took place in Rio de Janeiro, Brazil to evaluate the progress made on environmental policy 20 years after the Stockholm conference. The conference provided an understanding of the link between the earth's environmental problems and economic development (Brandon and Lombardi, 2005). Further, it showed that the economic development must not be deleterious to the environment in the long-term for both the North (perceived as wealthy) countries and South (perceived as poor) countries (Redclift, 2006; Brandon and Lombardi, 2005). In addition, the Earth Summit sought to create global partnerships between developed and developing countries through various declarations and guidelines, these include (Brandon and Lombardi, 2005): the Agenda 21, the United Nations Framework Convention on Climate Change (UNFCC), the Rio declaration on Environment and Development, the Statement of Principles on Forests, and the Convention on Biological Diversity.

(a) *The Agenda 21*

This is a programme of actions demanding new ways of investing into our future to reach global sustainability in the 21st Century. The Agenda 21 (1992) is also referred to as a "blueprint for sustainable development" and contains over 100 programme areas for global, national and local action, ranging from trade and environment, through agriculture and desertification to capacity building and knowledge transfer. The Agenda 21 (1992) has its focus on the reduction of economic disparities and poverty.

The Agenda 21 (1992) is divided into four sections: (i) social and economic dimensions, (ii) conservation and management of resources for development, (iii) strengthening the role of major groups, and (iv) means of implementation. In particular, the 7th Chapter: "*Promoting sustainable human settlement development*", in the first section of Agenda 21 (1992) was devoted to promoting sustainable construction industry activities.

(b) *The United Nations Framework Convention on Climate Change*

The United Nations Framework Convention on Climate Change (UNFCCC) was introduced to address the impacts of climate change by stabilising greenhouse gas[17] concentrations in the atmosphere at levels that will not upset the global climate system (http://unfccc.int/ kyoto _protocol /items/2830.php). The UNFCCC encouraged the Annex I (industrialized) countries to stabilise GHG emissions and initiated the development of the Kyoto Protocol which is a "cap[18]-and-trade" system that sets emission reduction targets (Kyoto Protocol, 1998). Under the Kyoto Protocol, 190 of the world's industrialised nations committed themselves to reducing their CO_2 and other greenhouse gas emissions by 5% below their 1990 levels by 2008 and 2012. South Africa, as a Kyoto Protocol non-Annex I country, is not required to reduce its emission of GHGs

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[17] Greenhouse gases include: Carbon dioxide ($C0_2$); Methane (CH_4); Nitrous oxide (N_20); Hydrofluorocarbons (HFCs); Perfluorocarbons (PFCs) and; Sulphur hexafluoride (SF_6);

[18] Cap – refers to a restricted upper limit.

during the first commitment period (2008 – 2012). However, climate change is a global problem that needs to be dealt with by all nations.

The countries involved in the Kyoto Protocol are required to implement policies and measures that enhance amongst other GHG stabilization measures, energy efficiency in relevant sectors of the national economies (Kyoto Protocol, 1998). For example, Germany has an energy strategy: 'Energiewende' which seeks to phase out nuclear power and use of fossil fuels, by advancing the country's renewable sources of energy e.g. solar and wind energy and also improving its efficiency in energy use. The German government gives subsidies to private investors to allow for full substitution between fossil fuels and renewable energy sources (http://www.bmu.de/en/topics/climate-energy/transformation-of-the-energy-system/general-information/).

In addition, Annex I countries are required to protect and enhance 'carbon sinks' through the promotion of sustainable forest management practices such as afforestation, and the implementation of carbon dioxide sequestration technologies which capture carbon dioxide from production plants e.g. cement kilns or power plants and then store it in the earth's surface or in the ocean. Three mechanisms are available to Annex I countries, to enable them reduce the costs of achieving emission targets outside the country's boundary. These are (http://unfccc.int/kyoto_protocol/items/2830.php): (i) International emissions trading; (ii) The clean development mechanism (CDM) and; (iii) Joint implementation.

- *Emissions trading* allows countries that have emission units to spare (i.e. emissions permitted them but not "used") to sell this excess capacity to countries that are over their targets (http://unfccc.int/kyoto_protocol/items/2830.php). However, for this mechanism to be in operation there has to be a market to trade emissions. Hence, such a market has a high risk of failure in case there are no 'buyers' or 'sellers'.
- *The CDM* allows Annex-I countries and companies to initiate and finance sustainable development projects in developing countries to reduce GHG emissions. An example of such a project would be the implementation of a rural electrification program using solar cells. Hence, the CDM mechanism in turn allows non-Annex I countries to contribute to the ultimate objective of the Convention (Kyoto Protocol, 1998).
- Under *the joint implementation*, Annex-I countries earn emission reduction units by initiating and implementing emissions reduction projects in non-annex I countries.

Subsequent Conferences of the Parties (COP) to Kyoto Protocol include the Copenhagen climate negotiations, in 2009, the combined 17th Conference of the Parties (COP17) to the United Nations Framework Convention on Climate Change (UNFCCC) and 7th Session of the

Conference of the Parties serving as the Meeting of the Parties (CMP7) to the Kyoto Protocol (COP17/CMP 7) held in Durban, South Africa in 2011. In the latter conference, China, a developing country, but which also emits majority of global GHG emissions, agreed to work towards the universal legal agreement on climate change before 2015.

(c) *The Rio Declaration on Environment and Development*

This contains a statement of 27 principles to guide the integration of environment and development policies by national governments. The principles address concerns on pollution, poverty, women's rights, and the importance of developed nations' support to developing nations' economic progress.

(d) *The Statement of Principles on Forests*

This was the first global consensus on the management, conservation and sustainable development of the world's forests.

(e) *The Convention on Biological Diversity*

This is a legally binding agreement between participating countries to undertake national and international measures to achieve three objectives (Hens and Nath, 2005): conserve the world's genetic species and ecosystem diversity; undertake sustainable use of its components and; share the benefits of its use in a fair and equitable way.

Amongst the five sets of agreements signed at the Rio conference, the Agenda 21 and the UNFCCC have played a role through which the sectors of an economy, including the construction industry, can commit themselves to promoting sustainable development.

Subsequent to the Rio conference was the 19th Special Session of the UN General Assembly (Rio + 5) in 1997 and the World Summit for Sustainable Development (WSSD) in Johannesburg, South Africa (2002) both of which were intended to review the 5 and 10 year progress, respectively, made following the 1992 Rio Earth Summit (Edwards and Orr, 2005). In WSSD it was confirmed that environmental degradation had worsened since the Rio Summit of 1992. Hens and Nath (2005) noted that during 1990 and 2000 global carbon emissions had grown by an average of 9.1% and the earth's forests had disappeared at a rate of 14.6 million hectares annually, while the proportion of coral reef loss due to human activities had increased from 10% in 1992 to 27% in 2000. To sum up, the practical implementation of the agreements made in the Rio conference had failed to materialise. As a result, the WSSD agreed to take a more effective action plan by reaffirming the full implementation of the "Agenda 21" and the Rio principles for sustainable development. The outcomes of the WSSD conference included a Plan of Implementation and the Johannesburg Declaration on Sustainable Development. The former designed a means of acting on the topics discussed at the Earth Summit, such as poverty eradication, consumption and production issues and health concerns. The

Johannesburg Declaration emphasized the current issues facing the world community and the significance of multilateralism and practical implementation of the strategies (Edwards and Orr, 2005).

In 2000, the Millennium Summit, gave a summary of the agreements and resolutions made in the UN world conferences held for the past 10 years since 1990 (Hens and Nath, 2005). The Summit then identified key global objectives to be met in the 21st Century. These include: (i) Peace and security; (ii) Development, including poverty eradication; (iii) Environmental protection; (iv) Human rights; (v) Protecting the vulnerable populations and; (vi) Strengthening of the United Nations to attain the aforementioned objectives (UN General Assembly, 2000). The outcome of the Summit was the Millennium Declaration, which set out an international agenda for the 21st Century: the Millennium Development Goals are detailed in http://www.unmillenniumproject.org/reports/goals_targets.htm.

Global sustainable development initiatives subsequent to this include the United Nations Conference on Sustainable Development (Rio + 20) in 2012. This conference addressed two main themes (http://www.uncsd2012.org/):

- The transition to ‘green economies’ in the context of sustainable development while focusing on poverty eradication. The concept of a ‘green economy’ was aimed at providing a response to the multiple crises facing the world i.e. over-exploitation of natural resources, climate change, economic crisis and poverty. It aimed to establish how to use the natural resources available to help promote growth while protecting the earth’s ecosystem.
- Reforming the UN Institutional Framework for Sustainable Development (IFSD) to create a solid basis from which to support and coordinate the implementation of sustainable development policies (Beisheim and Dröge, 2012).

In addition, the Rio + 20 noted that considerable progress had been made towards the achievement of some Millennium Development goals such as access to improved water. The goals of Agenda 21 on ozone protection, reduction in marine pollution and lead poisoning had also been met. However, little progress had been made towards the abatement of human-induced climate change, degradation of natural capital, desertification and loss of biodiversity.

2.2.2.1 *Contribution of this study to sustainable development*

Through the above review of the key international conferences on sustainable development it has been shown that the ‘sustainable development’ concept addresses concerns over the environment, and economic and society conditions such as poverty alleviation. Since the 1980’s to present (2014) the concept has expanded to not only include concerns for natural resource preservation but include equitable growth where social objectives such as poverty reduction are recognized to be as important as economic development.

In summary, a review has been made on the global conferences on sustainable development. The main themes of each of the conferences were given and the outcomes in terms of international agreements were noted. In particular is the theme of current conferences such as that by Rio + 20 on promoting a "green economy". In the context of this study, it is useful to show how the outcome of the study can contribute towards sustainable development. For example, it is envisaged that one of the main objectives of the study is the development of a framework for design that aims to bring about energy and resource efficiency in the concrete construction industry and hence enable "green growth". In addition, the proposed framework encourages the practitioner of structural concrete to use alternative or marginal materials. These materials are sourced locally using a local labour force, and hence enable the creation of a secondary materials industry for salvaged materials and recycled aggregates manufacturers.

2.2.3 Critique of the term 'sustainable development'

The term "sustainable development" has been found to have the following inherent limitations:

(a) *Ambiguity or vagueness of the definition*

The most commonly quoted definition of sustainable development by WCED (1987) was kept deliberately vague in order to include widely disparate parties. As a result there have been a number of alternative definitions to the term, "sustainable development" leading to the term being considered vague or ambiguous (Mebratu, 1998). In 1989 there were over 50 different definitions and interpretations of sustainable development, a list of which is given in Pezzey (1989). The various definitions differ as to whether it is the 'environment' or 'economic growth' that needs to be sustained.

(b) *Greenwashing*

The absence of a clear definition of the term 'sustainable development' has led to '*greenwashing*' whereby a service or product is branded 'green' for purposes of e.g. marketing, project procurement or for projecting a false corporate image (Najma, 1999; Greenpeace (stopgreenwash.org)). For example, in the construction sector there has been the aspect of "*greenwashing*" in eco-labelling[19] schemes whereby some construction products are termed sustainable with no indication of the amount of, for example, renewable and non-renewable energy used in their production. To deter this practice, techniques such as life-cycle assessments (see Chapter 3) have been developed for use in quantifying resources and wastes generated over the life-cycle of a product. It is essential to select a suitable metric(s) for decision making that shows the progress made towards sustainable development for any

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[19] Ecolabelling is a practice of assigning a 'green label' to a product to show that it has met certain criteria or is 'environmentally friendly'

particular product or system. A review of the different metrics used under the life-cycle assessment methodology is given in Chapter 3.

(c) *Dynamic nature of sustainable development*

There lacks a time-frame over which development is to be sustained. This presents difficulties especially when setting benchmarks (targets) for the achievement of sustainability. For these reasons the ‘sustainable development’ concept should be considered as an on-going process rather than a fixed goal. Thus, the emphasis should be placed on preserving the resilience and dynamic ability of ecosystems to adapt to change rather than conservation of some ‘ideal’ static state (Munasinghe, 1993).

2.3 The concept of sustainable development as applied to the concrete construction industry

2.3.1 Importance of sustainable development in the concrete construction industry

The importance of ‘sustainable development’ to the concrete construction industry relates to the fact that concrete has a high environmental burden due to the volume of concrete used worldwide. Aforementioned, in Chapter 1, the worldwide consumption of concrete has increased from 6.4 billion m^3 in 1997 (Aïtcin, 2000) to about 8 billion m^3 in 2009 (CEMBUREAU, 2009). This amount will continue to increase particularly in the developing countries due to exponential increase in population growth (***Figure 2-1***), urbanisation, and economic growth (Scheubel and Nachtwey, 1997; Humphreys and Mahasenan, 2002). However, while concrete production continues to grow and contribute towards economic development around the world, evidence suggests that this growth is associated with escalating impacts on the environment and society. Firstly, cement production and aggregate extraction and processing may lead to loss of arable/forestland coupled with the loss of bio-diversity, waste generation and resource depletion. (Uher, 1999; Alexander and Mindess, 2006; Cheng *et al*., 2006). Secondly, quarrying and construction activities may affect the society negatively due to the noise and air pollution that arise during the blasting of aggregates at the quarry/construction sites, transportation of materials and repair activities which also lead to user inconveniences. Thirdly, cement, the key constituent in concrete is energy intensive and accounts for 5-8% of global anthropogenic CO_2 emissions (WBCSD, 2002; Damtoft *et al*., 2008) as well as significant levels of SO_x, NO_x, particulate matter and other pollutants (USEPA, 1999). Lastly, concrete produces massive inert waste through construction and demolition activities. A comprehensive review of the environmental impacts of concrete are covered in Chapter 4. It is clear that if no action is taken, an increase in concrete production with time will cause an escalation of concrete’s environmental damage through depletion of natural resource base and pollution.

The sustainable development concept can be applied to the concrete construction industry to attempt to ensure that activities within the industry are carried out within the ecological capacity of the earth.

While there is little consensus about the definition for ‘sustainable development’, there are certain commonly accepted principles and practices that can nonetheless be used to guide sustainable development. ‘Principle’ as defined by the Oxford dictionary refers to ‘a *fundamental truth or a general doctrine that is used as a basis for reasoning or action*’. Sustainable development principles range from the views of International organizations such as the United Nations as detailed in International agreements such as the Agenda 21 agreed upon at the United Nations Conference on Environment and Development held in 1992 (***Figure 2-2***) to ones given by environmental groups and individuals such as the ‘cradle-to-cradle’ principles for sustainable design which were formulated by Michael Braungart and William McDonough (Braungart and McDonough, 2002). This set of principles can be used to operationalize the concept of sustainable development on different scales from government level when passing legislation and formulating policies to practitioners at local level institutions or businesses during decision making.

The subsequent section gives a review of principles that can be applied to the concrete construction industry in general.

2.3.2 Sustainable development principles for the concrete construction industry

2.3.2.1 *Circular materials design model*

Some of the negative anthropogenic activities on the physical environment, such as resource depletion, can be attributed to the current economic system model which follows a linear structure (Doppelt, 2003) as illustrated in ***Figure 2-4***.

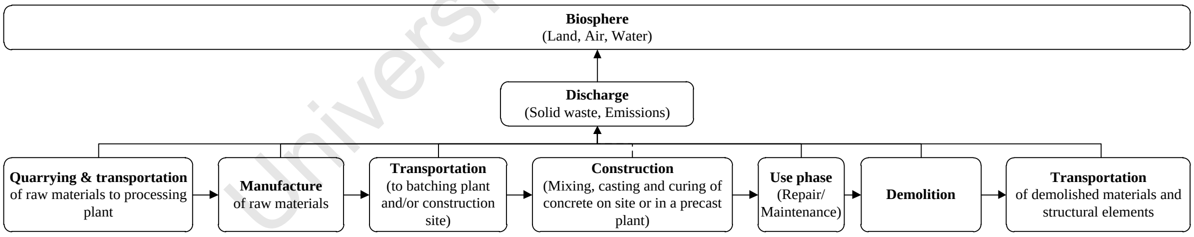

Figure 2-4: *Linear model applied in the life-cycle of a construction material (adapted from: Turner et al., 1993).*

The economic system model views the production of products and services as a linear progression, from extraction of materials to their final disposal into land-fills. Using the linear model, natural resources are extracted from the physical environment and refined into raw materials that are then re-manufactured into consumer products based on mainly cost and time-efficiency considerations and occasionally on quality. The latter point in this case refers to construction management skills that control the workmanship and curing of a concrete structure. Such construction practices determine whether additional materials will be consumed for repair and maintenance during the structure’s service life. Notwithstanding, a high quality may result in overconsumption of resources (materials and labour costs). Thus a balance has to be struck between the three bases of the economic systems model: time, cost and quality in order to avoid over- or under-consumption of resources.

The linear model makes the assumptions of infinite natural resources and hence may lead to their overexploitation and inequality in resource distribution between current and future generations. In addition, the linear model gives little thought if any to the discharge of waste products and emissions to the biosphere. In particular the generation of construction and demolition waste (C&DW) has increased substantially. C&DW refers to the non-hazardous waste resulting from the construction, remodelling, repair and demolition of structures (Macozoma, 2006). South Africa produces 5 to 8 Million tonnes per year of C&DW, 15% of which is from concrete construction (Macozoma, 2001). Of the total C&DW generated per year only 25% is recycled and the rest is disposed of by land (landfill sites, illegal dumps or backfills) (CSIR, 1991). Australia generates 13.7 Million tonnes of C&DW per year, 81% of which is concrete waste, whereas Japan generates only 0.75 Million tonnes of C&DW annually, of which 98% is recycled (Tam, 2009). In the global setting, approximately 1 billion tonnes of C&DW are generated yearly (Katz, 2004).

Growing demands for resource conservation and recycling due to scarcity of landfill capacity or sites, present considerable challenges not only to the concrete construction industry but to all large solid waste emitting industries. These challenges can be partially addressed through the adoption of the circular model, illustrated in ***Figure 2-5***. The circular model is a biomimetic (life-imitating) approach that borrows from ecosystem cycles which operate off solar energy, and allow for the flow of energy and matter, from the physical environment, and the release of wastes back to the physical environment.

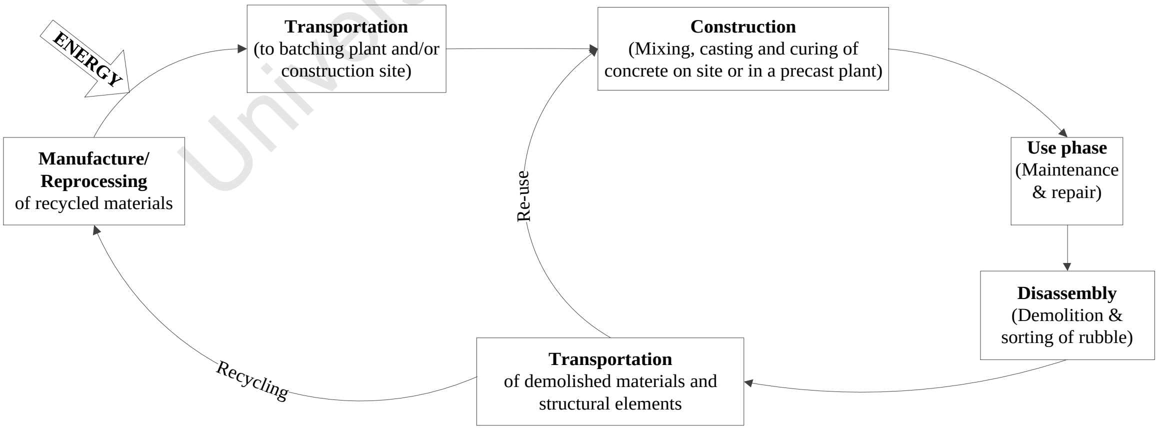

Figure 2-5: *Circular (or closed-loop) model applied in the life-cycle of construction material (Adapted from: Allenby, 1992)*

The circular model is also referred to as the ‘cradle-to-cradle’ approach to design by Braungart and McDonough (2002). The model encourages the designer to rethink ways the design product can relieve the environmental burden from waste disposal and also reduce the extraction of virgin materials. Following the circular model, economic activities including construction aim at utilizing wastes produced from all production processes as substitutes for natural resources. Waste management mechanisms that are available in a circular model include the biodegradation, reuse and/or recycling of wastes.

Biodegradation of wastes as explained in Braungart and McDonough (2002) involves the design of materials for the purpose of biodegradation and the absence of toxic substances after their useful life.

A product can also be designed for adaptive reuse. In this case the reuse of a structural component or material can be achieved if the structural engineer considers beforehand the possible changes in use of the structure, and designs the structure for adaptability. E.g. a building may be designed to have a flat slab, that avoids the use of beams to make it adaptable to different functions in future other than the one it was originally designed for.

Furthermore, C&DW can be recycled using two different processes (Calkins, 2009):

- Up-cycling – which occurs when C&DW is remanufactured to produce value added products e.g. the use of demolished waste for cement manufacture (Schepper *et al*., 2013) or as aggregates in concrete (Hansen, 1992; Olorunsogo and Padayachee, 2002; Kutegeza and Alexander, 2004).
- Down-cycling – which occurs when a material is used in low-grade applications due to its low durability or strength properties e.g. demolished concrete has a lower quality compared to natural aggregates due to mortar and cement paste which remains attached after the recycling process (Marinkovic *et al*., 2010). Hence, recycled aggregates are often used in the construction of road base and sub-base layers instead of concrete production for high strength applications.

Recycling creates value in the economy by reducing the input of virgin raw materials, reducing the need for landfills, and increasing labour force through the sorting out of demolished waste on site.

In summary, a circular model limits the use of virgin materials for economic activity and also minimizes the use of the environment as a sink for discharged solids and emissions. The adoption of such a model in economic activities requires product developers to design products to facilitate recycling both within the economy and via natural ecosystems cycles (biodegradability) (Daly, 1990).

Through the use of a circular model, the concrete practitioner is able to take on a life-cycle perspective to the design of a concrete structure. This is a conscious process that requires the designer to plan the life-cycle flow of resources and wastes of a structure.

2.3.2.2 Dematerialization

Concrete construction is marked by activities related to the quarrying and processing of raw materials which consist mainly of natural aggregates. Natural aggregates (NA) are non-renewable as their geological processes of formation take a long time (millions of years) and their continuous and increased consumption decreases their reserves. Currently, high-grade reserves of the earth's NA have been exploited in construction activities to a point where the availability of NA is now scarce if not practically unrealizable in some countries and particularly in urban areas. As a result, materials are transported for lengthy distances, and this in turn elevates the energy consumed and the construction project expenses, leading to a number of environmental problems such as greenhouse gas (GHG) emissions and resource depletion. Environmental concerns over the excessive mining of NA compared to other aggregate types such as recycled aggregates, can be addressed by changing raw material consumption patterns in concrete construction in a process referred to as dematerialization.

Dematerialization is defined as the reduction of the quantities of materials needed to serve an economic function or the decline over time in the weight of materials used in industrial end products (Wernick *et al*., 1996 *as cited in* Kibert *et al.*, 2002). This implies delivering the same performance with less volume of raw materials and hence minimizing the generation of waste and eliminating problems associated with waste disposal (Peng *et al*., 1997).

The application of dematerialization in concrete construction can be partially achieved through structural optimization of a structural component to reduce the volume of materials used, which in turn leads to a reduction in pollution generation.

2.3.2.3 *Increased production efficiency*

Improved efficiency in all manufacturing processes of a product, including the extraction of raw materials for its production and processing of these materials, can lower the energy requirements and emissions associated with their production.

For example, current solutions to aid in reducing the 5-8% global anthropogenic CO_2 emissions from cement manufacture (WBCSD, 2002; Damtoft *et al*., 2008) include improving the efficiency of cement kilns. Optimizing kiln processes and plant efficiencies during cement production results in the reduction of CO_2 emissions and also brings down the cost of production. Modern cement kilns should use the dry processing of raw materials, as opposed to the wet process. The former refers to the process whereby raw materials are first ground and heated before being fed into the kiln, whereas in the wet process, the raw materials are crushed, ground and mixed as slurry.

The most efficient dry-process kilns use approximately 2.9 GJ per tonne of clinker (http://www.energyefficiencyasia.org/docs/ industry sectors cementdraftMay05.pdf). Wet-process kilns are more energy intensive and can consume more than twice the amount used by dry process kilns (Gartner, 2004).

However, there is a thermodynamic limit where it is not possible to increase production efficiency and hence limit GHG emissions. Further reductions in energy used in materials production can be achieved through the substitution of renewable energy sources for fossil fuels. For example, waste tyres can help reduce the amount of coal energy used in cement kilns.

2.3.2.4 *Durability design*

Construction products are marked by a long life-time and can consume large resources in their life-cycle if they do not have adequate durability. Durability design of concrete structures is concerned with ensuring the ability of concrete to resist the penetration of aggressive agents during its intended service life. Most approaches to concrete durability design and specification rely on the so-called ‘prescriptive method’, i.e. the design and specification ‘rules’ are intended to provide for durability by prescribing limiting values for material properties and proportions, depending on the environmental conditions and life span of the structure. The specified parameters are usually the concrete cover to reinforcement, 28-day compressive strength, maximum water-cement (w/c) ratio, and minimum cement content. For example, both international and South African national design standards such as EN 206-1: 2000 and SANS 10100-2: 2005 respectively, give the limiting values of the concrete cover to be provided to all reinforcement, 28-day compressive strength and cement content in order to achieve a durable concrete for a range of w/c ratios. Besides the fact that these requirements can sometimes be mutually contradictory, this approach does not explicitly address rational, quantitative durability design, nor does it address sustainability issues. Regarding this latter point, prescriptive specifications are generally restricted to conventional materials and do not have the flexibility to address ‘new’ and marginal concrete materials such as recycled and site-derived materials. These materials may in certain circumstances be adequately durable but also bring savings on raw material resource use. Furthermore, by using the prescriptive method there is a danger of over-specification, since the prescriptive approach is inherently conservative and results in resource waste. Lastly, the approach assumes that the as-built quality of concrete is what has been specified, without the means to check actual as-built quality. It also does not account for variability in as-built quality that may occur due to material variability and variable site practices including poor workmanship and inadequate curing in as-built quality. Such practices may result in poor quality concrete which will require additional repair and maintenance during the structure’s service life resulting in additional unanticipated material consumption, social disruptions, and costs. Thus, the present prescriptive approach to durability specifications should be rapidly phased out, since in fact it contributes directly to un-sustainability.

On the other hand, performance-based approaches to durability design are specifically intended to limit the environmental consequences on the structure to defined acceptable levels or targets during the structure’s service life. The approach advocates use of service life prediction models that quantify environmental deterioration and provide an output in terms of the required material quality. From this requirement, the designer is left with the choice of selecting a suitable material (conventional, new or marginal) that will meet the requirements within the predefined acceptable level. The specified material quality is then verified on site using durability tests that characterize that quality.

Hence considerations of sustainability of concrete structures should relate to service life and performance requirements of the structure, in which durability considerations are embedded.

2.3.2.5 *Other considerations*

In addition to the above considerations, there are other sustainability principles that are specific to the type of concrete structure e.g. civil engineering structure or building, and relate to the use-phase of the structure. This includes the use of efficient heating and ventilating systems in buildings so as to reduce their operational energy.

Based on a review of life-cycle assessment (LCA) studies on nineteen journal articles describing forty LCA studies on various concrete residential and commercial buildings (see Appendix A), this present study established that the operational energy of both residential and commercial buildings was the dominant component representing approximately 59-98% of life-cycle energy, whereas the initial embodied energy[20] constitutes 1-59% of life-cycle energy. ***Figure 2-6*** compares the operation energy of commercial and residential buildings. It should be noted that the review study was on standard buildings and did not include passive house buildings.

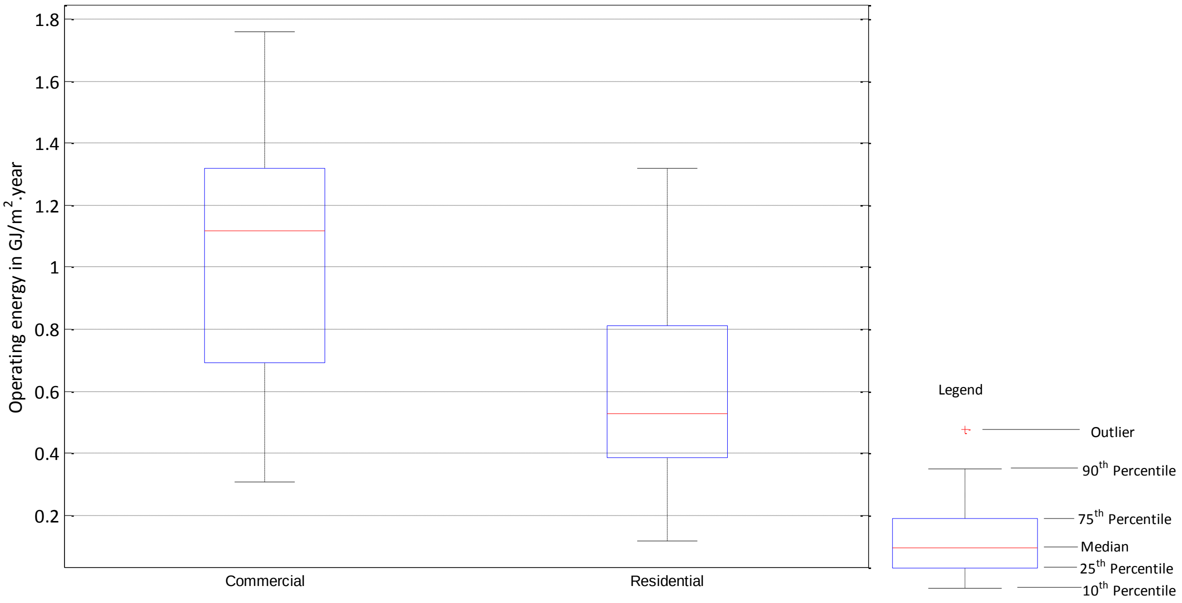

Figure 2-6: *Comparison of operation energy of commercial and residential concrete buildings (Reference: this study).*

The operation energy values of commercial buildings ranged from 0.3 to 1.8 GJ/m^2.year. In comparison, the operation energy of residential buildings was much lower and ranged from 0.1 to 1.3

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[20] Initial embodied energy refers to the energy used during the quarrying, manufacture of raw or recycled materials to produce construction materials and transportation of the materials to the construction site.

GJ/m^2. In general, commercial buildings were found to have a higher operation energy compared to residential buildings.

Figure 2-6 is a comparative boxplot showing the variation of embodied energy figures of commercial and residential buildings. The initial embodied energy of commercial buildings ranges from (1.25 to 16 GJ/m^2) and is higher than that of residential buildings which ranges from (1.1 to 7.6 GJ/m^2), excluding the outlier 9.8 GJ/m^2 for the low energy residential building investigated by Blengini (2009)

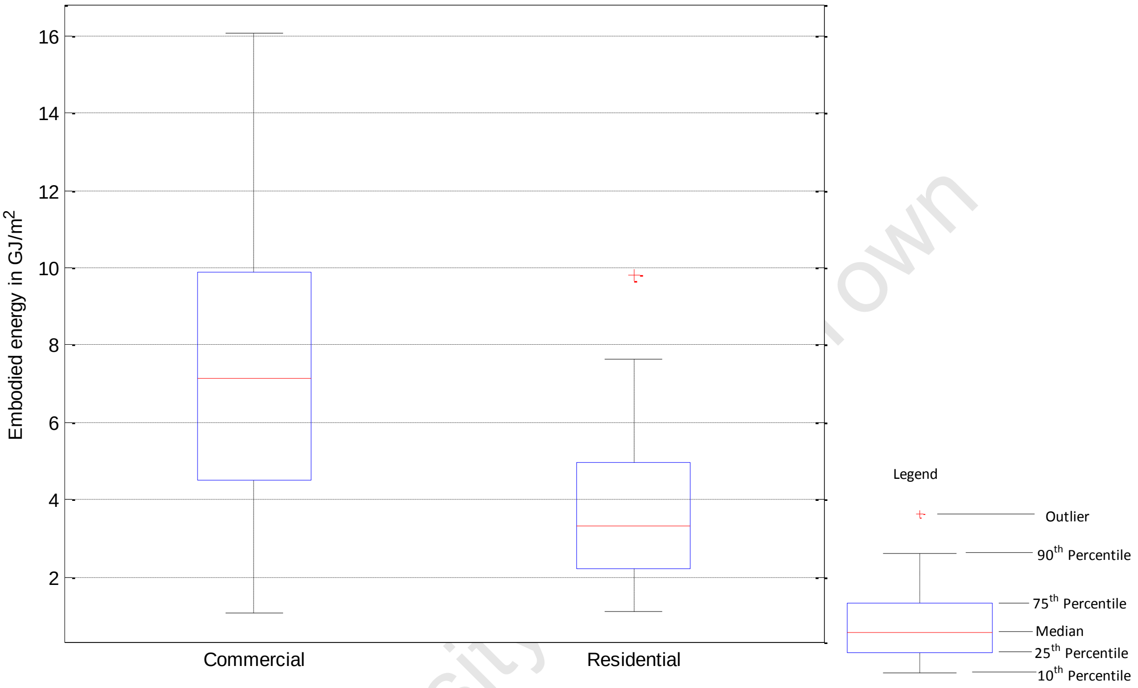

Figure 2-7: *Comparison of initial embodied energy of commercial and residential concrete buildings (Reference: this study).*

The large variation in embodied energy of commercial buildings and residential buildings is due to the fact that different LCA studies include different levels of detail based on available data.

In general, the majority of the impacts during the operational phase of residential and commercial buildings comes from the technical support systems used for lighting and ventilating buildings. Hence, the energy efficiency of buildings during their use phase can be improved through the use of renewable energy sources or passive design (*explained later in section 2.3.3.1.3*). In addition, the thermal performance of alternative construction materials should not be ignored by the designer, as they have a role to play in reducing the operation energy losses in heating and/or cooling a building. In particular, concrete has a higher thermal mass than other building materials, and its use in the exterior wall system can reduce the cooling and/or heating energy needs of a building.

2.3.3 Definition of a sustainable concrete structure

Integrating the concept of sustainable development into the concrete industry requires a clear and definite understanding of the term: ‘sustainable concrete’ structures. However, the definition of ‘sustainable concrete’ remains elusive. Several attempts have been made in literature to define ‘sustainable concrete’ and are reviewed here.

The ‘Concrete for the environment – Nordic network’ (2003) and Glavind *et al*. (2006) defined a sustainable concrete structure as:

“*…one that is constructed to ensure that the total environmental impacts during its life-cycle, including during its use, will be minimal*.”

This, they explain, requires that the structure be designed and produced in a manner which is tailor-made for its use, i.e. to the specified lifetime, loads, environmental impact, maintenance strategy, heating requirements, etc. – or simply selecting the right concrete for the right application. According to the study, this can be achieved by utilising the inherently environmentally beneficial properties of concrete, e.g. the high strength, good durability and the high thermal capacity. Furthermore, the concrete and its constituents are required to be extracted and produced in an environmentally sound manner (Concrete for the environment’ – Nordic network, 2003; Glavind *et al*., 2006).

Connal and Berndt (2009) defined sustainable concrete structures as:

“*…ones that strive to conserve natural resources and minimize waste (be an efficient, minimalist design, avoiding extravagant architectural statements), minimize the embodied energy in the structure (appropriate selection of materials and material sources for the functional demands of the project), and have a long life with minimal maintenance input*”.

This definition considers minimizing resource depletion of concrete structures over their life-cycle. Connal and Berndt (2009) make the assumption that the environmental burden during construction is approximately proportional to its life-cycle cost, based on a prior study conducted by Collings (2006). They therefore conclude that a structure that minimizes its resource consumption over its life-cycle is likely to have a low life-cycle cost. However, this basis may not necessary hold for high carbon emitting materials such as Portland cement which may have a high environmental impact but low cost.

Naik (2008) puts across several definitions of a sustainable concrete structure. The first is:

“*…one that is constructed such that the total societal impact during its entire life-cycle is minimal*”.

He explains that this involves accounting for short-term and long-term consequences of the structure and in particular focusing attention on the effects on human health, energy conservation, and physical, environmental, and technological resources for new and existing buildings. In addition Naik (2008) shows the need to take into account construction technologies and methods.

In the same study, a sustainable concrete structure is also defined as:

"*…one that is constructed such that the total environmental impact during its entire life-cycle is minimal*".

This is taken to mean: "*…that the concrete structure has a very low inherent energy requirement, is produced with little waste, is made from some of the most plentiful resources on earth, produces durable structures, has a very high thermal mass and is made with recycled materials*" Naik (2008)

In summary, most of the definitions given on sustainable concrete structure do not depict a life-cycle outlook of construction as the manufacturing and demolition phases are not considered. The definitions also put emphasis on ecological aspects and fail to capture the holistic nature of sustainable development. A more comprehensive definition of sustainable concrete is therefore required and is given in the next section. The definition touches on the principles of sustainable development covered in section 2.3.2.

2.3.3.1 *Sustainable concrete structure*

Based on the principles of sustainable development given in section 2.3.2, a definition of 'sustainable concrete' is suggested here as:

"*one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling*"

This definition encompasses the following:

2.3.3.1.1 Use of efficient production and construction technologies

The use of efficient production techniques for all concrete materials constituents may lead to a reduced energy throughput and carbon emissions. This can for example involve the use of renewable energy sources, the thermodynamic improvement of production machinery and/or, the installation of carbon capture and storage (CCS)[21] systems in high carbon emitting production processes e.g. cement kilns. The implementation of the latter is not yet economically feasible particularly in developing countries. However, the implementation costs can be off-set through the implementation of the Clean Development Mechanism established under the United Nations Framework Convention on Climate Change.

Construction technologies have an influence on the overall life-cycle energy of a structure. A study carried out by Cole (1999) established that construction represents 11-25% of the total initial embodied energy of buildings. This amount may be reduced through the selection of an appropriate construction technology e.g.: (a) use of self-compacting concrete in order to reduce construction noise when casting concrete; (b) the use of pre-cast concrete technology which offers numerous advantages including: the utilization of alternative materials (e.g. site waste and industrial waste) which would have otherwise ended up in land-fill sites; in addition, the pre-cast structure and components offer better quality control and a reduction in site work and therefore result in minimal traffic disruption.

2.3.3.1.2 *Selection of optimized material properties*

This refers to the selection of optimized material types and properties that not only meet the structural design requirements but also lead to minimized life-cycle environmental impacts. Cement, which is a key constituent in concrete, has a large influence on both the environmental impact and durability of concrete. The use of supplementary cementitious materials (SCMs) is advantageous with respect to these two aspects. SCMs are alternative materials such as ground granulated blast furnace slag (GGBS) from iron production, silica fume (SF) from the manufacture of silicon, and fly ash (FA) from coal combustion, and are prescribed as partial replacement of cement (Glavind, 2009; Naik *et al*., 2003; Malhotra, 2003). Blended cements are produced either by intergrinding SCMs with clinker[22] from cement production, or separate grinding of clinker followed by interblending with SCMs. The use of blended cements reduces the amount of clinker that needs to be produced, also lowers the CO_2 emissions and costs, and diverts wastes from landfills as SCM's are by-products of other industries that would have otherwise been disposed. The concrete produced using SCMs is also reported to have a higher durability quality compared to that produced using ordinary Portland cement for reinforced concrete structures located in saline environments (Aïtcin, 2008).

2.3.3.1.3 *Selection of an appropriate structural layout and optimized volume of a structural component*

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[21] Carbon capture and storage (CCS) is a method of CO_2 sequestration whereby CO_2 emissions are captured at the source and transported to storage reservoirs.

[22] Clinker is the main product of Portland cement manufacture and is generated by heating raw materials (limestone, iron ore and alumino-silicates such as clay) together at temperatures of about 1400 – 1500 °C.

An appropriate structural layout for buildings in particular is important as it helps minimize the energy requirements during the use phase of the building and the embodied energy. The layout of a building with respect to its location and orientation can be such that natural lighting and ventilation are provided to its users during its operational phase. This is also referred to as passive design.

For a civil engineering structure, an appropriate layout would enhance the aesthetic quality of the structure.

In addition, an optimized volume of materials in each of the structural components would lead to reduced quantities of materials needed for construction. This can also be achieved with the use of light-weight construction materials or through design optimization of structural components.

2.3.3.1.4 Design for deconstruction and recycling

The design for deconstruction is a long-term approach perspective of the use of the structure after its useful service life. This requires the key players in construction to consider the end-of life phase of a structure and consider ways in which it can be adapted or recycled.

2.4 Role of the structural engineer

In addition to ensuring structural performance, the practitioner in structural engineering is increasingly required by the client to synthesize a solution, which includes sustainability requirements of the structure as a whole. This can be made possible through the development of a framework for design which structural and materials engineers can use to consistently and rationally consider ‘sustainability’ in their designs.

2.5 Current certification tools for assessing the environmental performance of concrete structures

Currently, the design of concrete structures for sustainability is supported through the recently established Green Building Councils in both developing and developed countries, and the introduction of voluntary environmental certification and rating tools by the same councils. The certification tools on construction projects are a positive step towards the design of more sustainable structures as they determine whether or not a structure meets a prescribed qualitative environmental performance. The tools check environmental performance against a set of qualitative and quantitative criteria. The tools include the Leadership in Energy and Environmental Design (LEED) in the USA, Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan, Sustainable Building Assessment Tool (SBAT) tool in South Africa (S.A.) and Green Star Building tool developed in Australia and adapted by SA. Some characteristics of these rating tools are given in ***Table 2.1***.

The SA Green Star Building tool has been applied to help in environmental certification of buildings, and in assessing materials and heating and cooling installations in buildings. Some of the tools listed in ***Table 2.1*** such as LEED have been used internationally to facilitate the enforcement of key regulatory schemes such as the Energy directive by the European Union (Directive 2002/91/EC). This directive aims at improving the energy performance of buildings by setting minimum energy performance requirements in new and existing buildings, which have a floor area in excess of 1000 m^2 and undergo significant renovation over their service life.

Table 2.1: *Current building rating tools.*

Rating tool		***Country, Year of origin***	***Characteristics***	***References***
LEED	Leadership in Energy and Environmental Design	USA, 2000	• Rating: silver, gold or platinum • Covers 5 areas of sustainability	USGBC, 1996
BREEAM	Building Research Establishment Environmental Assessment Method	United Kingdom, 1990	• Rating: fair, pass, good, very good, excellent and outstanding • Scores given in 3 performance categories: Global resource, Local and Indoor environment	BREEAM, 2012
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency	Japan, 2004	• Available for different life-cycle design phases: pre-design, new construction and renovation of existing buildings	http://www.ibec.or.jp/CASBEE/english/certified_bldgs.htm
SBAT	Sustainable Building Assessment Tool	South Africa: Green Building Council, 2008	• Rating: on a scale of 0 to 6 stars • For commercial buildings only	http://www.gbcsa.org.za/greenstar/ratingtools.php
Green Star Building tool		South Africa: CSIR, 2008	• Performance criteria that recognizes social and economic factors • 15 performance areas and 5 performance criteria	Gibberd, 2008

CSIR – Council for Scientific and Industrial Research; BRE – Building Research Establishment; USGBC – United States Green Building Council

A general critique of rating tools has been given in Ding (2008). The main limitation on the use of these rating tools is their methodology. The rating tools grade the relative performance of a design against a set of prescribed qualitative criteria, rather than the quantified environmental performance of the suggested design. For example, the Green Star Building tool rates a structure in different categories including the use of materials. Under the category: "*use of waste materials from other industries*" the use of supplementary cementitious materials to produce concrete qualifies a structure for a higher rating than one constructed using conventional concrete. An improved method would be to select materials based on their quantified life-cycle environmental performance as well as other design requirements such as durability. This would avoid over- or under design of the materials and hence avoid wastage of resources.

2.5.1 Recommendations for further improvement of rating tools

Based on the limitations of the assessment tools, this study is of the view that these tools are necessary but not sufficient instruments to stimulate the design of more sustainable structures. There are improved and well established assessment tools which can be used to quantify the environmental impact of a structure using the life-cycle assessment (LCA) methodology. A review of the life-cycle assessment methodology is given in Chapter 3. Examples of tools developed using the LCA methodology includes ANTHENA Impact Estimator for Buildings in Canada (Athena Institute, 2008), BEES 2.0 (Building for Environmental and Economic Sustainability) in the USA (Lippiatt, 2007), and SimaPro 7 in Netherlands (PRé Consultants, 2008).

However, in addition to the environmental impact of a material, there are still other design considerations such as its durability and strength that should be considered in design. The overall considerations are encompassed in this study's definition of a 'sustainable concrete structure'.

The concept of 'sustainable concrete structures' in the context of this study, focuses on the materials design aspect and is limited to the selection of optimum material properties and quantities for concrete based on their environmental performance. The study proposes a novel framework for design of more sustainable concrete structures that allows the structural engineer to explicitly address rational, quantitative design of concrete for sustainability. The proposed framework is detailed in Chapter 5. The framework shows the important parameters and variables that need to be considered in the design of concrete. In addition the study develops a tool which can be used to integrate all the proposed parameters in design and allow the concrete practitioner to select optimal concrete constituent materials that lead to more sustainable concrete structures. The selection of a suitable metric(s) for assessing the sustainability of a concrete structure is important and is a backbone to the proposed framework. The topic of identifying a suitable metric for concrete structures is covered in Chapter 3.

2.6 Specific summary

Ecosystems provide useful natural resources such as fossil fuels and minerals (e.g. sand and gravel) that support human well-being and economic development. The ecosystems are self-regulating if wastes and emissions produced by biosystems are kept within the assimilative capacity of the physical environment, and natural resources are sustained within their regenerative capacity. However, since the mid-20th Century, anthropogenic activities, driven by a non-linear population increase have threated the ability of ecosystems to sustain the growing population. The high population growth signifies a high level of resource consumption and associated pollution. There have been inequitable patterns of resource consumption between the developed countries and developing countries. For example, of the 60 billion tonnes of engineering materials, 75% are consumed by the developed countries. In addition, 70% of the total 393 ppm GHG produced yearly is from developed countries.

However, the developing countries also contribute towards environmental degradation through changes in land-use cover from forest land to fuel energy use. It is questionable whether the present levels of consumption and pollution in developed countries can be generalized to developing countries, much less to future generations without destroying the ecosystems.

Intergovernmental and governmental organizations such as the UN have recognized ‘sustainable development’ as a guiding paradigm to create a new way of making decisions and doing things globally. Sustainable development requires that relative to their respective demographic bases, each generation bequeaths to its successor a non-decreasing stock of resources as great as that which it inherited from its predecessor (Dasgupta, 2007). However, this interpretation has been taken differently by various groups leading to two disparate schools of thought: ‘weak sustainability’ and ‘strong sustainability’. The latter shows the different forms of resources e.g. natural and man-made resources, are not substitutable whereas the former argues otherwise. The various international forums on sustainable development, discussed in this chapter, show that the development of ways to operationalize the sustainable development concept has been met with conflicting views between the developed and developing countries. The developing countries advocate for the need for ensuring that all people in the world obtain the resources they need for survival whereas the developed countries focus on eliminating the present environmental burdens such as global warming. In the latest international forum (Rio + 20) a solution to these multiple problems was created as that of the concept of creating a ‘green economy’. This aims at establishing how to use natural resources available to help promote growth while protecting the earth’s economy.

In the context of this study, it is necessary to show how the outcome of the study can contribute towards sustainable development. In Chapter 4 it is shown that the concrete industry is responsible for massive use of non-renewable aggregates which also leads to a number of environmental problems such as greenhouse gas (GHG) emissions. The natural aggregates exist in finite amounts and cannot be renewed following their depletion. In addition, the increased usage of concrete in construction has led to waste solids through construction and demolition waste.

One of the main objectives of the study is the development of a design framework that aims to bring about resource efficiency in the concrete construction industry and hence enable ‘green growth’. Further, the proposed framework encourages the practitioner of structural concrete to use alternative materials. These materials are sourced locally using a local labour force, hence result in the creation of a secondary materials market for salvaged materials and for recycled aggregate manufacturers.

2.7 General summary

In this chapter the concept of ‘sustainable development’ was reviewed. The concept has changed with time to address the varied needs of the human population in both developing and developed countries.

While there has been little consensus about the definition for ‘sustainable development’, certain commonly accepted principles exist and can be applied to the concrete construction industry.

The principles reviewed were:

(i) The circular materials design model – which encourages the designer to rethink ways the design product can relieve the environmental burden from waste disposal and also reduce the extraction of virgin materials. This can be achieved through design for reuse and recycling of waste materials.
(ii) Dematerialization – this requires the designer to reduce the quantities of materials needed by e.g. by volume and shape optimization or using light-weight products.
(iii) Increased production efficiency – which involves adapting technology that leads to increased efficiency in resource production and processing.
(iv) Durability design – this involves the use of quantifiable methods e.g. tests or service-life prediction models that give the concrete practitioner the flexibility to use of ‘new’ and ‘marginal’ materials that contribute to sustainability.

Following the review and for purposes of this research, a ‘sustainable concrete structure’, is: “*one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling*”. From this definition, the practising engineer can be able to establish whether their design contributes towards more sustainable concrete structures.

There are a number of options available at the design stage that can be used to ensure the construction of more sustainable concrete structures. This study focuses on the materials design of concrete structures. The contribution of this study is a design framework that allows and encourages the structural engineer to make specific optimum design choices of materials.

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Chapter 3

3 METHODS FOR ASSESSING THE ENVIRONMENTAL IMPACTS OF THE CONCRETE CONSTRUCTION INDUSTRY

3.1 Introduction

Folowing the critical review in Chapter 2, a working definition of the term ‘sustainable concrete structure’ was established as: “*one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling*”

Therefore, in order to achieve a sustainable concrete, it is important to select an accurate valuation technique that measures the use of different non-renewable and renewable materials and energy resources relative to their availability in the physical environment. The selected valuation technique should allow a decision maker to make comparisons of several material design alternatives using quantitative terms e.g. mass of resources depleted, amongst other criteria. The most widely used methodology for this kind of decision making is life cycle assessment (LCA). The LCA methodology was initially developed by SETAC (Society of Environmental Toxicology and Chemistry) (1990) and further developed by the International Standards Organization. The term LCA as used in this study refers to a family of methods for quantifying the environmental resources used and wastes produced by products, processes and technologies over their entire life-cycle (Kuo *et al*., 2001). The most common definition of LCA in literature is given in ISO 14040 (2006) and ISO 14044 (2006) as “*the compilation and evaluation of the inputs and outputs and potential environmental impact of a product throughout its life-cycle*”. However the latter definition only accounts for environmental impacts and is one of the methods that follow the LCA methodology. Other LCA methodologies include life-cycle cost and social LCA, which quantify the financial costs and the impacts on the product user, respectively.

Due to the various environmental impacts associated with concrete, it is essential to select a suitable metric(s) for decision making that allows for the selection of more sustainable concrete constituent materials. This Chapter gives a review of the life-cycle assessment methodology with the aim of achieving a general understanding of existing measurement methods (e.g. thermodynamic, monetary methods) for environmental sustainability within this methodology, and their suitability in measuring the environmental impacts of concrete structures.

3.1.1 Life-cycle assessment

The life-cycle assessment (LCA) methodology is the most widespread technique for evaluating environmental impacts related to a product or service. In terms of construction, a LCA tracks the inputs and outputs (for example, energy and materials, wastes and emissions) generated and the potential environmental impact on the physical environment of construction materials and/or structural assemblies over their life-cycle. This information assists the designer in making informed decisions regarding the selection of design and material options that will minimise a structure's life-cycle environmental impact. The LCA methodology is based on the general guidelines presented in international standard series ISO (International Standards Organization) 14000 environmental standards. The ISO 14000 series, which includes ISO 14040:2006 and ISO 14044:2006, provide general rules related to methods of assessing environmental loads mainly for industrial products and processes. Subsequently, ISO 15686-6 (2008) and ISO 21930 (2007), have been developed to cover buildings. ISO 15686-6(2008) gives the basic framework of the procedure for considering the environmental aspects of buildings, whereas ISO 21930 (2007) provides a methodology to be applied when issuing environmental declarations of building products. Environmental declarations provide information regarding the environmental impact of a product. In addition, ISO 13315-1:2012 shows the various activities and processes that contribute to the environmental impact of concrete (Sakai, 2010). These new standards in the construction industry (ISO 15686-6:2008, ISO 21930:2007 and ISO 13315-1:2012) are consistent with the existing ISO 14000 series.

The LCA methodology comprises four distinct steps, namely (ISO 14040: 2006): (i) Goal and scope definition; (ii) Life-cycle inventory analysis; (iii) Impact assessment and; (iv) Interpretation of the results (as shown in ***Figure 3-1***). The output of each of the four steps affects the other steps.

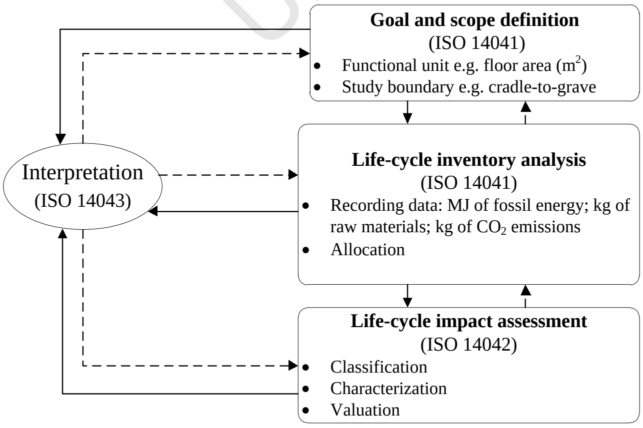

Figure 3-1: *General structure of an environmental life-cycle assessment (Adapted from: ISO 14040: 2006).*

- ISO 14041:1998 "Environmental management- Life-cycle assessment – Goal and scope definition and inventory analysis"; ISO 14042:2000 "Environmental management –Life-cycle assessment –Life-cycle impact assessment"; ISO 14043: 2000 "Environmental management –Life-cycle assessment –Life-cycle interpretation"
- The above standards have since 2006 been replaced by ISO 14040:2006 and ISO 14044: 2006

3.1.1.1 *Goal and scope definition*

The first step of an environmental LCA as shown in ***Figure 3-1*** defines the goal of the study, the study boundaries, and the functional unit (FU). FU is the quantified performance of a product system for use as a reference unit and enables comparison of the environmental performances of different types of products (ISO 14040: 2006). For concrete, the FU may be taken as *a unit volume* (m^3)*, concrete grade (MPa) or weight (kg)* of concrete that would serve as a common unit of comparison between different concretes.

3.1.1.2 *Life-cycle inventory*

(a) *Data recording*

The subsequent step of life-cycle inventory (LCI) analysis involves the collection of information on energy and material flows and emissions of a product's life-cycle. The inventory analysis generates a list of inputs (energy and materials) and outputs (emissions and wastes). For example the LCI of concrete will contain data on:

(i) Raw materials (kg) and energy (MJ) used in extracting, producing and transporting cement and aggregates, and the emissions (e.g. kg CO_2) from the processes.

(ii) Energy use (MJ) and emissions (e.g. kg CO_2) associated with the transport of materials, construction equipment, personnel to and from the construction site and on-site equipment.

A number of international and local inventory analysis studies on concrete structures have built up environmental inventory databases of raw materials for concrete production. In the UK, the University of Bath has drawn together an inventory of carbon emissions and embodied energy which covers a broad range of building materials including concrete (Hammond and Jones, 2008); in Australia a study carried out by Flower and Sanjayan, (2007) provides the greenhouse gas emissions of the constituents of concrete; a similar database for South Africa is given in the InEnergy report (2010); Kawai *et al*. (2005) in Japan provide inventory data on the environmental impact of raw materials for concrete, and in Switzerland is the EcoInvent database which comprises extensive LCI datasets including those of building materials (Frischknechnt *et al*., 2005).

(b) *Allocation*

An additional step in the LCI is allocation which involves assigning the environmental inputs and outputs generated by processes within a system to the products and co-products of the system, in proportionate shares (ISO 14044:2006). The allocation of three types of processes can be distinguished (Guinée *et al*., 1993): A process producing more than one product; a waste recovery process dealing with more than one waste component and; a recovery process of materials to be reused or recycled. The allocation of environmental inputs and outputs from the open-loop recycling (refer to Chapter 2) of waste are not explicitly addressed by ISO 14044:2006, however, various studies have suggested the use of two main allocation methods: (i) Recycled content (cutoff) approach (PAS 2050 (Publicly Available Specification 2050), 2008), and (ii) End-of-life recycling (avoided burden) approach (Frischknecht, 2010; Ekvall and Tillman, 1997). The recycled content approach assigns environmental inputs and outputs directly caused by a by-product to that product system. This means that the life-cycle system that utilizes the by-product has the responsibility for the environmental burden of the resources. The end-of-life recycling (closed-loop approximation) method considers the recyclability of a product at its end-of-life.

The allocation of environmental inputs and outputs for both methods can be made on the basis of the economic value (e.g. market value of the scrap material or recycled material in relation to market value of primary material); physical quantities (e.g. mass, volume or energy content) of the product or waste component or; the number of subsequent uses of the recycled material (ISO 14044:2006; Guinée *et al*., 1993).

This study focuses on the materials selection for more sustainable concrete structures and hence the recycled content approach is suited for this study as it helps account for the environmental performance of any recycled or supplementary materials used in concrete production. The recycled content approach also supports the concept of strong sustainability (*see Chapter 2; Section 2.2.2*), which is the basis of the definition of a sustainable concrete structure as given in Chapter 2.

3.1.1.3 *Life-cycle impact assessment*

Most LCA studies end at the LCI phase and do not look further at the environmental impact of the inputs and outputs to the ecosystem (Cole, 1999), which is the process referred to as life cycle impact assessment (LCIA). An impact assessment consists of several steps: classification; characterization, and valuation (normalization and weighting).

(a) Classification

This involves assigning inventory data to potential environmental effects, such as climate change and acidification. During classification, the LCI results (resource flows and emissions) are assigned to various impact categories (Guinée *et al*., 2002): For example, both CO_2 and methane (CH_4) have a potential to contribute to the greenhouse environmental effect and are thus assigned to the climate change impact category as detailed in ***Table 3.1***. Their collective contribution to a particular impact category is assessed with respect to a reference substance which for instance in climate change category is CO_2 gas. This latter step is referred to as characterisation in an LCIA.

Table 3.1 : *Environmental impact categories (Guinée, 2002; Frischknecht and Jungbluth, 2003).*

Examples of LCI data	***Impact category***	***Category indicator***	***Reference substance***	***Unit of measurement***[#]
• Carbon dioxide (CO_2) • Methane (CH_4) • Nitrous oxide (N_2O)	Climate change	Global warming potential (GWP) [23]	CO_2	kg CO_2-eq
• Chlorofluorocarbons (CFC) • Hydro chlorofluorocarbons (HCFC)	Ozone layer depletion	Ozone depletion potential (ODP)	CFC_{11}	kg CFC_{11}-eq
• Minerals e.g. metals; and Bulk materials e.g. sand, limestone • Fossil fuels	Natural resource depletion	Abiotic depletion potential (ADP)	kg Sb (antimony)	kg Sb-eq
		Surplus energy (SE)	MJ	MJ
		Monetary method	Currency	Currency
		Thermodynamic metrics	kg, MJ	kg, MJ
• Phosphates • Nitrogen oxides • Ammonia • Nitrogenous matter • Nitrates • Phosphorous.	Eutrophication	Eutrophication potential (EP)	PO_4^{3-} (Phosphate)	kg PO_4^{3-} -eq
Toxic substances on human health	Human toxicity	Human toxicity potential (HTP)	kg 1,4-DB dichlorobenzene equivalent	kg 1,4-DB-eq
• Sulphur oxides • Nitrogen oxides • Ammonia • Hydrogen fluoride • Hydrogen chlorides	Acidification	Acidification potential (AP)	SO_2 (Sulphur dioxide)	kg SO_2-eq

[#]eq – represents equivalent units.

Of importance to this study are the 'climate change' and 'natural resource depletion' impact categories, as they are related to the main environmental impacts arising from the production of constituent materials for concrete. From ***Table 3.1***, it can be noted that climate change is measured using equivalent kg CO_2 emissions whereas resource depletion can be measured using various indicators: the abiotic depletion potential (ADP); surplus energy (SE), monetary-based methods; and/or thermodynamic metrics.

ADP is given in *kg* of the reference resource, Antimony. It is calculated as the ratio of present use of a resource (*kg/year*) to a square of its reserve (*kg*) compared to that of Antimony (Guinée *et al*, 2002). Habert *et al*. (2010) investigated the suitability of ADP in measuring resource consumption in

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[23] Climate change = quantity of a given GHG (kg) × global warming potential (GWP) (Heijungs *et al*., 1992)

concrete construction. They showed that the ADP is not appropriate in evaluating the pressure on natural resources for building construction as it is not able to distinguish between the resource depletion due to use of natural aggregates compared to the use of recycled materials in concrete. ADP measures the total amount of bulk materials (e.g. sand and gravel) on a global scale and assumes these to be infinite. However, on a regional scale the availability of natural aggregates may deplete and when this happens aggregates may either have to be sourced from further sources requiring longer transportation distances or the use of recycled aggregates may be exploited. There would be a considerable increase in environmental impacts of aggregates transported over longer distances as opposed to those sourced locally. However, the environmental impact due to differences in transportation distances of aggregates cannot be distinguished using the ADP metric.

SE is defined as the energy needed to extract a resource now compared to extracting the resource at some point in the future (Muller-Wenk, 1998; Goedkoop and Spriensma, 1999). The method is based on the assumption that low-grade reserves of minerals and fuels require more energy in mining, and hence an increase in SE will be an indicator that resources are depleting. The main limitation of SE lies in the difficulty of predicting future energy requirements for resource extraction.

Monetary-based methods are the third class of methods, within the LCA methodology, of measuring resource consumption and attempt to characterize all related impacts, for example energy use and associated emissions, in monetary terms. Considerable difficulties arise when attempts are made to measure non-economic variables such as emissions. Although a number of extended valuation techniques for intangibles and/or externalities, based on willingness-to-pay (accept) principles have been developed, it is almost impossible in practice to arrive at totally reliable and fully accepted monetary values for all impacts. Further limitations of monetary-based methods are given in section 3.1.2.1.

Thermodynamic methods use mass and energy flows. Examples include energy analysis (IFIAS, 1974), exergy analysis (Wall, 1977) which represents the maximum amount of work that can be produced by a system or flow of matter or energy as it comes to equilibrium with its environment, and emergy analysis (Odum, 1996) which is similar to an exergy analysis and attempts to account for the total environmental resources provided by the biosphere to the system under study, expressed in terms of solar energy.

An appropriate measure of natural resource consumption is important and this study reviews the applicability of thermodynamic metrics in concrete construction in section 3.3.

(b) Characterization

The characterization step determines the relative importance of all LCI data in a particular impact category. This is facilitated by the use of characterization factors which express the relative contribution of the LCI data to the particular category indicator (see ***Table 3.1***). The result is then represented as equivalent units (eq) of a reference substance.

For example, for the climate change impact category the reference substance is CO_2, as shown in ***Table 3.1***, whereby the contribution of each measured greenhouse gas emission (e.g. carbon dioxide CO_2; methane, CH_4 and; nitrous oxide, N_2O) is calculated by converting the amount of emission into the equivalent amount (CO_2-eq) of the reference substance using characterization factors. The results within one impact category are then aggregated in units of the equivalent reference substance as exemplified by Equation (3-1) (IPCC "Fourth assessment report", 2007).

$$CO_2\text{-eq} = (CO_2 \times 1) + (CH_4 \times 23) + (N_2O \times 296) \tag{3-1}$$

where, 1, 23 and 296 are the characterisation factors for CO_2, CH_4 and N_2O, respectively. This means e.g. that 1 *kg* of methane (CH_4) causes the same amount of climate change as 23 *kg* of CO_2. Relative contributions of different greenhouse gases to global warming potential (GWP) [24] are given in the IPCC "Fourth assessment report" (2007). A GWP gives the potential contribution of CO_2-eq emissions to the greenhouse effect over periods of 20, 100 or 500 years. E.g. a GWP_{500} of 75" means that 1 kg of the substance has the same cumulative climate change effect as 75 kg of carbon dioxide during a 500 year time period. A GWP_{100} is selected to present the results of an LCA on two case studies in Chapter 6.

Further optional steps in an impact assessment include normalisation and weighting of the impact categories in order to present the results using a single score (Anderson *et al*., 2009).

(c) Valuation

Since each impact category is measured in different units and also the impact categories are not of the same importance, normalization and weighting are required, respectively. Normalization involves expressing different impact categories in a relative magnitude so that they can be compared (Anderson *et al*., 2009; Guinée, 2002). Weighting is a subjective task which involves assigning values (weighting factors) to the different category indicators (see ***Table 3.1***) depending on their relative importance.

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[24] Global warming potential (GWP) is a measure of the radiative effects of greenhouse gases, integrated over a chosen time horizon (e.g. 100 years), relative to an equal mass of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation." (IPCC Fourth Assessment Report, 2007)

3.1.1.4 Methods for carrying out a life-cycle impact assessment

There are two main approaches to categorizing life-cycle impacts: end-point approach and mid-point approach. The mid-point approach ends at the characterisation phase, whereby LCI results are assigned to different impact categories, whereas the end-point approach ends at the valuation step and hence considers the direct damage of the LCI results on the ecosystem (i.e. human beings, natural environment and resources). The latter approach has a higher level of uncertainty compared to mid-point results, due to the subjective manner of assigning values (weighting factors) to the different categories in order to combine them.

There are different impact assessment methods for each approach e.g. the end-point methods include the Eco-Indicator 99 (Goedkoop and Spriensma, 1999), and EPS (Steen 1999) methods whereas the mid-point approach has the CML (Centre of Environmental Science of Leiden University) 2 baseline 2000 method (Guinée, 2002) and the Intergovernmental Panel on Climate Change (IPCC) 2001 GWP (Frischknecht and Jungbluth, 2003).

3.1.1.5 Results interpretation

The last phase of a LCA involves analysing, summarising and reporting the impact assessment results for decision making.

3.1.1.6 LCA software

Due to the large amounts of data and complexity of the LCA methodology, there exist a number of software tools that are applicable in various industries, and which allow decision makers to carry out the LCA of a product/service. These tools include SimaPro (System for Integrated environmental Assessment of PROducts) (PRé Consultants, 2008), GaBi (Gabi, 2006) and the Athena EcoCalculator for commercial and residential buildings and building components in US (http://www.athenasmi.org/). The tools come with databases of environmental information of various products and processes. For example, the aforementioned Ecoinvent database is contained in the SimaPro 7.1 LCA software.

The main limitation of these LCA tools for the construction industry is that they require manual data input of the type of materials and their quantities. The solution to this problem is to link the LCA software tools and computer aided design (CAD) software to a common database. This reduces the workload of assembling the data and maintaining consistency between the data during the whole design process (Kohler and Lützkendorf, 2002). Currently, few LCA tools such as LEGEP® (Lebenszyklusanalyse in der Gebäudeplanungin (Life-cycle analysis in building planning)) Germany (Kohler and Lützkendorf, 2002) provide the possibility of importing geometric data from CAD applications for the LCA. In LEGEP, the environmental impact of a structure is assessed automatically from the 3D CAD drawings, by firstly extracting information (including structural dimensions and type of construction materials such as steel, concrete, timber) from the 3D CAD to calculate the quantities of materials in the respective structural component.

3.1.1.7 Alternative LCA methodologies

The LCA methodology detailed here is referred to as a process analysis whereby the LCA is carried out for the different processes (e.g. extraction, manufacture, use and disposal) of a product. This methodology will be applied in the assessment of materials for concrete structures in this Chapter and the proceeding Chapters of this study as it allows for comparisons to be made between different materials and processes.

In addition to the process analysis, there are two other distinct methodologies for LCA (Chapman, 1974; Bullard *et al*., 1978): (i) Input-Output analysis, and (ii) Hybrid analysis. A brief description, strengths and limitations of each of these methodologies is given in Appendix A of this study.

3.1.2 Other life-cycle methodologies

The LCA methodology as detailed involves measuring the environmental impacts. The methodology has been extended to cover monetary cost assessments of products and processes in what is referred to as life-cycle costing.

3.1.2.1 Life-cycle costing

Life-cycle costing (LCC) is a methodology for evaluating economic costs of a product/service over a period of analysis (ISO 15686-5: 2008). Several guidelines to LCC in the context of the construction industry are available and include: ISO 15686-5: 2008; NS 3454 (2002) (Norwegian standard); ASTM 917-2 (2002) and AS/NZS 4536 (1999) from Australia/New Zealand. In Great Britain and Canada, the expressions whole life costing (WLC) or whole LCC are used to emphasise that the cost analysis covers the entire life-cycle of a product and not just its economic life-span (ISO 15686-5: 2008). LCC as opposed to first-construction cost (traditional financial analysis), computes all the costs (and benefits) arising during the entire life-time of a product including operation, maintenance, and repair.

The first limitation of LCC is that there are often considerable difficulties that arise in measuring all relevant impacts of a product in monetary terms. Not all impacts can be converted into monetary units hence the impacts are classified as either monetary or non-monetary.

Monetary impacts deal with direct and indirect economic losses, such as repair works, loss of revenue, and user delay or inconvenience. The direct costs associated with such impacts are met by the ‘owner’ of the structure whereas the indirect costs are referred to as ‘social costs’ and are borne by parties not associated with the contractual agreement due to the construction process (Allouche *et al*., 2000).

Non-monetary impacts represent benefits or losses suffered by individuals or groups of individuals and on which a monetary value cannot be placed. The benefits may include the aesthetics and performance of materials which improve the quality of life of the society. The losses include death, injury, loss of long-term income and emotional distress due to e.g. structural failure. The “costs (benefits)” associated with these impacts are much harder to quantify using conventional estimation methods. For this reason, a number of techniques have been proposed to estimate the non-monetary cost (benefit) associated with the non-monetary impacts. These techniques include: (i) *hedonic pricing* – which can be used to analyse the impact on a product due to e.g. deterioration of the aesthetic quality (Gilchrist and Allouche, 2005). It shows the reduction in value between a new product and the deteriorated product**,** and (ii) *contingent valuation technique* – which gives the value of a product from the perspective of the society. Although these extended valuation techniques for intangibles and/or externalities have been developed, it is almost impossible in practice to arrive at totally reliable and fully accepted monetary values for all impacts.

The second limitation of LCC arises during the aggregation of the life-cycle costs into one value. The impacts of any product occur at different times over its life-cycle. Hence, to ensure equitable comparison between alternatives, the time-value of money has to be taken into consideration. All streams of future costs and benefits are multiplied by a discount factor (DF) to reduce them to their present value. The discounted costs of each process/activity are summed up to calculate the net present value (NPV) of that alternative using Equation (3-2) (ISO 15686-5:2008).

$$\mathrm{NPV} = \sum_{t=0}^{T}\left(\mathrm{C_t} \times \mathrm{DF}\right) = \sum_{t=0}^{T}\frac{\mathrm{C_t}}{\left(1+\mathrm{r}\right)^{t}} \tag{3-2}$$

where C_t –costs incurred at time, t; r – discount rate for converting time t costs; t – is the total time period of the study, and $\mathrm{DF} = \frac{1}{\left(1+\mathrm{r}\right)^{t}}$

In addition to the NPV, other methods exist that can also be applied to convert the life-cycle costs to a comparable index. These are: (i) The internal rate of return (IRR) on the investment, and (ii) The discounted payback period (DPP) which is the period required for an investment to recover the investment cost, taking into consideration the loss of money value with time and also due to inflation. These methods allow for a comparison of the LCC results. The higher the NPV and IRR (and the lower the DPP), the more attractive is the investment from the point of view of the investor. Of these methods the NPV is most popular.

The choice of discount rate (r in Equation (3-2)) has become a controversial issue especially for civil infrastructure such as concrete bridges, dams and pavements. The discount rate has undesirable consequences for concrete structures with long-term (positive or negative) impacts (Hanley, 1992). The further into the future cost streams occur, the lower their present value thus selecting an unrealistically high discount rate (6%), rather than a more reasonable discount rate (e.g. 2%-3%), will cause future cost streams to be insignificant (Thoft-Christensen, 2009). This creates intergenerational equity problems in that the present generations are considered more important than future generations.

Several studies have demonstrated the usefulness of LCC analysis in evaluating conventional versus alternative materials for concrete construction. These studies include Ehlen (1997) in which a methodology was developed to evaluate the LCC effectiveness of new technology materials and applied it to study the economics of fibre reinforced polymer (FRP) bridge decks as alternatives to conventional concrete. The durable and reliable tunnel structures (DARTS) project initiated by the European Union also developed a design method to carry out the economic optimization of tunnels. DARTS economic optimization method includes the direct and indirect costs and benefits of design alternatives (van Geldermalsen, 2004).

3.1.3 Single-score life-cycle assessments metrics

Ideally, an LCA of concrete and concrete structures should quantify various environmental aspects such as emissions, construction and demolition wastes and resource depletion associated with concrete over its life-cycle. The LCA results give the environmental impact of a product using either: (i) a set of mid-point indicators which are environmental impact categories such as the global warming potential (carbon equivalent emissions) and human toxicity or, (ii) end-point indicators which are a combination of a number of environmental impact categories. The mid-point LCA results represent considerable difficulty when selecting appropriate construction technologies or materials due to the different measures for environmental impacts, whereas the results of end-point indicators have a higher level of uncertainty compared to the mid-point methods, due to the subjective manner of assigning values (weighting factors) to the different impact categories in order to combine them.

Selecting a single metric eliminates the difficulty and complexity of combining different life-cycle results for use in decision making. The selected metric should be representative of a variety of environmental impacts of concrete that occur over its life-cycle. Currently, the single thermodynamic metrics applied in LCA construction studies include: carbon footprint and embodied energy. The present study carries out a review of different thermodynamic metrics for assessing environmental impacts with the objective of making a recommendation of a suitable metric that can be applied in selecting more sustainable construction materials. The selected metric will allow an engineer to compare different materials for concrete and avoid the complexity of combining different data sets for use in decision making.

3.2 Single-score thermodynamic metrics in life-cycle assessment

Thermodynamic methods covered in the current study include the carbon footprint, energy analysis (IFIAS, 1974), and exergy analysis (Wall, 1977) which represents the maximum amount of work that can be produced by a system or flow of matter or energy as it comes to equilibrium with its environment.

3.2.1.1 *Carbon footprint-based LCA*

The carbon footprint is a common metric used in construction studies. A carbon footprint is a LCA with the analysis limited to emissions that have an effect on the global warming potential (GWP). It gives the overall amount of equivalent carbon dioxide emissions (kg CO_2-eq) that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann and Minx, 2008). Huijbregts *et al*., (2006) observed a strong correlation between the GWP and the energy analysis results, for all processes in the EcoInvent database. It is assumed in literature that the results from a carbon footprint analysis would draw similar inferences about sustainable construction material choices as those from an energy analysis. However, this study shows contrary results in a later example given in Section 3.3.

3.2.1.2 *Energy–based LCA*

Energy analysis is applied to determine the amount of direct and indirect energy inputs per unit of product or service (IFIAS, 1974). The application of energy as an indicator of environmental impacts began during the politically motivated oil embargo[25] in the 1970's where oil was regarded as a core economic input (Brown and Herendeen, 1996). Though energy as an indicator for resource consumption was initially politically motivated, it is technically a suitable environmental indicator in that it is directly and indirectly linked to environmental impacts such as material and fossil fuel depletion and the emission of polluting substances which may cause global climate change.

The energy metric is a common metric used in building and construction because energy consumed during the use phase of a building or structure is significant (see Section 2.3.2.5). Estimates on the energy used in the production of materials e.g. cement, concrete and steel are documented in several studies: Hammond and Jones (2008 and 2011); Reddy and Jagadish (2003) and; Alcorn (2003). This makes the energy indicator useful for making comparisons of different studies.

Energy is a measure of the gross amount of energy requirements of the analyzed construction material, structural component or structure (Ashley and Lemay, 2008). In the energy method, all the material and energy inputs to the analyzed material/component/structure are multiplied by appropriate oil equivalent factors (g/unit), and the cumulative energy of the system is then computed as the sum of the individual oil equivalents of the inputs which can be converted to energy units (megaJoules (MJ)

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[25] Oil embargo occurred at the outbreak of the Arab-Israeli war in October 1973, when the Arabian members of OPEC imposed an oil embargo against selected Western countries, and cutback on production (Hinrichs, 1991)

or gigaJoules (GJ) per unit weight (kg or tonne) or volume (m^3)) by multiplying by the standard calorific value of 1g of oil (41 860J/g) (Ulgiati *et al*., 2006).

The term 'embodied energy' refers to the amount of energy used in a product. There is inconsistency in literature in the scope of an embodied energy analysis. Various studies have defined the scope of an embodied energy to range from "*cradle-to-gate*" whereas others (e.g. Hammond and Jones, 2008) give embodied energy values for the "*cradle-to-grave*". This latter process includes the energy used during the extraction of raw materials and processing the raw materials to the final demolition of the structure. Therefore, to distinguish the scope of embodied energy values reported in literature the embodied energy can be classified into four depending on its occurrence over the life-cycle of a structure (Cole and Kernan, 1996): (i) *Initial embodied energy* – used during resource extraction, manufacturing of raw or recycled materials to produce construction materials and transportation and construction works. (ii) *Recurring embodied energy* – associated with maintenance and repair activities over a structure's service-life. (iii) *Operation energy* – required to maintain the structure and for buildings this includes energy used during heating, cooling, ventilating and lighting of spaces inside the building. (iv) *Disassembly/ Demolition and disposal energy* – to disassemble, transport, and dispose of the materials.

3.2.1.3 *Exergy-based LCA*

The term "exergy" was introduced in the 1950's by Rant (1956) but is based on concepts founded by Carnot in 1824. Other terms used to describe exergy include: 'availability', 'available work', 'essergy' and 'available energy'. Exergy represents the maximum amount of work that can be produced by a system or flow of matter or energy as it comes to equilibrium with its environment with respect to a standard temperature T_o of 25ºC (298.15K) and pressure P_o of 1 atmosphere (101.325 kPa), and with respect to the chemical potential, μ_o of stable chemical species in the environment (Szargut *et al*., 1988; Çengel and Boles, 2011).

Thus, exergy is a measure of the potential for carrying out work contained in a material (i.e. its potential to cause changes to the surrounding environment). The exergy metric is interpreted as an assessment of the 'quantity' (energy and mass) and 'quality' (environmental impact due to use of energy and matter) of resources.

For any particular process, exergy (E_x) can be found in different forms: mechanical (potential, kinetic and electrical), physical (arising from pressure or temperature differentials) and/or chemical (arising from differences in chemical composition) (Szargut *et al*., 1988). A material generally has only the physical and chemical exergy components. Thus, the total exergy of a material is calculated as the sum of its chemical and physical (thermal) exergy as shown by Equation (3-3).

$$E_x^{Total} = E_x^{Chem} + E_x^{Thermal} \tag{3-3}$$

where: E_x^{Total} – Total exergy flow of a material [MJ]; E_x^{Chem} – is the chemical exergy of a material [MJ] given by Equation (3-5); and $E_x^{Thermal}$ is the exergy of an energy carrier [MJ], and is calculated as shown in Equation (3-4) (Szargut 2005).

$$E_x^{Thermal} = \left(1 - \frac{T_0}{T_p}\right) Q_p \tag{3-4}$$

where: Q_p – Energy from the heat source in [MJ], T_p – constant temperature of the heat source and T_o – is the reference temperature of the environment taken as 298.15K. The values in brackets are collectively referred to as the Carnot efficiency factor and represent the quality of the fuel. The Carnot efficiency factor is also equivalent to the ratio of exergy of the fuel to its gross calorific value.

The chemical exergy $\left(E_x^{Chem}\right)$ of a material is due to: (i) the reactivity of a substance that enables it to undergo a chemical reaction, and (ii) a difference in its activity relative to a reference species in the environment. E_x^{Chem} (in MJ) is computed using Equation (3-5) (Szargut 1989):

$$E_x^{Chem} = \sum_i n_i\left(\mu_i - \mu_{i0}\right) + RT\sum_i n_i \ln\left(\frac{c_i}{c_{i0}}\right) \tag{3-5}$$

where: n_i – number of moles of the material i; μ_i – is the chemical potential for the material i in its present state [J/mol]; μ_{io} – is the chemical potential for the material i in the environment in relation to its standard state [J/mol]; R – is the universal gas constant, 8.314Jmol^{-1}k^{-1}; T – is the absolute temperature [K]; c_i – is the concentration for material i in its present state and; c_{io} – is the concentration for material i in the environment in relation to its standard state. Appendix A5 shows the intermediate steps involved in the exergy calculations of materials.

Published data of standard chemical exergies of materials, including natural aggregates, are documented in Szargut (2005), Finnveden and Ostlund (1997) and Morris and Szargut (1988). DeMeester *et al*. (2006) have in addition provided up-to-date thermochemical data for minerals that are considered incomplete and inconsistent in the previous published sources. In addition, various studies give Carnot efficiency factors for different energy types, to facilitate the computation of thermal exergy of different manufacturing or construction processes. The exergy data in these studies have also been incorporated in the Swiss Ecoinvent database as well as in a number of construction studies: DeMeester *et al*. (2009) and Dewulf *et al*. (2009).

3.3 Applicability of thermodynamic metrics in selecting construction materials

This study examines the applicability of the three previously discussed metrics: carbon footprint, energy and exergy, in decision making based on a number of criteria: (i) reliability, (ii) robustness, and (iii) support in decision making. The evaluation is carried out with the objective of making a recommendation of a suitable single-score environmental quantification metric that can be applied by designers in selecting more sustainable construction materials.

3.3.1 Application of the carbon footprint, exergy and energy metrics in evaluating resource consumption in the concrete construction industry

3.3.1.1 *Example*

This section exemplifies the calculation of the carbon footprint, energy and exergy in the manufacture of materials for production of five different concrete mixes, which differ depending on the incorporation of fly ash, admixtures, and recycled aggregates. The amounts and type of materials required in producing 1 m^3 of concrete for the five different concrete types are given in ***Table 3.2***. These are necessary inputs for the carbon footprint, energy and exergy computations.

Table 3.2: *Summary of material requirements for the production of 1 m^3 for concrete grade C25/30.*

Material requirements	***Mix I***	***Mix II***	***Mix III***	***Mix IV***	***Mix V***
	NAC[##] *Quantity (per m^3)*	*Fly ash concrete* *Quantity (per m^3)*	*RAC[###]* *Quantity (per m^3)*	*RAC[###] with fly ash* *Quantity (per m^3)*	*NAC[##] with admixture* *Quantity (per m^3)*
Portland cement (CEM I 42.5 R)	337 kg	260 kg	350 kg	275 kg	290 kg
Fly ash (FA) (~30% replacement)	-	110 kg	-	115 kg	-
Fine aggregates (Quartz sand)	837 kg	802 kg	718 kg	625 kg	930 kg
Coarse aggregates (19 *mm* Granite[#])	1 050 kg	1100 kg	735 kg	770 kg	1 050 kg
Recycled concrete aggregates (~30% replacement)	-	-	315 kg	330 kg	-
Water	185 L	175 L	195 L	185 L	160 L
Chemical admixture: Superplasticizer	-	-	-	-	2.52 kg
Air volume (1.5%)	15 L	15 L	15 L	15 L	15 L
w/c ratio[####]	0.55	0.47	0.55	0.47	0.55

L : Litres.

: The dosage of superplasticizer is 0.75% by mass of cement, which corresponds to a 15% reduction in water content.

[#] : Granite aggregates have been used in this example as their chemical exergy with respect to their chemical composition is readily available in literature.

[##] : The mix proportions for the natural aggregate concrete (NAC) and fly ash concrete have been calculated using the mix design procedure for concrete given in Addis and Goodman (2009).
Fly ash has spherical particles which lower the inter-particle friction compared to angular cement particles. This in turn results in the use of less water to attain a given slump and hence, fewer capillary pores. Typical water reduction ranges from 5 – 15% in comparison with Portland cement concrete (Ballim, 2001). A 5 % water reduction level for fly ash concrete has been applied to the mix-designs

[###] : The mix proportions for recycled aggregate concrete (RAC) have been adjusted relative to those of NAC using the following recommendations given by various references:

- Limiting the content of coarse recycled aggregates content up to 20-30% by weight out of the total weight of coarse aggregates, in a structural concrete with 30 MPa. With this limitation, the final properties of the RAC have minimal effect compared to the results obtained using NAC (Kikuchi *et al*., 1988; BS 8500-2:2006)
- An increased water content of up to 5% and a corresponding increase in cement content to maintain the *w/c* ratio (Rao *et al*., 2011; Poon & Lam, 2008).
- The recycled aggregates are assumed to have a reduced relative density of up to 10% compared to that of natural aggregates (Hansen, 1992).

[####] : the *w/c* ratio (*w/b* ratio) to achieve Grade C25/30 concrete varies for plain vs. extended concrete mixes, to account for the relative cementing efficiences

In ***Table 3.2***, concrete mix I is a conventional concrete mix that uses natural aggregates and 100% Portland cement. Mix V is used to show the influence of chemical admixtures on the environmental impact of concrete. Chemical admixtures improve the workability of concrete and have been shown to produce more cost-effective concrete mixes by reducing the water content and hence the cement content to maintain the original *w/c* ratio. The concrete mixes II to IV use recycled wastes and industrial by-products as partial replacements for natural aggregates and/or Portland cement. The recycled aggregates are recovered from construction and demolition waste, whereas fly ash (FA) is a by-product of coal combustion in electricity producing plants.

30% of the natural coarse aggregates in mixes III and IV are replaced with recycled aggregates. A substitution level of up to 20-30% is assumed to have no effect on the mechanical and strength properties of concrete (Kikuchi *et al*., 1988; BS 8500-2:2006) but can result in an increase in cement and water content, due to the higher water absorption capacity of recycled aggregates compared to that of natural aggregates. Recycled aggregates have porous residual mortar lumps that result in increased water requirements of the concrete mix as shown in ***Table 3.2***. An increase in the water content results in a similar increase in the cement content in order to maintain the required water/cement (*w/c*) ratio, which in this case is 0.55 (except for FA concrete which is kept at a constant 0.47). Fly ash has spherical particles which lower the inter-particle friction compared to angular cement particles. This in turn results in the use of less water to attain a given slump. In practice, recycled aggregates are pre-soaked prior to their use or additional water for absorption is added to the mix.

3.3.1.2 *Goal, scope, functional unit and system boundary*

The goal of study in this Chapter is to assess and compare the environmental performance of 5 concrete mixes using the carbon footprint, exergy and energy environmental LCA metrics. The LCA is limited to the cradle-to-gate phase and comprises all the activities from raw material extraction to the transportation of the finished product to the construction site. The functional unit used in comparing the different concrete mixes is the volume (m^3) of concrete produced.

The system boundary for evaluating resource use in all concrete types is given in ***Figure 3-2***.

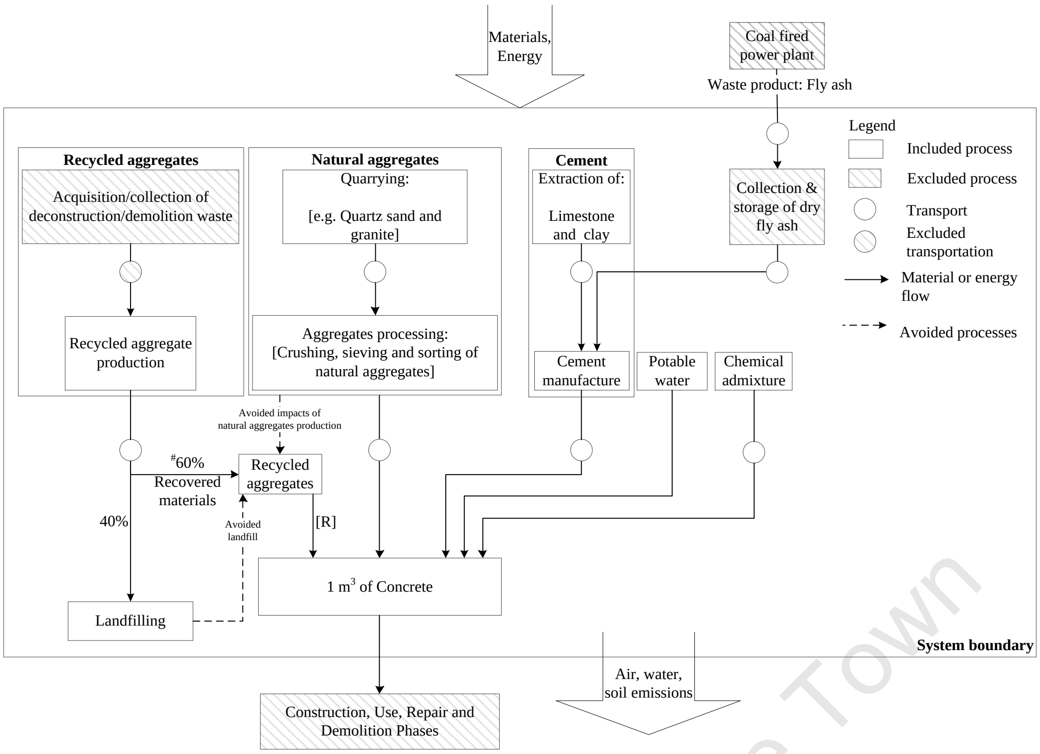

Figure 3-2: *System boundary for the concrete production case study.*

\# : The recovery ratio of recycled aggregates to waste is assumed to be 60:40 respectively (Nagataki *et al*., 2004). This means that 1.67 *ton* of debris is used in the manufacture of 1 *ton* of recycled aggregates and the amount of waste produced is 0.67 *ton*.

: The waste (unusable fine particles) produced by recycling demolition waste is assumed to be disposed of in landfill and cannot be used for other purposes

R : Proportion of material in 1 m^3 of concrete

The system boundary in ***Figure 3-2*** covers the following activities: (i) Quarrying of raw materials and manufacturing processes for all concrete constituents; (ii) Recycling processes of aggregates recovered from demolition waste and processing of fly ash which is a waste product from coal-fired power plants; (iii) Transportation of materials within processing plants and to the construction site; (iv) Avoided impacts related to the use of recycled aggregates and fly ash in concrete.

The recovery of recycled aggregates includes resource inputs and outputs due to processing and transportation of recycled materials from the recycling facility to site. However, only 60% of the recovered waste can be used as recycled aggregates and the rest is land-filled. Using recycled aggregates in concrete avoids both natural aggregate production and landfilling of demolition waste. Similarly, the use of fly ash avoids the environmental impacts due to Portland cement production. The net impacts/gain from recycling are allocated to the RAC (mix III and IV) and fly ash concrete (mix II and IV) using the 'recycled content approach'[26] represented by Equation (3-6) (which is *adapted from* PAS 2050 (Publicly Available Specification 2050), 2008).

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[26] The recycled content approach assigns environmental inputs and outputs directly caused by a product to that product. This means that the life-cycle system that utilizes resources (recycled or natural) has the responsibility for the environmental burden of the resources.

$$\text{Net recycling impact/gain} \begin{aligned} &= (1-\mathrm{R})\times \mathrm{E_V} + (\mathrm{R}\times \mathrm{E_R}) - (\mathrm{R}\times \mathrm{E_D}) \\ &= \mathrm{E_V} + (\mathrm{R}\times \mathrm{E_R}) - (\mathrm{R}\times \mathrm{E_V}) - (\mathrm{R}\times \mathrm{E_D}) \end{aligned} \tag{3-6}$$

where:

R : Proportion of recycled material input.

E_V : Environmental impacts arising from virgin material input, per unit of material.

E_D : Environmental impacts arising from disposal of waste material, per unit of material.

E_R : Environmental impacts arising from recycled material input, per unit of material.

Finally, concrete production which involves mixing of the concrete constituents and the subsequent life-cycle phases are excluded from the system boundary as they do not directly influence the concrete mix-design comparison carried out in this study. The resource inputs in the latter phases of concrete are the same for all concretes as it is assumed that all concrete mixes have similar strength (grade C25/30).

3.3.1.3 *Cradle-to-gate analysis*

This study carries out a cradle-to-gate impact assessment using three metrics: carbon footprint, energy and exergy to show the environmental effects of:

– replacing natural aggregates with recycled aggregates,
– using supplementary cementitious materials as partial replacements for Portland cement, and
– the use of chemical admixtures, in particular superplasticizers.

The exergy calculations are carried out using Equation (3-4) and Equation (3-5), on physical (thermal) and chemical exergy, respectively. Both exergies are calculated using the standard temperature of 298.15 K and pressure of 1 Atmosphere as reference conditions.

3.3.1.4 *Probabilistic analysis*

The inventory datasets in any LCA exhibit variability arising from different sources as detailed in Huijbregts (1998) and Weidema (1998). The first sources of uncertainties are termed as physical and relate to variations in material production processes, measurement errors, data handling and transcription errors depending on the quality assurance observed during the data collection, and geographical differences in data due to e.g. differences in the electrical energy mixes in different countries. The second source of uncertainty is associated with the use of simplified models or relationships between basic variables to represent actual physical phenomena. The physical uncertainty in datasets make it difficult if not impossible to say with conviction that there is a uniquely defined energy or exergy value for each material. Rather, there is a certain probability range of energy or exergy values. Thus, a probabilistic approach is a rational approach to dealing with data variability caused by physical and model uncertainties.

For this study, a statistical quantification of the input data is important as it enables a more meaningful assessment to be made on the suitability of all metrics in terms of their '*reliability*', compared to the use of deterministic values. In addition, the probabilistic approach determines whether there are significant differences in the environmental performances of the different concrete mixes investigated in the example presented in ***Table 3.2***, and also on the metrics used. The relevant statistical parameters (e.g. average (μ) and standard deviation (σ)), and probability distributions (e.g. normal, log-normal, uniform, triangular) for the input datasets have been included to improve the reliability of the results.

Ideally, the relevant statistical parameters are determined by quantifying the uncertainty in a particular dataset. An example of this is shown in ***Figure 3-3*** which gives a histogram of the number of kilns and their respective thermal energy amounts used in cement manufacture. The dataset are for a sample size (*n*) of 20 dry process kilns in South Africa (see Chapter 4). From the dataset, the mean was estimated as 3.77 *MJ/kg* of clinker and a standard deviation of 0.13 *MJ/kg*. This value of thermal energy is higher than the aforementioned World's best practice of 2.9 *MJ/kg* (http://www.energyefficiencyasia.org/docs/industrysectorscement_draftMay05.pdf).

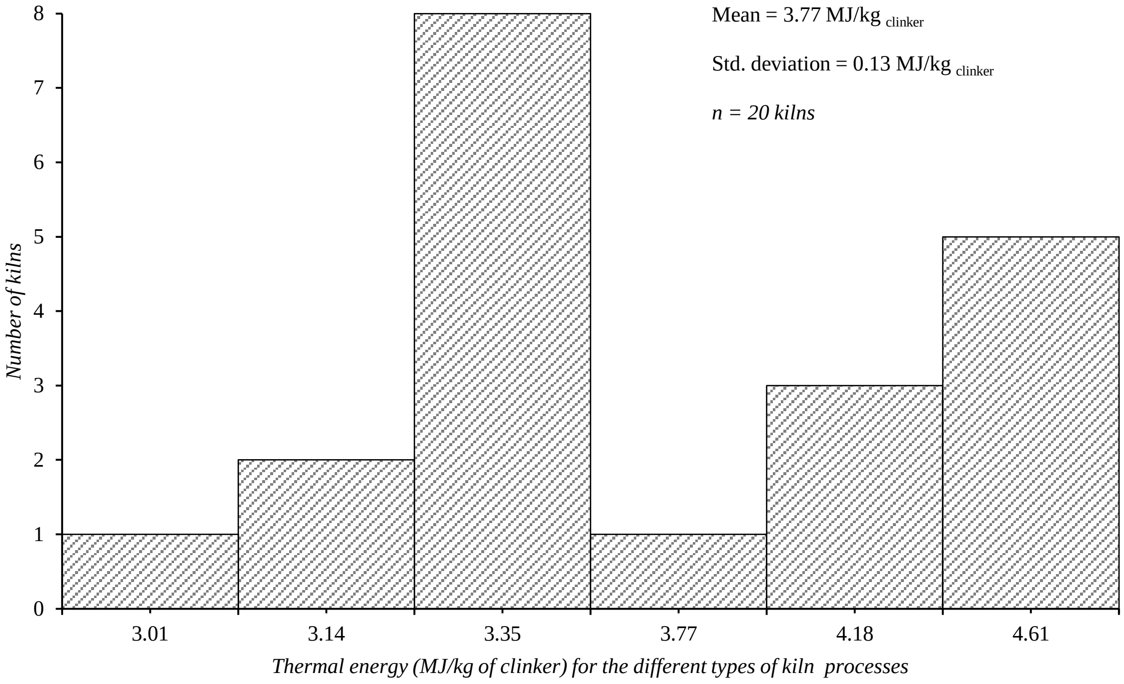

Figure 3-3: *Histogram of the thermal energy used in dry process kilns in South Africa.*

Statistical distributions are then fitted to the histogram and the best fit selected using a goodness-of-fit test such as the Kolmogorov-Smirnov (K-S) test, Chi-squared (χ) test or Anderson–Darling (A-D) test (Ang and Tang, 2007).

However, the data available, for the input variables in ***Table 3.3***, were limited to a small sample size ($n < 30$) and it was not possible to quantify the data uncertainty in the respective variables. As a result, a qualitative uncertainty estimate for each data input was determined, using a 'pedigree matrix' uncertainty estimation approach described in Frischknecht and Jungbluth (2007). The pedigree matrix (given in Appendix A) allows for an estimation of the uncertainty in data sets based on a set of 6 descriptive indicators: "reliability", "completeness", "temporal correlation", "geographic correlation", "further technological correlation" and "sample size". The uncertainty is reported as the square of the geometric standard distribution, (SD_g^2) (*refer to Appendix A*). In addition, the uncertainty estimation involves assigning a probability distribution to the input data. The pedigree matrix approach assumes a log-normal distribution for all data sets.

The unit cradle-to-gate energy and exergy of all concrete constituents are represented in energy units Mega Joules per tonne (MJ/ton) of the respective constituent and are given in ***Table 3.3***. The values in ***Table 3.3*** are presented as average (μ) and geometric standard deviation (SD_g^2).

The data sources used for the environmental impact of all concrete mix constituents, except for the superplasticizer (European Federation of Concrete Admixture Associations, 2006) were the Ecoinvent database 2.0 and the ELCD (European reference Life Cycle Database), in the SimaPro 7.1 software. The following abbreviations are used in ***Table 3.3*** to show the geographical boundaries for the life-cycle inventory data: DE = Germany; RER = Europe; CH = Switzerland.

Table 3.3: *Energy and exergy for the cradle-to-gate analysis (T^o of 25ºC and P^o of 101.325 kPa).*

*Material component***	*Life-cycle activity*	*Designation in the Ecoinvent v2.0 database*	*Energy/unit [MJ/ton]*		*Carbon equivalent/unit [kg CO_2-eq/ton]*		*Exergy/unit [MJ/ton]*	
			Mean (μ)	*SDg^2*	*Mean (μ)*	*SDg^2*	*Mean (μ)*	*SDg^2*
Portland cement (CEM I 42.5R)	Extraction of raw materials, onsite transportation and manufacture	*Portland cement, strength class CEM I 42.5, at plant/kg/CH U*	*3 800*	*1.30*	*821*	*1.30*	*74 200*	*1.30*
	Transportation to site (100 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*327*	*2.01*	*20*	*2.01*	*1 420*	*2.01*
	Total		***4 127***		***841***		***75 620***	
Fly Ash	Transportation to processing plant from the coal fired power plant (5 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*16.3*	*2.01*	*1*	*2.01*	*71.2*	*2.01*
	Transportation to cement plant from processing plant (5 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*16.3*	*2.01*	*1*	*2.01*	*71.2*	*2.01*
	Transportation to site (100 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*327*	*2.01*	*20*	*2.01*	*1 420*	*2.01*
	Total		***360***		***22***		***1 562***	
Fine Aggregates (NFA)	Extraction of raw materials, onsite transportation and manufacture	*Sand, at quarry/CH U*	*57.9*	*1.14*	*2.39*	*1.14*	*1 430*	*1.14*
	Transportation to site (50 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*163*	*2.01*	*10*	*2.01*	*712*	*2.01*
	Total		***221***		***12.4***		***2 142***	
Natural Coarse Aggregates (NCA)	Extraction of raw materials, onsite transportation and manufacture	*Crushed stone 16/32, open pit mining, production mix, at plant, undried RER S*	*265*	*1.40*	*0.9*	*1.40*	*374*	*1.40*
	Transportation to site (50 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*163*	*2.01*	*10*	*2.01*	*712*	*2.01*
	Total		***428***		***10.9***		***1086***	

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[a] : Typical transportation distances of materials to site; A sensitivity analysis will be carried out later to show the influence of transportation distances on the environmental impact of concrete.

[b] : The recovery ratio of recycled aggregates to waste is assumed to be 60:40 respectively (Nagataki *et al*., 2004). This means that 1.67 ton of debris is used in the manufacture of 1 ton of recycled aggregates and the amount of waste produced is 0.67 ton.

[c] : Superplasticizer data source is the European Federation of Concrete Admixture Associations (2006)

: E_V, E_R and E_D are defined in Equation (3-6); SD_g geometric standard deviation
U – Unit LCI processes (cradle-to-cradle); S – system LCI that includes the subsystems of all inputs (from cradle-to-gate)

*Continued…**Table 3.3:** Energy and exergy for the cradle-to-gate analysis (T^o of 25ºC and P^o of 101.325 kPa).*

*Material component***	*Life-cycle activity*		*Designation in the Ecoinvent v2.0 database*	*Energy/unit [MJ/ton]*		*Carbon equivalent/unit (kg CO_2-eq/ton)*		*Exergy/unit [MJ/ton]*	
				Mean (μ)	*SDg^2*	*Mean (μ)*	*SDg^2*	*Mean (μ)*	*SDg^2*
Recycled Concrete Aggregates (RCA)	**E_V**	Avoided natural aggregate production	-	*428*		*10.9*		*1086*	
	E_R	RCA production (Includes all processes from the feeding of rubble into the plant to production of final product)	*(Based on material and fuel input flows from SARMa (Sustainable Aggregates Resource Management) (2011))*	*43.8*	*1.40*	*2.66*	*1.40*	*711*	*1.40*
		Transportation of recycled aggregates to site (50 *km*)[a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*163*	*2.01*	*10*	*2.01*	*712*	*2.01*
		Transportation of non-recyclable waste to landfill (25 *km*) (0.67 tonnes)[b]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*54.7*	*2.01*	*3.4*	*2.01*	*239*	*2.01*
		Disposal of non-recyclable waste (0.67 tonnes)[b]	*Disposal, concrete, 5% water, to inert material landfill/ CH U*	*133*	*1*	*4.76*	*1*	*408*	*1*
	E_D	Avoided landfill: Transportation of waste to landfill (25 *km*)	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*81.7*	*2.01*	*5*	*2.01*	*356*	*2.01*
		Avoided landfill: Disposal of demolition waste to landfill (25 *km*)	*Disposal, concrete, 5% water, to inert material landfill/ CH U*	*198*	*1*	*7.1*	*1*	*608*	*1*
Water		**Total**	*Tap water, at user/CH U*	***6***	***1.07***	***0.2***	***1.07***	***251***	***1.07***
Super-plasticizer		Processing [c]	*Input resources and emissions to air, land and water [c]*	*17 500*	*1*	*751*	*1*	*17 200*	*1*
		Transportation to site (30 *km*) [a]	*Transport, Truck 20-28t, fleet average/tkm/CH U*	*98*	*2.01*	*6*	*2.01*	*427*	*2.01*
		Total		***17 598***		***757***		***17 627***	

---

[a] : Typical transportation distances of materials to site; A sensitivity analysis will be carried out later to show the influence of transportation distances on the environmental impact of concrete.

[b] : The recovery ratio of recycled aggregates to waste is assumed to be 60:40 respectively (Nagataki *et al*., 2004). This means that 1.67 ton of debris is used in the manufacture of 1 ton of recycled aggregates and the amount of waste produced is 0.67 ton.

[c] : Superplasticizer data source is the European Federation of Concrete Admixture Associations (2006)

: E_V, E_R and E_D are defined in Equation (3-6); SD_g geometric standard deviation as given in Appendix A2
U – Unit LCI processes (cradle-to-cradle); S – system LCI that includes the subsystems of all inputs (from cradle-to-gate)

Figure 3-4 gives the flow of materials and energy required in the production of *mix I* and the corresponding energy of 2.02 x 10^3 MJ/m^3.

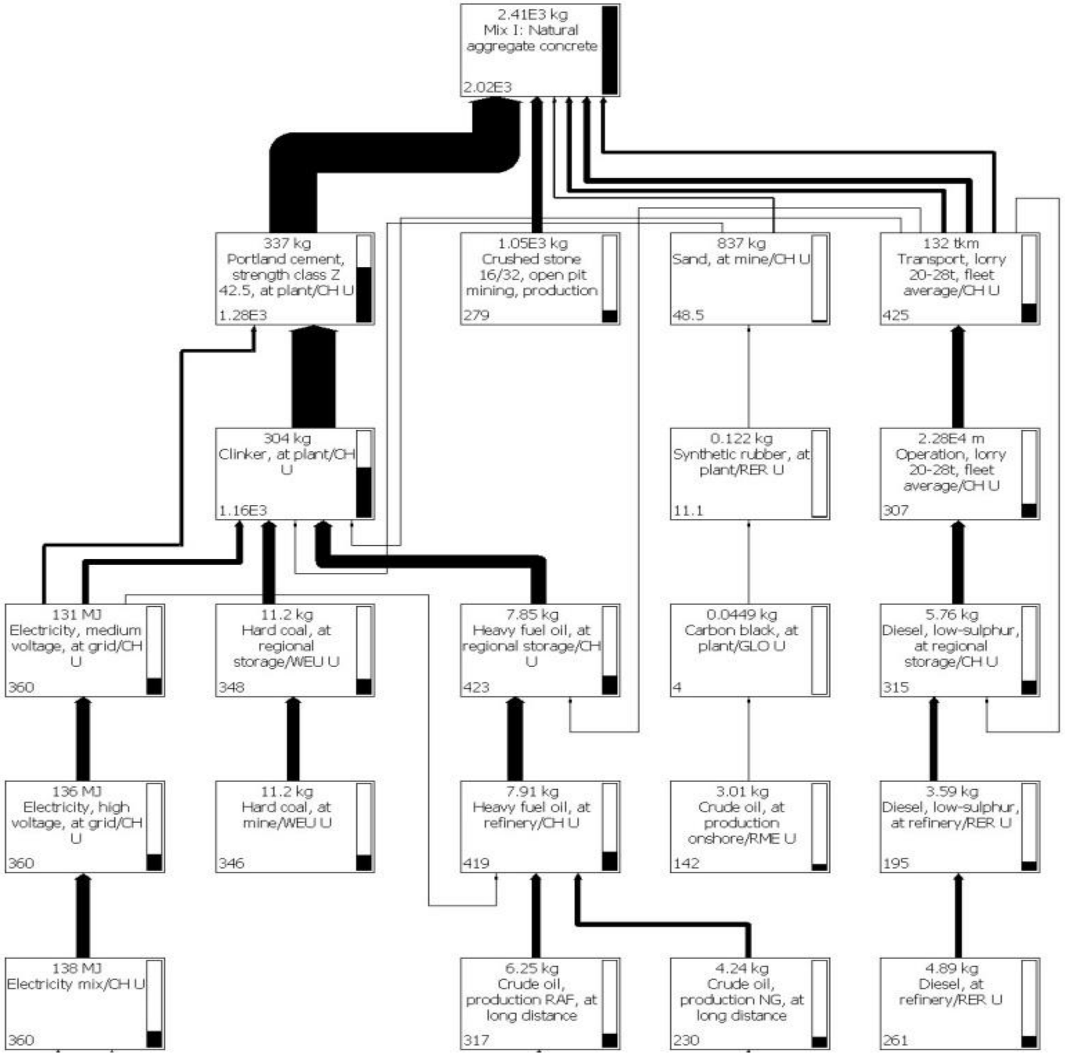


Figure 3-4: *Environmental impact flow for the production of 1* m^3 *of natural aggregate concrete (calculated using SimaPro 7.1: PRé Consultants, 2008).*

3.3.2 Results

3.3.2.1 *Carbon footprint analysis results*

Results for the cradle-to-gate carbon footprint analysis for all concrete types are summarized in ***Figure 3-5***. The bar charts show the average kg CO_2-eq values per unit volume of concrete.

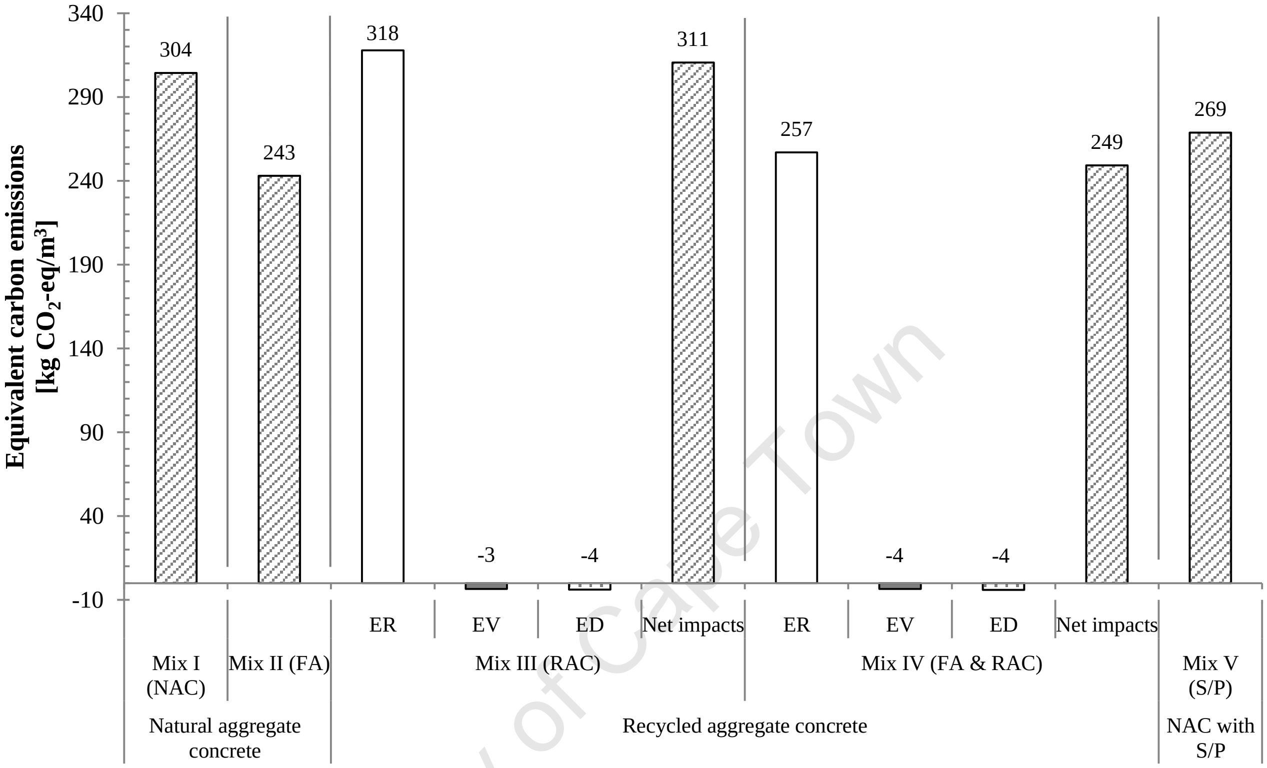


Figure 3-5: *Comparative assessment of embodied carbon estimates (and avoided impacts) for 5 concrete types.*

ER : Environmental impacts arising from fly ash replacement and/or recycled aggregate input.
EV : Environmental impacts from avoided production of virgin materials.
ED : Environmental impacts from avoided landfill/ashdump of recycled aggregates and fly ash.
S/P : Superplasticizer

Figure 3-5 shows that mix II (NAC with fly ash) has the lowest impact of 243 kg CO_2-eq/m^3 whereas the highest is that of mix III (RAC) with 311 kg CO_2-eq/m^3. The use of a chemical admixture in mix V resulted in a 12% reduction in embodied CO_2-eq emissions than mix I. In summary, the order of preference for the five concrete mixes based on a carbon footprint analysis is: mix II, mix IV, mix V, mix I, and lastly mix III.

3.3.2.2 *Embodied energy analysis results*

Results for the cradle-to-gate energy analysis for all concrete types are summarized in ***Figure 3-6***. The bar charts show the average energy values per unit volume of concrete.

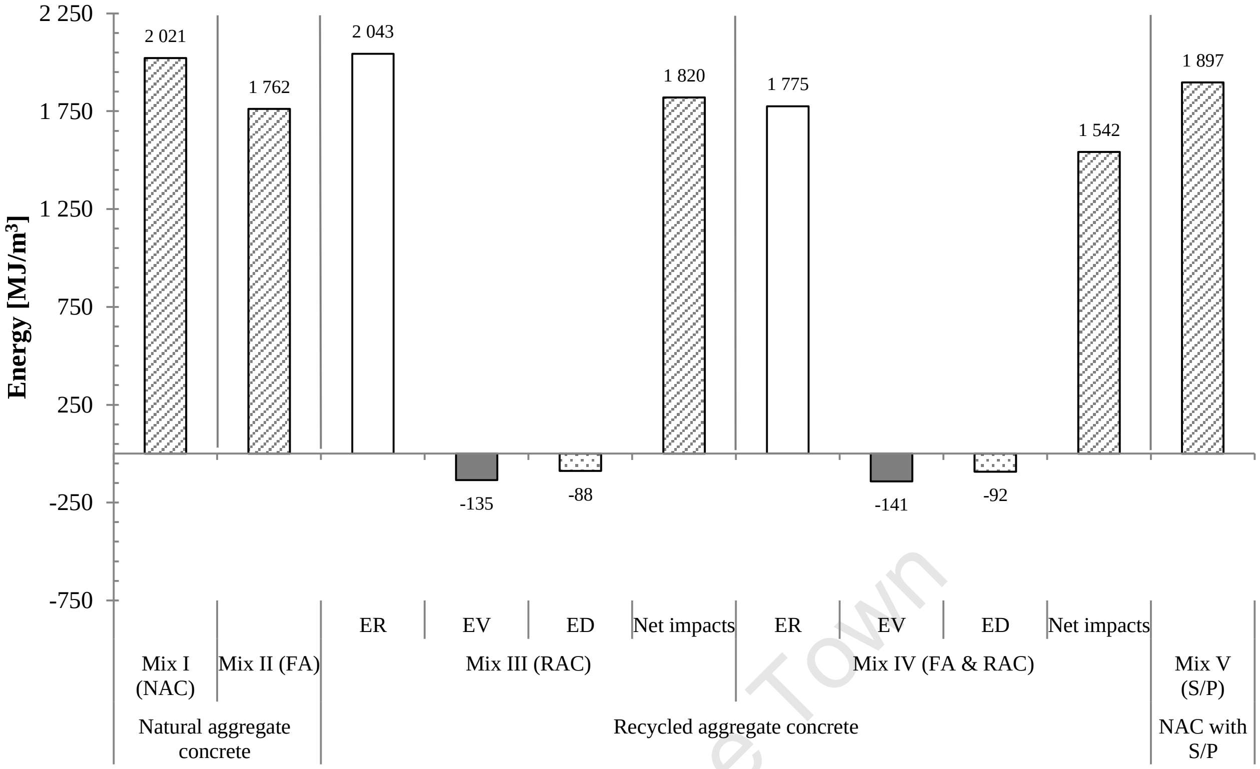


Figure 3-6: *Comparative assessment of embodied energy estimates (and avoided impacts) for 5 concrete types.*

ER : Environmental impacts arising from fly ash replacement and/or recycled aggregate input.
EV : Environmental impacts from avoided production of virgin materials.
ED : Environmental impacts from avoided landfill/ashdump of recycled aggregates and fly ash.
S/P : Superplasticizer

Figure 3-6 shows that mix IV (RAC with fly ash) has the lowest 'initial embodied' energy 1 542 MJ/m^3 whereas the highest is that of mix I (NAC) with 2 021 MJ/m^3. The use of a chemical admixture in mix V resulted in a 7% reduction in embodied energy than mix I. In summary, the order of preference for the five concrete mixes based on an energy analysis is: mix IV, mix II, mix III, mix V, and lastly mix I.

3.3.2.3 Embodied exergy analysis results

Figure 3-7 shows the values of exergy for the 5 different concrete mix designs. The bar charts show the average exergy values per unit volume of concrete.

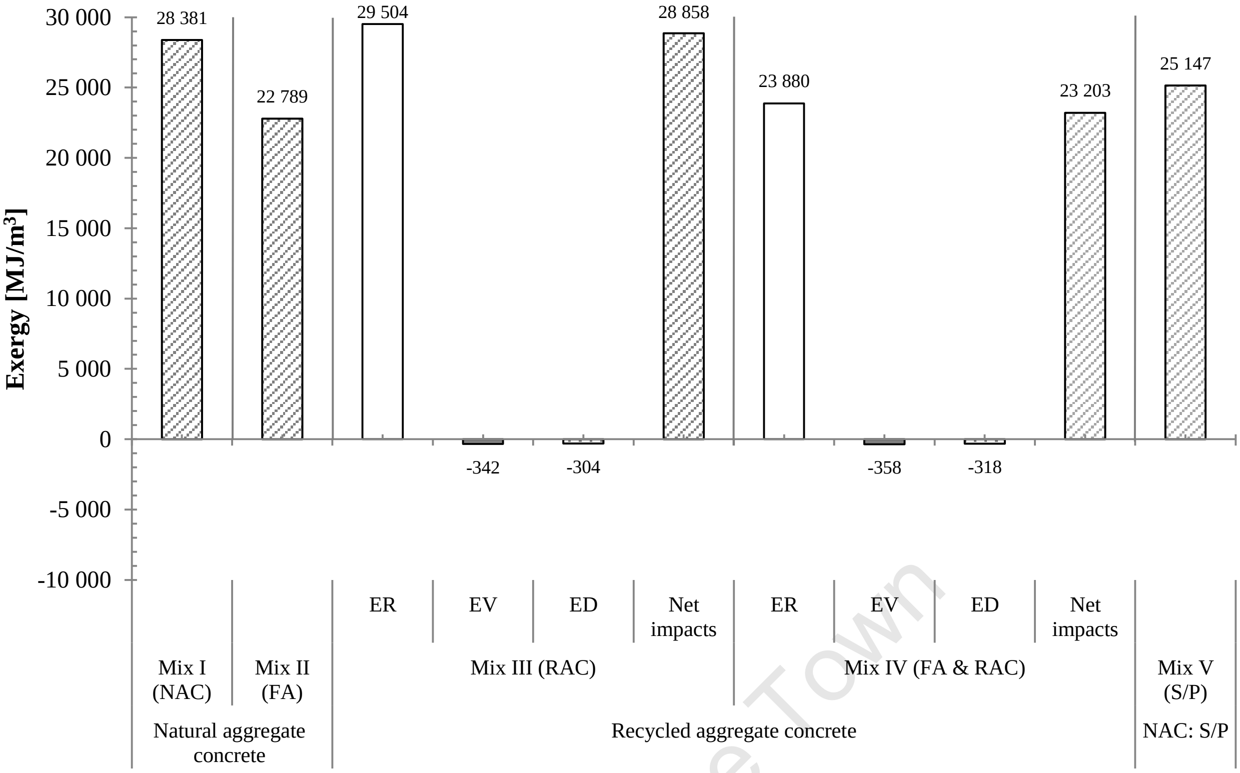


Figure 3-7: *Comparative assessment of exergy estimates for 5 concrete types.*

ER : Environmental impacts arising from fly ash replacement and/or recycled aggregate input.
EV : Environmental impacts from avoided production of virgin materials.
ED : Environmental impacts from avoided landfill/ashdump of recycled aggregates and fly ash, respectively.

From ***Figure 3-7***, the use of a chemical admixture in mix V resulted in a 12% reduction in embodied exergy than mix I. Also, the use of fly ash in mix II resulted in a 20% reduction in embodied exergy than mix I. The order of preference for the five concrete mixes is: mix II, mix IV, mix V, mix I, and finally, mix III.

3.3.2.4 Comparison of energy and exergy analysis results

From ***Figure 3-6*** and ***Figure 3-7*** it is clear that use of the two different metrics leads to different decisions on concrete mix choices. For the energy analysis mix designs containing recycled aggregates are preferred whereas this is contrary for the exergy analysis.

The different outcomes arise from the fact that the exergy metric is a more comprehensive indicator and accounts for both the energy and non-energy resources. For example when comparing the use of concrete made using natural aggregates (mix I) and recycled aggregates (mix III), the exergy of the latter is higher whereas the energy metric gives a converse result. The production of recycled aggregates results in the consumption of additional non-energy resources (e.g. water). These additional non-energy resources are not accounted for by the energy metric hence its preference for the use of recycled aggregate concrete (*mix III*) to natural aggregate concrete (*mix I*).

3.3.2.5 Comparison of energy and carbon footprint analysis results

Figure 3-5 and ***Figure 3-6*** show that the use of the carbon footprint and energy metrics leads to different decisions on concrete mix choices. This is because in addition to the energy use the carbon footprint also accounts for the carbon emissions from materials e.g. calcination of limestone. Calcination refers to the decomposition of limestone ($CaCO_3$) to calcium oxide (CaO), in the process liberating CO_2. The calcination process is shown later, in Chapter 4, to account for over half of the CO_2-eq emissions generated during cement production.

3.3.2.6 Comparison of carbon footprint and exergy analysis results

From ***Figure 3-5*** and ***Figure 3-7*** it is shown that the two different metrics leads to similar decisions on concrete mix choices. The practice of blending cements contributes to the conservation of natural resources and a reduction in the amount of CO_2-eq emissions. These two effects are captured by the exergy metric and carbon footprint, respectively. However, in a case where the amount of Portland cement is minimal for all concrete mixes under comparison e.g. such as with the use of geopolymer binders, then exergy would be the preferred metric as it is able to capture the effect of resource conservation due to the use of chemical admixtures and the use of recycled materials.

3.3.2.7 Probabilistic comparative assessment of natural aggregate concrete with recycled aggregate concrete

This study shows the exergy and carbon footprint methods lead to similar choices of concrete mixes. Exergy is able to account for both mineral resources and energy in the same units, whereas the carbon footprint accounts for the carbon emissions from cementitious materials and energy sources. In future cases, where the amount of Portland cement use in concrete will be much reduced, then it is foreseeable that exergy would be a more suitable metric.

The study also showed that the exergy metric gave different results to the energy metric particulary with the choice of use of recycled aggregates in concrete. It is important to investigate whether there are significant differences in the environmental impact results from these two metrics in the use of recycled aggregates. This investigation can be carried out using a probabilistic analysis of mix I (NAC) and mix III (RAC).

The probabilistic computations of energy, and exergy for mix I and III is carried out using Monte Carlo Simulation (MCS) techniques, specifically the bootstrapping technique. This requires the use of an estimated probability distribution that would provide the best fit to the data (Efron and Tibshirani, 1993). Random values are then sampled from each of the defined probability distributions to obtain possible exergy/energy values of each concrete mix. The process is repeated a sufficient number of trials (10 000 iterations) to reduce the inherent error involved in a MCS process. The results are then presented in the form of probability density functions.

The probability density functions for the cradle-to-gate energy and exergy of *mix I* and *mix II* are given in ***Figure 3-8*** and ***Figure 3-9***, respectively.

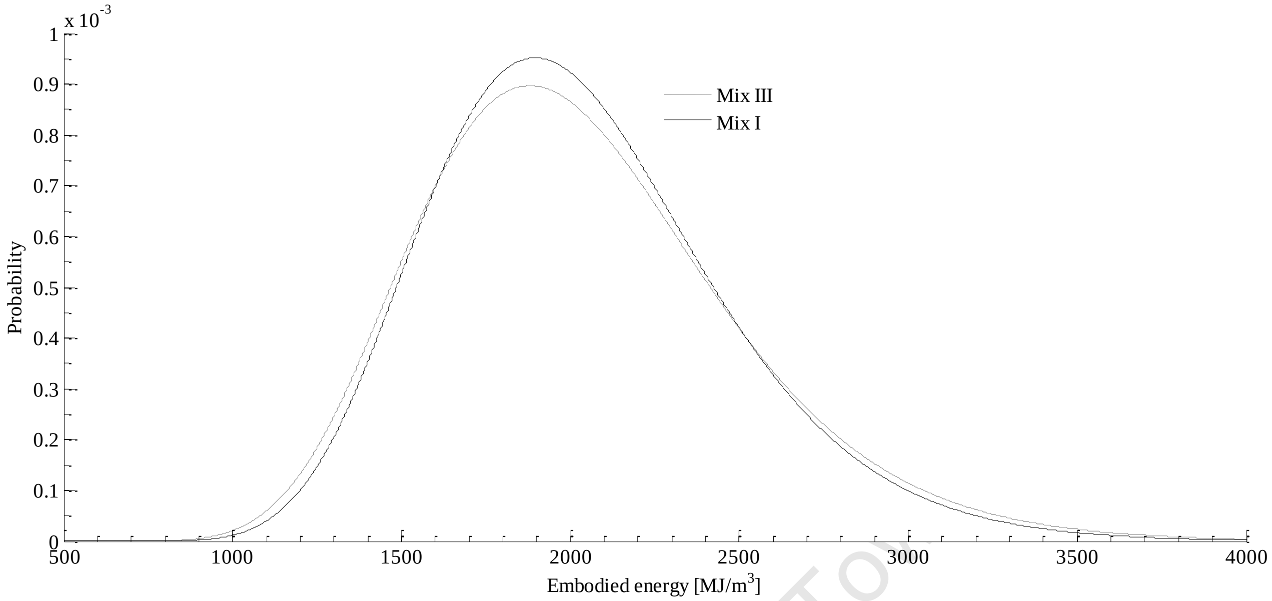


***Figure 3-8**: Probability density functions giving a comparison of energy estimates for natural aggregate concrete (Mix I) and recycled aggregate concrete (Mix III).*

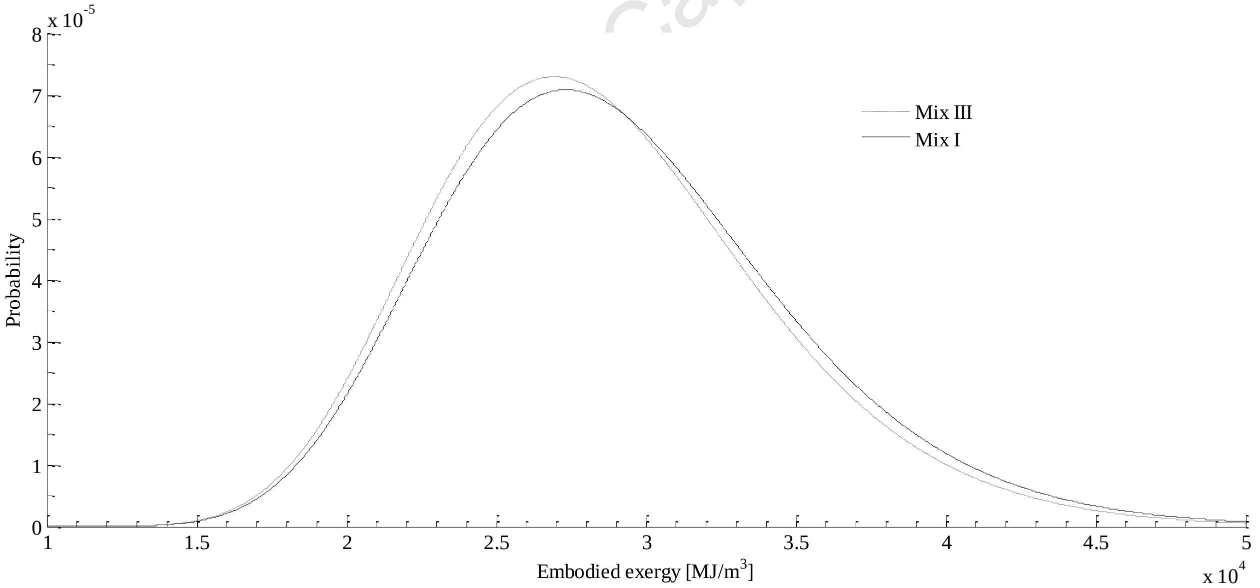


***Figure 3-9:** Probability density functions giving a comparison of exergy estimates for natural aggregate concrete (Mix I) and recycled aggregate concrete (Mix III).*

The probability density functions for mix I and mix III overlap for both metrics. However, the significance of the difference between the two mix designs using a comparison index (CI) (Huijbregts, 1998b) shows the two mixes to be distinct. A CI is described as the ratio between the environmental impact for the two mix designs, for each Monte Carlo simulation run, as expressed by Equation (3.7).

$$\text{Comparison index} = \frac{n(EI\ mixIII > EI\ mixI)}{N} \tag{3-7}$$

where:

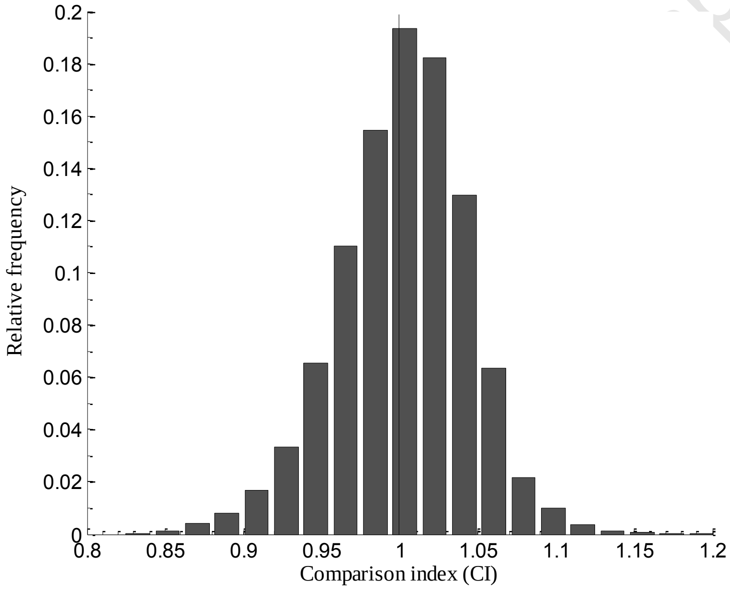
N : number of Monte Carlo simulation runs

n : Number of times the environmental impact of Mix III exceeds that of Mix I

EI : Environmental Impact

For Equation (3.7), if the CI is significantly lower than 1, then, the design mix III has a lower impact than design mix I, and vice versa.

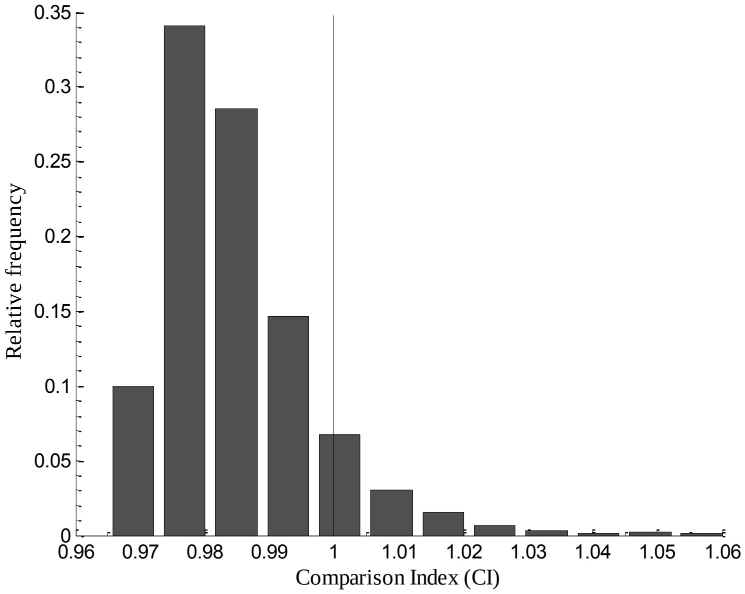
The frequency distributions for the CI using the energy metric (***Figure 3-10***) shows that the use of recycled aggregates in concrete (mix III) has a lower environmental impact compared to natural aggregates (mix I), at a 60% significance level. However, at a 90% significance level, there is no difference in the results of both concrete types.



$$CI = \frac{Energy\ \ Mix\ \ III}{Energy\ \ Mix\ \ I}$$

Figure 3-10: *Relative frequency histogram showing the comparison index of energy estimates for natural aggregate and recycled aggregate concrete types.*

The frequency distributions for the CI of exergy (***Figure 3-11***) show that the environmental impact of mix I is less than that of mix III, at a 90% significance level.



$$CI = \frac{Exergy\ \ Mix\ \ I}{Exergy\ \ Mix\ \ III}$$

Figure 3-11: *Relative frequency histogram showing the comparison index of exergy estimates for natural aggregate and recycled aggregate concrete types.*

Thus, based on the probabilistic analysis, both metrics are found to suggest different concrete mix choices with regard to the decision of using recycled aggregates in concrete. Using the energy metric, the use of recycled aggregates in concrete was found to have a lower environmental impact compared to natural aggregates, at a 60% significance level. However, the exergy metric showed the environmental impact of natural aggregate concrete (NAC) to be less than that of recycled aggregate concrete (RAC) at a 90% significance level. This simply means that with the exergy metric, the use of NAC is preferred to RAC, 90% of the time.

3.3.2.8 *Sensitivity analysis of material transportation distances*

A sensitivity analysis was performed to investigate the influence of the transportation distances for recycled aggregates and supplementary cementitious materials on the environmental impact of concrete.

Figure 3-12 shows the results of a sensitivity analysis on the transportation distance of fly ash, from the processing plant to the cement factory.

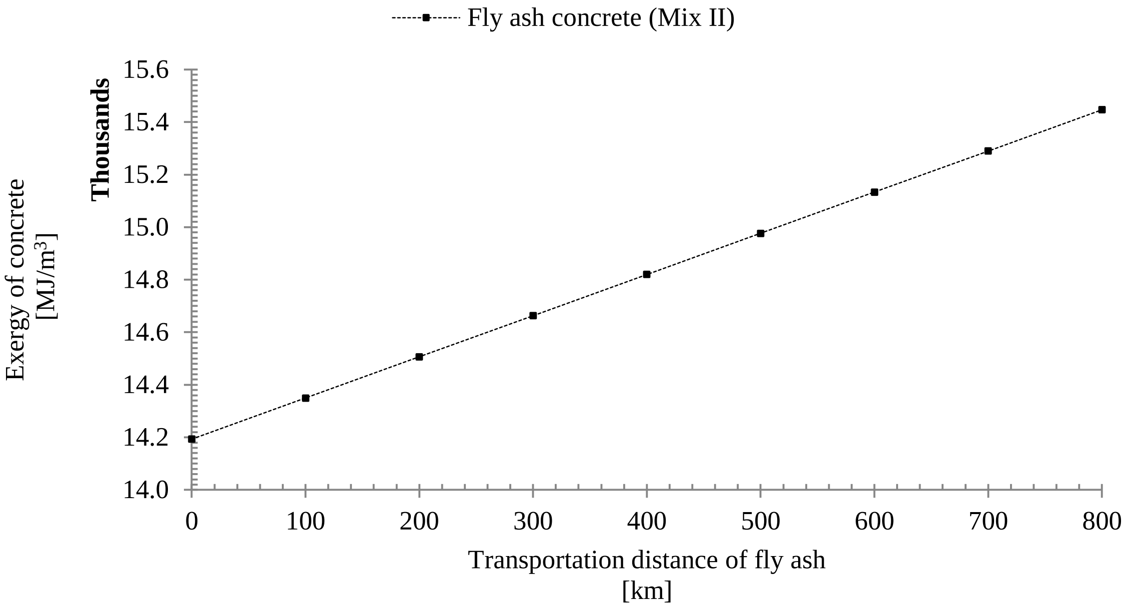


Figure 3-12: *Sensitivity of transportation distances of fly ash on the embodied exergy of a cubic metre of concrete.*

From ***Figure 3-12***, it can be observed that increasing the transportation distance from 0 km to 800 km, by increments of 100 km, whilst holding all other parameters in ***Table 3.3*** constant, increases the embodied exergy by a rate of 1.0% ~ 1.1% for every 100 km. Thus, the transportation distance of fly ash from the processing plant to the cement factory has a minimal effect on the embodied exergy of concrete made using fly ash.

Figure 3-13 illustrates the results of the second sensitivity analysis, whereby the transportation distance of recycled aggregates was varied between 0 km (site-derived) and 100 km.

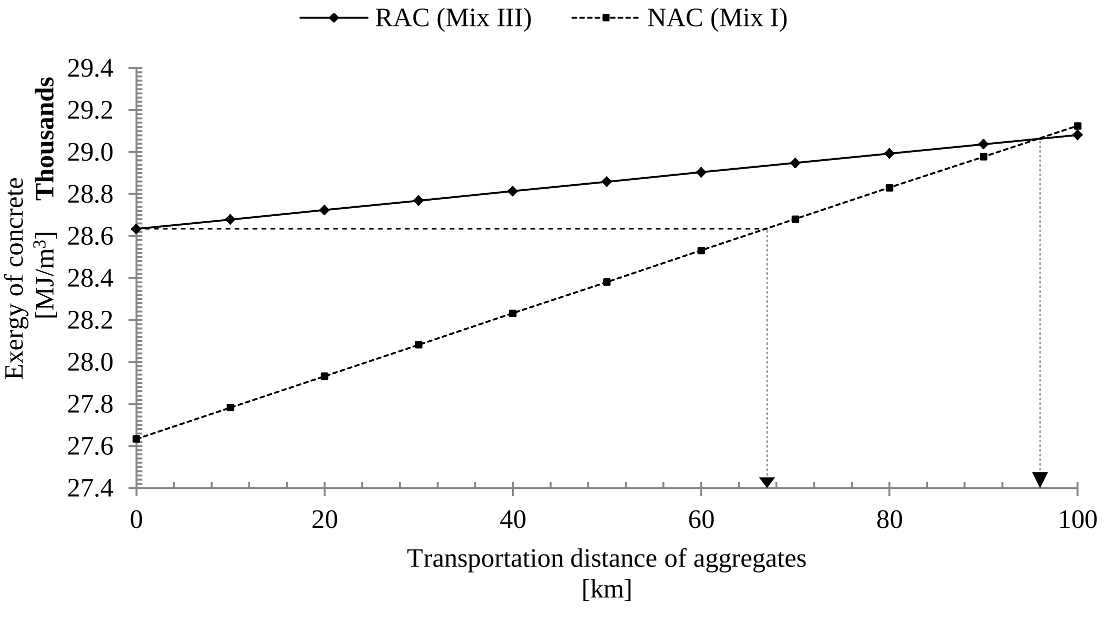


Figure 3-13: *Sensitivity of transportation distances of aggregates on the embodied exergy of a cubic metre of concrete*

The recycled aggregate concrete (RAC) results in ***Figure 3-13*** are obtained by increasing the transportation distance of recycled aggregates from 0 km to 100 km, by increments of 10 km, whilst holding all other parameters in ***Table 3.3*** constant. The constant parameters include the 50 km transportation distance of natural aggregates in the RAC mix.

From ***Figure 3-13***, it can be observed that concrete made using site-derived recycled aggregates has the same environmental impact as concrete made using natural aggregates that have been transported for a distance of 67 km. Also at a transportation distance of over 96 km for natural aggregates, the use of recycled aggregates is more environmentally feasible.

3.4 Discussion

This section compares the results of the three thermodynamic metrics: carbon footprint, energy and exergy, and examines their applicability in decision-making based on their ability to meet a set of criteria: (i) *reliability*; (ii) *robustness*; and; (iii) s*upport in decision making*. The following comparison between the metrics is summarized in the order of these criteria.

3.4.1.1 Reliability of the metric

Theoretically all metrics should give consistent results since they measure resource consumption in physical units, independent of time and place, and are not prone to inflation or other economic factors. The reliability of the energy and exergy metrics was further evaluated based on the results of an uncertainty analysis of the data. From the cumulative density functions of energy and exergy given in ***Figure 3-8*** and ***Figure 3-9***, respectively, the reliability of the results at 95% confidence level is summarized in ***Table 3.4*** (*see Appendix A for calculations*).

Table 3.4: *Summary statistics for the embodied energy and exergy results from a probabilistic analysis*

Statistic	***Confidence level***	***Embodied energy values of concrete[MJ/m^3]***		***Embodied exergy values of concrete [MJ/m^3]***	
		NAC (mix I)	RAC (mix III)	NAC (mix I)	RAC (mix III)
Average		2 038	2 034	28 589	29 058
Standard deviation		475	444	5 742	5 923
Lower percentile (5th Percentile)	0.025	2 029	2 025	28 476	28 941
Upper percentile (95th percentile)	0.975	2 047	2 043	28 702	29 174
Confidence interval width	-	18	18	113	233
Margin of error	-	9	9	57	117

References in Table 3.4
NAC : Natural aggregate concrete
RAC : Recycled aggregate concrete
COV : Coefficient of variation

The variability in both metrics in ***Table 3.4*** is compared using the margin of error[27]. A confidence interval of 95% in the NAC (mix I) embodied energy gives a margin of error of 9 MJ/m^3 whereas the

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[27] Margin of error is calculated as the confidence interval divided by 2

respective spread for exergy in mix I is 57 MJ/m^3. Hence, the exergy analysis is reported to have higher variability compared to energy analysis.

However it should be noted that although similar standard deviations, measured using the square of the geometric standard deviation (SD_g^2) were assigned to the energy and exergy values of the parameters in ***Table 3.3***, the overall variability of the exergy values is higher than that of energy as the exergy data has higher mean values. Further studies are required to establish the actual standard deviation of the respective energy and exergy values. This should be arrived at by collecting energy and exergy datasets for each parameter in ***Table 3.3*** and quantifying their respective uncertainty.

3.4.1.2 *Robustness*

Energy provides weak reflections of the environmental impacts of non-fuel materials e.g. mineral resources and metallic ores (Ayres, Ayres and Martinas 1998). An energy analysis *per se* does not account for consumption of non-energy resources such as natural aggregates and water and only energy consumed in their transportation or processing is considered. Other complementary methods e.g. material flows [in kg] (Griffiths, Smith and Kersey, 2003) are usually applied to cover impacts due to consumption of non-fuel resources. However, the different units, *kg* vs. *MJ*, make them difficult to combine during decision making, and thus a comparison can only be done qualitatively or by weighting the results. Exergy foregoes this hindrance by accounting for both mineral and fuel resources in the same units, and hence is a more robust metric compared to energy. Also, the carbon footprint accounts for the CO_2-eq emissions from energy resources and cementitious materials used in concrete. Hence, it is also a more robust metric compared to energy.

3.4.1.3 *Support in decision making*

Based on the review of literature, it can be seen that the carbon footprint and energy are well-established environmental impact indicators. On the other hand, the focus of exergy analysis has previously been on the optimization of thermal industrial processes. However, based on this study, exergy analysis can be extended to account for resource consumption in the construction industry and in particular provide information for decision making during the design process of concrete structures.

3.5 Recommended metric for resource consumption

Based on the comparison of three thermodynamic metrics: the carbon footprint, energy and exergy, this study showed that the exergy and carbon footprint methods are more suitable metrics than energy in selecting sustainable materials, due to the following:

- The exergy analysis gives not only the mass of raw materials (i.e. quantity) but also their quality expressed as exergy content and is therefore an improved measure compared to energy analysis.
- Exergy is a robust metric and is able to account for both fuel and non-fuel resources using one set of units. This avoids subjective weights setting in the evaluation of resource consumption.

- The carbon footprint accounts for the carbon emissions from cementitious materials and energy sources. However, it should be noted that in future cases, where the amount of Portland cement use in concrete is much reduced, then it is foreseeable that exergy will be a more suitable metric.

However, the study shows that the exergy method, though suited for the application, is tedious in its computations and requires detailed knowledge of the chemical compositions of the materials. In addition exergy values for mineral ores presented in this study refer to those of a specific region, a petrologic examination is required for determining the composition of ores or rock in a particular region.

Current databases on exergy values are contained in the Ecoinvent database (Bösch, Hellweg, Huijbregts and Frichknecht 2007) which gives an inventory of exergy values for a number of different resources for the Swiss construction industry. In addition, there is a need to develop a software tool for the design of concrete structures that integrates the carbon footprint/exergy analysis and also consider other aspects, such as functionality and costs, which are necessary in the design of more sustainable concrete structures.

Although exergy is suggested herein as a suitable indicator for the resource consumption in the concrete construction industry, it is not applied in the subsequent Chapters for the following reasons:

1. Chapter 4 requires the use of case-specific environmental impact data on the local construction industry. The available data are presented in terms of the GWP_{100} potential.
2. Chapter 6 gives the LCA results of the two case studies in this study. To compare the results with other LCA studies there is a need to use the GWP_{100} and/or energy metrics, which are currently the main single score metrics used.
3. The available exergy data in Ecoinvent database are not comprehensive and exergy data on a number of building elements e.g. Polyvinyl chloride, expandable polystyrene etc. are not available. These data are therefore not included in the building LCA results in Chapter 6.

3.6 Summary

This study found it necessary to identify a suitable ‘single-score’ measure for evaluating the use of different non-renewable and renewable materials and energy resources by RC structures relative to the availability of these resources in the physical environment. A ‘single-score’ metric represents a variety of environmental impacts and eliminates the difficulty and complexity of combining a number of environmental impact categories such as ‘mineral resource depletion’ and ‘fossil fuel depletion’. A ‘single-score’ metric would be useful for decision making and allow for the selection of more sustainable concrete constituent materials and production processes.

It was mentioned in Chapter 3 that an appropriate metric should be integrated into the existing life-cycle assessment procedure (ISO 14040: 2006; ISO 14044: 2006) for assessing environmental aspects of products and processes. In addition, the proposed metric should be founded on scientific principles. This means that the metric should quantify life-cycle environmental impacts of materials in physical units and should give consistent results, independent of time and place, i.e. it should not be prone to inflation or other factors. As such, this study used five concrete mix-designs to examine the applicability of three metrics: carbon footprint, energy and exergy, in decision making. A carbon footprint is a life-cyle assessment (LCA) with the analysis limited to emissions that have an effect on the global warming potential. It gives the amount of equivalent carbon dioxide emissions that is accumulated over the life stages of a product. Energy is a measure of the gross amount of energy requirements of a product, whereas exergy is a measure of the potential for carrying out work contained in a material (i.e. its potential to cause changes to the surrounding environment). The exergy metric is interpreted as an assessment of the ‘quantity’ (energy and mass) and ‘quality’ (environmental impact due to use of energy and matter) of resources.

Using the three single-score metrics, the environmental impact of five concrete mixes were assessed and compared to show the effects of:

- replacing natural aggregates with recycled aggregates,
- using supplementary cementitious materials as partial replacements for Portland cement, and
- the use of chemical admixtures, in particular superplasticizers.

An environmental assessment of the five mix designs showed that the use of the energy metric leads to different decisions on concrete mix choices than those arrived at using the exergy and carbon footprint metrics. For the energy analysis, concrete mix designs containing recycled aggregates were preferred over those with 100% natural aggregates, whereas the converse was found to be true for the exergy metric and carbon footprint. The different outcomes arise from the fact that the exergy metric is more comprehensive and accounts for both energy and non-energy resources. The production of recycled aggregates results in the consumption of additional non-energy resources (e.g. additional water in the concrete mix-design). These additional non-energy resources are not accounted for by the energy metric hence its preference for the use of recycled aggregate concrete to natural aggregate concrete. Similarly, the carbon footprint and energy metric give different results. This is because in addition to the energy use the carbon footprint also accounts for the carbon emissions from materials e.g. calcination of limestone. Calcination refers to the decomposition of limestone ($CaCO_3$) to calcium oxide (CaO), in the process liberating CO_2. The calcination process was shown, in this study (Chapter 4), to account for over half of the CO_2-eq emissions generated during cement production.

The carbon footprint was shown to give similar results to the exergy metric. The practice of blending cements contributes to the conservation of natural resources and a reduction in the amount of CO_2-eq emissions. These two effects are captured by the exergy metric and carbon footprint, respectively. However, in a case where the amount of Portland cement is minimal for all concrete mixes under comparison e.g. such as with the use of geopolymer binders, then exergy would be the preferred metric as it is able to capture the effect of resource conservation due to the use of chemical admixtures and the use of recycled materials.

All the metrics captured the benefit of using superplasticizers in concrete mixes. Both the carbon footprint and exergy metric showed that the use of superplasticizers leads to a 12% reduction in the embodied impacts of concrete made using natural aggregates and Portland cement. The energy metric showed a 7% reduction for the same mix. The use of chemical admixtures is beneficial to the environment as it leads to resource conservation i.e. chemical admixtures lead to a reduction in the water content of the mix-design and hence its binder content.

Further, the three metrics (carbon footprint, exergy and energy) were evaluated using a number of criteria: (i) reliability, (ii) robustness, and (iii) support in decision making.

A statistical quantification of the input data was found to be important as it enabled a more meaningful assessment to be made on the suitability of the single-score metrics in terms of their '*reliability*', compared to the use of deterministic values. In addition, the probabilistic approach determined whether there were significant differences in the environmental performances of the different concrete mixes investigated. A qualitative uncertainty estimate for each data input was determined, using a 'pedigree matrix' uncertainty estimation approach described in Frischknecht and Jungbluth (2007). Since the carbon footprint and the exergy metric had been shown to give similar results, the study singled out the exergy and energy metrics for the reliability analysis. The variability in both the exergy and energy metrics were compared using the margin of error[28]. A confidence interval of 95% in the NAC embodied energy gave a margin of error of 9 MJ/m^3 whereas the respective spread for exergy in NAC was found to be 57 MJ/m^3. Hence, the exergy analysis is reported to have higher variability compared to energy analysis. However it should be noted that although similar standard deviations, measured using the square of the geometric standard deviation (SD_g^2) were assigned to the energy and exergy values of the input variables, the overall variability of the exergy values is higher than that of energy as the exergy data has higher mean values. Further studies are required to establish the actual standard deviation of the respective energy and exergy values. This should be arrived at by collecting energy and exergy datasets for each input variable and quantifying their respective uncertainty.

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[28] Margin of error is calculated as the confidence interval divided by 2

In terms of robustness, an energy analysis *per se* does not account for consumption of non-energy resources such as natural aggregates and water and only energy consumed in their transportation or processing is considered. Other complementary methods e.g. material flows [in kg] are usually applied to cover impacts due to consumption of non-fuel resources. However, the different units, *kg* vs. *MJ*, make them difficult to combine during decision making, and thus a comparison can only be done qualitatively or by weighting the results. Exergy forgoes this hindrance by accounting for both mineral and fuel resources in the same units, and hence is a more robust metric compared to energy. Also, the carbon footprint accounts for the CO_2-eq emissions from energy resources and cementitious materials used in concrete. Hence, it is also a more robust metric compared to energy.

All three metrics were found to be consistent in their methodology and give reliable results as they are based on sound scientific principles. However, this study showed that the exergy and carbon footprint methods are more suitable metrics than energy for measuring resource consumption of concrete structures. Exergy is able to account for both mineral resources and energy in the same units, whereas the carbon footprint accounts for the carbon emissions from cementitious materials and energy sources. In future cases, where the amount of Portland cement use in concrete is much reduced, then it is foreseeable that exergy will be a more suitable metric. However, the exergy method is tedious in its computations and requires a consistent database of the exergy of resources, which is not yet complete. In conclusion, exergy metric and the carbon footprint were found to be the more appropriate metrics in assessing resource consumption of concrete structures compared to the energy metric. Notwithstanding, this study uses only the carbon footprint in Chapter 4 as it required the use of case-specific environmental impact data on the local construction industry. The available data are presented in terms of the GWP_{100} potential. Again in Chapter 6, the LCA results of the two case studies are presented in terms of the GWP_{100} and energy metrics. This facilitates the comparison of the LCA results with other LCA studies in literature.

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Chapter 4

4 THE SUSTAINABILITY PERFORMANCE OF THE SOUTH AFRICAN CONCRETE CONSTRUCTION INDUSTRY

4.1 Introduction

The concrete industry in South Africa comprises cement manufacturers, aggregate producers, admixture suppliers, cement extender (fly ash and slag) suppliers, ready-mix and precast concrete producers, concrete product manufacturers (including producers of cement bricks and building blocks, fibre cement roof sheets, concrete pipes and concrete roofing tiles), designers of structural concrete (civil and structural engineers), building and civil engineering contractors, and small-scale cement and concrete product consumers (e.g. home builders).

The South African concrete industry is represented by several institutions and organizations (www.concretesociety.co.za):

(i) The Cement and Concrete Institute of South Africa (C&CI)[29], which had its main mission as increasing the market for concrete through excellent marketing and educational services.

(ii) The Concrete Society of Southern Africa (CSSA) which is an association of professionals and practitioners and provides a forum for networking and the sharing of knowledge and information on concrete.

(iii) The Concrete Manufacturers' Association (CMA) which is the national coordinating body for the precast industry. It is responsible for representing the concrete floor slab, pipe, masonry, roof tile, paving and retaining block industries in all matters relating to the manufacture and use of its members' products.

(iv) The Aggregate and Sand Producers Association of Southern Africa (ASPASA) who are tasked with the role of promoting the aggregate and sand industry, and coordinating the policy and activities of this industry.

(v) The South African Ready Mix Association (SARMA) which represents the interests of ready mix suppliers and lobbies for legislation and other measures affecting them.

(vi) Other allied organizations are Master Builders South Africa (MBSA), Consulting Engineers South Africa (CESA), the South African Federation of Civil Engineering Contractors (SAFCEC), the Construction Industry Development Board (CIDB), the National Home Builders Registration Council (NHBRC), and the South African Black Technical and Allied Careers Organization (SABTACO).

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[29] In 2013 the C&CI was dissolved and gained a new corporate identity: The Concrete Institute (TCI).

The activities of the parties comprising the South African concrete industry have been more pronounced in the recent past due to government and private industry investment in new (and replacement) construction of 2010 FIFA World Cup stadia and other infrastructure projects e.g. the Gautrain Rapid Rail Link, airports, and so on. Further consumption of large quantities of energy and resources for concrete production is expected in the foreseeable future to meet the demands of the expanding population and the need for infrastructure development.

The objective of this Chapter is to provide an understanding of the South African concrete industry's environmental impacts in terms of natural resource consumption and CO_2-eq emissions[30]. The review covers current practices in the concrete construction field in South Africa (S.A.) and their implications for the environment. Elaboration in terms of detail and quantification is given for the environmental impacts generated during the manufacture of raw materials for concrete and their transportation to site. 6-year average (2005-2010) data are provided for resources consumed and wastes emitted during the quarrying and manufacture of raw materials for concrete. Energy and carbon-equivalent emissions data per unit of material produced were obtained from the InEnergy Report (2010) of the Cement and Concrete Institute (C&CI) (S.A.). These data on resource consumption and CO_2-eq emissions of the concrete industry are then applied to make comparisons with other local industries and additionally with other construction industries globally in order to establish where SA ranks and establish the way forward.

This Chapter is important as it helps show the roles of the key players in the concrete industry, including the structural and materials engineers, in improving the environmental performance of the cement and concrete industry. The roles were established based on the definition of 'a sustainable concrete structure' given in Chapter 2, which is: "*one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling*".

4.2 Life-cycle of concrete

Modern concrete is composed of a mixture of aggregates (65-80 % volume per unit volume (v/v)), cement (10-12 % v/v), water (14-21 % v/v) and usually includes other constituents such as mineral

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[30] It should be noted that even though the exergy metric is recommended in Chapter 3 as a more suitable metric for measuring resource consumption in the construction industry, there is still lack of local specific data on the exergy values for minerals and ores. This chapter uses local data to quantify the environmental impact of the concrete industry and the available local data is presented in GWP_{100} [kg CO_2-eq] units. Hence, this chapter uses the CO_2-eq emissions and corresponding energy values in the analysis.

components (cement extenders/additives) and chemical admixtures (e.g. air-entraining agents, water reducers and accelerators), and occasionally fibres (<1 % v/v) (van Oss and Padovani, 2003). Concrete is used in the construction of reinforced (including prestressed) and unreinforced concrete structures. The life-cycle of concrete covers all activities spanning from the extraction and processing of raw/recycled materials to the final decommissioning and deconstruction/demolition of the structure for waste/recycling/reuse of its materials. The scope of studying the life-cycle phases of concrete varies and can be classified into four phases as shown in ***Figure 4-1***. The first phase is the '*cradle-to-gate*' and comprises all relevant processes from raw materials extraction (cradle), manufacturing and processing of the materials and their transportation: to the processing plant, within the plant and to the batching plant and/or construction site (gate). The '*gate-to-grave*' phases cover the concrete placement, construction of the structure, on-site transportation activities, operational phase, demolition of the structure and the disposal of demolished material to a landfill (grave). The third and final phases, '*grave-to-gate'* and '*grave-to-cradle*', respectively, refer to end-of-life material recovery strategies that include the reuse and recycling of the deconstructed concrete components and demolished materials.

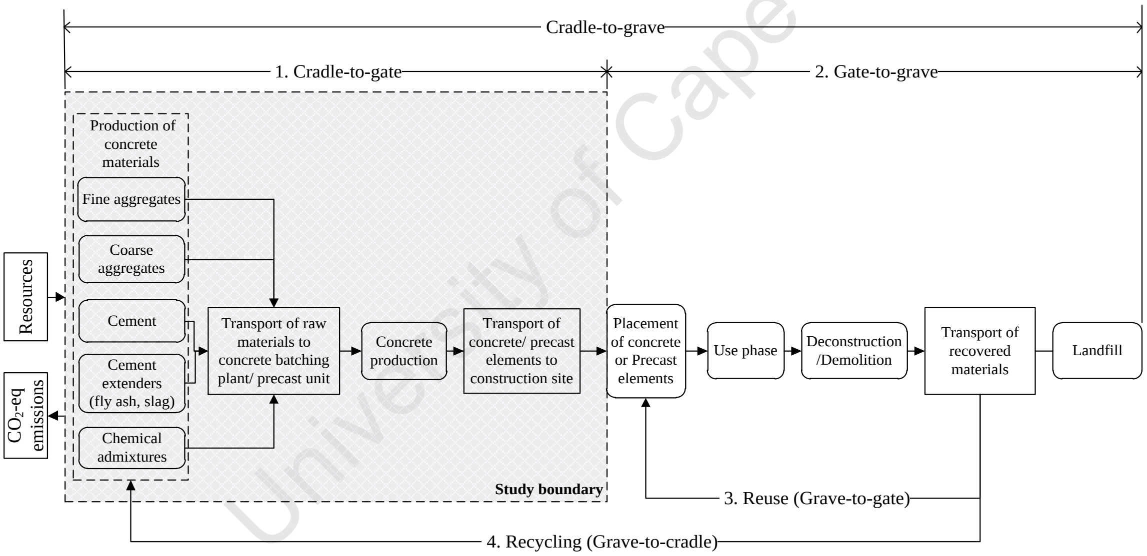

Figure 4-1: *Life-cycle phases of a concrete structure.*

This chapter gives information on the '*cradle-to-gate*' environmental impacts of concrete in SA and compares the results with those of other similar studies carried out in other countries. The environmental impacts covered by this review refer to the resources (energy and materials) consumed during the '*cradle-to-gate*' phase (refer to ***Figure 4-1***) and the corresponding CO_2-eq emissions.

The environmental impact related to the '*cradle-to-gate*' phase is not limited to resource consumption and carbon emissions but may include acidification and loss of arable/forest land. For example, aggregate extraction and processing may lead to (Uher 1999; Alexander and Mindess 2006; Cheng *et al*. 2006): (i) Loss of land used for other competing land uses such as human settlement and agriculture and; (ii) Environmental damage in the form of resource depletion and loss of bio-diversity due to the consumption of renewable and non-renewable resources e.g. water and minerals respectively. In addition, cement contains alkaline ingredients such as lime (CaO) and trace constituents such as chromium, derived from the clay and shale, which cause human toxicity upon contact (Winder and Carmody, 2002). However, due to limitations in data availability, the scope of this Chapter only covers resource consumption and carbon equivalent emissions.

The environmental impacts related to the '*gate-to-grave*' phase of concrete are case specific, i.e. they depend on the type (e.g. building or bridge) and make (e.g. precast) of concrete structure. Hence again due to data limitations the subsequent phases after the '*cradle-to-gate*' phase for South African concrete structures are omitted in this study. However, the influence of the '*gate-to-grave*' phase is mentioned in the discussion section and included in the proposed framework for design in Chapter 5. In summary, the scope of this Chapter includes:

1. Investigating and quantifying resources (materials and energy) directly consumed in the extraction, manufacture and transportation of materials for concrete production. The review omits the environmental impacts arising from the production of mining machinery and processing of secondary materials such as gypsum.
2. Identifying and quantifying the corresponding CO_2-eq emissions generated directly in the extraction, manufacture and transportation of the materials.
3. The data are for a 6-year period from 2005 to 2010. The data sources used are specific to South Africa.
4. In the broader context of this study and in line with the main objectives of this study (as given in Chapter 1), this Chapter provides an insight on how the key players in the cement and concrete industry can improve the environmental performance of the industry. The respective roles of the key players are based on the definition of a 'sustainable concrete structure' given in Chapter 2.

4.3 Source of the data

Existing data on CO_2-eq emissions from concrete production in SA are available in the InEnergy Report (2010)[31]. These emissions are reported in accordance with the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) Protocol (which gives a methodology for calculating CO_2-eq emissions). In the WRI/WBCSD Protocol three sets of emissions from different processes are aggregated to give the specific emissions for a product. The three emissions are categorised as: Scope 1 (direct) emissions which refer to those from raw material calcinations, fuel combustion, site transport of raw materials and personnel, and emissions from

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[31] InEnergy report contains CO_2-e data on the cradle-to-gate phase of concrete constituents and concrete products in South Africa.

explosives detonation at the quarry; Scope 2 (indirect) emissions refer to those from use of purchased electricity; and Scope 3 (other indirect) emissions are those from off-site transportation of raw materials or intermediate products (e.g. clinker). The InEnergy report (2010) provides a CO_2-eq inventory database for concrete and concrete products.

The main limitation of the InEnergy report (2010) is that it does not give CO_2-eq data relating to phases beyond the cradle-to-gate phase of concrete structures.

4.4 Environmental impacts of concrete constituent materials

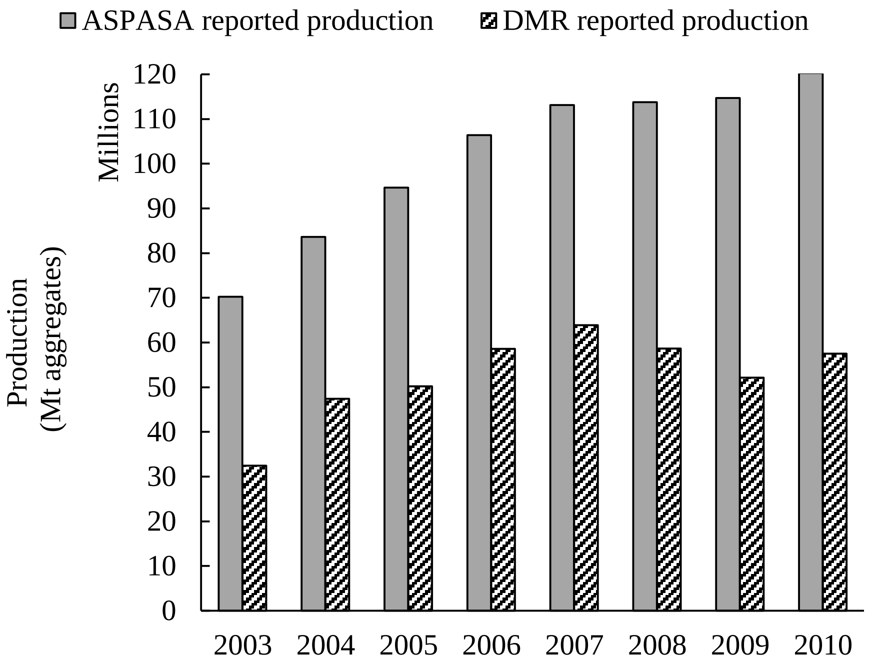
4.4.1 Coarse and fine aggregates

Aggregates – both fine (< 4.75 *mm*) and coarse (> 4.75 *mm* – 40 *mm*) – account for 65-80 % of the volume of concrete. Sources of coarse and fine aggregates can be quarries, alluvial sources such as river sands and gravels, or recycled industrial waste (e.g. mineralogical sands, foundry sands, metallurgical wastes and construction and demolition wastes etc.). Presently, gravel pits and rock quarries provide the main sources for aggregates and raw materials for concrete production in SA, with coarse aggregates being virtually totally sourced from crushed rock. In addition, there is limited use of recycled aggregate mainly for pavement base construction (Kutegeza and Alexander, 2004). Though not stated in local studies, the main hindrances to the use of recycled aggregates for structural applications are that the recycling facilities and equipment require a high cost of investment (Tam, 2009). In addition, there is lack of regulatory requirements (e.g. policies and strategies) on concrete recycling that seek to coordinate various stakeholders (e.g. client, contractor) in the management of construction and demolition waste (Tam, 2009). Other than the waste management aspects, recycled aggregates in concrete have been shown to exhibit a large variability in their quality especially when they are sourced from different sites. This variability can however be lowered by using site-based recycling. Local data on the mechanical strength and durability characteristics of recycled aggregates in concrete is contained in Kutegeza and Alexander (2004) and Olorunsogo and Padayachee (2002). However, the existing local standards and codes for design of concrete structures (e.g. SANS 10100-1:2000; SANS 10100-2:2005) do not have provisions for the use of recycled aggregates in concrete and hence designers are generally not willing to specify these in the design.

4.4.1.1 *Aggregate production for the period 2005-2008*

There are conflicting data on the total production (for all uses e.g. in concrete, road base and sub-base layers, mortar, etc.) of fine and coarse aggregates in South Africa, reported by the Aggregate and Sand Producers Association of South Africa (ASPASA) and the Department of Mineral Resources (DMR). ASPASA reported that in 2008, the aggregate sector in South Africa quarried 114 Mt of fine and coarse aggregates, while the total industry sales reported by DMR were approximately 50 % of the ASPASA figures as illustrated in Figure 4-2.

The large discrepancy in the data is due to a lack of reliable data reporting procedure in the aggregate sector coupled with illegal mining. The figures reported by ASPASA in this case are more realistic and are computed based on the aggregate sales to their members and on the yearly cement sales in South Africa (Pienaar, 2013). The ASPASA figures also account for the aggregates used by the bitumen industry and other users who do not require cement in their applications. This study utilizes the ASPASA data to further quantify the environmental performance of the SA concrete industry.



Year	*ASPASA*	*DMR*
	Annual average production (tonnes)	*Annual average production (tonnes)*
2005	94,684,000	50,186,608
2006	106,373,000	58,563,381
2007	113,118,000	63,872,783
2008	113,799,000	58,608,454
2009	114,714,000	52,157,111
2010	120,312,000	57,467,000
2005-2010	**110,500,000**	**56,809,223**

Figure 4-2 : *Annual fine and coarse aggregates production, for all uses (e.g. in concrete, road base and sub-base layers, mortar.), in South Africa (2003-2010) (Support Programme for Accelerated Infrastructure Development (SPAID) 2008; Kohler, 2011).*

4.4.1.2 *Aggregates for concrete production and other uses*

Figure 4-3 shows percentage estimates of the various applications of aggregates in construction.

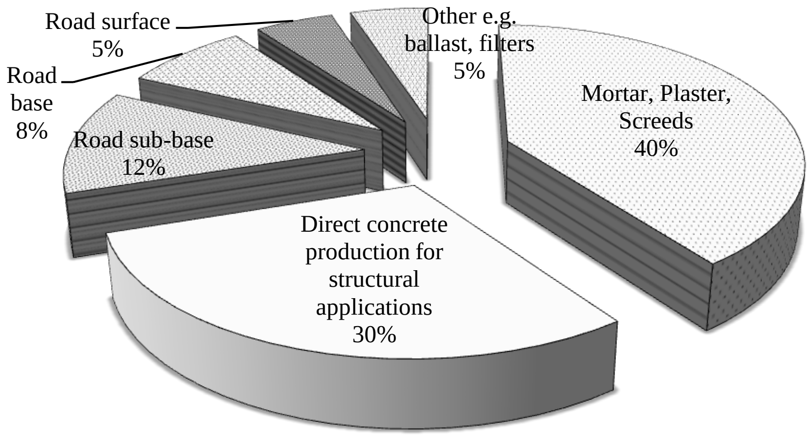


Figure 4-3: *Application of aggregates in construction in S.A. (Support Programme for Accelerated Infrastructure Development (SPAID), 2008).*

It is estimated that 30% of fine and coarse aggregates produced in SA is used for concrete production, which includes on-site production of concrete by civil engineering contractors and home builders, concrete production by ready-mix producers and concrete product manufacturers (CPM). Thus for 2005-2010, an average of 33.2 Mt (30% x 110,500,000 tonnes) of aggregates based on ASPASA production figures, were used in concrete production.

25% of aggregates produced go towards the construction of road layers i.e. sub-base, base and surface layers. 40% of aggregates are used in the production of mortar and plaster screeds whereas the remainder (5%) of the total fine and coarse aggregates sales are used in non-concrete products e.g. track ballast for railways and by the water industry for filters in treatment works (Support Programme for Accelerated Infrastructure Development (SPAID), 2008).

This study is limited to investigating the environmental impacts related to the materials used in concrete production. A further limitation in this study is that it does not distinguish between the types of aggregates produced i.e. natural (pit-derived) fine aggregates, or crushed fine and coarse aggregates. Further research is required on this aspect (see Chapter 7). In this case, the study assumes that all aggregates consumed are crushed and will quantify the amount of energy and carbon emissions from the quarrying and processing of crushed coarse and fine aggregates for concrete.

4.4.1.3 Energy use and carbon-equivalent emissions from the production of aggregates for concrete

Extraction of primary aggregates from rock quarries begins with the blasting of quarry rock using explosives, following which the rocks are transported, using diesel powered trucks, to the processing plant where they are crushed, shaped and screened to their required sizes using electrically driven equipment.

Figure 4-4 shows the system boundary (dashed line) for investigating energy use and CO_2-eq emissions associated with extracting both coarse and fine aggregates. Recycled aggregates are not considered in the analysis.

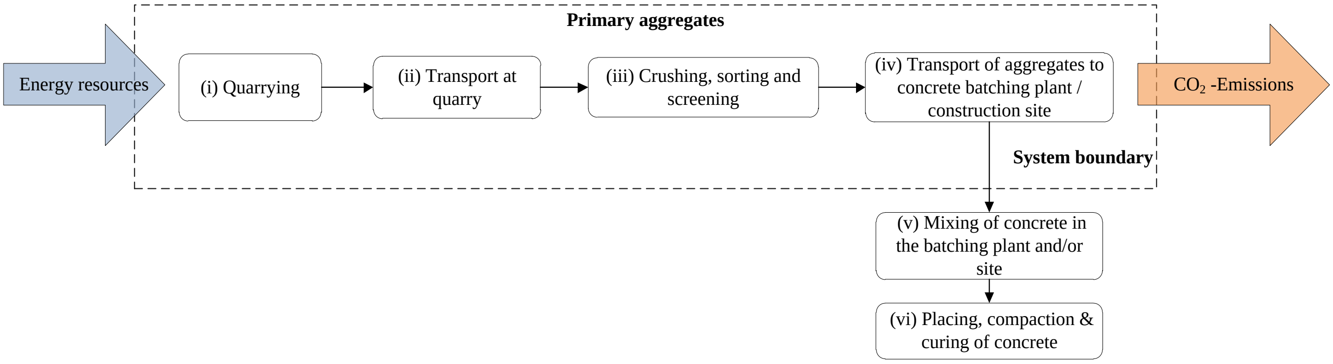


Figure 4-4 : *System boundary for the study of the environmental impacts of coarse and fine aggregates for concrete.*

There are no readily available local energy and emissions data distinguishing the impact of production of crushed fine aggregates from that of coarse aggregates. Extracting and processing a tonne of both fine and coarse aggregates generates an average 8.1 kg CO_2-eq (InEnergy Report, 2010) and consumes 93.3 MJ of energy as detailed in ***Table 4.1***. The variability in the data is also not reported.

Table 4.1 : *Energy consumed and CO_2-eq emissions per tonne of aggregate produced (Source: InEnergy Report, 2010).*

Activity	*Energy source*	*Energy consumed [MJ/ton]*	*Unit CO_2 emission [kg CO_2-eq /MJ]*	*Total CO_2 emissions [kg CO_2-eq/ton] (InEnergy Report, 2010)*
Quarrying (explosives)	ANFO[c]	0.045 [a]	0.044	0.002
Onsite transportation	Diesel	26.41 [b]	0.073	1.928
Crushing, sieving and sorting	Electricity	28.80	0.119	3.43
Transportation to construction site and/or ready-mix plant (50 km) [b]	Diesel	38	0.073	2.774
Total		**93.3**	**-**	**8.1**

[a] Based on the assumption that diesel oil constitutes 99.9% of the energy and explosives are 0.1% during quarrying

[b] Typical transportation distance of materials to site is 50 km; the capacity of the truck is estimated to be 25 t for aggregates. This assumption is made on the basis of data collected for the two local case studies reported in Chapter 6.

[c] ANFO –Ammonium Nitrate - Fuel Oil

Table 4.2 gives the total amount of energy and CO_2-eq emissions generated in the production of aggregates for concrete for 2005 to 2010, based on the ASPASA data given in ***Figure 4-2***.

Table 4.2: *Environmental impacts of aggregates for concrete during the period 2005-2010.*

Year /Units	*Amount of fine and coarse aggregates consumed in concrete production in SA based on ASPASA data (Refer to Figure 4-2 and Figure 4-3)*	*Total Energy*	*Total CO_2-eq emissions*
	Tonnes	*MJ*	*kg CO_2-eq*
2005	28.4×10^6	2.65×10^9	230×10^6
2006	31.9×10^6	2.98×10^9	258×10^6
2007	33.9×10^6	3.17×10^9	275×10^6
2008	34.1×10^6	3.19×10^9	276×10^6
2009	34.4×10^6	3.21×10^9	279×10^6
2010	36.1×10^6	3.37×10^9	292×10^6
6-year Annual Average	**33.2 x 10^6**	**3.10 x 10^9**	**269 x 10^6**

ASPASA – Aggregates and Sand Producers Association of South Africa

The amount of fine and coarse aggregates used in concrete production steadily increased over the 6-year period (2005-2010). An annual average of 33.2 Mt of aggregates was used in concrete production, which led to the annual average consumption of 3.1 x 10^6 GJ of energy and 269 x 10^6 kg CO_2-eq emissions.

4.4.2 Cement

Portland cement production involves the chemical transformation of raw materials (Grieve, 2009): calcium oxides (63 – 69 % by mass in cement); silica (19 – 24 %); alumina (4 – 7 %) and iron oxide (1 – 6 %) into various types of cementitious products, by-products and wastes. The Portland cement manufacturing process consists of five main steps:

(i) Quarrying of limestone and transportation of raw materials to the processing plant. The mining process involves the use of explosives, while usually diesel fuel is consumed in the transportation of the quarried materials to the processing plant.

(ii) Preparation of “raw meal” for pyroprocessing, whereby all raw materials (crushed limestone, iron ore, clay or shale) are mixed together in the correct proportions (raw meal homogenisation) and finely ground.

(iii) Pyroprocessing of raw materials to produce Portland cement clinker using the wet or dry process. The latter refers to the process whereby raw materials are first ground and heated before being fed into the kiln, whereas in the wet process, the raw materials are crushed, ground and mixed as slurry. The most efficient dry-process kilns use approximately 2.9 GJ per tonne of clinker (http://www.energyefficiencyasia.org/docs/industrysectorscement_draftMay05.pdf). Wet-process kilns are more energy intensive and can consume more than twice the amount used by dry process kilns (Gartner, 2004). All cement kilns in SA use the dry process.

(iv) Final grinding of the clinker together with inter-grinding with a small proportion of gypsum to produce Portland cement. Waste products from e.g. power stations (fly ash) and iron/steel manufacturers (slag) and others can be used as partial replacements for Portland cement to form blended cement, either by intergrinding with the clinker, or separate grinding followed by interblending.

(v) Transportation of finished product to the consumer in bulk or in bags. Typical transportation distances of the cement to site can vary. This study assumes a 100 km[32] distance from literature (Mclntyre *et al*., 2009).

The unit energy and material flows in the production of 1 ton of Portland cement are illustrated in ***Figure 4-5***.

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[32] This distance may be much greater e.g. up to 600 – 800 km. A sensitivity analysis of the transportation distances of materials to the environmental impact of concrete was carried out in Chapter 3 (Section 3.3.1.4).

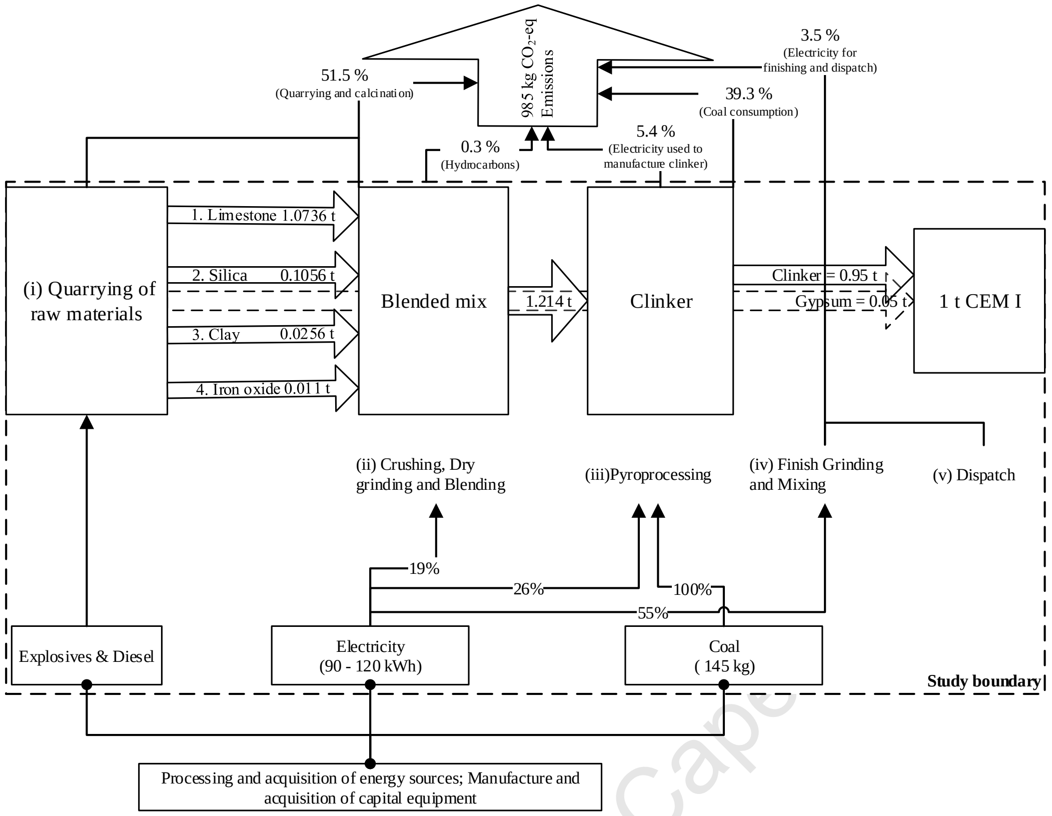


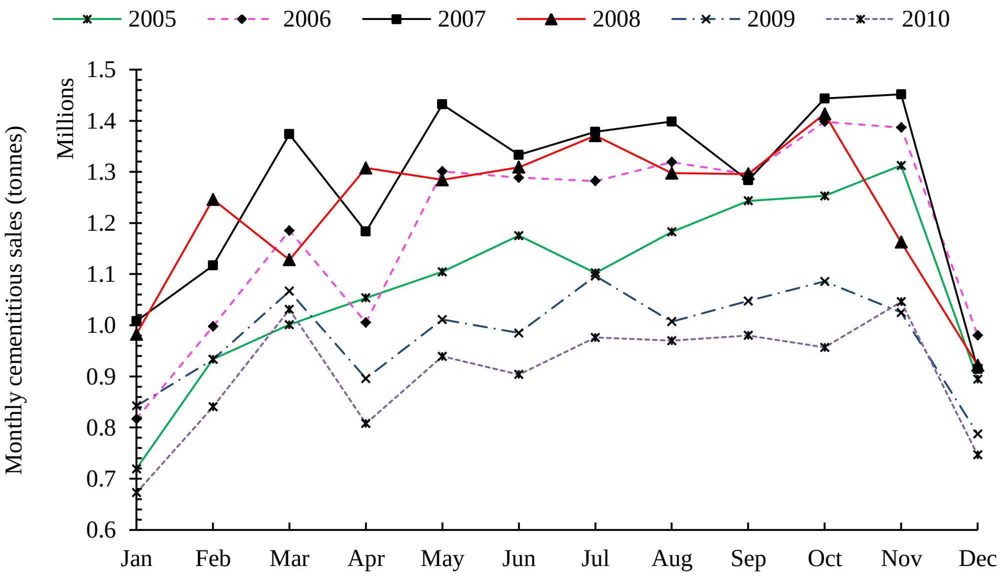
Figure 4-5 *: Typical materials and energy required in the production of 1 ton of Portland cement using the dry process and resultant carbon emissions (adopted from: ftp:ftp.jrc.es/pub/eipccb/doc/clm_brief_0510.pdf; Association of Cementitious Material Producers (ACMP), 2011).*

- The electrical energy consumption per tonne of cement falls between 90 -120 kWh/ton of cement (Eskom, 2011).
- The average requirement to produce 1000 tonnes of cement clinker is approximately 145 tonnes of coal (145 kg/tonne of clinker) (http://www.groundwork.org.za/Cement/Dudfield%20AFR%20-%20BID.pdf).

On average 1.52 tons of raw materials (limestone, silica, clay, and iron ore) are required to produce 1 ton of clinker.

4.4.2.1 Total cement production for the period 2005-2010

Cementitious sales in SA are made by a cement industry characterized by four major producers (as of 2009): Pretoria Portland Cement (PPC), AfriSam, Lafarge and NPC-Cimpor. Other producers are expected to enter the industry in coming years. The term ‘cementitious products’ refers to cements complying with SANS 50197-1:2000 (which correspond to equivalent EN 197 specifications), and cement extenders (fly ash and slag) sold directly to end users such as ready-mix concrete producers. The monthly cementitious sales in tonnes for the period 2005 to 2010 are given in ***Figure 4-6***.



Year	*Annual average cementitious sales (tonnes)*
2005	12,975,262
2006	14,257,032
2007	15,315,721
2008	14,718,654
2009	11,783,670
2010	10,870,394

Figure 4-6 : *Monthly cementitious sales in SA for the six-year period (2005 to 2010) (data source: Cement and Concrete Institute, South Africa).*

The sales for the period 2006 to 2008 are higher compared to other years due to government and private industry investment in new (and replacement) construction for the 2010 FIFA World Cup stadia and other infrastructure projects (e.g. Gautrain Rapid Rail Link). The global economic crisis in 2008 was a factor that caused the low cementitious sales in 2009 and 2010.

For each year, the cementitious products consist of a number of cement types and it is useful to show the particular amount of each type of cement produced. For example, the total production of cementitious products in SA in 2008 amounted to 14.7 Mt (C&CI, 2008). This tonnage included 1.4 Mt of fly ash and slag. Data showing the breakdown of the type of cements produced annually are only available for 2005-2008. From 2009 onwards the cementitious sales data are a consolidated figure. ***Figure 4-7*** gives the tonnage for each cement type produced during the period 2005-2008 and a consolidated figure for 2009-2010.

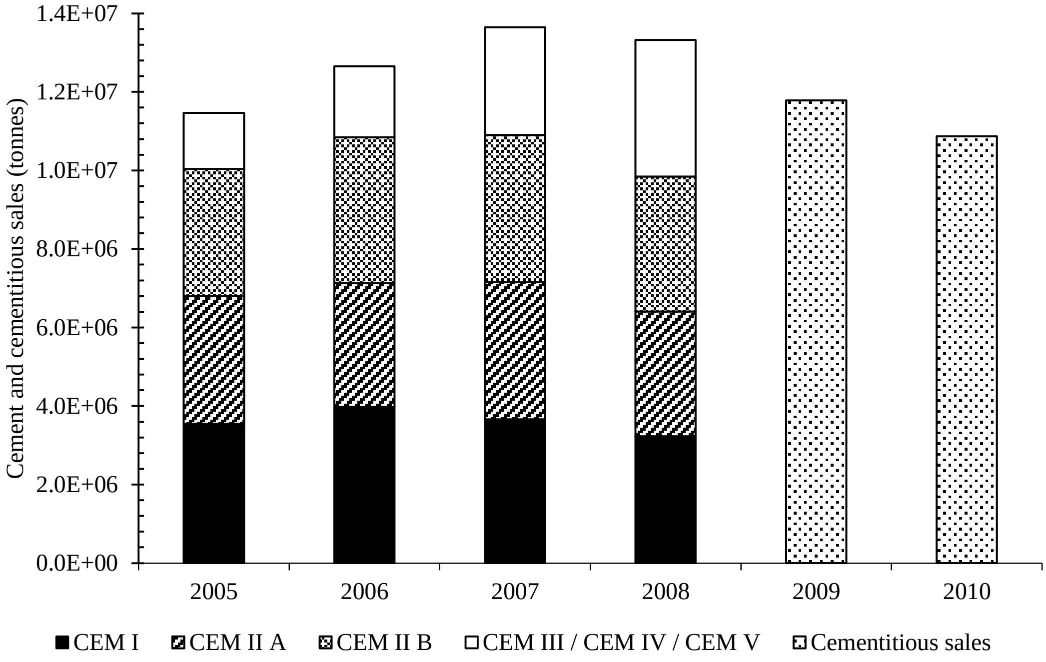
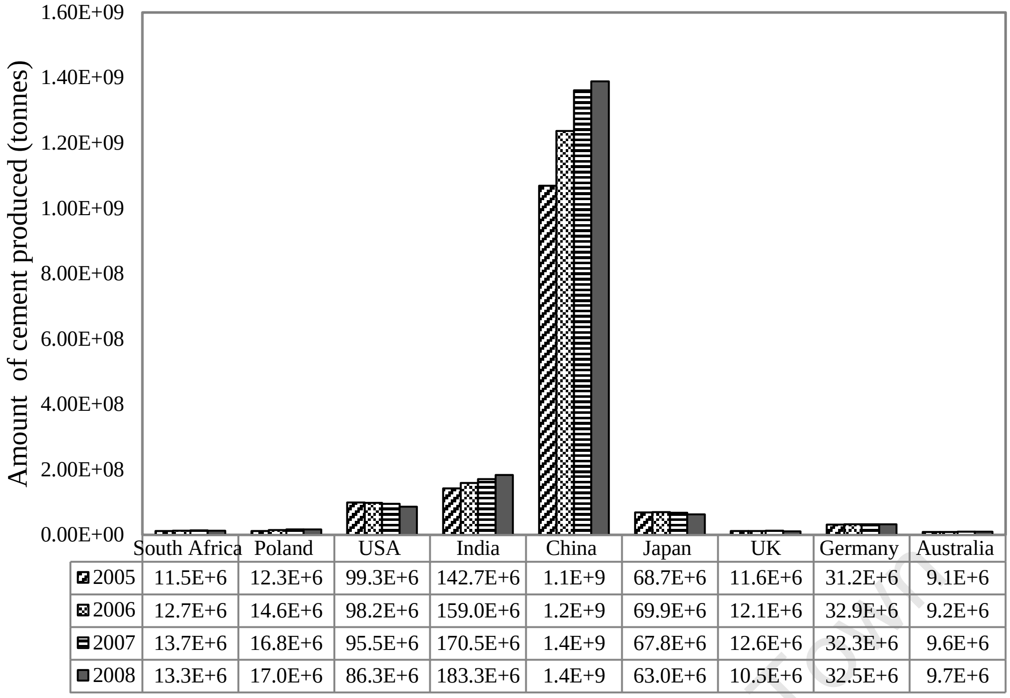


Figure 4-7 : *Tonnage of cements produced for the six-year period (2005 to 2010) (data source: C&CI, 2008).*

From ***Figure 4-7***, it can be noted that the only cement showing growth in demand was the CEM III/CEM IV/CEM V grouping. Using 2005 as a baseline for comparison the CEM III/CEM IV/CEM V grouping has increased by 27 % in 2006, through 93 % in 2007 to 144 % in 2008. The designation of the various cements is explained later in ***Table 5.1*** (Chapter 5).

In the global setting, the cement industry in SA produced an average 0.48 % of global cement production for the period 2005-2008. This percentage is very small compared to China and India which produced 47.5 % and 6.2 % of global cement, respectively, during the same period (CEMBUREAU, 2011). A comparison is given in ***Figure 4-8*** of global cement production figures for the period 2005-2008. The quantity of cement produced in SA currently compares to that of the United Kingdom.



	South Africa	Poland	USA	India	China	Japan	UK	Germany	Australia
▨ 2005	11.5E+6	12.3E+6	99.3E+6	142.7E+6	1.1E+9	68.7E+6	11.6E+6	31.2E+6	9.1E+6
⊠ 2006	12.7E+6	14.6E+6	98.2E+6	159.0E+6	1.2E+9	69.9E+6	12.1E+6	32.9E+6	9.2E+6
▤ 2007	13.7E+6	16.8E+6	95.5E+6	170.5E+6	1.4E+9	67.8E+6	12.6E+6	32.3E+6	9.6E+6
■ 2008	13.3E+6	17.0E+6	86.3E+6	183.3E+6	1.4E+9	63.0E+6	10.5E+6	32.5E+6	9.7E+6

Figure 4-8 : *Tonnage of cement produced by country from 2005-2008 (CEMBUREAU, 2011; C&CI, 2008).*

4.4.2.2 Average amount of cement used in concrete production for the period 2005-2010

Figure 4-9 gives a breakdown of material flows in cement production in SA for the year 2008.

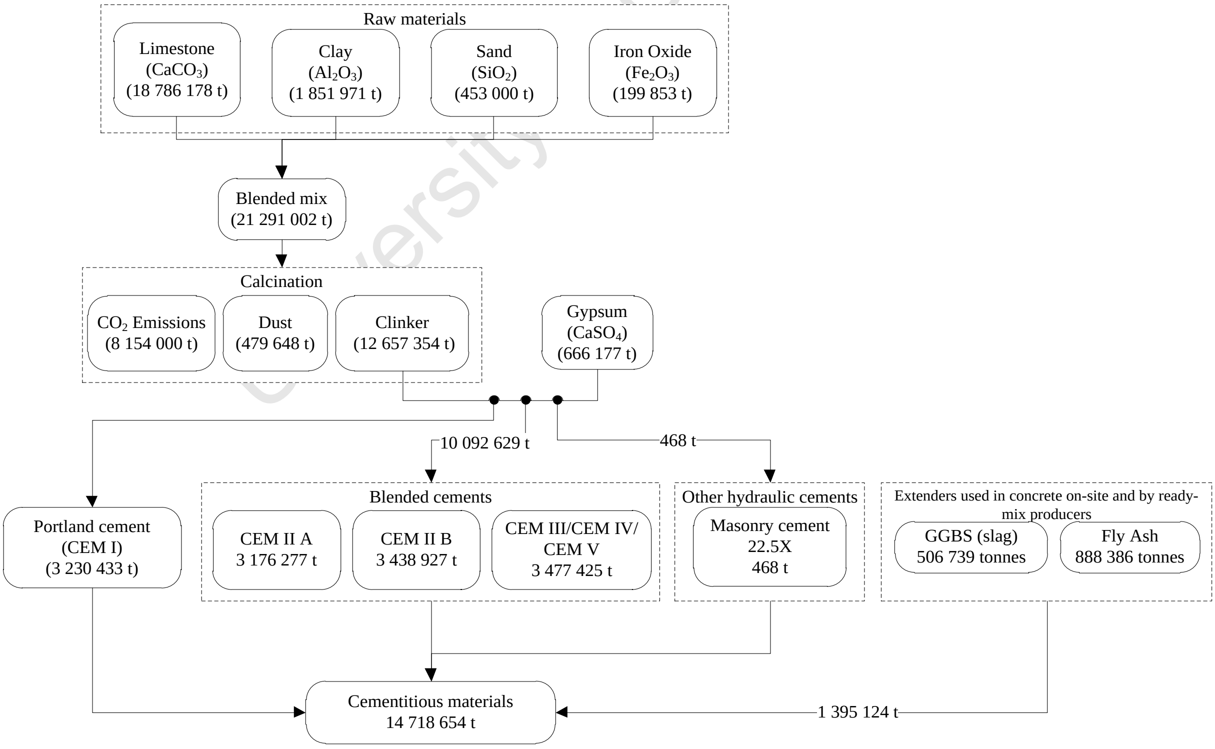


Figure 4-9 : *Material flows and quantities of cement produced in South Africa in 2008 (data source: C&CI, 2008).*

Note: In these estimates, a gypsum content of 5% relative weight of contained clinker is assumed for all cements.

The amount of additives used in the factory blended cements has not been included in the material flows.

The unit raw materials in the production of 1 tonne of Portland cement has been adopted from Rundman, Unpublished report

The total amount of raw materials (limestone, silica, iron and clay) used in the production of cementitious materials amounted to 21.3 Mt in 2008. When considering the 6-year average (2005-2010), approximately 19.1 Mt of raw materials per year were used in the production of cementitious materials. On average, 11.9 Mt of binders were produced per year. The binders produced include Portland cement and blended cements such as CEM II A, CEM IIB, CEM III, CEM IV and CEM V, all produced in accordance with SANS 50197-1:2000.

Of the total 11.9 Mt of binders produced per year on average between 2005 and 2010, 37 % (4.4. Mt) went towards the direct production of concrete, comprising 17% ready-mix production, 16 % concrete product manufacturers and 4 % directly for civil construction works, as shown in ***Figure 4-10***.

58 % (6.9 Mt) of total cement sales went to: independent blenders (6 %), cement resellers[33] (49 %) and mining and other construction related uses (3 %). It is assumed that the substantial amount sold to resellers will be used by housing developers and home owners in mortar-based applications and in the construction of reinforced concrete structural components such as foundations and floor slabs. To apportion the amount sold to resellers to its respective use, this study used a typical single-storey residential building constructed using bricks and approximated the percentage amount of cement used in plaster and mortar applications and that used in the construction of its reinforced concrete ground floor slab and the strip foundations (*Calculations are reported in Appendix B*). These percentages were found to be 32 % for mortar applications and 68 % for reinforced concrete. Hence the amount of cement used in concrete applications from cement resellers is (49% x 68 %) = 33 %.

Similarly, a part of the 5% cement sold directly to building construction represents that used in the production of concrete buildings and another part in mortar based applications (masonry mortar, plastering and a base/sub-base for flooring). The same concept used in apportioning cement resellers sales was used to apportion the 5% cement sales to building construction. From the calculations (Appendix A), it was found that (5 % x 68 %) = 3.4 % of cement sold directly to building construction was used for concrete applications.

Hence in total, approximately 73.4 % (37 % + 33 % + 3.4 %) (9 Mt) of cement produced in SA went towards concrete production in the years 2005-2010. Approximately 14 Mt of raw materials were used annually for the production of the binders used in concrete production.

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[33] Cement resellers are the retail distributors of cement e.g. hardware stores, building supply retailers etc.

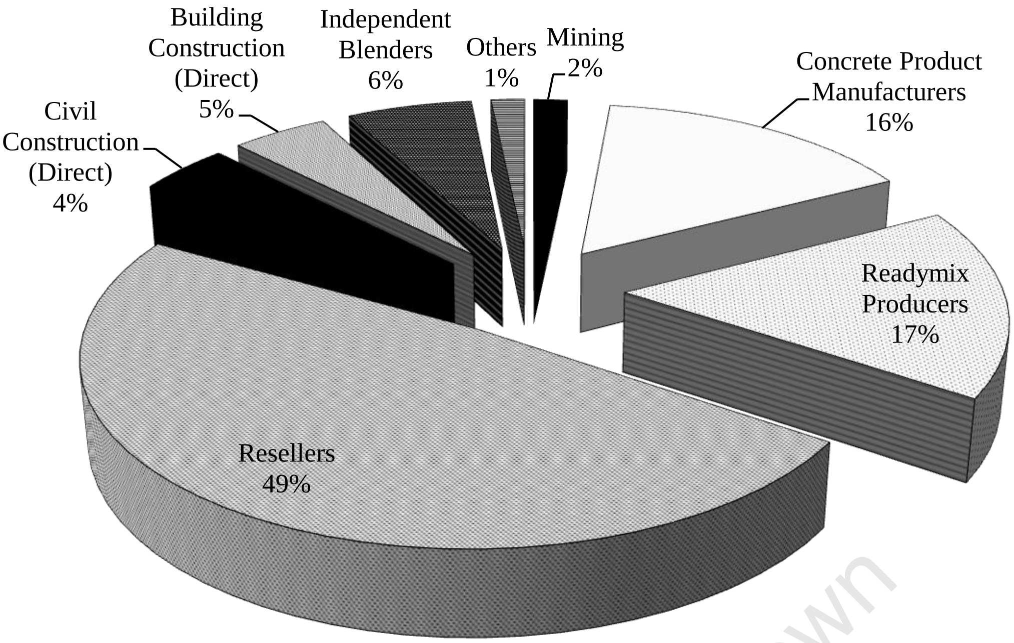

Figure 4-10 : *Approximate values of the applications of cement in South Africa (C&CI, 2008).*

4.4.2.3 Total average energy use during cement production for the period 2005-2010

Cement manufacture is an energy intensive process due to the use of thermal energy to fire kilns and electrical energy required for the mechanical processes (i.e. crushing and grinding the clinker). The total primary energy consumed is a mix of electrical energy for operating the kilns and thermal energy mainly from fossil fuels. The weighted average data on total global electricity energy consumption per tonne of cement falls between 90 – 120 kWh (Eskom, 2011). An average consumption of electricity of 100 kWh per tonne of clinker (300 MJ/tonne) is assumed for this study. 74% of the electricity is used in grinding raw materials and clinker, and 26% is needed in rotating the kiln during pyroprocessing as was shown in ***Figure 4-5***. It is also assumed that 100% of the thermal energy goes towards pyroprocessing. Coal is the primary source of thermal energy in pyroprocessing, while industrial wastes (e.g. tyres and plastics) are sometimes used as alternative sources of energy in the kilns. This follows the enactment of the South African government policy on the use of waste as an alternative fuel source (Waste Act 59/2008) which allows cement companies in SA to co-process wastes and use less non-renewable fossil fuels. The amount of thermal energy consumed in cement production depends on the type of kiln and its efficiency, with the dry process being less energy intensive. ***Table 4.3*** gives thermal energies for different kiln types for dry process cement manufacture. These figures apply to all similar kiln types worldwide.

Table 4.3 : *Unit thermal energy consumption in different cement kilns (http://www.energyefficiencyasia.org/docs/industrysectorscement_draftMay05.pdf).*

Type of kiln	***Unit thermal energy consumption (GJ/$t_{clinker}$)***
Long dry process with internals	*4.60*
1-stage cyclone preheater	*4.18*
2-stage cyclone preheater	*3.77*
4-stage cyclone preheater	*3.35*
4-stage cyclone preheater plus pre-calciner	*3.14*
5-stage preheater plus calciner plus high efficiency cooler	*3.01*
6-stage preheater plus calciner plus high efficiency cooler	*<2.93*

Aforementioned, the total energy consumed in cement manufacture is a mix of electrical energy used mainly for operating the kilns and thermal energy used in pyroprocessing. The amount consumed by the latter depends on the type of cement kiln and the type of cement production process (see ***Table 4.3***). All the 11 cement production facilities in SA use the dry process for cement production but have different kiln types.

Table 4.4 gives a summary of energy use of different cement kilns operated by the major cement producing companies in SA.

Table 4.4: *Unit thermal energy consumption in clinker production by the major cement manufacturers in South Africa (Walker, 2006).*

Company	*Facility*	*Kiln type*	*Unit thermal energy consumption* [a]	*Capacity*	*Weighted average energy consumption for each cement company*
			[GJ/ton of clinker]	[tonnes of clinker/annum]	[GJ/ton of clinker]
PPC	Hercules	1 stage preheater	4.18	230 000	3.74
		4 stage preheater	3.35	350 000	
	Slurry	Long dry	4.60	170 000	
		Long dry	4.60	170 000	
		1 stage preheater	4.18	350 000	
		4 stage preheater	3.35	830 000	
	Dwaalboom	5 stage preheater	3.01	640 000	
	Riebeeck	Long dry	4.60	240 000	
		1 stage preheater	4.18	280 000	
	De Hoek	4 stage preheater	3.35	400 000	
		4 stage preheater	3.35	480 000	
	Port Elizabeth	Long dry	4.60	250 000	
	Jupiter	1 stage preheater	4.18	440 000	

Continued... ***Table 4.4:*** *Unit thermal energy consumption in clinker production by the major cement manufacturers in South Africa (Walker, 2006).*

Company	*Facility*	*Kiln type*	*Unit thermal energy consumption*[a]	*Capacity*	*Weighted average energy consumption for each cement company*
			[GJ/ton of clinker]	[tonnes of clinker/annum]	[GJ/ton of clinker]
AfriSam	Dudfield	2 stage preheater	3.77	750 000	3.48
		4 stage preheater and pre-calciner	3.14	630 000	
	Ulco	4 stage preheater and pre-calciner	3.14	1 200 000	
Lafarge	Lichtenburg	4 stage preheater	3.35	300 000	3.27
		4 stage preheater	3.35	750 000	
		4 stage preheater	3.35	950 000	
NPC-Cimpor	Simuma	Dry with preheater	3.35	600 000	3.35
Weighted average =			3.53 GJ/tonne of clinker		

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[a] Refer to ***Table 4.3***

Assuming that all kilns in ***Table 4.4***, run at full capacity, the weighted average amount of energy consumed per kg of clinker produced is approximately 3.53 MJ. In comparison with other countries, SA falls slightly below the world average thermal energy consumption (3.78 MJ) per kg of clinker as shown in ***Figure 4-11***.

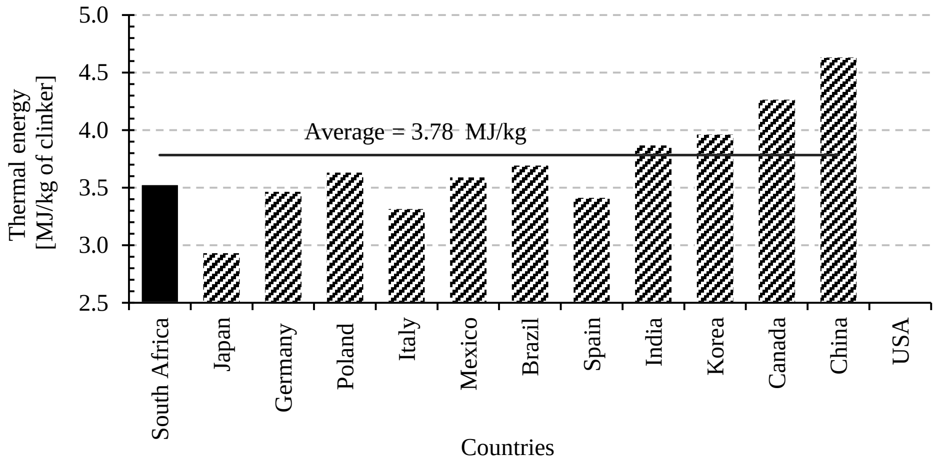

Figure 4-11: *Comparison of country average thermal energy used in cement clinker production in 2008 (adopted from Gielen and Taylor 2009 with the addition of South Africa (****Table 4.4****) and Poland (Deja et al., 2010)).*

With regard to final product, the '*cradle-to-gate*' energy consumed by production of a tonne of cement is 4 085 MJ as shown in ***Table 4.5***. The thermal energy represents by far the greater component of the total energy, at 92.6 %.

Table 4.5: *"Cradle-to-gate" unit energy consumption per ton of Portland cement (InEnergy report, 2010).*

	Activity	***Equipment***	***Energy source***	***Amount of energy*** [a]	***Calorific value***	***Energy [MJ/ton]***
(i)	Quarrying	Explosives	ANFO (Sasol explo-gel)	-	-	0.045
(ii)	Onsite transportation	Trucks	Diesel	0.557 kg	47.4 MJ/kg	26.41
(iii)	Crushing	Impact crusher	Electricity	1 kWh	3.6 MJ/kWh	3.6
(iv)	Grinding	Roller press	Electricity	15 kWh	3.6 MJ/kWh	54
(v)	Calcination	4-stage short-preheater and precalciner	Electricity	21.7 kWh	3.6 MJ/kWh	78
		Assume weighted average computed in ***Table 4.4***	Coal	145 kg	25.6 MJ/kg	3 716 [b]
(vi)	Grinding	Ball mill	Electricity	45.8 kWh	3.6 MJ/kWh	165
(vii)	Transportation to site (100 *km*) [c]	Trucks	Diesel	-	0.42 MJ/km.ton	42
	Total Unit Energy (MJ/ton) (S.A Average)					**4 085**

[a] : Worell *et al*. (2001) source of energy data for cement production

[b] : 3 716 MJ/ton of cement is calculated as follows: 3 530 MJ/ton of clinker x 1(cement)/0.95 (clinker)

[c] : Typical transportation distances of materials to site of 100 km; the capacity of the truck is estimated to be 45 t for cement (Mclntyre *et al*. 2009)

For the average 9 Mt of cement used in concrete per year, for the period 2005-2010, a total amount of 37 x 10^6 GJ of energy was consumed in cement production.

4.4.2.4 Carbon equivalent emissions from cement manufacture for the period 2005-2008

The main CO_2-eq emissions from cement are due to: (i) calcination or decomposition of limestone ($CaCO_3$) to calcium oxide (CaO), in the process liberating CO_2, and (ii) coal burning in pyro-processing. Secondary sources of CO_2-eq emissions arise from the combustion of fossil fuel required to produce the electricity consumed by cement manufacturing operations and from the transport of raw materials and the finished product to consumers (Association of Cementitious Material Producers (ACMP), 2011). Based on the assumption that 73.4 % of the cement produced goes into the production of concrete, approximately 9 x 10^9 kg CO_2-eq are emitted per year as shown in ***Table 4.6***.

Table 4.6 : *Average total greenhouse gas emissions from cement manufacture (InEnergy Report, 2010).*

Year	*Total cement production*	*kg CO_2-eq emissions*			*Total emissions*
	[*t* x 10^7]	*Scope 1* [$\times 10^9$]	*Scope 2* [$\times 10^9$]	*Scope 3* [$\times 10^9$]	*[kg CO_2-eq]* [$\times 10^9$]
2005	1.15	9.38	1.67	0.25	11.3
2006	1.27	10.4	1.84	0.28	12.5
2007	1.37	11.2	1.98	0.30	13.5
2008	1.33	10.9	1.94	0.29	13.1
2009	1.07	8.73	1.55	0.23	10.5
2010	0.98	8.05	1.43	0.22	9.70
6-year average kg CO_2-e from cement industry					11.8
Contribution from the Portland cement used by the concrete industry (73.4 %) kg CO_2-eq					**9E+09 kg CO_2-eq**

4.5 Discussion

4.5.1 Data included in the analysis

The data on the annual average mass of aggregates consumed in SA were from ASPASA and were used in further analysis of the environmental performance of the SA concrete construction industry. In addition, the data are for the period 2005-2010.

A summary of the results obtained are reported in ***Table 4.2***.

Table 4.7: *Summary of resources and emissions in concrete constituent's production in SA, during the period 2005-2010.*

Data	*Material*	*Units*	*Average annual* [$\times 10^7$]
Raw material	Aggregates	tonnes	3.3
	Cement	tonnes	1.4
	Total	**tonnes**	**4.7**
Energy	Aggregates	MJ	160
	Cement	MJ	3700
	Total	**MJ**	**3860**
CO_2-eq	Aggregates	kg CO_2-eq	14
	Cement	kg CO_2-eq	900
	Total	**kg CO_2-eq**	**914**

4.5.2 Raw materials for concrete production in South Africa

Based on the data given previously, on average, about 47 Mt of raw materials per year were used for concrete production in SA for the period 2005-2010.

Of these, 33 Mt were coarse and fine aggregates (ASPASA data) and 14 Mt were the raw materials: limestone, silica, iron ore and clay, used in the production of 9 Mt of cement.

On average, coarse and fine aggregates account for 70 % by mass of the total raw materials consumed per year in concrete production.

4.5.3 Energy use

A total of 39 x 10^6 GJ of energy per annum was used in extraction, production and transportation of constituent materials for concrete, for the period 2005-2010.

Cement is more energy intensive compared to aggregates and consumes on average 95 % of the total energy by the concrete industry in SA.

4.5.4 Carbon equivalent emissions

The dependence on non-renewable energy resources (e.g. coal) in the manufacture of constituent materials for concrete in SA has led to the production of global greenhouse gas (GHG) emissions. An average of 9.1 x10^9 kg CO_2-eq emissions per year were emitted in SA for the period 2005 and 2010. These CO_2-eq emissions per annum relate to the 'cradle-to-gate' activities for cement and aggregates used for concrete production.

Cement is the main contributor of CO_2-eq emissions, contributing on average 98 % of the total carbon equivalent emissions by the concrete industry in SA.

4.5.5 Concrete production in South Africa

Based on ***Figure 4-10*** an average of 6.2 million m^3 (15 Mt) of ready-mix concrete [34] was produced per year for the period 2005-2010. Also, 5.9 million m^3 (14 Mt) of concrete was used in the production of concrete products: paving blocks, roof tiles, masonry, floor slabs, retaining blocks and infrastructure products. In addition 1.5 million m^3 (3.6 Mt) was used in civil engineering construction. ***Table 4.8*** gives a summary of the total annual average amount of concrete produced and corresponding environmental impacts.

Table 4.8: *Summary of resources and emissions in concrete production in SA, during the period 2005-2010.*

Concrete products	*Annual average amount of concrete*	*Annual average emissions from concrete mixing and transportation from ready-mix plant/ precast unit/ material retailers to site* *(*12.2 kg CO_2-eq/tonne: *InEnergy report, 2010)*	
Units	*[million m^3 (Mt)]*	*[kg CO_2-eq][* x 10^8*]*	*%*
Ready-mix concrete	6.2 (15)	1.83	23
Concrete products: Blocks, tiles, pipes	5.9 (14)	1.71	21
Civil Engineering infrastructure	1.5 (3.6)	0.44	6
Building construction	13.3 (32.6)	3.98	50
Total	27 (65.2)	7.96	100

In total an average 27 million m^3 of concrete (65.2 Mt) was produced in SA per annum for the period 2005-2010. These amounts are expected to increase in future due to government and private industry investment in new (and replacement) construction to cope with the rapid rate of urbanization and population growth in SA.

The amount of concrete produced in SA relative to the size of its population[35] is relatively low in comparison to developed countries. SA produced approximately 1.4 tonnes of concrete per person. A similar study carried out by Woodward and Duffy (2011) on the cement and concrete flow analysis of the Republic of Ireland's concrete industry found that 32.8 Mt of concrete were consumed by the

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[34] The consumption of concrete is based on cement sales figures. The calculations are based on the assumption that on average 325 kg of cement is used to produce 1m^3 of concrete.

Thus, the yearly amount of ready-mix concrete produced in SA is $\frac{17\% \times 11.9 \times 10^9\, kg}{325 kg/m^3} = 6.2$ million m^3.

[35] South Africa's population in 2008 was around 48 million with a GDP of US$ 277 billion (GDP per capita= US$ 5 770) (World Development Indicators database, 2009)

country (population approximately, 4.2 million) in 2007. On a per capita basis, Ireland produced 8 metric tonnes in 2007 (Woodward and Duffy, 2011).

When compared to the worldwide consumption of concrete, SA produces only 0.49% of the estimated 8 billion m^3 per year **(**CEMBUREAU, 2009). The latter worldwide estimate of concrete is based on the assumption that all cementitious products go towards the production of concrete. A more accurate estimate can be arrived at if the end-uses of cement in the various countries worldwide are reported.

4.5.6 Gate-to-grave phases of concrete structures

The '*gate-to-grave*' phases of concrete covers all activities from the construction of the structure, on-site transportation activities to the demolition of the structure. The '*gate-to-grave*' phase of a concrete structure is case-specific in that it depends on the type of structure. For example, for a concrete bridge structure, the traffic during the service-life of the bridge and traffic deviation during maintenance and repair actions on the bridge would be included in the 'gate-to-grave' phase, whereas for concrete buildings, the heating, lighting and cooling energy requirements would be considered for the same phase.

This phase is excluded from the scope of the work in this Chapter. However in Chapter 6, when dealing with 2 case studies of a RC building and a post-tensioned concrete bridge, a sense of the relative weighting of the grave-to-gate environmental impacts will be assessed with respect to the cradle-to-gate phase.

4.6 Comparison of the environmental impacts of other South African local industries

On average, SA produced 477 Mt CO_2-eq emissions annually for the period 2005-2010 (Carbon Disclosure Project, 2012). ***Figure 4-12*** gives a comparison of the CO_2-eq emissions of the overall aggregate and cement industry in SA with other local industries. The two major contributors are electricity generation (47%) from South Africa's electricity utility supplier, Eskom, and Synfuels (15%) produced by South African Coal and Oil (SASOL) Company. The cement and aggregate industry contribute 2.1% and 0.2% respectively of the total CO_2-eq emissions emitted in SA.

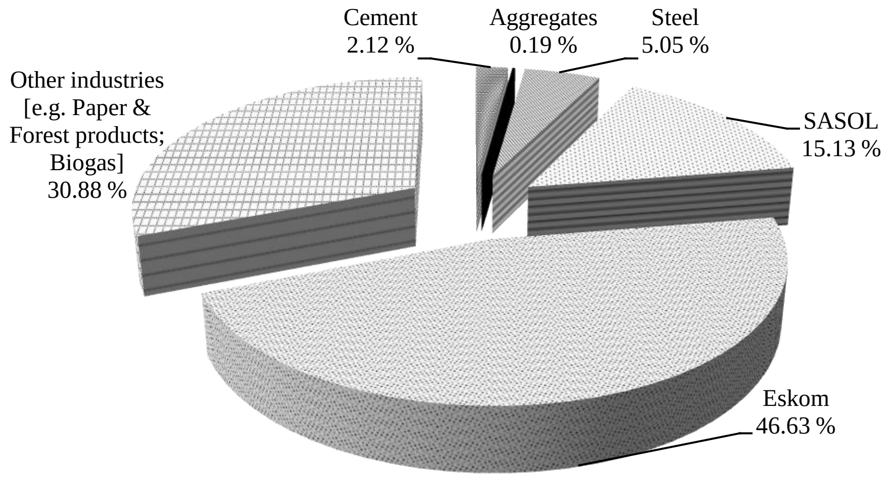

Figure 4-12: *Scope 1 CO_2-eq emissions by sector in SA.*

Data sources for Figure 4-12			
Industrial sector	*Average annual production (2005-2010)*	*Average emissions/unit of production*	*Source of data*
Cement industry	12,291,952 tonnes	818 kg CO_2-eq /ton	(http://www.cnci.org.za/)
Aggregates industry	110,500,000 tonnes	5.36 kg CO_2-eq /ton	(Kohler, 2011): ASPASA data
Steel industry	2 229 140 tonnes	2 735 kg CO_2-eq /ton	(http://www.saisi.co.za/ (South African Iron & Steel Institute (SAISI))
Electricity generation	258,296,160 MWh	1 021kg CO_2-eq/MWh	(Eskom 2011)
Synfuels production	442,828,000,000 MJ	1 021kg CO_2-eq/MWh	http://www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=1&rootid=1

For all industrial carbon emitters, the SA National Treasury is in the process of introducing an economic mechanism in the form of a tax on industries of R75/ton CO_2-eq which will be increased to R200/ton CO_2-eq with time in order to achieve the emission targets it voluntarily sought to achieve during the Copenhagen climate negotiations (refer to Chapter 2) (http://www.treasury.gov.za/public%20comments/Discussion%20Paper%20Carbon%20Taxes%2081210.pdf). This is expected to bring about a change in the way materials are currently processed by all local industries.

Although the cement and aggregate industries are not a major source of the CO_2-eq emissions in SA, they do contribute to the overall environmental impacts from local industries in SA. *Section 4.5.2* to *4.5.5* showed that the concrete construction industry is a major consumer of the products of the cement and aggregate industries. Hence, providing solutions to reduce the environmental impacts of the concrete industry would not only assist in reducing the individual environmental impacts of the aggregates and cement industry but in general SA's overall environmental impacts.

4.7 Solutions to reducing the environmental impacts of the concrete industry

Coarse and fine aggregates account for 70 % by mass of the total raw materials consumed per year in concrete production in SA. To reduce the use of primary aggregates in concrete, the Waste Management Act (2008) in SA, provides incentives that encourage use of alternative materials such as recycled aggregates. Substituting primary aggregates with recycled aggregates where it is technically feasible, allows for current levels of demand for aggregates to be met while conserving primary aggregates. Aforementioned, the major limitation to the use of recycled aggregates in concrete in SA, is the lack of design provisions for the use of recycled aggregates in concrete in current standards and codes (e.g. SANS 10100-1: 2000; SANS 10100-2:2005). Also, while some work has been done on the use of recycled aggregates in concrete (e.g. Kutegeza and Alexander, 2004), considerably more research is required in this area to give confidence in use of these materials.

In addition to legislative measures and design code provisions for recycled aggregates, economic instruments such as taxes and charges are possible interventions which can be put in place to minimise primary aggregate consumption. For example, countries such as the UK and Denmark have introduced an aggregate levy. The UK levy imposes a tax of £2.10 per tonne of quarried aggregates (2010 figure) for primary extraction of aggregates and on landfill disposal (Aggregates Levy, 2002). The tax is expected to bring about a greater efficiency in the use of primary aggregates and greater use of alternative materials. However, the possible introduction and implementation of a similar levy in SA is currently impossible due to the reported disaggregation of the sand and aggregate industry. This disaggregation is evidenced by the significant difference in data, on aggregates production, reported by both ASPASA and DMR.

Cement is the main contributor of CO_2-eq emissions, contributing on average 98 % of the total emissions by the concrete industry in SA. It is also energy intensive compared to aggregates and consumes on average 95 % of the total energy by the concrete industry in SA. Techniques to reduce the CO_2-eq emissions of cement and energy use can be found in literature (Damtoft *et al.*, 2008; Gartner, 2004) and include:

(a) *Improved thermal and electrical energy efficiency of cement kilns*

Optimizing kiln processes and plant efficiencies during cement production results in the reduction of CO_2-eq emissions and also brings down the cost of production. Modern cement kilns should use the dry processing of raw materials, as opposed to the wet process.

(b) *Co-processing of alternative fuels*

Substituting wastes for fossil fuels is referred to as co-processing alternative fuels (Ziegler *et al.*, 2007). Substituting wastes such as waste tyres and biofuels for primary fuels (e.g. coal) can help reduce the fossil fuel energy use in cement kilns. SA has accepted that co-processing of waste in cement kilns as best practice under the Waste Incineration Directive 2000/76-EC. Previously, co-processing of wastes in cement kilns has been met with opposition from local communities and environmental organizations. Communication to public representatives about the opportunities and potential benefits of co-processing is required, for example, the use of waste fuels presents a number of benefits: it increase the capacity to divert land-fill wastes, reduces the energy intensity of fossil fuel consumption, and creates jobs (e.g. sorting of wastes).

(c) *Reducing the clinker content in cementitious materials*

Blended cements are produced by inter-grinding Portland cement clinker with supplementary cementitious materials (SCMs) or by blending Portland cement with SCMs such as fly ash from coal combustion in electricity producing plants or blast furnace slag from iron-making plants. The blended cements produced should comply with SANS 50197-1:2000, SAN 50413-1:2004 and SANS 1491 parts 1, 2 and 3. The use of blended cements reduces the amount of clinker that needs to be produced, also lowers the CO_2-eq emissions, and diverts wastes from landfills, as SCMs are by-products of other industries that would otherwise have been disposed.

In ***Figure 4-7*** it was shown that between 2005 and 2008 there was a growth in demand of blended cements: CEM III/CEM IV/CEM V whereas the demand for CEM I Portland cement reduced. This has a positive impact towards the reduction of the CO_2-eq emissions of the concrete industry in SA.

(d) *Carbon capture techniques*

These include techniques for the separation and possible capture and storage of CO_2-eq from exhaust gas in cement plants which is then stored underground or in the ocean (Baker *et al*., 2009; Gartner, 2004). However, the implementation of carbon capture techniques is not yet economically feasible.

4.8 Roles of the key players in the cement and concrete industry

Based on the definition of a 'sustainable concrete structure' given in Chapter 2 and the findings of this chapter 4 on the major environmental impacts of the cement and concrete industry, there is a need to establish the roles of the key players in the construction industry in a bid to establish their potential in contributing towards the environmental performance of the cement and concrete industry. This information is summarized in ***Figure 4-13***.

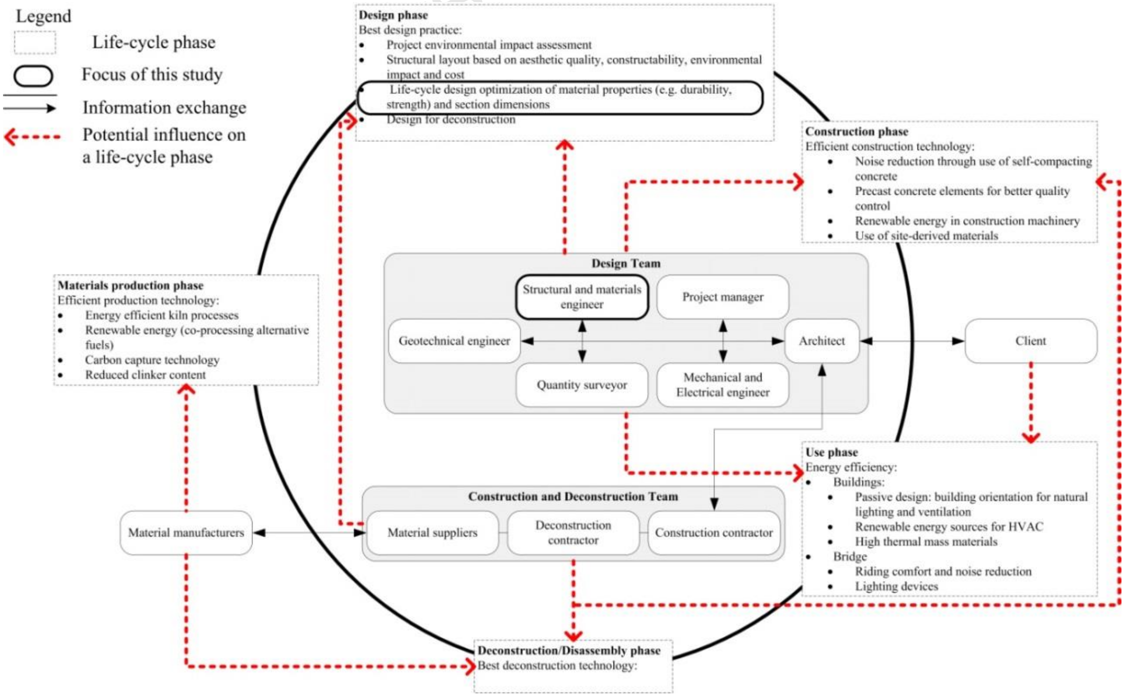

Figure 4-13: *Roles of the key players in the cement and concrete industry.*

The key players in the industry consist of the material producers, the design and construction team which includes: the architect, structural and materials engineer, geotechnical engineer, mechanical and electrical engineer, the quantity surveyor, the project manager and the contractor and the user /owner of the structure.

Figure 4-13 shows the potential areas in which these key players can influence in order to improve the overall environmental performance of the industry. Of importance and the focus of this study is potential of structural engineers in reducing the embodied impacts of concrete structures through materials selection and section dimensions optimization. From ***Figure 4-13***, it is noted that the structural and materials engineer is faced with a major role in selecting materials which not only perform well during their use phase (e.g. moderate building indoor performance for human comfort) but in addition have minimal initial and recurring environmental impacts due to e.g. deterioration.

4.9 Summary

The purpose of this Chapter was to evaluate the extent of resource use and emissions associated with the production of concrete construction materials in South Africa. Six year average (2005-2010) data are provided for resources consumed, energy consumed and wastes emitted to the air due to quarrying and processing of raw materials and production of concrete in SA. The findings from the review are summarised in ***Table 4.9***.

Table 4.9: *Summary of the cradle-to-gate environmental impact of the cement and concrete industry in SA, during the period 2005-2010.*

Data	***Units***	***Cradle-to-gate phases***		***Total***
		Raw materials quarrying, processing and transportation	*Concrete production and transportation to site*	
Materials	tonnes	47×10^6	65.2×10^6	0.11×10^9
Emissions	kg CO_2-eq	9.1×10^9	0.8×10^9	10×10^9
Energy	GJ	39×10^6	-	39×10^6

In addition to policy instruments such as carbon taxes, there are a number of techniques to reduce the CO_2-eq emissions and energy use of the cement industry. These include: improving the energy efficiency of cement kilns, co-processing of alternative fuels in cement kilns, reducing the clinker/cement ratio by substituting part of the clinker with SCMs and the use of carbon capture techniques. However, it was noted that a viable method of reducing and monitoring the evaluation of a reduction in the overall environmental impacts of concrete would be through design.

In total an average 27 million m^3 of concrete (65.2 Mt) was produced in SA per annum for the period 2005-2010. This amount is only 0.49% of the estimated 8 billion m^3 of concrete produced worldwide. However, it was noted that based on the continued government and private industry investment in new (and replacement) construction to cope with the rapid rate of urbanization and population growth, these values are expected to rise in future. This shows the need to engage the concrete practitioner on innovative ways that can further reduce the overall impacts of concrete structures.

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Chapter 5

5 TOWARDS THE DESIGN OF MORE SUSTAINABLE REINFORCED CONCRETE STRUCTURES: A PROPOSED FRAMEWORK FOR MATERIALS SELECTION AND DESIGN

5.1 Introduction

This study aims to contribute towards the design of more sustainable concrete structures by developing a framework for design of concrete structures that encapsulates structural, materials and environmental considerations for these structures over their life-cycle.

The proposed framework for design is outlined in this chapter and relies heavily on the results of the previous review chapters made in this study. Chapter 2 of this study showed the importance of applying sustainable development principles in the design of concrete structures. This requires first a re-definition of a '*sustainable concrete structure*' in a way that makes it easier to quantify the sustainability of a concrete structure and include it as a main design objective, amongst other objectives such as durability and structural safety. Following a critical literature review of the '*sustainable development'* concept in Chapter 2, a definition of what constitutes a 'sustainable structure' was arrived at as: *"…one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling"*. In addition, Chapter 2 showed the various aspects of a RC structure which the structural engineer can influence in order to reduce the overall environmental impacts of concrete structures (*Section 2.4, Chapter 2*). A further critical literature review in Chapter 3 identified various metrics for assessing the environmental sustainability of reinforced concrete (RC) structures. The results of these past reviews have been applied in this chapter as part of a broader framework for performance-based sustainability design.

The proposed framework allows a RC practitioner to address explicitly the sustainability of a RC structure over its life-cycle in the detailed design phase. In summary, the framework shows how sustainability can be adequately addressed in the material design and specification process with the aim of expanding the existing performance-based material design process to fit into a broader proposed framework that considers sustainability. A background of the current performance-based design methodology is given next followed by its application to the proposed design framework. Later in this chapter the application of the proposed framework will be demonstrated with the design of a RC beam.

5.2 Background

Since the invention of RC in the mid-19th century, key design issues for structural concrete[36] have gradually moved from considerations of strength[37] and costs to include durability and sustainability considerations. The historical development of the use of structural concrete with time and the design issues under consideration at different points in time are illustrated in ***Figure 5-1***.

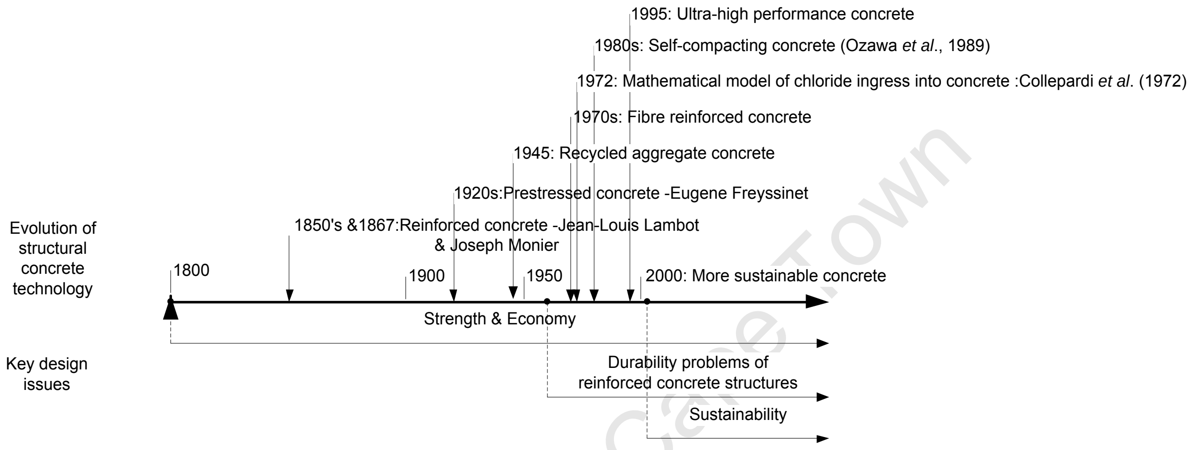

Figure 5-1: *Timeline of concrete and concrete technologies.*

RC served as the main structural component 70 years after its discovery, up and till the mid-1920s when Eugène Freyssinet showed that concrete can be reinforced with high strength steel wires to reduce creep deformation and cracking. The use of prestressed concrete increased rapidly in the mid-20th Century due to severe shortage of steel for RC during the Second World War.

However, in the 60's and 70's durability concerns with both prestressed and RC structures caused by lack of quality control during construction and inadequate maintenance led to considerable amount of resources being spent on repair actions. Consequently, durability became the key design issue of RC structures, particularly from the 1990s and especially for those structures located in aggressive environments. Durability design of RC structures is concerned with ensuring the ability of the concrete to resist degradation under environmental conditions during its design working life without significant deterioration. In 1972, the first mathematical model of chloride ingress into concrete was developed by Collepardi *et al*. (1972). The model has been modified and applied to current durability design of RC.

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[36] Structural concrete as referred to in this study is that used in the construction of buildings and major infrastructure such as bridges and dams. It can take various forms such as precast or cast-in situ concrete. In addition, the term also refers to reinforced and prestressed concrete

[37] Strength is used to refer to structural capacity, resistance to creep and shrinkage deformation, fire resistance etc.

In the mid-20th Century and beginning of the 21st Century, increased uptake of RC as a structural material has led to sustainability issues. The worldwide consumption of concrete has been estimated to be approximately 8 billion m^3 in 2009 (20 000 million tonnes) (CEMBUREAU, 2009). This amount of material consumption translates to approximately 3 tonnes per capita making concrete the most widely used material on earth. The use of concrete as a structural material will continue to increase particularly in developing countries due to the exponential increase in population growth and industrialization. However, while concrete production continues to grow and contribute towards economic development around the world, evidence suggests that this growth is associated with an escalating burden on the environment as detailed previously in Chapter 2.

The current key driver for design of more sustainable concrete structures has been the need to minimize use of natural resources and greenhouse gas emissions over the life-cycle of concrete. Environmental concerns of concrete have led to increased use of industrial by-products in concrete e.g. ground granulated blast furnace slag (GGBS) from iron-making plants and fly ash (FA) from coal combustion in electricity producing plants. These supplementary cementitious materials (SCMs) replace part of the Portland cement and hence reduce carbon emissions associated with cement manufacture. In addition, the use of SCMs has been shown to produce highly durable concrete in saline environments. During material design, the selection of different SCMs is carried out on the basis of their performance with respect to necessary design requirements of concrete such as its compressive strength, durability and with respect to the focus area of this study, sustainability. For the latter design requirement, the *fib* model code for concrete structures[38] (*fib* Bulletin No. 34, 2006) gives initial ideas with regard to the design of more sustainable concrete structures using a reliability-based (probabilistic) approach. In this approach, the performance of the structure (R), with respect to e.g. its impact on the environment is verified against a target performance (S). The reliability performance based approach has previously been applied to structural safety (Ang and Cornell, 1974; Faber and Sørensen, 2003) and durability design (Gehlen and Schiessl, 1999). A review of the application of a performance-based approach to the design of concrete structures and its inherent limitations is given in the next sub-section.

5.2.1 Design of reinforced concrete structures

Broadly, 'design' is defined as the activity of transforming the functional requirements of a project into a solution concept or concepts for fulfilling requirements (Chakrabarti and Bligh, 1994). The term 'design' as used in this study refers to the design of RC that uses mathematical models and tests and/or experienced-based mix-design compositions to achieve the required concrete properties in the hardened state.

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[38] The *fib* model code for concrete structures was approved by the 11th General Assembly of the *fib* (fédération international du beton) on October, 2011, and acts as a basis for national code development.

Performance-based design of reinforced concrete structures is recommended by the *fib* (fédération international du beton) model code for service life design (*fib* Bulletin No. 34, 2006). Three levels of sophistication of the performance-based approach can be distinguished (*fib* Bulletin No. 34, 2006):

(i) The deemed-to-satisfy approach
(ii) Partial safety factor, and
(iii) Probabilistic approach, the latter being the most sophisticated.

5.2.2 Performance-based design approach

The deemed-to-satisfy approach (*(i)* above) requires the concrete practitioner to prescribe limiting values for concrete composition to satisfy the performance requirements for e.g. strength and durability for a set of environmental exposure classes. The current European Standard EN 206-1:2000 to concrete design adopts a deemed-to-satisfy approach and prescribes minimum cement content, maximum *w/c* ratio, and minimum compressive strength class for concrete components in various environmental exposure classes. The main limitation of this approach is that it does not show/allow the verification of the actual performance of the concrete over its service life. Thus it is not possible to establish that e.g. there would be no repair action on the structure for the prescribed service life.

A performance-based partial safety factor and probabilistic approach (*(ii)* and *(iii)* above, respectively) involve the quantitative evaluation of durability of concrete using the limit-state approach. The approach is based on limit-state theory, documented in ISO 2394: 1998, in which four limit states can be distinguished: ultimate limit-state (ULS) design, serviceability limit-state (SLS) design, durability-limit-state (DLS) and sustainability limit-state. The ULS depicts the point at which the safety of the structure is addressed e.g. excessive deformation and loss of stability (EN 1990-1: 2002). SLS considers failures due to material deterioration (e.g. corrosion induced cracking), or excessive deflection, cracking and vibration whereas DLS marks the onset of durability failure e.g. corrosion initiation in a RC structure (ISO 13823: 2008). It is suggested here that the sustainability limit-state encompasses the previous 3 limit-states and in addition ensures that the quantified life-cycle environmental/social/cost impacts of a structure is minimized for a set of quantifiable structural and material design variables.

The limit-state approach to design of concrete structure is currently applied to the durability design of concrete structures (Muigai *et al*., 2012; Gehlen and Schiessl, 1999) but not to the extent it has been for structural safety design. The application of the limit-state approach to sustainability studies is proposed by the '*fib* model code for concrete structures' but actual application of the methodology in design is yet to be realized.

Using the limit-state approach would involve measuring e.g. the life-cycle environmental impacts of concrete using quantitative metrics such as e.g. exergy and the amounts of greenhouse gas emissions generated over the life-cycle of concrete. Alternatively, the environmental impact can be defined positively in terms of renewable resources used in a concrete structure and/or the amount of waste minimized through recycling demolished concrete. The ‘*fib* model code for concrete structures’ recommends that the environmental performance of concrete be verified by ensuring that the retained performance (R) is larger than the target set requirements (S). This condition is expressed by Equation (5-1).

$$R \geq S \tag{5-1}$$

where,

R: Estimated environmental performance of concrete

S: Target performance requirement e.g. 5% reduction in the environmental impact of e.g. alternative concrete relative to conventional concrete.

Due to the inherent uncertainty in measuring the environmental impact, a probabilistic approach is suggested. In a probabilistic approach, the statistical information of the parameters in R and S, in Equation (5-1), is exploited to provide improved uncertainty estimates in the output, which is usually stated in terms of the probability that the condition represented by Equation (5-1) occurs. The probability of this occurring during the life-cycle of the structure is termed the probability of failure. This condition is represented by Equation (5-2).

$$P_f = P(R - S < 0) \tag{5-2}$$

P_f is compared with an acceptable probability of failure, P_{target}, such that:

$$P_f = P(R - S < 0) \leq P_{target} \tag{5-3}$$

A demonstration of this performance-based approach to sustainability design is given in Lepech *et al*., (2011) where a probabilistic-based approach is proposed to be used in selecting alternative construction and repair technologies. The study shows the computation of P_f to meet sustainability goals as follows:

$$P_f = P\left(\frac{I_{old}(t_G) - I_{new}(t_G)}{I_{old}(t_G)} - G(t_G) \geq 0\right) \tag{5-4}$$

where, $I_{old}(t_G)$ – is the cumulative impact of the conventional construction/repair strategy, $I_{new}(t_G)$ is the cumulative impact of the alternative construction/repair strategy, $G(t_G)$ – is the target reduction in the environmental impact and t_G is the time in future at which the goal reduction should be achieved.

Though the study by Lepech et al., (2011) does not give the parameters/variables to be included in the $I_{old}(t_G)$ and $I_{new}(t_G)$ functions, Equation (5-5) can be used to represent the cumulative impact (I_{tot}) of the construction/repair strategy.

$$I_{tot} = I_{in} + I_m + p_1 I_1 + p_2 I_2 \tag{5-5}$$

where

I_{in} : environmental impact of design and erection of structure

I_m : environmental impact of maintenance

$p_1.I_1$: environmental impact of repairing the structure that is likely to happen with the probability, p_1

$p_2.I_2$: environmental impact of demolition with probability, p_2

The study by Lepech *et al*., (2011) also recommends the selection of suitable target performance criteria based on scientific principles rather than environmental policies such as the 5% CO_2 reduction target recommended by the Kyoto Protocol (*see Section 2.2.2: The United Nations Framework Convention on Climate Change*).

5.2.2.1 *Limitations of the performance-based probabilistic approach*

There are various limitations to the application of the limit-state approach in the design of concrete structures for sustainability. These limitations are as follows:

(a) *Uncertainty in design parameters*

The first limitation of the performance-based probabilistic approach to sustainability design of concrete structures arises from the fact that the method relies on characterizing each life-cycle assessment parameter in terms of mean, standard deviation and statistical distribution. Currently, one of the major problems is the lack of reliable local environmental data on various constituent materials of concrete (*as was previously discussed in Section 3.3.1.4, Chapter 3*).

Due to shortage of data on environmental variables, the present study applies a deterministic performance-based approach to the design of sustainable RC structures. The proposed framework in this study is however adaptable to the use of either a deterministic or probabilistic performance-based approach to design.

(b) *Acceptable target probability of failure for sustainability*

A consensus has not been reached on an acceptable target probability of failure for sustainability performance. This is mainly because of a lack of a unified definition of sustainable concrete structures. A target probability of failure should be evaluated on the basis of a balance between the quantified quality of a material and its financial and social cost and environmental impact over the material's life-cycle.

This study does not apply a target sustainability performance measure in the deterministic limit-state methodology but shows how more sustainable material compositions can be selected based on a comparative analysis of the available materials.

5.3 Proposed framework for design of concrete structures

5.3.1 Introduction

This study proposes a framework for design that encapsulates the current limit-state design methodology for concrete and which enhances sustainability considerations of concrete structures at the design stage. The proposed framework allows for the design of a more sustainable concrete structure through selection of appropriate materials and section dimensions. The application of the framework is demonstrated later in this chapter using a simple RC beam. Further applications of the framework will be demonstrated in Chapter 6 using two case studies: a reinforced concrete-framed building and a post-tensioned concrete box girder.

5.3.2 Design framework

The concept of designing for more sustainable concrete structures, calls for the design team to adopt a different approach to thinking about the decisions regarding the choice of constituent materials for concrete and their long-term effects on the environment and society. To facilitate this process, a framework for design is proposed as shown in ***Figure 5-2*** that consists of key criteria that should be taken into consideration for RC design. These are:

(i) *A set of quantifiable design parameters and variables* – consisting of the geometry of a structural component, concrete mix-design constituents and concrete hardened properties that have an influence on the life-cycle sustainability of concrete. The framework is limited to quantifiable parameters and variables. However, there are other qualitative related parameters that have an influence on the overall sustainability of concrete e.g. construction site practices such as curing, compaction and good workmanship. These qualitative factors also play a major role in the long-term structural performance of concrete. However, they are excluded from this study as they cannot be quantified in physical units. Suffice to say that best practice in these aspects is necessary to realize sustainable concrete structures.

(ii) *Performance measures* – that consist of quantitative indicators that allow for the selection of appropriate design variables and parameters.

(iii) *A database* – of alternative materials for concrete, repair methods and end-of-life strategies for concrete, and their associated unit environmental life-cycle impacts and costs/benefits to the user and owner of the structure.

5.3.2.1 *Description of the framework*

The framework (***Figure 5-2***) consists of the following processes:

(i) A set of functional design requirements of a RC structure, as specified by the client and/or the design codes and standards. For example, structural design codes such as EN 1991-1 gives guidelines for the expected loading on structures.

Other functional requirements include the desired service-life of the structure, which may be specified by the client/owner of the structure. To ensure that the expected design service life is met, the designer should take into consideration the service environment of the structure and classify it based on the requirements of EN 206-1: 2000. In essence, the designer is required to establish the environmental actions i.e. those chemical and physical actions to which the RC structure is exposed and that result in deterioration of the concrete or reinforcement. Deterioration of RC results from reinforcement corrosion, alkali-silica reaction, chemical attack, leaching by non-basic (and non-alkaline) solutions, and high temperatures generated in case of fire (EN 1992-1: 2004). The main environmental action on a RC structure is frequently related to corrosion caused by ingress of chlorides or CO_2 gas.

In addition it is necessary to include sustainability considerations with respect to: (a) allowances for maintenance and/or repair, and (b) material recycling after the end-of life and/or the reuse of structural components. The former requirement allows the designer to select alternative materials that require maintenance/repair during the service life of the structure. This can be socially beneficial particularly in developing countries[39] that utilize human labour in the sourcing of alternative materials (e.g. site-derived materials) and in repair and maintenance activities.

Additionally, the designer is expected to consider beforehand the possible changes in use of the structure and design it for adaptability. For example, a building may be designed to have a flat slab, that avoids the use of beams to make it adaptable to different functions in future other than the one it was originally designed for. All these sustainability considerations allow the designer to take on a life-cycle perspective in design.

(ii) The functional design requirements are translated into measurable design requirements which consist of structural and material requirements and sustainability performance requirement in terms of e.g. the life-cycle environmental impact of the structure and the recycling potential of a material. The latter requires knowledge of the quality of the material at the end of its service life.

(iii) The framework contains a set of measurable design variables which have an influence on the sustainability of RC structures. A sensitivity analysis is carried out later in this study to determine the influence of the design variables on the life-cycle environmental impact of a structure.

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[39] In developing countries, the construction and maintenance of infrastructure is labour intensive. When low quality materials are selected for e.g. the construction of a rural road that has low-volume traffic, or low cost housing, then it has been shown that the opportunity cost of disruption to road traffic is lower compared to the opportunities created for the poor to work on construction and maintenance of rural roads and buildings.

(iv) The design requirements have different measurement units. Consideration should be given to the selection of a suitable integrated unit for comparing the performance of different materials with respect to the design requirements. The selected integrated performance measure is expressed as a function of the design requirements.

(v) The framework also consists of a reliable database of the unit environmental impact and costs of materials and construction activities. A single-score metric for environmental impacts is proposed in this study. A discussion of what constitutes an appropriate measure for environmental impacts of concrete was carried out in Chapter 3. It was mentioned that an appropriate metric should be founded on scientific principles. This means that the metric should quantify environmental impacts of materials in physical units and should give consistent results, independent of time and place, i.e. it should not be prone to inflation or other factors. Based on a quantitative evaluation, the exergy metric was recommended as a suitable metric that can be applied in selecting more sustainable construction materials. For comparison purposes, the current study also includes the global warming potential (GWP_{100}) [kg CO_2-eq] metric.

(vi) The design verification is an optimization process seeking to ensure that the selected design variables satisfy the performance requirements and result in minimum life-cycle environmental/social/cost impact. This assessment involves a limit-state approach as discussed previously.

(vii) The outputs of the framework are the optimal material properties and structural dimensions for the construction of more sustainable concrete structures.

5.3.2.2 *Application of the proposed framework for design in this study*

The proposed framework for design is extensive and the integration of all the design variables contributing to more sustainable concrete structures is beyond the scope of the current study.

The study focuses on materials selection of a concrete structure at the detailed design phase, hence excludes design aspects such as planning of the layout of the structure and determining the structural form and shape of the concrete structure.

The present study is also limited to considerations of the life-cycle environmental aspects of concrete structures and does not include social impacts/benefits. Aforementioned in Chapter 3, an appropriate method of quantifying social impacts is still under contention and further studies are required to establish this.

Further, in the application of the framework, later in Chapter 6, it is assumed that the design solutions yield the same service life. In addition, in the optimization process an assumption is made that the environmental burden of the structural elements investigated is approximately proportional to its life-cycle cost.

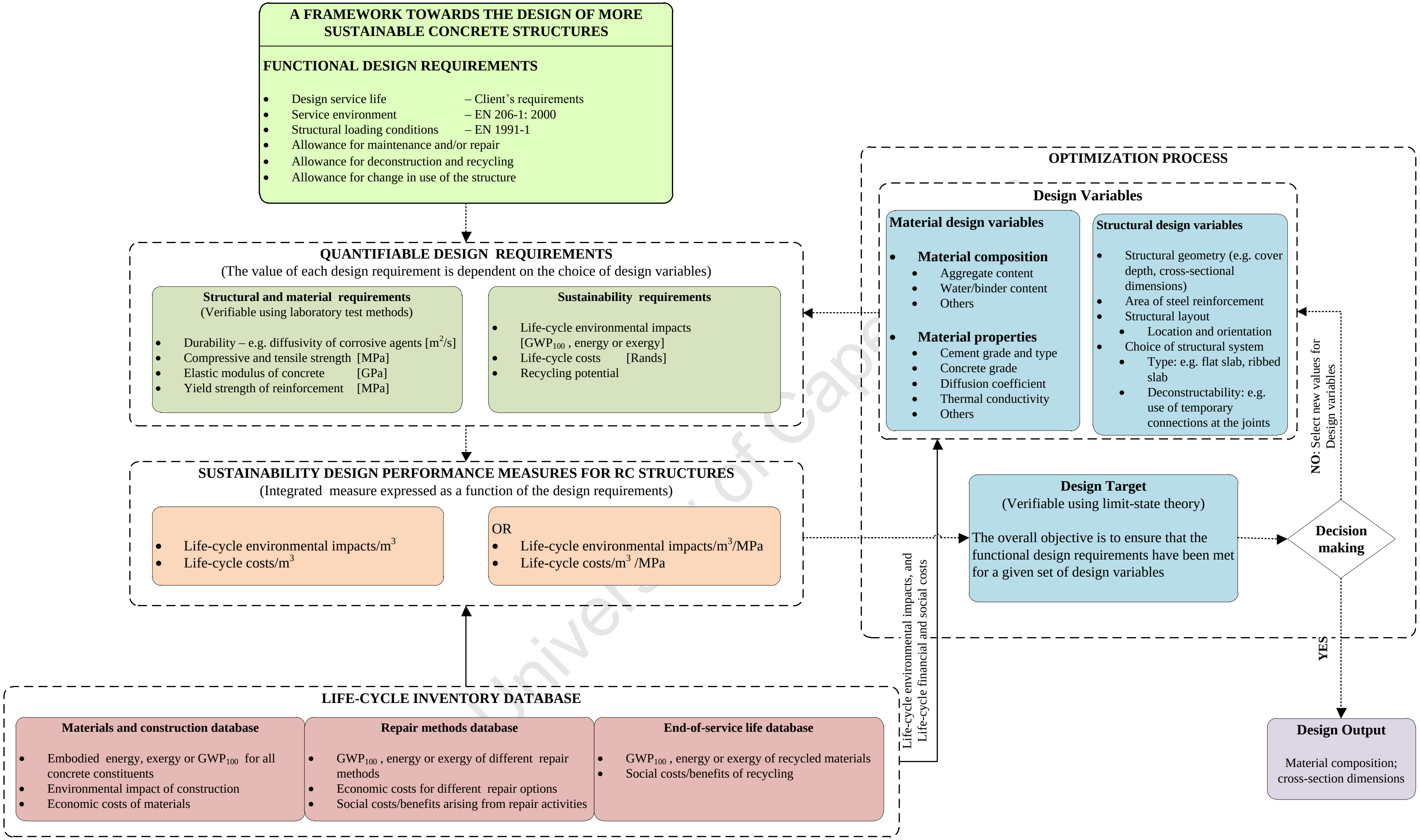

Figure 5-2: *Proposed design framework.*

The design variables selected for the proposed framework (***Figure** 5-2*) and performance indicators are ones that have been found to have a link to the sustainability of concrete structures as discussed in *section 5.3.3*. These variables are selected as they are measurable and their performance can be quantified. However, there are a number of other non-quantifiable variables that have not been included in the study.

The quantifiable and non-quantifiable design variables and parameters that have an influence on concrete sustainability are discussed in sub-sections *5.3.3.1* to *5.3.3.4*.

5.3.3 Design variables and parameters

The design variables considered in the proposed framework for design (***Figure** 5-2*) have a direct influence on the sustainability of concrete. To investigate the influence of the design variables on the sustainability of concrete, one has to consider the analysis at two levels: (i) the materials level which considers the selection of materials (natural and recycled), mix-design parameters and the resulting hardened concrete properties e.g. concrete compressive strength and concrete quality measured in terms of e.g. its diffusivity to ionic solutions and gases, and (ii) the structural level considers the section dimensions of a concrete element, repair and maintenance activities on the structure, and its deconstruction to open ways to the reuse of its structural components and their disposal if not recycled or reused. The materials and structural level are illustrated in ***Figure** 5-3*.

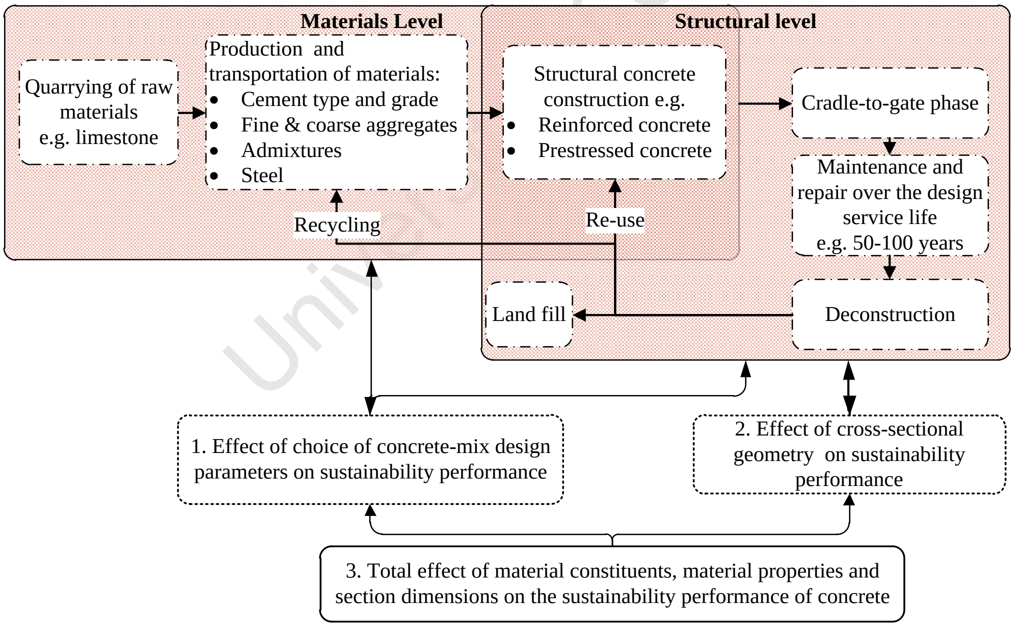

***Figure** 5-3: Design considerations for more sustainable concrete.*

The proposed framework for design (***Figure** 5-2*) takes account of the influence of the concrete mix-design constituents and material properties on the sustainability performance of concrete and in addition, the influence of structural dimensions on the sustainability of a RC structure. The choice of design variables for the proposed framework for design is discussed next.

5.3.3.1 The cement (binder) type

The cement type is selected as a design parameter in this study since it has a very significant influence on the environmental impacts of concrete when compared to other constituents of concrete. In Chapter 4 (Section 4.5.4), it was shown that cement production is an energy intensive process that accounts for approximately 98% of the total carbon equivalent emissions by the concrete industry in SA. Hence, selecting an appropriate cement (binder) type can contribute significantly in reducing the overall environmental impacts of concrete.

The common design practice towards reducing the environmental impact of cement is the replacement of a part of the Portland cement clinker, with uncalcined limestone and/or industrial by-products such as fly ash (FA), silica fume (SF) and/or ground granulated blast furnace slag (GGBS) (Glavind, 2009; Naik *et al*., 2003; Malhotra, 1993). The common types of blended Portland cements are given in SANS 50197-1 (EN 197-1) and are classified depending on the proportion of Portland cement clinker included e.g. (i) Portland cement (CEM I) has at least 95 % of Portland cement clinker; (ii) Portland-composite cements (CEM II) contain up to 35% of a mineral constituent such as GGBS, SF, natural pozzolanas, FA, burnt shale or limestone. (iii) Blast furnace slag cement (CEM III/A-S) contains 35-64% GGBS and; (iv) Pozzolanic cement (CEM IV) contains 11-55% of pozzolanic material such as SF, natural pozzolana or FA and; (v) Composite cements (CEM V) contain 18-50% natural pozzolana or siliceous FA. In addition, all the binder types have 0-5% of minor additional mineral constituents which include specially selected inorganic mineral materials. The cement types listed in ***Table 5.1*** are currently the most commonly used in South Africa in the inland and marine regions in concrete construction.

Table 5.1: *The commonly used cement types in structural concrete construction in South Africa as at October, 2012 (http://www.cnci.org.za/Uploads/Documents/Cement_Grid_Oct_%202012.pdf).*

Region in SA	***Nomenclature*** *(SANS 50197-1)*	***Strength class*** *(SANS 50197-1)*	***Clinker content***	***Secondary constituent***	***Minor (≤5% by mass) additional constituents***
Inland region (Gauteng, Northern Cape, Limpopo, Mpumalanga, Free State North West)	CEM I	52.5N	100% PC	-	0-5%
	CEM I	52.5R	100% PC	-	
	CEM II/A-V	52.5N	80-94% PC	6-20% FA	
	CEM II/A-M	42.5R	80-94% PC	6-20% Composite #	
	CEM II/B-L	32.5R	65-79% PC	21-35% L	
	CEM II/B-V	32.5R	65-79% PC	21-35% FA	
	CEM III/A-S	42.5N	36-65% PC	35-64% GGBS	
Coastal region (Western Cape, KwaZulu Natal, Eastern Cape)	CEM I	52.5N; 52.5R	100% PC	-	
	CEM II/A-V	52.5N; 42.5R	80-94% PC	6-20% FA	
	CEM II/A-M	42.5R	80-94% PC	6-20% Composite #	
	CEM II/B-L	32.5R	65-79% PC	21-35% L	
	CEM II/B-M	42.5N	65-79% PC	21-35% Composite#	
	CEM II B-S	42.5 N	65-79% PC	21-35% GGBS	
	CEM II/B-V	42.5 N	65-79% PC	21-35% FA	
	CEM III/A-S	32.5N	36-65% PC	35-64% GGBS	

PC – Portland cement; S/GGBS – Ground granulated blast furnace slag; FA – Fly Ash; L – Limestone; SF – Silica fume; V – Class 'F' Fly Ash

M – a composite of two or more of the previous additives;

"*B"* – indicates a medium proportion of the binder, "*A*" would be higher and "*C"* lower; N – Normal strength; R – rapid early strength

#Composite constituents – are ternary or quaternary cement blends that contain 2 or 3 supplementary cementitious materials such as GGBS, FA, SF, L, Burnt shale and Pozzolana, in addition to PC

Each of the cement types given in SANS 50197-1 (EN 197-1) can be produced at three different strength classes: 32.5, 42.5 and 52.5 N/mm^2 which are based on the 28-day compressive strengths of mortar prisms

(SANS 50197-1). The cement strength classes are sub-divided into high early (R) and ordinary (N) development of strength.

The amount of CO_2-eq emissions for manufacturing[40] a ton of binder is always highest for CEM I as shown in ***Figure 5-4***. Even though GGBS has 128.6 kg CO_2-eq emissions per ton compared to FA which has only 1.5 kg CO_2-eq emissions per ton[41], CEM III/A gives the lowest CO_2-eq emissions (550 kg CO_2-eq/ton) because it replaces 35-64% of the Portland cement content with GGBS compared to FA cement (CEM II/B-V) which has a replacement level of 21-35%.

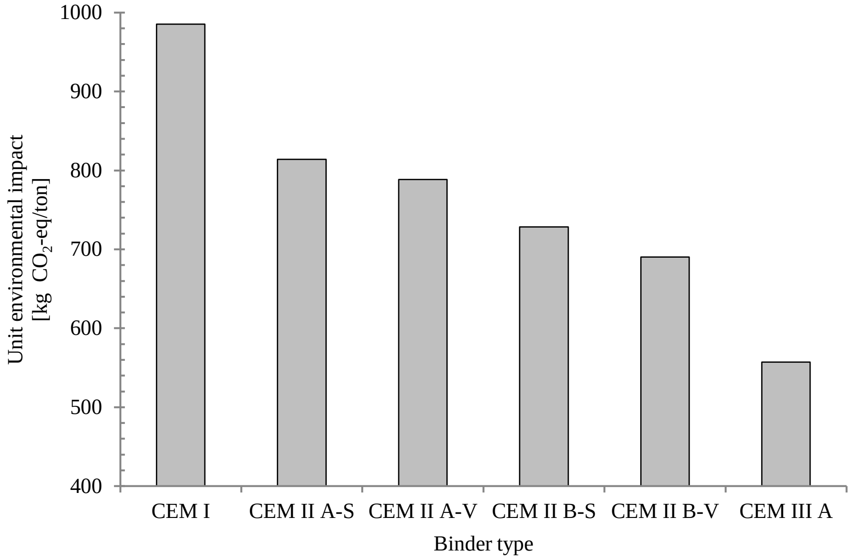

Figure 5-4: *Variation of kg CO_2-eq emissions per ton of different binders (InEnergy Report, 2010).*

However, the variability of the information presented in ***Figure 5-4*** has not been quantified. This may present considerable limitations in material selection for different cement combinations, for example: the average 690 kg CO_2-eq emissions reported for CEM II/B-V is for typical replacement values of 70%: 30% (CEM I: FA). However, within the same cement category, there is a range of varying cement combinations of 79%: 21% (CEM I: FA) to 65%: 35% (CEM I: FA) that can be produced. It is evident that these cement combinations will have significant differences in their CO_2-eq emissions per tonnage produced. It should be noted that the environmental impacts of different cement combinations can be approximated from first principles given the specific replacement levels of binders reported in ***Figure 5-4***.

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[40] The environmental impacts in Figure 5-4 relate to the extraction processing and transportation of materials for cement production. The avoided impacts due to use of the supplementary cementitious materials have not been included in this Figure as was previously illustrated in Chapter 3.

[41] The carbon equivalent emissions for GGBS are higher than those from FA as GGBS requires a further granulation process whereby it is rapidly quenched with water and ground. This allows it to develop binding properties suitable for its application as a cement substitute. The carbon equivalent emissions of FA arise from storage and transporting it to site or ready-mix plant.

The practice of blending cements not only contributes to the conservation of natural resources and a reduction in the amount of CO_2-eq emissions but also improves the chemical and physical properties of fresh and hardened concrete. Blended cements lead to desirable fresh and hardened properties of concrete such as: improved workability, reduced water demand, reduced heat of hydration, and hence reduced thermal cracking, and improved durability due to their high particle packing (Glavind, 2009; Malhotra, 1993) and chemical resistance.

In addition, the environmental impacts for a particular binder strength e.g. CEM I 42.5 N differ from other CEM I strength grades, but only very slightly. ***Table 5.2*** gives different strength grades for CEM I and their corresponding 'cradle-to-gate'[42] CO_2-equivalent emissions. Local (S.A.) data that distinguishes between the environmental impacts of different cement grades are not available, but it can be expected to be very similar to ***Table 5.2***.

Table 5.2: *Variation of the amount of CO_2-eq emissions/ton depending on cement grade (Ecoinvent database v2.0).*

Cement type (EN 197-1)	***kg CO_2-eq emissions /ton***
CEM I 42.5 N	821
CEM I 52.5 N	832

From ***Table 5.2***, the amount of CO_2-eq emissions from high strength cements are slightly higher due to the additional energy used in grinding their clinker to achieve their high fineness.

In summary, the cement type and grade has a potential influence on the environmental impact of concrete and on the fresh and hardened properties of concrete. The environmental impacts of different cement combinations and grades for a particular cement category can be calculated from first principles given the blend ratio and unit environmental impact of that particular binder.

This study will show the influence of selecting an appropriate binder type, grade and quantity in the design of more sustainable RC structures.

5.3.3.2 *The concrete cover depth*

The concrete cover is defined as the thickness of concrete between the outer surface of the outermost reinforcing steel and the face of concrete (as cast) (SANS 10100-2: 2005). Other technical terms such as 'nominal cover' and 'minimum cover' are also used to describe the concrete cover. Nominal cover (x_{nom}) is often used in design and is indicated on engineering drawings, whereas minimum cover (x_{min}) is specified in prescriptive design codes and building standards to cover durability and fire provisions (Ronné, 2005). x_{nom} constitutes the minimum cover (x_{min}), plus an allowance in design for deviation (Δx_{dev}) as shown by Equation (5-6) (EN 1992-1-1:2000).

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[42] The term 'cradle-to-gate' refers to all processes and activities from extraction of raw materials for cement production to final transportation of cement to the construction site.

$$x_{nom} = x_{\min} + \Delta x_{dev} \tag{5-6}$$

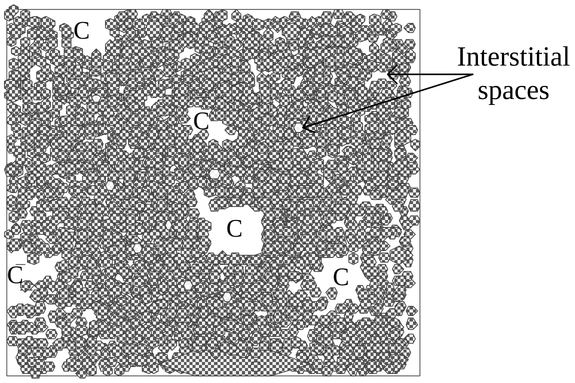
Δx_{dev} is normally taken as 10 *mm*. If an approved quality system on cover (e.g. in-situ measurements) is specified, Δx_{dev} can be reduced to 5 *mm* (Mosley *et al.*, 2007)

Concrete cover plays an important role in the transfer of bond forces between concrete and reinforcing steel, fire resistance, and protecting the embedded reinforcement against corrosion (Mosley *et al*, 2007). Failure to achieve adequate cover during construction has been found to be the single most important factor in premature deterioration of reinforced and prestressed concrete structures (Sharp, 1997). This shortfall in concrete cover may be due to three reasons; first, failure to appreciate the severity of exposure conditions by the designer may result in a design error when specifying the cover, secondly, workmanship error during construction, and lastly, design and detailing error which occurs when the designer specifies rebar details, bar lapping, and formwork tolerances, that are complex and do not allow for adequate compaction of the concrete.

Selecting an appropriate cover for reinforcement is achieved by making a compromise between the required quality of concrete and the volume of concrete used. A high cover depth (> 40 *mm*) translates in to a higher volume of concrete, and hence higher environmental impacts and cost to the owner whereas, a low cover leads to the premature deterioration of the concrete and inconveniences to the user during the subsequent repair of the structure.

5.3.3.3 Diffusion coefficient

The durability of reinforced concrete has been observed to be largely controlled by the quality of the cover depth (Alexander and Stanish, 2001). The quality of concrete is measured in terms of its penetrability, which is defined as the ease with which liquids gases and/or ionic species move through concrete (Paul *et al.*, 2005; Alexander and Mindess, 2006). The penetrability of concrete is mainly affected by the pore structure of the cement paste. The pore structure refers to the size, distribution and continuity of pores within the cement paste (Richardson, 2002). It is assumed to consist of capillary pores and gel pores as shown in ***Figure 5-5*** (Neville, 2011). Further, inter-layer spaces between the products of hydration, (calcium silicate hydrate (C-S-H)) also contribute to concrete's penetrability.



where:

C – refers to the capillary pores;

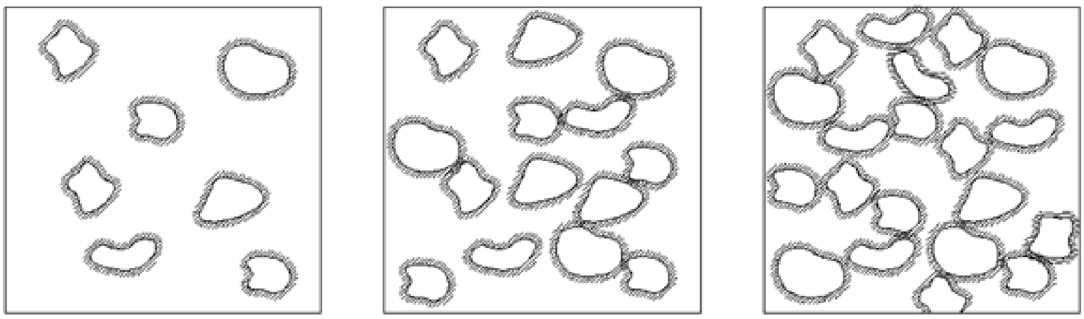
Solid dots represent the gel particles and;

Interstitial spaces are gel pores.

Figure 5-5: *Schematic representing the micro-structure of cement paste (Neville, 2011).*

Capillary pores are the remains of originally water-containing spaces between cement particles that have not been filled up by products of hydration (Neville, 2011; Ballim and Basson, 2001). They are of diameter 0.01 to 1.0 μm (Mehta and Monteiro, 2006), and their number and interconnectivity control the ingress of ions, oxygen and moisture into concrete (Ballim, 2001). Gel pores and interlayer spaces between the C-S-H sheets are believed to be too small (ø of 0.001 μm to 0.004 μm) (Mehta and Monteiro, 2006) and discontinuous to allow for transport of aggressive agents into concrete. Concrete can be porous but still have low penetrability as long as the pores are not interconnected. Hence it is generally the interconnectivity of the pores, rather than the total porosity that is essential in establishing the ease with which aggressive agents penetrate the concrete (Zhang *et al*., 2006).

The penetrability of concrete is also affected by aggregates. The combination of the cement phase with the aggregate phase produces an interfacial transition zone (ITZ) in the composite concrete material, which increases the penetrability of concrete. At sufficient aggregate volume concentration, the ITZ phases become percolated, leading to increased penetrability (Alexander and Mindess, 2006). Percolation occurs due to the ITZs overlapping and thereby creating additional paths for penetration to occur as shown in ***Figure 5-6***.



a) Unpercolated, discrete isolated particles

b) Unpercolated, some continuous ITZ regions

c) Percolated, continuous ITZ regions

Figure 5-6*: Schematic of penetrability and percolation related to the interfacial transition zones (Alexander and Mindess, 2006).*

From Figure 5.6, it can be seen that as aggregate concentration increases, and aggregate particles approach each other more closely, the ITZs begin to overlap and create possible continuous paths for transport of substances (Alexander and Mindess, 2006).

Depending on the environmental exposure conditions, the penetrability of aggressive agents can occur by three mechanisms namely, diffusion, capillary absorption (sorption) or permeation, or a combination thereof (Kropp and Hilsdorf, 1995; Hobbs, 1996). Of these three mechanisms, diffusion is considered as the major mechanism for carbon dioxide and chloride ingress through concrete based on the assumption that concrete is generally moist (Kropp and Hilsdorf, 1995).

The diffusion process is defined as the motion of molecules from a point of higher concentration to a point of lower concentration through a concentration gradient. The diffusion coefficient (D_0) is used to signify the rate at which aggressive agents penetrate the concrete, and is represented in m^2/s. D_0 is influenced by the water/cement (*w/c*) ratio, supplementary cementitious materials (SCMs) especially those that have high fineness such as silica fume (SF), the chemical nature of the SCM, and the degree of compaction of the concrete (Richardson, 2002; Kwan and Wong, 2006).

The *w/c* ratio affects the penetrability of concrete to aggressive ions, moisture and oxygen and its strength. For low *w/c* ratios (below 0.38), the penetrability of the cement paste may be considerably reduced due to the extent of calcium silicate hydrate (C-S-H) gel formation which fills up the available pore spaces (Neville, 2011; Ballim, 2001). For *w/c* ratios between 0.38 and 0.6, the amount of C-S-H gel formation is usually significant enough to disrupt the continuity of the capillary pores provided that complete hydration of the cement is allowed to occur. Low *w/c* ratios present a problem with the workability of the mix. This can be avoided by the use of chemical admixtures such as water reducers and superplasticizers to disperse the mix constituents and hence make the mix workable. Chemical admixtures not only improve the workability of concrete but have been shown to produce more cost-effective and environmentally sustainable concrete. In Chapter 3 (Section 3.3.2) it was illustrated using an example, that the use of a chemical admixture in concrete results in a lower (12%) embodied exergy value than a concrete mix with no admixture.

The use of SCMs influences the diffusivity of concrete in a saline environment. Cement extenders especially those of high fineness such as silica fume (SF), reduce the permeability of the cement paste. SF is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of ferro-silicon and silicon metal. The fume contains between 85 and 98% silicon dioxide, and consists of extremely fine spherical glassy particles. Hamad and Itani (1998) stated that the average particle size of SF is 0.1 micro-meters or about two orders of magnitude finer than cement particles. This high-fineness improves the packing of cementitious materials and by so doing, reduces the pore volume and size in the bulk of cementitious products resulting in a denser pore structure (Kwan and Wong, 2006). In addition, the silica content of the SF reacts with the lime in the concrete to form additional gel products, thereby reducing the porosity of concrete (Kwan and Wong, 2006). Similarly, fly ash, which is another type of SCM, has spherical particles which lower the inter-particle friction compared to angular cement particles. This in turn results in the use of less water to attain a given slump and hence, fewer capillary pores. Typical water reduction ranges from 5 – 15% in comparison with Portland cement concrete (Ballim, 2001). In terms of sustainability, the use of cement extenders in concrete reduces Portland cement consumption, and results in the use of waste materials that would otherwise be land-filled. For example, in Chapter 3 (Section 3.3.2) it was shown that concrete made using 70% Portland cement and 30% fly ash has 25% less embodied exergy than one made using 100% Portland cement. In addition, the use of SCMs allows the designer to prescribe lower values of concrete cover and hence leads to reduced cross-sectional dimensions, which translates to reduced volume of materials.

Poor construction practices such as inadequate compaction, inappropriate curing of the concrete, insufficient cover to the reinforcement, and leaking joints also affect the diffusivity of concrete (Mehta and Burrows, 2001). Early age concrete (1 day) exposed to an ambient environment, undergoes a loss of water due to cement hydration resulting in the development of empty capillary pores. In addition, as the concrete dries, shrinkage cracks develop through the C-S-H gel. These cracks intersect capillary pores and render them once again continuous. Curing can effectively reduce water loss during the hydration process (Powers *et al*., 1947 *as cited in* Garboczi *et al*., 1996). Consolidation or compaction of concrete is also necessary for low diffusivity. Voids or excessive air resulting from poor placing practices, lack of vibration or congested reinforcement will increase diffusivity.

The predominant deterioration mechanism due to the diffusion of aggressive agents in RC structures is reinforcement corrosion. Mathematical models have been applied to estimate the diffusion coefficient parameters for corrosion in RC structures caused by the ingress of either chlorides or carbon dioxide. The mathematical models for carbonation- and chloride-induced corrosion are based on Fick's first and second law of diffusion, respectively (Collepardi *et al*., 1972). By using these models the designer is able to predict the diffusion coefficient given the concrete mixture proportions, geometry and the service environment of the structure. The mathematical model for predicting chloride ingress in concrete is expressed by Equation (5-7) (DuraCrete, 2000).

$$C_{(x,t)} = \left[C_s - \left(C_s - C_i \right) \, erf\left(\frac{x}{2\sqrt{D(t)\ t}} \right) \right] \tag{5-7}$$

where,

C_s	[% of chlorides by mass of cement]	:	chloride concentration at the concrete surface, and is dependent on the service environment and binder type (see ***Table 5.3***)
C_i	[% of chlorides by mass of cement]	:	initial chloride content in the concrete and is taken as 0.1% in Duracrete (2000)
erf	[-]	:	mathematical error function
D(t)	[m^2/s]	:	apparent diffusion coefficient as given by Equation (5-8)
x	[m]	:	cover to reinforcing steel
t	[years]	:	exposure time of the concrete component to the marine environment

The value of C_s varies with the proximity to the marine environment and binder type as detailed in ***Table 5.3***.

Table 5.3*: Chloride surface concentrations (% by mass of binder) for different binders in two marine environmental classes (Mackechnie, 2001).*

Binder type	***Marine exposure class***	
	XS1$^{\#}$	***XS2***$^{\#\#}$ ***/XS3***$^{\#\#\#}$
100% PC	1.5 -2.0	3.0 -4.0
10% SF	1.3 -1.5	2.5 -3.0
30% FA	2.3 -2.5	4.5 -5.0
50% SL	2.5 -3.0	5.0 -6.0

#	XS1	:	Exposed to airborne salt but not in direct contact with sea water	PC	:	Portland cement
##	XS2	:	Permanently submerged	SF	:	Silica fume
###	XS3	:	Tidal, splash and spray zones	FA	:	Fly Ash
	It should be noted that values of *Cs* vary in different literature studies.			SL	:	Slag

The higher surface concentrations given for fly ash or slag concrete are due to their superior chloride binding characteristics (which increase their capacity to hold chlorides) when compared to concrete made using 100% Portland cement (Mackechnie, 2001).

The apparent diffusion coefficient (*D(t)*) decreases with time due to progressive hydration of binders. *D(t)* is expressed as (Mangat and Molly, 1994):

$$D(t) = D_0 \left(\frac{t_0}{t} \right)^n \tag{5-8}$$

where, D_0 is the diffusion coefficient at reference time t_0 (taken as 28-days) and *n* is the ageing factor.

D_0 is related to the 28-day results of chloride migration tests such as the rapid migration test (Tang and Nilsson, 1992) and the chloride conductivity test (Alexander *et al*., 1999). However, in this study the D_0 [m^2/s] is related to mix design proportions as follows (Papadakis *et al*., 1996):

$$D_0 = 0.15 \frac{1 + \rho_c \, c/w}{1 + \rho_c \, w/c + \frac{\rho_c}{\rho_a} \, a/c} \left(\frac{\rho_c \, w/c - 0.85}{1 + \rho_c \, w/c} \right)^3 D_{H_2O} \tag{5-9}$$

where,

w	[kg]	:	water content
c	[kg]	:	cement content
a	[kg]	:	aggregate content
ρ_c	[kg/m^3]	:	density of cement
ρ_a	[kg/m^3]	:	density of aggregates
D_{H2O}	[m^2/s]	:	diffusion coefficient in an ionic solution of 0.5 M NaCl and is equal to 1.6×10^{-9} m^2/s (50458 mm^2/year)

Equation (5-9) was selected for this study to predict the chloride diffusion coefficient in concrete as it accounts for the concrete mix proportions (aggregate-to-cement ratio; water-to-cement ratio and mass densities of cement and aggregates). The model has also been shown by Vu and Stewart (2000) to be the best fit to the available field data on chloride diffusion in concrete from different literature sources. The *w/c* ratio is estimated from Bolomey's formula (Equation (5-18)) given the concrete compressive strength of a standard test cylinder. It was also important to have a reliable mathematical expression for D_0 in order to implement the optimization technique (see Section 5.4.5.4).

The ageing coefficient values depend on the binder type and service environment of the structure and are given in ***Table 5.4***.

Table 5.4*: Ageing coefficients for different binders and environmental classes (Van der Wegen et al., 2012).*

Binder type	***Marine exposure class***	
	XD2, XS2, XS3	***XD1, XD3, XS1***
CEM I	0.40	0.60
CEM I, 25-50% slag; CEM II/ B-S; CEM III A (<50% slag)	0.45	0.65
CEM III/A or /B, 50%-80% slag	0.50	0.70
CEM I with 21-30% fly ash	0.70	0.80
CEM V/A composite with 25% slag and 25% fly ash	0.60	0.70

XS1 : Exposed to airborne salt but not in direct contact with sea water
XS2 : Permanently submerged in seawater
XS3 : Marine tidal, splash and spray zones
XD1 : Moderate humidity e.g. concrete surfaces exposed to airborne chlorides
XD2 : Wet, rarely dry e.g. concrete components exposed to industrial waters containing chlorides.
XD3 : Cyclic wet and dry e.g. parts of a bridge exposed to spray containing chlorides
It should be noted that ageing coefficient values vary in different literature studies.

Similarly for carbonation, the mathematical model given by Equation (5-10) is applied to predict the depth (x_c) of CO_2 in carbonated concrete (Papadakis *et al*., 1996).

$$x_c = \sqrt{\frac{2D_{e,CO_2}\left(CO_2/100\right)\ t}{0.218\ \left(C+kP\right)}} \qquad (5\text{-}10)$$

where,

t	[years]	:	age of the concrete
$D_{e,CO2}$	[m^2/s]	:	effective diffusivity of CO_2 in carbonated concrete as given by Equation (5-11) (Papadakis and Tsimas, 2002)
CO_2	[%]	:	CO_2 concentration at the concrete surface
C	[kg/m^3]	:	cement content
k	[-]	:	cementing efficiency factor with respect to carbonation as given in ***Table 5.5***
P	[kg/m^3]	:	supplementary cementitious material content

$$D_{e,CO_2} = 6.1\times10^{-6}\left(\frac{\left(w-0.267\left(C+kP\right)\right)/1000}{\dfrac{C+kP}{\rho_c}+\dfrac{w}{\rho_w}}\right)^3 \times\left(1-RH/100\right)^{2.2} \qquad (5\text{-}11)$$

where,

RH	[%]	:	relative humidity
w	[kg/m^3]	:	water content
ρ_w	[kg/m^3]	:	density of water
ρ_c	[kg/m^3]	:	density of cement

Table 5.5: *Carbonation resistance efficiency factors (k-values) for various supplementary cementitious materials (Papadakis and Tsimas, 2002).*

	Supplementary cementitious materials (SCMs)			
	Low calcium fly ash (Pozzolanic)	*High-calcium fly ash (Pozzolanic and cementitious)*	*Silica fume*	*Blast furnace slag (Cementitious)*
Carbonation resistance	-	0.7	0.3	-

The carbonation efficiency factors given in ***Table 5.5*** are valid for a certain amount of SCM in concrete. The valid range for FA content in concrete is given in Papadakis and Tsimas (2002) as 25 – 50% of the cement mass. Efficiency factors for blast furnace slag and low calcium fly ash have not been experimentally verified.

This study applies Equation (5-7) and Equation (5-10) to show the relation between the concrete composition and the diffusion coefficient of concrete due to chloride ingress or carbonation, respectively. With this relationship the durability performance of a structure based on chloride concentration or carbon dioxide concentration can be predicted. Further, it should be noted that although the study adopts the above model for service life prediction, the framework can readily be generalized to any other representative relationship for service-life modelling, which takes account of the important mix-design constituents.

5.3.3.4 *Compressive strength*

The compressive strength is an important hardened concrete property. The compressive strength of concrete can be determined using a cylinder test and/or a cube test (Perrie, 2009). The European concrete design standard, EN 1992-1-1:2004, uses both tests to prescribe minimum 28-day characteristic compressive strengths for concrete, which are both denoted by letter *C*, followed by the characteristic (5%) cylinder and cube compressive strengths of concrete, respectively e.g. C35/45 MPa (see ***Table 5.6***). Concrete can be further classified into four classes depending on its compressive strength performance: (i) Ultra-high-performance concrete (>150 MPa), (ii) High strength concrete (50 – 150 MPa), (iii) Moderate strength concrete (20 – 55 MPa), and (iv) Low strength concretes (< 20 MPa) (Aïtcin, 2008). Moderate-strength concretes are commonly used in buildings and bridges (Aïtcin, 2008) and will be the focus of this study.

Table 5.6: *Compressive strength classes of concrete (EN 1992:1-1: 2004).*

Concrete class	***Cylinder compressive strength (f_{ck}) [MPa]***	***Cube compressive strength [MPa]***	***Additional classification (Aïtcin, 2008)***
C12/15	12	15	Low strength concretes
C16/20	16	20	
C20/25	20	25	Moderate strength concretes
C25/30	25	30	
C30/37	30	37	
C35/45	35	45	
C40/50	40	50	
C45/55	45	55	
C50/60	50	60	
C55/67	55	67	
C60/75	60	75	High strength concrete
C70/85	70	85	
C80/95	80	95	
C90/105	90	105	

The compressive strength of concrete is influenced by a number of factors that includes the properties and proportions of materials that make up the concrete mixture, degree of compaction, age of concrete and conditions of curing (Mehta and Monteiro, 2006; Perrie, 2009)

Calcium silicate hydrates, which are the products of cement hydration, are primarily responsible for the strength of concrete. Tricalcium silicate ($3CaO.SiO_2$ or C_3S) and dicalcium silicate ($2CaO.SiO_2$ or C_2S) in cement react with water to form calcium silicate hydrates (*C-S-H*) as follows (Neville, 2011):

$$\begin{aligned} 2C_3S + 6H &\rightarrow C_3S_2H_3 + 3Ca\left(OH\right)_2 \\ 2C_2S + 4H &\rightarrow C_3S_2H_3 + Ca\left(OH\right)_2 \end{aligned} \tag{5-12}$$

where, $C = CaO$; $H = H_20$; and $S = SiO_2$. *C-S-H* or $C_3S_2H_3$ is calcium silicate hydrate which facilitates the strength development of concrete whereas *C-H* is the calcium hydroxide contributing mainly to the durability of concrete. In the presence of pozzolanic materials, additional strength can be obtained through a pozzolanic reaction that occurs between the pozzolan and the *C-H*, as follows:

$$\text{Pozzolan} + \text{CH} + \text{H} \rightarrow \text{C-S-H} \tag{5-13}$$

As the pozzolanic material reacts with the *C-H*, an additional *C-S-H* is formed, as shown by Equation (5-13). The strength development of the concrete containing the pozzolanic material is reduced at first, but as time proceeds it gains higher strengths.

Supplementary cementitious materials (SCMs), such as silica fume (SF), have been found to contribute favourably to the compressive strength due to the fineness of SF resulting in high particle packing (Perrie, 2009; Brandt, 1995). The small particles of SCMs fill the voids between the cement grains that otherwise would be occupied by water and this improves particle packing (Brandt, 1995). This effect results in an increase in the density and strength of the hardened cement paste.

The *w/c* ratio affects the compressive strength of concrete. An increase in *w/*c ratio means that there is more water between the solid particles in the fresh concrete, and consequently there would be a greater volume of pores left in the hardened concrete, increasing the porosity and thereby decreasing the compressive strength of concrete (Perrie, 2009; p.101).

The aggregate characteristics such as the size, shape, surface texture, gradation and mineralogy influence the characteristics of the interfacial transition zone and therefore affect the strength of concrete (Mehta and Monteiro, 2006).

In general, the compressive strength of concrete increases with age provided that sufficient curing is provided to enable cement hydration. The concrete design codes e.g. EN 1992-1-1:2004 specify the 28-day compressive strength. Several mathematical relationships, such as those represented by Equations (5-14) to (5-16), have been formulated using experimental results to allow for the prediction of the compressive strength of concrete (f_{ck}) based on its mix-design composition, primarily the *w/c* ratio and age of concrete. Equation (5-14) represents the Féret strength relationship (Féret, 1896 *as cited in* Neville, 2011).

$$f_{ck} = K_F \left(\frac{V_c}{V_c + V_w + V_a} \right)^2 \tag{5-14}$$

where, K_F (MPa) – is the Féret constant that depends on the type of cement and granular skeleton of concrete; V_c, V_w and V_a are the volumes of cement, water and air in concrete [m^3/m^3], respectively.

A linear approximation (in $1/(w/c)$) to Féret's formula is the Bolomey strength relationship (Bolomey 1935):

$$f_{ck} = K_B \left(\frac{1}{w/c} - a \right) \tag{5-15}$$

where, f_{ck} – is taken in this study as the characteristic cylinder compressive strength[43] of concrete at 28-days [MPa]; *c* and *w* are the cement and water contents, respectively, per unit volume of concrete [kg/m^3]; K_B – is the Bolomey coefficient that depends mainly on the compressive strength and age of the concrete [MPa] and *a* depends on the time and curing of the concrete. '*a'* is estimated as 0.5 for f_{ck} at 28 days for moderate strength concretes (Brandt, 1995).

A third mathematical model used to predict f_{ck} is Equation (5-16), which is also referred to as Abram's law (Abram, 1919 *as cited in* Neville, 2011).

$$f_{ck} = \frac{A}{B^{1.5(w/c)}} \tag{5-16}$$

where, f_{ck} [MPa]– is the characteristic compressive strength of concrete at 28-days, *A* and *B* are empirical constants. *A* – is a strength coefficient taken to be 96.5 MPa (Mindess *et al*., 2004) whereas *B* – is a constant value approximated as 4 (Mindess *et al*., 2004) and depends on the cement type and strength, aggregate, admixtures, curing regime, testing conditions, and concrete age at the time of test (Popovic, 1990).

However, Abram's formula does not apply to high strength concrete with low *w/c* ratios (< 0.3) as the interfacial transition zone of high strength concrete is improved in terms of strength compared to low- or

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[43] The target mean compressive strength (f_{cm}) is derived from the characteristic compressive strength value as follows:-
$f_{cm} = f_{ck} + 8$

medium-strength concrete (Mehta and Monteiro, 2006). With a low *w/c* ratio, the hydration products of high strength concrete are much smaller and the corresponding surface area higher.

Various studies such as Popovic (1990) have shown the need to modify Equations (5-14) to (5-16) to include concrete mix-design parameters and proportions such as cement type and air content in concrete. This is because the latter can vary significantly or be entrained into the concrete mix whereas the cement type has an influence on compressive strength, such that, at a constant *w/c* ratio the compressive strength depends on the fineness and chemical composition of cements (Nagaraj and Banu, 1996).

The different SCMs in blended cements affect concrete strength differently and it is questionable whether a single quantitative equation can capture the complex relationships. Various researchers such as Papadakis and Tsimas (2002) and Papadakis *et al*. (2002) and Oner, Akyuz *et al*. (2005), have proposed the use of an efficiency factor as a measure of the relative performance of SCMs in comparison to Portland cement. The efficiency factor (*k*) describes the efficiency of Pozzolanic reaction[44] of an SCM with respect to the rate of hydration of Portland cement. The total equivalent cement content is then expressed as:

$$b = c + kP \qquad (5\text{-}17)$$

Where, b – is the equivalent binder content [eq-kg/m^3]; c – is the Portland cement content [kg/m^3]; P – is the amount of SCM [kg/m^3], and k – is the efficiency factor of the SCM [-]. For $k = 1$, the additive is considered to be equivalent to Portland cement.

Similarly, the water/binder ratio is expressed as: $w/(c + kP)$. The cementing efficiency factor (*k*) varies depending on the percentage replacement of the SCM and also with the age of concrete. The *k*-value increases with increasing replacement percentage of the SCM up to a certain threshold for each particular SCM. ***Table 5.7*** gives 28-day cementing efficiency factors for 3 different cementitious materials at their optimum replacement levels.

Table 5.7: *Cementing efficiency factors for various supplementary cementitious materials at optimum replacement levels (EN206-1: 2000)*[45].

Supplementary cementitious material	*Cement type CEM I*	*Optimum % replacement*	*k-value at 28 days*
Silica fume	All CEM I strength classes	Silica fume/cement < 0.11% by mass	2.0
Siliceous fly ash	CEM I 32.5	Fly ash/cement < 0.33 % by mass	0.20
	CEM I 42.5 and CEM I 52.5	Fly ash/cement < 0.33 % by mass	0.40
Ground granulated blast furnace slag	-	GGBS < 50% by mass	0.6

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[44] Pozzolanic reaction is the ability of SCMs, such as silica fume and fly ash and blast furnace slag, to react with the free lime produced during cement hydration.

[45] The *k*-value concept in EN 206-1:2000 refers to durability only and not strength. However, this study assumes the same *k*-value for both durability and strength.

It should be noted that the *k*-values also vary depending on the source (chemical and mineralogical composition) of the SCM and the curing conditions of the concrete. This study adopts the generalized *k*-values given in ***Table 5.7*** but gives a recommendation for further studies that seek to verify *k*-values of local supplementary cementitious materials and further investigations on the influence of construction practices such as curing and compaction on the *k*-values.

Since the proposed framework for design considers the influence of concrete mix proportions on hardened concrete properties, it is necessary to adopt a physical model from the ones already established in literature. This study adopts a modified Bolomey strength relationship represented by Equation (5-18).

Equation (5-18) is a modified version of the Bolomey strength relationship, and includes an efficiency factor (*k*) that accounts for various binder types (Papadakis and Tsimas, 2002).

$$f_{ck} = K_B\left(\frac{1}{w/(c+kP)} - a\right) \tag{5-18}$$

where, K_B – is the Bolomey coefficient that depends on the aggregate type and concrete strength [MPa], and is assumed to be 21.3 MPa for all concrete types; w – is the water content [kg/m^3]; c – is the cement content [kg/m^3]; P – is the content of the supplementary cementitious material (SCM) in concrete [kg/m^3]; and a depends on the time and curing of the concrete and is estimated as 0.5 for f_{ck} at 28 days (Papadakis and Tsimas, 2002); k – is the cementing efficiency coefficient[46] of the respective SCM as previously given in ***Table 5.7***. The study applies this empirical model (Equation (5-18)) to predict the strength of concrete for all the different cement types.

5.3.3.5 *Limitations in the selection of design variables*

The selected design variables (*section 5.3.3.1 to 5.3.3.4*) have a potential influence on the sustainability of concrete structures. A sensitivity study to quantify the significance of these variables on the design is carried out in *section 5.5* of this chapter. It should also be noted that other factors such as construction quality, planning of the layout of the structure, structural form, and structural span affect the design of sustainable concrete structures but have been excluded as they fall out of the scope of the study. Selection of the structural form is carried out at the conceptual design phase and this study is concerned with design factors that can be influenced at the detailed design phase. In summary, this study only considers quantitative material variables which a structural designer is able to control at the detailed design phase.

5.3.4 *Performance measures*

Performance measures allow for a proper choice of design variables to be made. The sustainable performance measures developed in this study relate to the life-cycle material performance. Being able to

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[46] The cementing efficiency factor (*k*) is the mass of CEM I cement which gives a similar performance as a unit mass of the supplementary cementitious material (EN 206-1:2000).

measure sustainability performance of concrete makes it possible to evaluate and select optimum values for the design variables of alternative structural concrete systems[47].

5.3.4.1 *Strength performance with respect to sustainability*

The 28-day compressive strength of concrete has been selected in this study as a design variable as it represents the main function of structural concrete i.e. its ability to resist imposed loads without failure (Mehta and Monteiro, 2006). In addition, it is a function of the mix design and materials such as the binder type, amount of binder and the *w/c* ratio. For example, the production of high strength concretes (>50 MPa) require the use of higher cement contents (>350 kg/m^3) with low *w/c* ratios (< 0.4). This also translates to a higher initial embodied environmental impact for high strength concretes. However it should be noted that the use of high strength concrete in construction leads to a reduction in cross-sectional areas and hence material usage.

Regarding compressive strength data for local concrete using plain Portland cement, extensive data are available in Alexander (1990). ***Figure 5-7***, gives the best-fit curve for compressive strength data from Alexander (1990) and the calculated kg CO_2-eq per m^3 for each concrete mix. The best fit curve (in ***Figure 5-7***) shows that an increase in concrete strengths results in a corresponding increase in kg CO_2-eq emissions. This is consistent with other studies such as Park *et al*. (2012) who found an increase in embodied CO_2 emission of concrete from 302.85 kg-CO_2-eq/m^3 to 448.75 kg-CO_2-eq/m^3 with increasing corresponding compressive strengths ranging from 18 MPa to 35 MPa, respectively.

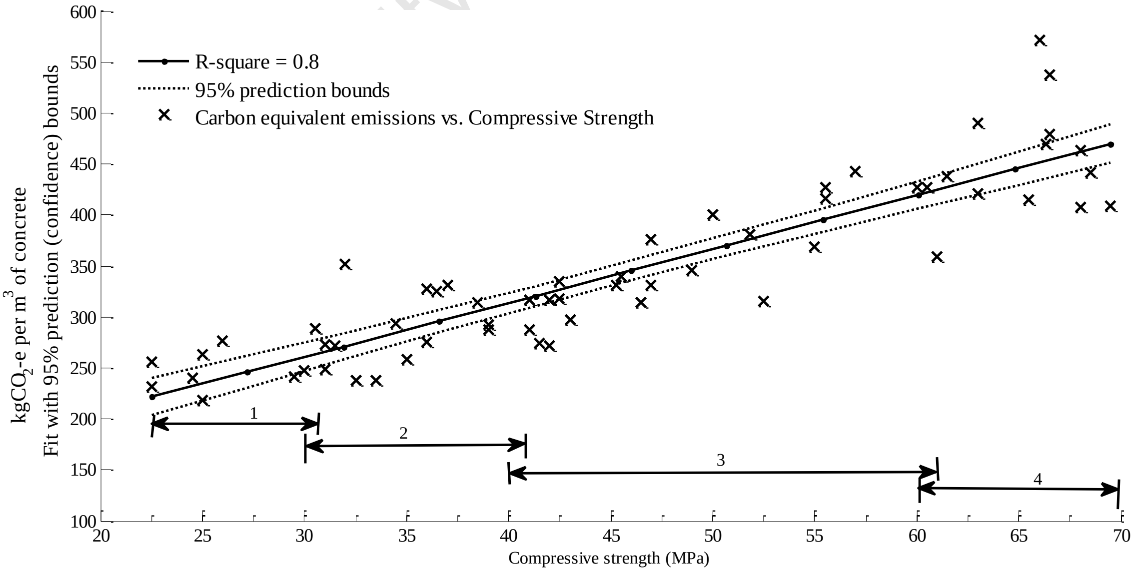

Figure 5-7: *Relationship between compressive strength and the initial embodied CO_2-eq emissions of plain Portland cement* concretes (Compressive strength data source: Alexander (1990))*.

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[47] Structural concrete systems here refers widely to e.g. types of slabs: ribbed slab, flat slab or solid slab; prestressed or reinforced concrete etc.

where:

1	*Portland cement= 200 - 259 kg/m^3* *w/c ratio = 0.71 - 0.84* *Target design strength = 20 MPa*
2	*Portland cement = 240 - 314 kg/m^3* *w/c ratio = 0.59 - 0.69* *Target design strength = 30 MPa*

3	*Portland cement = 298 - 402 kg/m^3* *w/c ratio = 0.46 - 0.59* *Target design strength = 40 MPa*
4	*Portland cement = 393 - 560 kg/m^3* *w/c ratio = 0.36 - 0.45* *Target design strength = 60 MPa*

*The Portland cements used in the study by Alexander (1990) were for a period prior to the EN 197 (SANS 50197) cement requirements and classification.

In ***Figure 5-7*** a comparison is made of different compressive strengths of plain Portland cement concretes, to show the influence of compressive strength on the environmental impacts (measured in kg CO_2-eq). The comparative unit used in ***Figure 5-7*** is the volume of concrete (m^3). The limitation of using the volume of concrete as a comparative unit in concrete sustainability studies is that it does not relate the environmental impacts to the resultant structural performance. This limitation has been discussed in literature (Purnell and Black, 2012). A suitable unit of comparison would be the resultant compressive strength [MPa], whereby the impact of different concretes of different concrete grades are represented as e.g. kg CO_2-eq/m^3 per MPa as shown in ***Figure 5-8***.

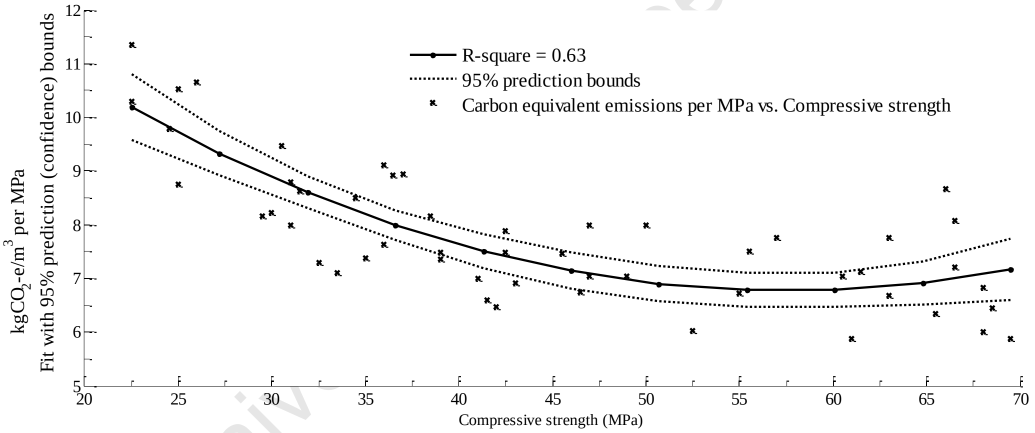

Figure 5-8: *Influence of compressive strength and the initial embodied CO_2-eq emissions for plain Portland cement concretes (Compressive strength data source: Alexander (1990)).*

From ***Figure 5-8***, it can be seen that high strength concretes (50~65 MPa) can be regarded as optimum design strength as they provide a higher strength at a lower environmental impact compared to low strength concrete (<30 MPa). This proves that consideration should be given to the selection of a suitable unit for comparing the sustainability performance of different concretes.

5.3.5 A Database

A local (S.A.) database of the environmental impact of raw materials for concrete is contained in the C&CI InEnergy report, (2010) which gives the "cradle-to- factory gate" kg CO_2-eq emissions for concrete and concrete products such as in-situ concrete and precast concrete products based on 2007 data. Further work is still required in South Africa to cover impacts that relate to the "gate-to-grave" phase of a concrete product. This study uses the Ecoinvent database v2.0 and the ELCD (European reference Life Cycle Database) in

SimaPro 7.1 software (*refer to Chapter 3 Section 3.1.1.6*). The latter databases are more comprehensive and include cradle-to-grave environmental impact data.

5.3.6 Design output

The proposed framework in ***Figure 5-2*** involves the consideration of a number of variables (*Section 5.3.3.1 to 5.3.3.4*), some of which mutually oppose each other, and hence finding an overall solution makes the design an optimization problem. The proposed framework for design is extensive and the integration of all the design variables contributing to more sustainable concrete structures is beyond the scope of the current study. The optimization problem is limited to considerations of the life-cycle environmental aspects of concrete structures and does not include life-cycle costs.

5.3.6.1 *Optimization problem*

A general structure of an optimization (minimization) problem is of the form (Marler and Arora, 2004; Christensen and Klarbring, 2009):

$$\left.\begin{array}{llll}
\multicolumn{4}{l}{\text{Minimize } f(X,Y)} \\
\multicolumn{4}{l}{\text{Subject to}} \\
h_j(X,Y)=0 & j \;\; = 1,\ldots,s & s & \text{Equality constraints} \\
g_k(X,Y)\le 0 & k \;\; = 1,\ldots,t & t & \text{Inequality constraints} \\
\begin{array}{l} lb_i \le x_i \le ub_i \\ lb_i \le y_i \le ub_i \end{array} & i \quad 1,\ldots,q & q & \text{Side constraints}
\end{array}\right\} \qquad (5\text{-}19)$$

where,

f : the objective function in the present study is the sustainability performance expressed as the life-cycle environmental impact or the life-cycle impact per MPa

$\{X\}=(x_i)=[x_1,x_2,\ldots x_n]$: a vector of n design variables; i =1, …n

$\{Y\}=(y_i)=[y_1,y_2,\ldots y_m]$: for a given design [X], [Y] is a vector of m response variables of the structure. For a material the response can be diffusivity, and for a structure the response can be displacement; ; i =1, …m

$h_j(X,Y)$: j^{th} equality constraint function

$g_k(X,Y)$: k^{th} inequality constraint function

lb_i, ub_i : are respectively the lower and upper bounds (also referred to as side constraints), of the i^{th} design variable

The constraint functions define the region of feasible solutions. Equation (5-19) relates to a minimization optimization problem. Similarly, a maximization optimization problem is obtained by multiplying the $f(X,Y)$ by (-1). In general, the optimization problem is concerned with finding a vector of design variables, $X = \{x_1, x_2,..x_n\}$, and response variables $Y = \{y_1, y_2,...y_m\}$ that minimizes (maximizes) a vector of the objective function, $f(X,Y)$.

5.3.6.2 *Optimization procedure*

In this study, the optimum solution for the objective function is obtained by following the procedure outlined in ***Figure 5-9***.

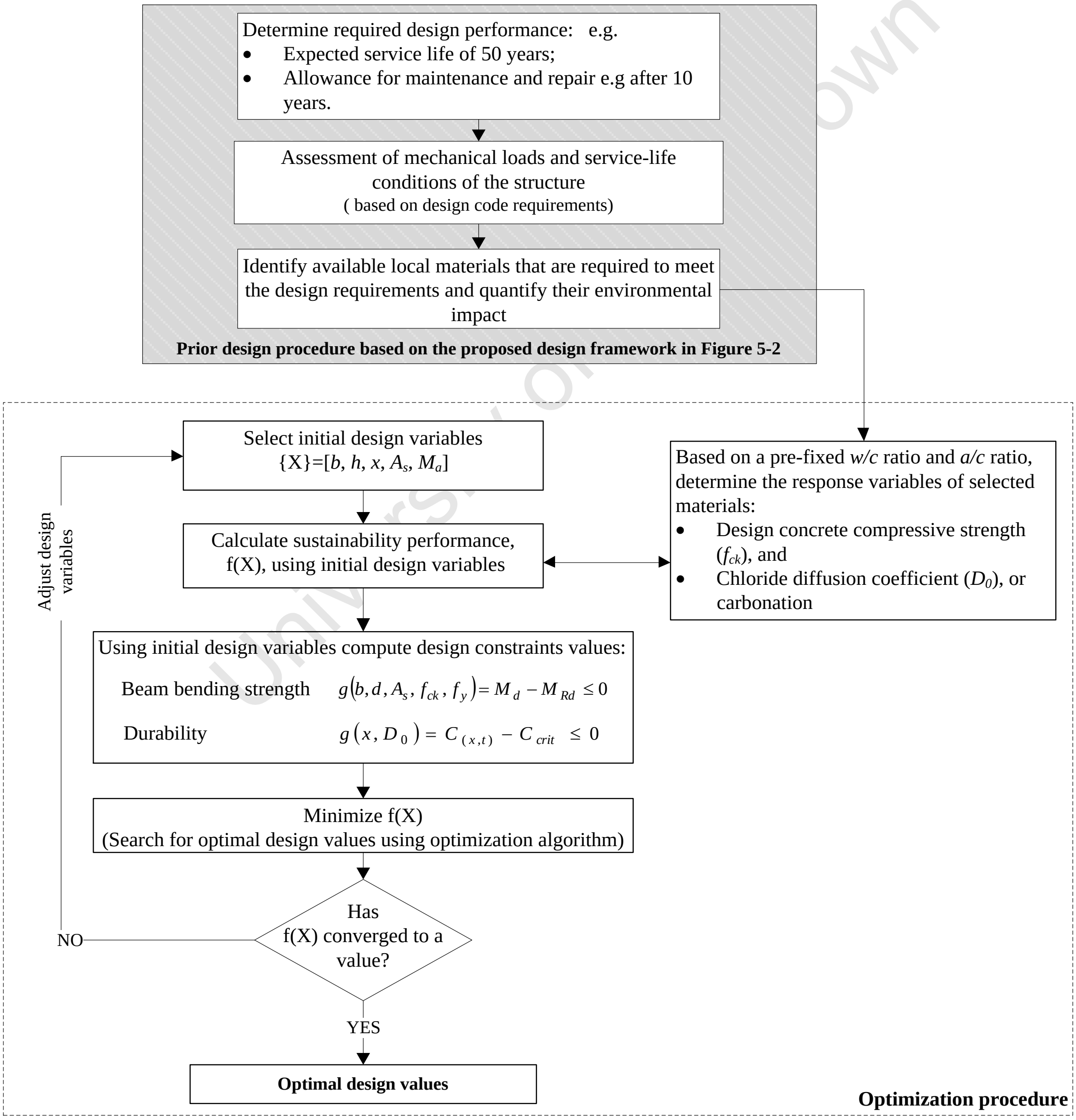

Figure 5-9: *Optimization procedure.*

The variables b, d, A_s, f_{ck}, f_y, x, D_0, and M_a; and functions $C_{(x,t)}$, C_{crit}, M_{Ed}, and M_{Rd} are defined in section 5.4

The optimization procedure schematized in ***Figure 5-9*** is as follows:

(i) Determine the serviceability requirements of the structure based on:

- The client brief that specifies the expected service-life of the structure e.g. 50 years.
- Design plan allowance for maintenance and repair after e.g. 10 years

(ii) Carry out an assessment of:

- The loading conditions on the structure based on design standards requirements e.g. EN 1991-1, EN 1992-1-1: 2004 etc., and
- The environmental service conditions on the structure and classify this based on the environmental classifications given in EN 206-1: 2000.

(iii) Identify suitable materials e.g. locally available aggregates and binder types, and quantify their corresponding environmental impact.

(iv) Based on a given *w/b* ratio and aggregate-cement (*a/c*) ratio determine the response variables as follows:

- Design compressive strength using Equation (5-18).
- Diffusion coefficient using Equation (5-9) or Equation (5-11).

(v) Determine the values of the objective function and constraint functions using initial values for the design variables [**X**].

(vi) Search for optimal design variables using an optimization algorithm. This study utilizes the generalized reduced gradient (GRG) optimization algorithm (*refer to Appendix C*). The GRG method was chosen as it is able to solve a set of nonlinear equations, which are a characteristic of the optimization problem at hand.

(vii) Verify whether the optimization has converged to a solution. If not, then adjust the design variables accordingly.

(viii) Select optimum design variables: binder type and strength and cross-sectional geometry specifications.

In summary, the optimization procedure involves the selection of a set of design variables following an iteration procedure that involves the initial estimation of design variables. The estimated variables are then optimized with respect to a set of design constraints, and objective function, and are thereafter specified for the design of a more sustainable RC structural component.

5.4 Reinforced concrete design optimization

5.4.1 Outline of the design problem

The aim of the optimization problem is to find the geometry and materials specifications for structural components that result in the lowest environmental impact while meeting design requirements for serviceability and safety. To demonstrate this, the study uses a simplified reinforced concrete (RC) beam idealised in ***Figure 5-10***. The span (*l*) of the RC beam is determined a priori at the conceptual phase of design and is indicated in ***Figure 5-10***. While the example below is ideally simplistic, it should be noted that more complex geometries and shapes could be adopted for further refinement.

The RC beam is assumed to be part of a structure located in a marine environment. For this example, it is assumed that the environmental condition corresponds to the exposure class *XS1* in EN 206-1:2000. For the *XS1* marine zone, the concrete is exposed to airborne salts, but not in direct contact with sea water. The design service life of the structure is specified as 30 years. In addition to its self-weight, the RC beam is expected to support uniformly distributed loads of: 30 kN/m live load; 60 kN/m dead load.

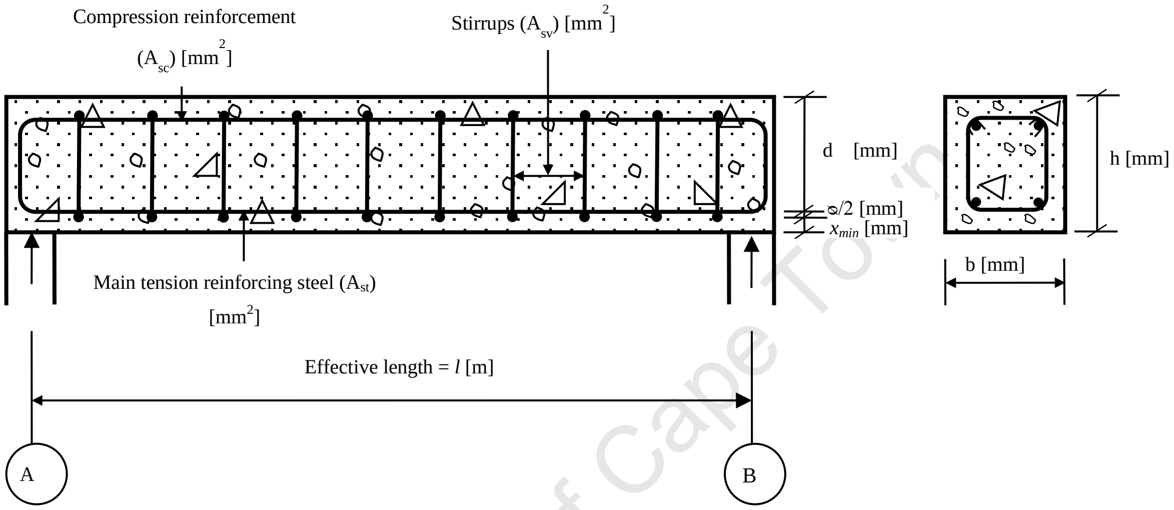

Figure 5-10: *Design example of a simply-supported RC beam.*

where: d [mm] :– is the effective depth of the beam ; b [mm] :– width of the beam; l [m] = 6 m :– is the span of the beam; Ø [mm] : – is the diameter of the tension steel (A_{st}) and is assumed to be 25 mm (in Section 5.5.4, a sensitivity analysis is carried out on the effect on the design of different choices of Ø) ; x_{min} [mm] :– is the minimum cover to reinforcement; and h [mm] :– is the total height of the beam ; b, h, x_{min}, and A_{st} are the structural design variables in the optimization problem. A_{sc} and A_{sv} are taken as nominal reinforcement.

5.4.2 Design variables

This study utilizes a vector of design variables [**X**] represented as:

$$[\mathrm{X}]=\{x_1,x_2,x_3,x_4,x_5,x_6,x_7\}=\left\{\ b,\ h,\ x_{\min},A_{st},w/b,\ M_w,\ M_a\right\} \qquad (5\text{-}20)$$

where, *b* [*mm*] – is the width of the beam; *h* [*mm*] – is the overall depth of the beam; x_{min} [*mm*] – is the minimum concrete cover; A_{st} [mm^2] – is the area of tension steel reinforcement; *w/b* [-] – is the water/binder ratio of the concrete design mix (which depends on the choice of the binder system); M_w [kg/m^3] – is the water content; and; M_a [kg/m^3] – mass of fine and coarse aggregates. These design variables have been selected as they have been shown to have an influence on concrete sustainability as discussed in *section*

5.3.3.1 up till *5.3.3.4*. In addition, there are response variables describing the resultant material properties represented by vector [**Y**] as follows:

$$[\mathrm{Y}] = \{y_1, y_2\} = \{D_o, f_{ck}\} \tag{5-21}$$

where, D_o [m^2/s] – the chloride diffusion coefficient of the concrete; and f_{ck} [MPa] – the concrete characteristic compressive strength. The two variables are dependent on: the binder system, *w/b* ratio, and aggregate/binder ratio.

5.4.3 Design parameters

Other than the design variables, there are particular design parameters which have an influence on the sustainability of concrete. These design parameters relate to items (*a*) to (*d*) below.

(a) *Span*

The span (*l*) of the structural member is determined by architectural and structural considerations at the conceptual design phase, which is out of the scope of this study. This study focuses on design decisions made at the detailed design phase of concrete construction.

(b) *Yield strength of steel*

The use of steel reinforcement in concrete serves to resist stresses in the concrete due to bending moments, shear and axial forces. Steel is susceptible to corrosion and is the main factor influencing the durability of reinforced concrete. ***Table 5.8*** gives the different types and diameters of steel reinforcement typically used in South Africa and their corresponding characteristic yield strengths.

Table 5.8: *Types and properties of reinforcement steel available in South Africa (Roberts and Marshall, 2006).*

Reinforcement type	***Symbol***	***Rebar diameter*** *(ϕ)* *[mm]*	***Minimum characteristic yield strength*** *(f_{yk})* *[MPa]*	***Identification***
Hot rolled mild steel	R	8, 10, 12, 16, 20, 25, 32, 40	250	Smooth bars without any marks
Hot rolled high-yield steel	Y		450	Ribbed bars with pairs of longitudinal marks
Cold worked high-yield steel	Y		450	Ribbed bars without longitudinal marks
Welded wire fabric	FS[#] or FD[##]	2.5 → 12	485	Ribbed bars without longitudinal marks welded together at fabric junctions

where:
[#]FS = Fabric using standard spacing of wires
[##]FD = Fabric using designed spacing of wires

(c) *Unit environmental impacts*

Table 5.9 gives the unit environmental impacts of the constituent materials in concrete and of steel, indicated in units of greenhouse warming potential (GWP$_{100}$) [kg CO$_2$-eq] and exergy (MJ). Both metrics were introduced and defined in Chapter 3 of this study. The unit environmental impacts are due to: the quarrying, production and on-site transportation of each material during processing. The environmental impacts due to transportation of the materials to site/ready-mix facility/precast unit have also been considered. The data source for all materials, except for the superplasticizer (European Federation of Concrete Admixture Associations, 2006) is the Ecoinvent database v2.0 and the ELCD (European reference Life Cycle Database), in SimaPro 7.1. The following abbreviations are used in ***Table 5.9*** to show the geographical boundaries for the life-cycle inventory data in SimaPro: DE = Germany; RER = Europe; NL = Netherlands; GLO: = Global; CH = Switzerland.

Table 5.9*: Unit environmental impacts of concrete constituents (SimaPro 7.1; European Federation of Concrete Admixture Associations, 2006).*

Acronyms	***Material***	***Reference in SimaPro 7.1.***	***Unit carbon equivalent emissions*** *[kg CO$_2$-eq/ton]*	***Exergy*** *[MJ/ton]*
$\text{Env}_{\text{binder}}$	CEM I/ 42.5 N	*Portland cement, strength class 42.5 N, at plant/CH U*	*821*	*74 200*
		Transport, Truck 20-28t, fleet average/tkm/CH U (100 km)	*20*	*1 420*
		Total	***841***	***75 620***
	CEM I/ 52.5 N	*Portland cement, strength class 52.5 N, at plant/CH U*	*832*	*82 600*
		Transport, Truck 20-28t, fleet average/tkm/CH U (100 km)	*20*	*1 420*
		Total	***852***	***84 020***
	CEM III/A-S 42.5 N (50% CEM I: 50% GGBS)	[#]*Blast furnace slag cement, at plant/CH U*	*445*	*64 700*
		Transport, Truck 20-28t, fleet average/tkm/CH U (100 km)	*20*	*1 420*
		Total	***465***	***66 120***
	CEM II A-V 52.5 N (80% CEM I: 20% FA)	*Portland cement, strength class 42.5 N, at plant/CH U (80%* x *74 200)*	*657*	*59 360*
		[#]*Fly ash (see E_R in Table 3.3, Chapter 3) (20%* x *2921)*	*1.6*	*584*
		Transport, Truck 20-28t, fleet average/tkm/CH U (100 km)	*20*	*1 420*
		Total	***679***	***61 364***
	CEM II/ B-V 42.5 N (70% CEM I: 30% FA)	*Portland cement, strength class 52.5 N, at plant/CH U (70% x 82 600)*	*582*	*57 820*
		Fly ash (see E_R in Table 3.3, Chapter 3) (30% x *2921)*	*1.4*	*876*
		Transport, Truck 20-28t, fleet average/tkm/CH U (100 km)	*20*	*1 420*
		Total	***604***	***60 116***
Env_{Ad}	Superplasticizer	*Input resources and emissions to air, land and water* [c]	*751*	*17 200*
		Transport, Truck 20-28t, fleet average/tkm/CH U (30 km)	*6*	*427*
		Total	***757***	***17 627***
Env_{a}	Fine aggregates (Pit sand)	*Sand, at quarry/CH U*	*2.39*	*1 430*
		Transport, Truck 20-28t, fleet average/tkm/CH U (50 km)	*10*	*712*
		Total	***12.39***	***2 142***
	Fine aggregates (Crushed stone)	*Gravel 2/32, wet and dry quarry, production mix, at plant, undried RER U*	*0.2*	*101*
		Transport, Truck 20-28t, fleet average/tkm/CH U (50 km)	*10*	*712*
		Total	***10.2***	***813***
	Coarse aggregates (Crushed stone)	*Crushed stone 16/32, open pit mining, production mix, at plant, undried RER S*	*0.9*	*374*
		Transport, Truck 20-28t, fleet average/tkm/CH U (50 km)	*10*	*712*
		Total	***10.9***	***1 086***

where:
CEM I: : *Portland cement (Refer to* ***Table 5.1*** *for the full designation of the subsequent acronyms).*
Env: : *Unit environmental impact of the: binder (binder); admixture: superplasticizer (Ad); aggregates (a); water (w); and steel (steel).*
S : *System LCI that includes the subsystems of all inputs (from cradle-to-gate)*

U : *Unit LCI processes (cradle-to-cradle)*
E_R : *Environmental impacts arising from recycled material input;*
E_V : *Environmental impacts arising from virgin material input, per unit of material;*
E_D : *Environmental impacts arising from disposal of waste material, per unit of material.*
R : *Proportion of material that is recycled*
$^{\#}$: *Environmental impacts from avoided processes (landfilling and production of raw materials) have not been included in the particular Ecoinvent inventory but have been included in the current study*

*Continued…****Table 5.9****: Unit environmental impacts of concrete constituents (SimaPro 7.1; European Federation of Concrete Admixture Associations, 2006).*

Acronyms	***Material***	***Reference in SimaPro 7.1.***	***Unit carbon equivalent emissions*** *[kg CO_2-eq/ton]*	***Exergy*** *[MJ/ton]*
Env_a	Recycled concrete aggregates	*Recycled aggregate production (see Table 3.3, Chapter 3)*	*11*	*1 358*
		Transport, Truck 20-28t, fleet average/tkm/CH U (50 km)	*10*	*712*
		Total = E_R	***21***	***2 070***
		Avoided production = E_V	*10.9*	*1 086*
		Avoided disposal = E_D	*12*	*964*
Env_w	Water	*Tap water, at user/CH U*	***0.2***	***251***
Env_{steel}	Hot rolled high-yield steel (***Table 5.8***)	*Reinforcing steel, at plant/RER U*	*1 450*	*200 000*
		Transport, Truck 20-28t, fleet average/tkm/CH U (100 km)	*20*	*1 420*
		Total	***1 470***	***201 420***

where:
CEM I: : *Portland cement (Refer to **Table 5.1** for the full designation of the subsequent acronyms);*
Env: : *Unit environmental impact of the binder (binder), admixture: superplasticizer (Ad), aggregates (a), water (w), and steel (steel);*
S : *System LCI that includes the subsystems of all inputs (from cradle-to-gate)*
U : *Unit LCI processes (cradle-to-cradle)*
E_R : *Environmental impacts arising from recycled material input;*
E_V : *Environmental impacts arising from virgin material input, per unit of material;*
E_D : *Environmental impacts arising from disposal of waste material, per unit of material.*
R : *Proportion of material that is recycled*
$^{\#}$: *Environmental impacts from avoided processes (landfilling and production of raw materials) have not been included in the particular Ecoinvent inventory and will therefore be calculated in the current study*

(d) *Others*

A list of other design parameters and concrete properties that are included in the optimization problem are summarized in ***Table 5.10***.

Table 5.10*: Other design parameters and concrete properties.*

Symbol	***Units***		***Name of parameter***	***Value***
$E_{c,28}$	[GPa]	:	28-day modulus of elasticity of concrete (EN 1992-1-1: 2004)	$E_{c,28} = 1.05 \times 22\left[\frac{(f_{ck}+8)}{10}\right]^{0.3}$
E_s	[GPa]	:	Modulus of elasticity of steel	200
k	[-]	:	Cementing efficiency factor	***Table 5.7***
RD_a	[-]	:	Relative density of aggregates	Appendix C: Table 3.1
RD_{binder}	[-]	:	Relative density of binder	Appendix C: Table 3.1

5.4.4 Objective function

The optimization problem in this study considers the non-linear objective function $f(X)$ (Equation (5-22)) that represents the life-cycle environmental impacts of the structural component. The aim is to select a vector of material variables, [**X**] and [**Y**] that gives the minimum environmental impact for the concrete section.

$$\text{Minimize } f\,(X,Y) \tag{5-22}$$

where, X and Y represents vectors of design variables (see [**X**] and [**Y**] in Equation (5-20) and Equation (5-21), respectively); *f(X,Y)* represents the environmental impact per-unit length of the structural component. Equation (5-23) gives the expanded form of *f(X,Y)*. Equation (5-23) includes the environmental impacts of concrete and steel. The environmental impacts of the formwork and placing of concrete have been excluded as these are assumed to be similar for all the concrete mixes to be compared.

$$f\left(X,Y\right)=\left[\rho_s A_s Env_{steel}+\left(b\left(d+\frac{\phi}{2}+x_{\min}\right)-A_s\right)Env_{concrete}\right] \tag{5-23}$$

where,

X,Y		:	Vector of material design variables (in Equation (5-20) and (5-21)) which optimize the value of the objective function
ρ_s	[kg/m^3]	:	Density of steel
A_s	[mm^2]	:	Reinforcement area for a unit length of beam (consists of tension steel – A_{st}, nominal compression steel – A_{sc}, and nominal stirrups – A_{sv}). A_s is a function of ϕ and the number of steel bars in the beam section.
b	[*mm*]	:	Width of the concrete component
d	[*mm*]	:	Effective depth of the concrete component
ϕ	[*mm*]	:	Diameter of the steel reinforcement
x_{min}	[*mm*]	:	Minimum concrete cover to reinforcing steel
$\mathrm{Env}_{\mathrm{steel}}$	[kg CO$_2$-eq/ton]	:	Unit environmental impact of steel per unit mass as given in ***Table 5.9***
$\mathrm{Env}_{\mathrm{concrete}}$	[kg CO$_2$-eq/m^3]	:	Unit environmental impact of concrete per unit volume as given by Equation (5-24)

Equation (5-23) gives the quantified cradle-to-gate environmental impacts of materials in the RC beam (i.e. the concrete and steel) in units of kg CO$_2$-eq per unit length of the beam.

Further, Equation (5-24) gives the environmental impact of concrete per unit volume (kg CO$_2$-eq/m^3), needed for Equation (5-23), and is computed as a function of its compressive strength. The derivation of Equation (5-24) is given in Appendix C.

$$\begin{aligned}Env_{concrete} = {} & \left[M_w\left(\frac{f_{ck}}{K_B}+a\right)-kM_P\right]Env_{binder}+\left[M_w\left(\frac{f_{ck}}{K_B}+a\right)-M_c\right]\frac{Env_{binder}}{k}+1000RD_a Env_a - \\ & \frac{RD_a}{RD_{binder}}\left[M_w\left(\frac{f_{ck}}{K_B}+a\right)-kM_P\right]Env_a-\frac{RD_a}{RD_{binder}}\left[M_w\left(\frac{f_{ck}}{K_B}+a\right)-M_c\right]\frac{Env_a}{k}- \\ & RD_a\left[\frac{M_c+kM_P}{\left(\frac{f_{ck}}{K_B}+a\right)}\right]Env_a-RD_a w_a Env_a+\left[\frac{M_c+kM_P}{\left(\frac{f_{ck}}{K_B}+a\right)}\right]Env_w+M_{Ad}Env_{Ad}\end{aligned} \qquad (5\text{-}24)$$

where,

K_B	[MPa]	:	is the Bolomey coefficient (refer to section 5.3.3.4) that depends on the aggregate and cement type and is assumed to be 21.3 MPa for all concrete types
f_{ck}	[MPa]	:	characteristic compressive strength of concrete, at 28-days.
a	[-]	:	is a parameter that depends on the time and curing of the concrete and is estimated as 0.5 for f_{ck} at 28 days (Papadakis and Tsimas, 2002)
w_a	[%]	:	air content in fresh concrete
k	[-]	:	is the efficiency factor of the respective supplementary cementitious material as given in ***Table 5.7***
M_c	[kg/m^3]	:	is the mass of Portland cement per cubic metre of concrete
M_w	[kg/m^3]	:	is the mass of water per cubic metre of concrete
M_P	[kg/m^3]	:	is the mass of supplementary cementitious materials per cubic metre of concrete. This is expressed as a percentage of the mass of Portland cement e.g. 30 % M_c
M_{Ad}	[kg/m^3]	:	is the mass of superplasticizer per cubic metre of concrete
RD_{binder}	[-]	:	relative density of the binder
Env_a	[kg CO$_2$-eq/ton]	:	environmental impact of aggregates per unit mass as given in ***Table 5.9***
Env_{binder}	[kg CO$_2$-eq/ton]	:	environmental impact of the binder per unit mass as given in ***Table 5.9***
Env_{Ad}	[kg CO$_2$-eq/ton]	:	environmental impact of superplasticizer per unit mass as given in ***Table 5.9***
Env_w	[kg CO$_2$-eq/1000 L]	:	environmental impact of water per 1000 litres as given in ***Table 5.9***

The parameters in Equation (5-24) represent the mix-design composition and the resultant concrete property (compressive strength) which have an influence on the life-cycle environmental performance of concrete.

5.4.5 Design constraints

The design constraints relate to the ultimate limit states (ULS) and serviceability limit states (SLS) for reinforced concrete given in EN 1992-1-1: 2004. The constraints include: (i) the ultimate-limit state of bending resistance of the structural component, (ii) the durability of the structural component in its service environment, (iii) deflection in the member due to service loads. In addition, the optimization problem includes two side constraints: (i) the upper and lower boundaries of the area of steel reinforcement, and (ii) the upper and lower boundaries of the geometry of the cross-section of the structural member.

5.4.5.1 Bending moment constraint

Beams are usually subjected to flexural moments, shear forces, and possibly torque. Only the flexural moment is considered in this example. The study provides nominal reinforcement for the compressions steel and stirrups.

At ULS, the applied bending moment should be less than the yielding moment of the beam section as expressed by the inequality constraint (C_1) in Equation (5-25).

$$C_1 \equiv M_{Ed} - M_{Rd} \leq 0 \tag{5-25}$$

where, M_{Rd} [kNm] – is the resistance bending moment of the RC beam, and M_{Ed} [kNm] – is the bending moment due to a uniformly distributed dead load (g_k) and live load (q_k) on the beam. For this example an applied live loading of 30 kN/m is assumed. The dead load includes an assumed load of 60 kN/m and the self-weight of the beam which is dependent on the cross-sectional dimensions of the beam.

M_{Rd} is evaluated using simplified design formulations based on the rectangular stress-block shown in Appendix C. Also, the maximum M_{Ed} due to g_k and q_k occurs at mid-span of the beam and is given as:

$$M_{Ed} = \left(\gamma_g g_k + \gamma_q q_k\right) l^2 \big/ 8 \tag{5-26}$$

where,

γ_g	[-]	:	partial load factor for the dead load and is given as γ_g = 1.35, in EN 1992-1-1:2004
γ_q	[-]	:	partial load factor for the live load and is given as γ_q = 1.5, in EN 1992-1-1:2004.
l	[m]	:	effective span of the beam

'q_k' is assumed to be 30 kN/m whereas the dead load, 'g_k', is a variable represented as:

$$g_k = \frac{\rho_c}{100}\left(\frac{b}{1000} \times \frac{h}{1000}\right) \text{ kN/m} + \frac{\rho_s}{100}\left(\frac{A_{st} + A_{sc}}{1000}\right) \text{ kN/m} + 60 \text{ kN/m} \tag{5-27}$$

where, ρ_c [kg/m^3] – is the density of concrete; ρ_s [kg/m^3] – is the density of steel; and the other variables are as defined in ***Figure 5-10***.

In summary, C_1 is a non-linear limit-state function represented by Equation (5-28).

$$C_1 \equiv \left[\left(\gamma_g g_k + \gamma_q q_k\right)\frac{l^2}{8}\right] - \left[0.87 A_{st} f_{ym} d - 0.67 \frac{A_{st}^2 f_{ym}^2}{b f_{cm}}\right] \leq 0 \tag{5-28}$$

where, f_{cm} [MPa] – is the design mean strength of concrete and is equal to (f_{ck} + 8) MPa; f_{ym} [MPa] – is the mean strength of steel and is taken as f_{yk}; d [mm] – is the effective depth of the beam; and the other variables are as defined in ***Figure 5-10*** and Equation (5-26).

5.4.5.2 *Shear strength constraint*

The shear constraint (C_2) of the beam is given as follows:

$$\mathrm{C}_2 \equiv V_{Rd} - V_{Rd,c} \leq 0 \tag{5-29}$$

where, $V_{Rd,c}$ [kN] – is the design shear resistance;. V_{Rd} [kN] – is the ultimate shear force in the beam. Detailed calculations of $V_{Rd,c}$ and V_{Rd} are given in *Appendix C*.

5.4.5.3 *Deflection constraint*

For serviceability requirements, there is a need to verify that the beam deflection under service loads is not excessive. Based on rules of thumb, a limit is placed on the ratio of the span to the effective depth of the beam as follows:

$$C_3 \equiv \frac{l}{d} - \frac{l}{250} \leq 0 \tag{5-30}$$

where,

d	[mm]	:	effective depth of the beam
l	[m]	:	span of the beam

5.4.5.4 *Durability constraint*

The structural component is in an *XS1* environment and is susceptible to chloride-induced corrosion during its service life. The RC beam in this case is designed to avoid repair actions on the component during its service-life by applying the durability limit-state Equation (5-31). The decision to avoid or include repair activities during the service life of a structure is made by the client/designers and can be factored into the optimization problem.

$$C_4 \equiv C_{(x,t)} - C_{crit} \leq 0 \tag{5-31}$$

where,

C_{crit}	[% of chlorides by mass of cement]	:	is the threshold value of chloride concentration for corrosion initiation, and is taken as 0.4 % chlorides by mass of cement
$C_{(x,t)}$	[% of chlorides by mass of cement]	:	is the chloride concentration at depth x at a given time t , and is given by Equation (5-7).

5.4.5.5 *Maximum and minimum bending reinforcement*

In addition, a side constraint (C_5) in Equation (5-32) is applied to ensure that the value of A_s in a beam section is within the minimum ($A_{s,min}$) and maximum area of steel ($A_{s,max}$) specified by EN 1992-1-1:2004.

$$C_5 \equiv \lfloor A_{s,\min} \leq A_s \leq A_{s,\max} \rfloor$$

such that,

$$A_{s,\min} = 0.13\% b\left(d + \frac{\phi}{2} + x_{\min}\right) \tag{5-32}$$

$$A_{s,\max} = 4\% b\left(d + \frac{\phi}{2} + x_{\min}\right)$$

where, the design parameters, b, d, x_{min} and Ø are as shown in ***Figure 5-10***.

$A_{s,min}$ minimizes thermal and shrinkage cracking whereas $A_{s,max}$ allows for adequate placing and compaction of concrete around the reinforcement.

5.4.5.6 Minimum width of the beam

The minimum width of the beam should be able to accommodate the reinforcement bars as expressed by Equation, (5-33), which is based on first principles.

$$C_6 \equiv b - \left(n_b\phi + 2x_{\min} + 2\phi_{str} + (n_b - 1)S_{\min}\right) \leq 0 \tag{5-33}$$

where, n_b –is the number of reinforcement bars; x_{min} – is the minimum cover depth; s_{min} – is the minimum clear spacing between reinforcement bars, and is taken as the maximum bar size; b – is the width of the beam; d – is the effective depth of the beam; Ø - is the diameter of the main reinforcement bar $Ø_{str}$ - is the diameter of the stirrups.

5.4.5.7 Depth-to-width constraint

Based on rules of thumb, an additional side constraint (C_7) is applied to the optimization problem that relates to the standard cross-sectional areas of the beam: width (b) and the effective depth (d) such that:

$$C_7 \equiv 1.5 \leq d/b \leq 4 \tag{5-34}$$

The upper limit of 4 is to avoid the occurrence of deep beam sections whereas 1.5 is selected for practical purposes.

5.4.6 Results and discussion

The section and material design involves the selection of optimum cross-section dimensions and concrete mix-design properties for the RC beam. This is achieved by optimizing the objective function (Equation (5-23)), subject to a set of design constraints (*see section 5.4.5*). Due to the non-linear nature of the objective and constraint functions, the optimization problem is solved using a non-linear programming technique based on the generalized reduced gradient optimization algorithm (Drud, 1994). This optimization algorithm is discussed further in *Appendix C.* The algorithm is implemented in this study using MATLAB® software.

5.4.6.1 *Optimized concrete mix-design and structural geometry for the RC beam*

The following procedure is used to evaluate and select the optimum concrete mix-design, material properties and geometry of the RC beam:

(i) A set of commonly used binder types are selected from ***Table 5.1*** for evaluation. In general, this selection will depend on binder types available in the locality of concern, and a measure of judgement. The binder types are: CEM I 52.5 N, CEM II/ B-V 42.5N, CEM II/ A-V 52.5 N, and CEM III/ A-S 42.5 N.

(ii) The corresponding composition of the binder types and efficiency factors were determined from ***Table 5.1*** and ***Table 5.7***, respectively. The proportions of the binders are indicated in ***Table 5.11***.

(iii) Input parameters for analysing the optimization problem (objective function and constraint functions) were obtained from ***Table 5.8***, ***Table 5.9***, and ***Table 5.10***.

(iv) A common concrete grade of C30/37 was selected for all concrete made using the four binder types.

(v) Using MATLAB® software, a generalized reduced gradient optimization algorithm is used to solve the optimization problem and give optimized values for the design variables and response variables represented by Equation (5-20) and Equation (5-21), respectively.

(vi) A comparative analysis of the optimum design variables for the different binder types was then carried out.

Using the optimization procedure given above, the optimum design variables for the different concretes made using the four binder types with similar binder contents are given in ***Table 5.11***. Also in ***Table 5.11***, it can be seen that the water content varies with binder type in order to give a constant slump for all concrete mixes.

Table 5.11: *Optimized material and structural design variables for a C30/37 RC beam.*

Variables [X]and [Y]	***Units***	***Optimized solution***			
		Mix I	***Mix II***	***Mix III***	***Mix IV***
		CEM II/B-V 42.5 N (30%:70% FA:PC)	CEM II/A-V 52.5 N (20%:80% FA:PC)	CEM III/A-S 42.5 N (50%:50% GGBS:PC)	CEM I 52.5 N (100% PC)
M_{binder} *(Mass of binder)*	$[kg/m^3]$	*425*	*350*	*450*	*370*
M_{water} *(Mass of water)*	$[kg/m^3]$	*170*	*175*	*180*	*185*
w/b ratio	*[-]*	*0.4*	*0.5*	*0.4*	*0.5*
M_a *(Mass of aggregates)*	$[kg/m^3]$	*1 805*	*1 750*	*1 780*	*1 848*
b (width)	*[mm]*	*170*	*185*	*175*	*180*
d (effective depth)	*[mm]*	*680*	*730*	*685*	*720*
x_{min} *(minimum cover depth)*	*[mm]*	*20*	*40*	*25*	*75*
h (overall depth)	*[mm]*	*715*	*785*	*740*	*810*
n_b *(number of 25 Ø bars)*	*[mm]*	*6*	*5*	*6*	*5*
$A_{st,\ required}$	$[mm^2]$	*2 792*	*2 489*	*2 676*	*2 477*
Diffusion coefficient (D_o)	m^2/s	6.7×10^{-13}	3.0×10^{-12}	1.3×10^{-12}	4.5×10^{-12}
f(X,Y)	$[kg\ CO_2\text{-}eq/m]$	*66*	*67*	*60*	*78*

*where: CEM :– Cement (Refer to **Table 5.1** for the full designation of the subsequent acronyms)*

From ***Table 5.11***, it can be seen that concrete made using CEM III/A-S 42.5N has the lowest environmental impact compared to other concrete types. This is followed by CEM II/B-V 42.5, CEM II/A-V 52.5, and finally CEM I 52.5 N.

In comparison to conventional prescriptive-based design, the minimum cover depth design provisions for CEM III/A-S 42.5N and CEM II/B-V 42.5 concretes for the optimized RC beam are lower than the recommended value of 40 *mm* by EN 206-1: 2004 at a *w/b* ratio of 0.4. The latter comparison shows that the design provisions by current design codes are conservative for certain binder types.

Generally, the following deductions can be made from ***Table 5.11***:

(i) Even though a lower binder content (higher *w/b* ratio) results in a reduced environmental impact, it leads to a greater reduction in compressive strength, and a corresponding increase in cross-sectional dimensions, and hence for a particular concrete strength grade, there is a reported increase in the kg CO_2-eq/m with decrease in binder content (increase in the *w/b* ratio).

(ii) Specifying higher compressive strengths leads to a reduction in cross-sectional dimensions.

(iii) It is important to select an appropriate binder content for a binder system, and vice versa, as the choice of binder system is based on its environmental impact at a particular binder content.

(iv) The use of SCMs allows the designer to prescribe lower values of concrete cover and hence leads to reduced cross-sectional dimensions, which translates to reduced volume of materials.

In conclusion, the optimization enables the selection of the optimum section dimensions; binder content; type and strength of binder that meets the required performance in terms of characteristic compressive strength (f_{ck}) and durability requirements of concrete and in addition minimizes the environmental impact.

5.5 Sensitivity analysis of design variables and parameters

5.5.1 Method of sensitivity analysis of design variables and parameters

In order to evaluate the influence of the design parameters on the optimal solution, a sensitivity analysis is performed. In a sensitivity analysis, the design parameters are varied (either within some percentage of the initial values or over a range of values) while other input values remain constant and the influence on the optimal result is noted. A sensitivity analysis is important as it establishes the relative importance of the design variables and parameters. However, a sensitivity analysis has a major limitation in that it evaluates the sensitivity of each variable independent of the others and is not able to evaluate the combined and simultaneous influence of inter-dependent variables (Christensen *et al*., 2005).

A sensitivity analysis was carried out by varying the parameter of interest over a valid range, and maintaining the other variables at their respective base settings. ***Table 5.12*** gives the data used in the sensitivity analysis. The base case refers to CEM III/A-S 42.5 N concrete in ***Table 5.11*** which was found to have the least environmental impact of 60 kg CO_2-eq/ m.

Table 5.12 *Input parameters for sensitivity analysis.*

Input parameters for sensitivity analysis	***Symbol***	***Units***	***Base case (Design value)***	***Range of values***
Percentage replacement of Portland cement with supplementary cementitious material (GGBS)	*P*	%	50 %	35% → 64%
w/b ratio	*w/b*	-	0.40	0.40 → 0.75
Reinforcing steel bar diameter[a]	*Ø*	*mm*	25	12, 16, 20, 25, 32,40
Characteristic compressive strength	f_{ck}	*MPa*	30	20 → 60
Effective depth-to-width ratio	*d/b*	*mm*	4	1.5 → 4.5

---

[a] Although the unit environmental impact of steel reinforcement (1470 kg CO_2-eq/ton) is higher than that of concrete (~110 kg CO_2-eq/ton), a discussion on the relative impacts of steel reinforcement and concrete would be interesting but would not be possible without the use of an actual reinforced concrete structure. Later in Chapter 6, for the first case study, in Table 6.11 it is shown that steel contributes 31.6% of the total embodied energy of the building, whereas concrete contributes 41.61%.

The sensitivity of the solution of the objective function (Equation (5-23)) to changes in the parameters presented in ***Table 5.12*** is presented next.

5.5.2 Sensitivity of the Portland cement replacement percentage

A sensitivity study is carried out to show the effect of the percentage of replacement of Portland cement with ground granulated blast furnace slag on the RC beam's environmental impact. Concrete made using CEM III/ A-S 42.5N was used to demonstrate this effect. The typical percentage replacement levels in CEM III/ A-S 42.5N range from 35% to 64%.

Figure 5-11 shows the change in kg CO_2-eq per unit length of the RC beam with change in the SCM percentage.

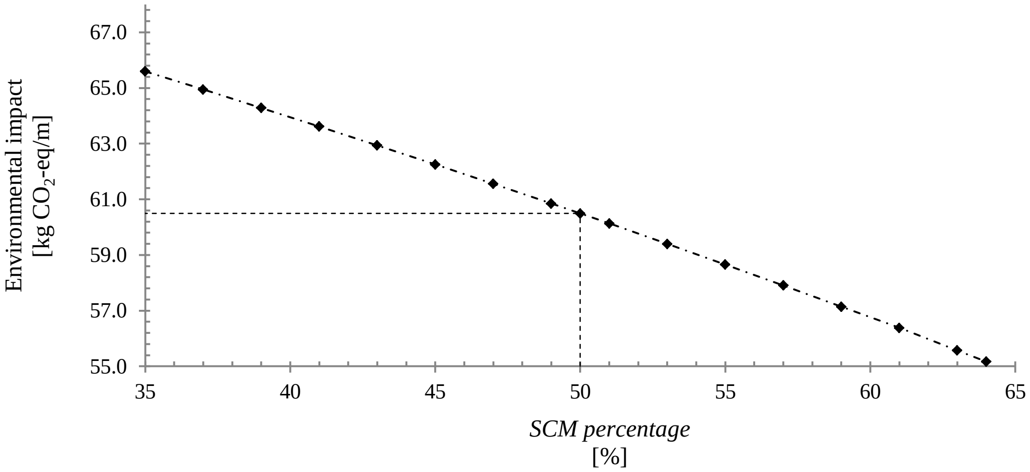

Figure 5-11: *Sensitivity of the environmental impact to variations in the SCM percentage.*

From ***Figure 5-11***, it can be observed that an increase in the SCM percentage level leads to decrease in the environmental impact per unit length of the RC beam. For example, increasing the replacement level by increments/decrements of ~2% (each step from 0.50 base-case whilst holding all other parameters constant) increases the kg CO_2-eq/*m* by a rate of 0.59% ~ 1.44% as shown in ***Table 5.13***.

Table 5.13: *Sensitivity of percentage replacement level of Portland cement to the environmental impact*

Replacement level *[%]*	***Environmental impact*** *[kg CO_2-eq/ m]*	***Rate of change of environmental impact*** *[%]*
35	65.59	-
37	64.94	0.99
39	64.29	1.02
41	63.62	1.04
43	62.94	1.06
45	62.25	1.09
47	61.56	1.12
49	60.85	1.15
50	60.49	0.59
51	60.13	0.59
53	59.40	1.22
55	58.66	1.25
57	57.91	1.28
59	57.14	1.32
61	56.38	1.33
63	55.57	1.44
64	55.17	0.73

#Base case = 50%

5.5.3 *Sensitivity of the water-binder ratio*

The *w/b* ratio affects the penetrability of concrete to aggressive ions, moisture and oxygen and its strength. ***Figure 5-12*** shows the change in kg CO_2-eq per unit length of the RC beam with change in the *w/b* ratio. A constant water content is maintained for all *w/b* ratios.

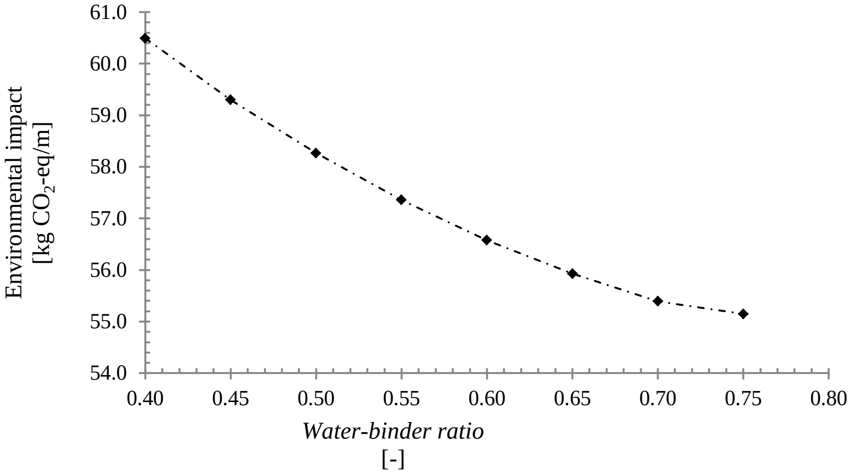

Figure 5-12: *Sensitivity of the environmental impact to variations in the water-to-binder ratio.*

From ***Figure 5-12***, it can be observed that an increase in the *w/b* ratio leads to a decrease in the environmental impact per unit length of the RC beam. For example, increasing the *w/b* ratio by increments/decrements of

±12.5% (each step from 0.40 base case whilst holding all other parameters constant) decreases the kg CO_2-eq/ *m* by a rate of 0.44 % ~ 1.97 % as shown in ***Table 5.14***.

Table 5.14: *Sensitivity of water-to-binder ratio to environmental impact*

w/b ratio *[-]*	*Environmental impact* *[kg CO_2-eq/ m]*	*Rate of change of environmental impact* *[%]*
0.40	60.49	-
0.45	59.30	1.97
0.50	58.27	1.74
0.55	57.36	1.56
0.60	56.58	1.36
0.65	55.93	1.14
0.70	55.39	0.96
0.75	55.15	0.44

#Base case = 0.40

At constant water content, a higher *w/b* ratio leads to a reduction in binder content and hence a reduction in the environmental impact/m. An increase in the *w/b* ratio increases the porosity of concrete and thereby decreases its compressive strength and increases its diffusivity to aggressive agents.

5.5.4 Sensitivity of diameter of steel

The steel reinforcement in concrete serves to resist stresses in the concrete due to the effects of mechanical loading. ***Figure 5-13*** shows the change in kg CO_2-eq/ *m* of concrete with change in diameter of reinforcing steel.

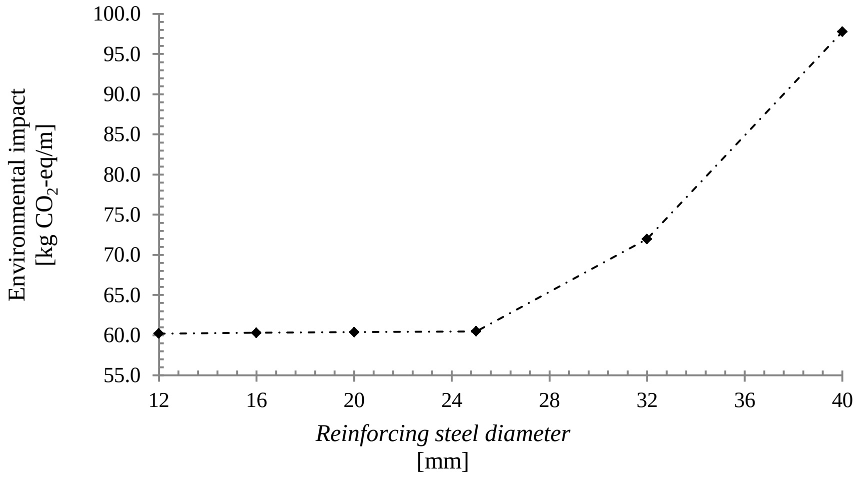

Figure 5-13: *Sensitivity of the environmental impact to variations in the diameter of reinforcing steel.*

From ***Figure 5-13*** it can be observed that the reinforcing steel diameter has an influence on the environmental impacts of concrete. For example, ***Table 5.15***.shows that an increase in reinforcing steel diameter from 12 *mm* to 40 *mm*, whilst holding all other parameters constant, increases the kg CO_2-eq per unit length by a rate of 0.14 % ~ 35.83 %.

Table 5.15: *Sensitivity of reinforcing steel diameter to environmental impact*

Steel diameter [mm]	*Environmental impact [kg CO_2-eq/ m]*	*Rate of change of environmental impact [%]*
12	60.21	-
16	60.29	-0.14
20	60.38	-0.14
25	60.49	-0.18
32	71.99	-19.01
40	97.78	-35.83

#Base case = 25 mm

This effect results from the fact that a higher steel diameter translates to an increase in the volume of steel used and in turn the environmental impact of concrete.

5.5.5 Sensitivity of compressive strength

The compressive strength is dependent on the binder system, *w/b* ratio, aggregate characteristics (size and shape), and age of concrete. ***Figure 5-14*** shows the change in kg CO_2-eq per unit length of the RC beam with change in 28-day cylinder compressive strength.

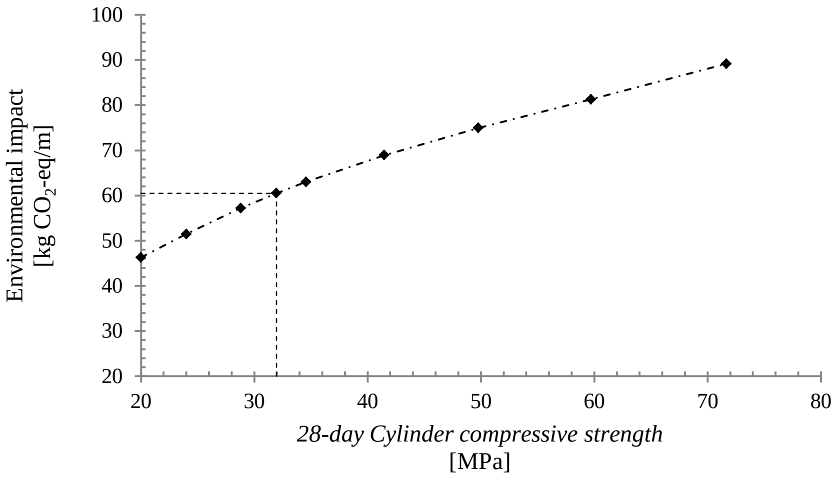

Figure 5-14: *Sensitivity of the environmental impact to variations in the characteristic compressive strength.*

From ***Figure 5-14***, it can be observed that at constant cross-section dimensions, an increase in the concrete compressive strength leads to an increase in the environmental impact per unit length of the RC beam. For example, increasing the compressive strength by increments/decrements of ±20% (each step from 32 MPa whilst holding all other parameters constant) increases the kg CO_2-eq /*m* by a rate of 4.2 % ~ 11.2 % as shown in ***Table 5.16***.

Table 5.16: *Sensitivity of compressive strength to environmental impact*

Characteristic compressive strength [MPa]	*Environmental impact [kg CO_2-eq/ m]*	*Rate of change of environmental impact [%]*
20	46.29	-
24	51.47	11.2
29	57.18	11.1
32	60.49	5.8
35	63.01	4.2
41	68.92	9.4
50	74.95	8.8
60	81.26	8.4
72	89.15	9.7

5.5.6 Sensitivity of effective beam depth to width ratio

Figure 5-15 shows the change in GWP_{100}/ m of concrete with change in the effective beam depth-to-width ratio.

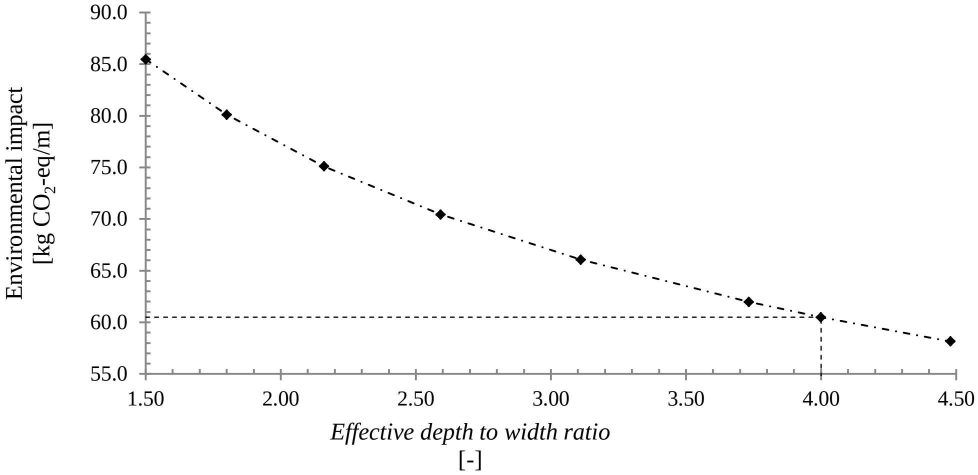

Figure 5-15: *Sensitivity of the environmental impact to variations in the effective beam depth-to-depth ratio.*

From ***Figure 5-15***, it can be observed that an increase in the effective depth-to-width ratio leads to a decrease in the environmental impact per unit length of the RC beam. For example, decreasing the ratio each step from 4 base case whilst holding all other parameters constant increases the kg CO_2-eq/ m by a rate of 2.39 % ~ 6.27 % as shown in ***Table 5.17***.

Table 5.17: *Sensitivity of effective depth-to-width ratio to environmental impact*

Effective beam depth to width ratio [-]	*Environmental impact [kg CO_2-eq/ m]*	*Rate of change of environmental impact [%]*
1.50	85.47	-
1.80	80.11	6.27
2.16	75.11	6.25
2.59	70.43	6.23
3.11	66.06	6.21
3.73	61.97	6.19
4.00	60.49	2.39
4.48	58.15	3.87

[#] *Base case = 4*

An increase in the effective depth-to-width ratio translates to a decrease in the volume of concrete used and in turn the environmental impact of concrete.

5.5.7 Summary of sensitivity analysis of design parameters

The results from the sensitivity analysis of the design parameters are summarized in ***Table 5.18***.

Table 5.18: *Sensitivity of the design parameters to the environmental impact.*

Design variables	***Symbol***	***Sensitivity range***
Reinforcing steel bar diameter *w/b* ratio	*Ø* *w/b*	0.14 % ~ 35.83 %. 0.44 % ~ 1.97 %
Percentage replacement of Portland cement with supplementary cementitious material (GGBS)	*P*	0.59 % ~ 1.44 %
Effective depth-to-width ratio	*d/b*	2.4 % ~ 6.3 %
Characteristic compressive strength	*fck*	5 % ~ 24 %

A tornado chart presented in ***Figure 5-16*** is used for a better visualization of the sensitivity results. The tornado chart demonstrates the sensitivity of the kg CO_2-eq per unit length to changes in each of the variables and parameters.

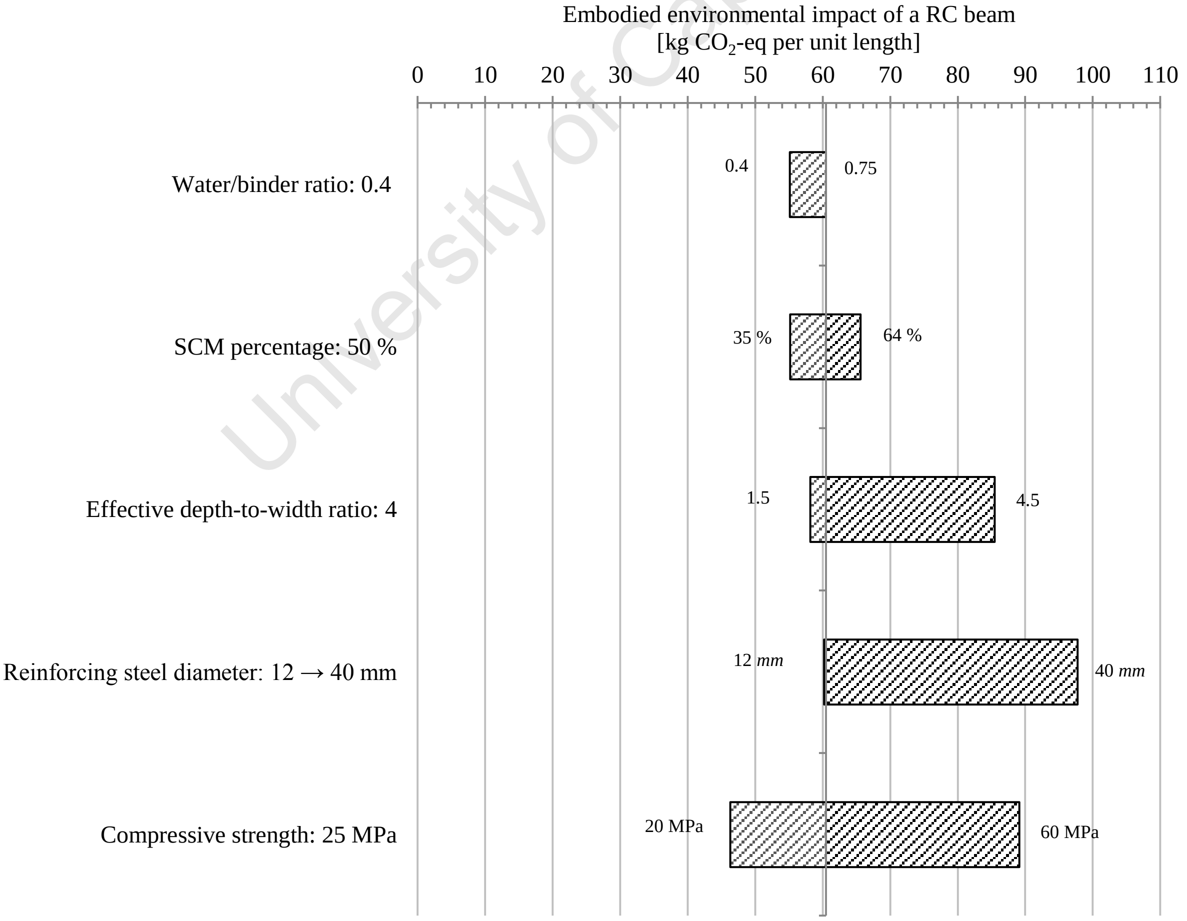

Figure 5-16: *Tornado chart showing the sensitivity of design variables and parameters.*

The point where the vertical axis crosses in ***Figure 5-16*** represents the base case (CEM III/A-S 42.5 N concrete in ***Table 5.11***) which has an embodied environmental impact of 60 kg CO_2-eq/ m.

The tornado chart shows the sensitivities of the design variables as they are increased within some percentage of the base values or over a range of values, given in ***Table 5.12***.

From ***Figure 5-16***, the parameter, which has the highest sensitivity on the embodied environmental impact of concrete, is the compressive strength. This is followed by the diameter of reinforcing steel, effective depth-to-width ratio, SCM percentage and finally, the *w/b* ratio.

5.6 Simplified design procedure using the design framework

The aforementioned optimization process may present an arduous task to a practising engineer who may not be conversant with optimization techniques. Hence, this Study recognizes the need for a simplified design approach that can be applied in routine design of RC structures. This simplified design process involves the selection of the optimum binder type, and *w/b* ratio for a given concrete grade, and is put forth as a set of charts shown in ***Figure 5-17*** (a) and (b).

The graphs in ***Figure 5-17*** were arrived at using the following steps:

(i) First this study identified locally available binder types such as those listed in ***Table 5.1***.

(ii) Using standard practice in concrete technology, and assuming “normal” aggregates and water requirements, suitable water contents were assigned to the selected binder types in order to satisfy the design slump requirement and achieve sufficient workability e.g. for 100 *mm* slump, the water contents for the respective binders are: 170 L/m^3 for CEM II/B-V 42.5; 185 L/m^3 for CEM II/A-V 52.5; 175 L/m^3 for CEM III/A-S 42.5; 185 L/m^3 for CEM I 52.5; 160 L/m^3 for CEM I 52.5 with an admixture.

(iii) Following this, the binder content was varied to obtain various *w/b* ratios for each selected binder type.

(iv) For each *w/b* ratio, a corresponding concrete compressive strength was computed using established formulas (Equation (5-18)) to obtain ***Figure 5-17*** (b). Note that ***Figure 5-17*** (b) can also be obtained empirically. In practice, binders change all the time and hence a margin of error should be allowed for when using the values in this Figure.

(v) ***Figure 5-17*** (a) was derived using Equation (5-24) which gives the unit environmental impact of concrete based on: its compressive strength, the concrete constituents, and their corresponding environmental impacts.

For a selected strength grade e.g. C25/30, the engineer selects the required binder type from ***Figure 5-17*** and the appropriate *w/b* ratio that gives the least environmental impact per cubic metre of concrete.

For example, it can be seen from the arrows in ***Figure 5-17*** that for a C25/30 grade concrete it would be beneficial to select CEM III/A-S 42.5 N (50% GGBS: 50% PC) binder at a *w/b* ratio of 0.45 over all other binder types in the graph. This binder combination results in a C25/30 grade concrete with an embodied environmental impact of 196 kg CO_2-eq/m^3. A 31 % reduction in the unit environmental impact of concrete can be achieved by selecting the aforementioned binder combination over a CEM I 52.5N (100% PC), at a *w/b* ratio of 0.55. This shows the importance of selecting the correct binder systems (i.e. binder types and *w/b* ratios) as compared to the current practice of simply selecting binder types based on their unit environmental impact.

In addition, it can be seen from ***Figure 5-17*** that the use of a chemical admixture in concrete made using CEM I 52.5 results in a 12% reduction in the unit environmental impact of concrete. These results are similar to those in Section 3.3.2 (Chapter 3) of this thesis. This shows that the use of chemical admixtures is beneficial to the environment as it leads to resource conservation i.e. chemical admixtures lead to a reduction in the water content of the mix-design and hence the binder content in order to maintain the original *w/b* ratio.

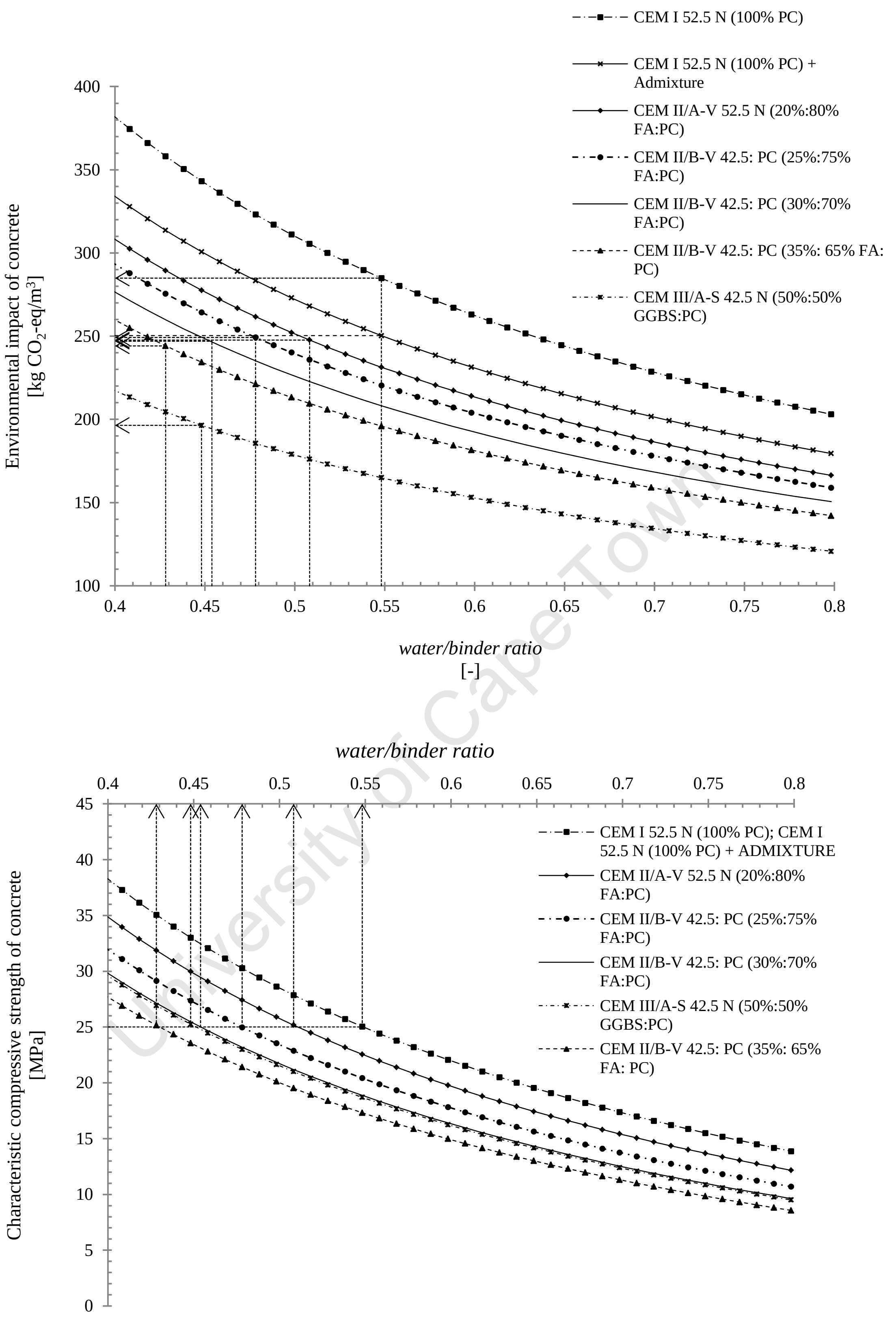

Figure 5-17: *(a) The environmental impact of concrete for different binder types; (b) Variation of w/b ratio and compressive strengths for different binder types.*

In summary, the graphs in ***Figure 5-17*** are used to guide the designer in selecting the appropriate *w/b* ratio and binder type for a chosen concrete grade.

However, it should be noted that the graphs do not account for member sizes/dimensions. The designer can however consider that specifying higher compressive strengths leads to a reduction in cross-sectional dimensions and hence reinforcement steel. In addition, the use of blended cements leads to the provision of lower cover depths and hence reduces the volume of materials.

The selected *w/b* ratio and binder type can change depending on the durability requirements of the RC component. For example, if the designer selects a CEM III/A-S 42.5 N (50% GGBS: 50% PC) binder at a *w/b* ratio of 0.45, and thereafter notes that the *w/b* ratio is too high for durability in the structure's service environment, then the next best *w/b* ratio can be selected that will achieve the durability and strength requirements simultaneously.

5.7 Detailed summary

The current key driver to the design of more sustainable RC structures has been the need to minimize resource use of natural resources and greenhouse gas (GHG) emissions over the life-cycle of concrete. This study identified volume reduction through section optimization and GHG emission reduction through proper selection of materials as viable ways in which the structural engineer could contribute towards sustainability in the concrete industry.

This study formulated a design framework that consisted of a set of quantifiable design parameters and variables that have an influence on the life-cycle sustainability of concrete. These consisted of the geometry of a structural component, concrete mix-design constituents and concrete hardened properties. The proposed framework was found to be extensive and covered the entire life-cycle of a typical RC structure. For purposes of this study it was not possible to integrate all the design variables contributing to more sustainable RC structure. The scope of this study was limited to materials selection at the detailed design phase, excluding design aspects such as planning the layout of the structure and determining the structural form and shape of a RC structure. The study was also limited to considerations of the cradle-to-gate environmental aspects and did not include maintenance/repair and subsequent phases of a RC structure. The study did not include the life-cycle social impacts/benefits of RC structures.

The selected design variables and parameters selected from the proposed framework were found to mutually oppose each other, and hence finding an overall solution made the design an optimization problem. The optimization problem was exemplified using a simplified RC beam. The aim of the optimization problem was to identify the optimum geometry and material specifications for the RC beam that would result in the lowest environmental impact whilst meeting the serviceability and safety design requirements of the RC beam over its service life.

Based on the output of the optimization problem, it was noted that there is a need for the designer to select an appropriate binder content for a binder system, and vice versa, as the choice of binder system is based on its environmental impact at a specific binder content. In general, it was found that the use of SCMs allow the designer to prescribe lower values of concrete cover and hence leads to reduced cross-sectional dimensions, which translates to reduced volume of materials.

A sensitivity analysis was carried out in this study to determine the influence of the design variables and parameters on the cradle-to-gate environmental impact of a RC beam. The results showed that the structural variables: number of reinforcing steel bars and the width of the RC beam had a higher influence compared to the mass quantities of the concrete constituents.

This study also recognized the need for simplifying the optimization process for purposes of assisting the practising engineer in routine design of RC structures for sustainability. This simplified design was presented in form of charts that allow for the selection of the optimum binder type, and *w/b* ratio for a given concrete grade.

5.8 General summary

The chapter details a main contribution of this study which is the development of a novel framework to support the design of more sustainable concrete structures. Using this framework, this study developed an optimization model to optimize the structural geometry, concrete mix-design constituents, and hardened properties of concrete such as its compressive strength and durability quality for it to have low life-cycle environmental impacts.

This study adopted existing empirical relationships from literature to estimate the hardened material properties of concrete with different binder systems and water-to-cement ratios. The empirical relationships are derived by correlating experimental data to a numerical model. The study applied a Fickian chloride diffusion model and a modified Bolomey strength model to predict a concrete’s diffusion coefficient and compressive strength, respectively. The empirical models have been developed and verified using international data. Further studies are required to verify the models using local data. Alternatively, local models can be developed to allow the structural engineer to predict the properties of concrete and hence produce reliable results when using the proposed framework.

The framework for design was applied to the environmental optimization of a RC beam section. Further application of the framework and methodology on real life structures is given in Chapter Six.

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Chapter 6

6 CASE STUDIES

6.1 Introduction

The framework for design developed in Chapter 5 is applied using two case studies. The first case study considers a reinforced concrete new engineering building (NEB) at the University of Cape Town, South Africa. The second case study considers an incrementally launched post-tensioned concrete switch ramp, located in Gauteng Province, South Africa. The concrete mix-design composition and structural dimensions of selected structural components from these structures are considered and compared with predictions of the proposed design framework.

The case studies selected have contrasting applications, i.e. the building is a host of offices and laboratories for university staff and students whereas the switch ramp facilitates vehicular transportation. The use of these two diverse case studies is meant to show the multifaceted nature of the design framework.

This study first carries out a life-cycle assessment on both structures, to establish the contribution of the various structural components and construction materials on the overall life-cycle environmental impacts of each of the structures. This is followed by the materials and structural design, of selected structural components in the two case studies, using the proposed design framework. The selected components are re-designed using the proposed framework. The scope of the study is on design decisions made at the detailed design phase of concrete construction.

6.2 Case study 1: Reinforced concrete building

6.2.1 Building description

The first case study is a six-storey engineering building located at the University of Cape Town's Upper campus (Latitude: 33° 57´ South; Longitude: 18° 27´ East). The building structure, shown in ***Figure 6-1***, was designed by local architects, SAOTA (Stefan Anthony Olmesdahl Truen Architects) in 2009 and construction commenced in 2011. The building was completed in 2013. The building is constructed with reinforced concrete as the main material for the column-beam structure, envelope walls and floors. The building has a total floor space of 14 540 m^2 (Table 4.1 in Appendix D) and has six floors, each of 4 m height. On completion, the building will have two computer laboratories, materials, structures, geotechnical and hydraulics laboratories, classrooms lecture venues and offices on the four upper levels.

Figure 6-1: *3-D model view of the new engineering building (Wentworth, 2012).*

6.2.2 Objective and scope of case study I

The objectives of the case study will be to first investigate the life-cycle environmental impacts of the building to show the contribution of the various life-cycle phases, structural components and construction materials to the overall life-cycle of the building. Secondly, the proposed framework for design of more sustainable concrete structures is applied in the materials and structural design of one of the structural components in the building i.e. a reinforced concrete ribbed floor slab.

6.2.3 Life-cycle assessment of the building

6.2.3.1 *Goal definition and scoping*

A life-cycle assessment (LCA) was carried out on the building. The LCA is performed in accordance with ISO 14040:2006 standard for LCA using SimaPro 7.1 LCA software (PRé Consultants, 2008). The scope of the LCA study includes investigating the resources used by the building over its life-cycle.

A life-cycle inventory of processes and material quantities used in the building were obtained from the project team[48]. For cases where this was not possible, generic data on the impact of the life-cycle processes were obtained from the Ecoinvent database and the ELCD (European Life-Cycle Database), both of which are contained in the SimaPro LCA software. Data in these databases are representative of the Swiss and the European Union context, respectively. The following abbreviations are used to show the geographical boundaries for the life-cycle inventory data in SimaPro: *DE* = Germany; *RER* = Europe; *NL* = Netherlands; *GLO*: = Global; *CH* = Switzerland.

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[48] The project team comprised the following South African-based companies: SAOTA (Stefan Anthony Olmesdahl Truen Architects), the MSINGI project managers, LDM Quantity Surveyors Pty, AfriSam material suppliers, Sutherland Structural Engineers and Filcon Contractors.

Based on the results of the inventory analysis, an impact assessment was carried out using two single score metrics: global warming potential (GWP_{100}) [kg CO_2-eq] and embodied energy [MJ], both of which have been discussed previously in Chapter 3. 3. The available exergy data in Ecoinvent database are not comprehensive and exergy data on a number of building elements e.g. Polyvinyl chloride, expandable polystyrene etc. are not available. The exergy metric is therefore not applied in the LCA study carried out in this Chapter.

In order to make a comparison between different building materials, and construction components on a common basis, a functional unit of the environmental impact per *unit floor area [m^2] of the building* was selected. This means that the cumulative environmental impact of the building is divided by the total building floor area.

6.2.3.2 *System boundary*

This study investigates the life-cycle environmental impacts of the building from the extraction of raw materials to the construction phase of the building. ***Figure 6-2*** gives the system boundary for the LCA.

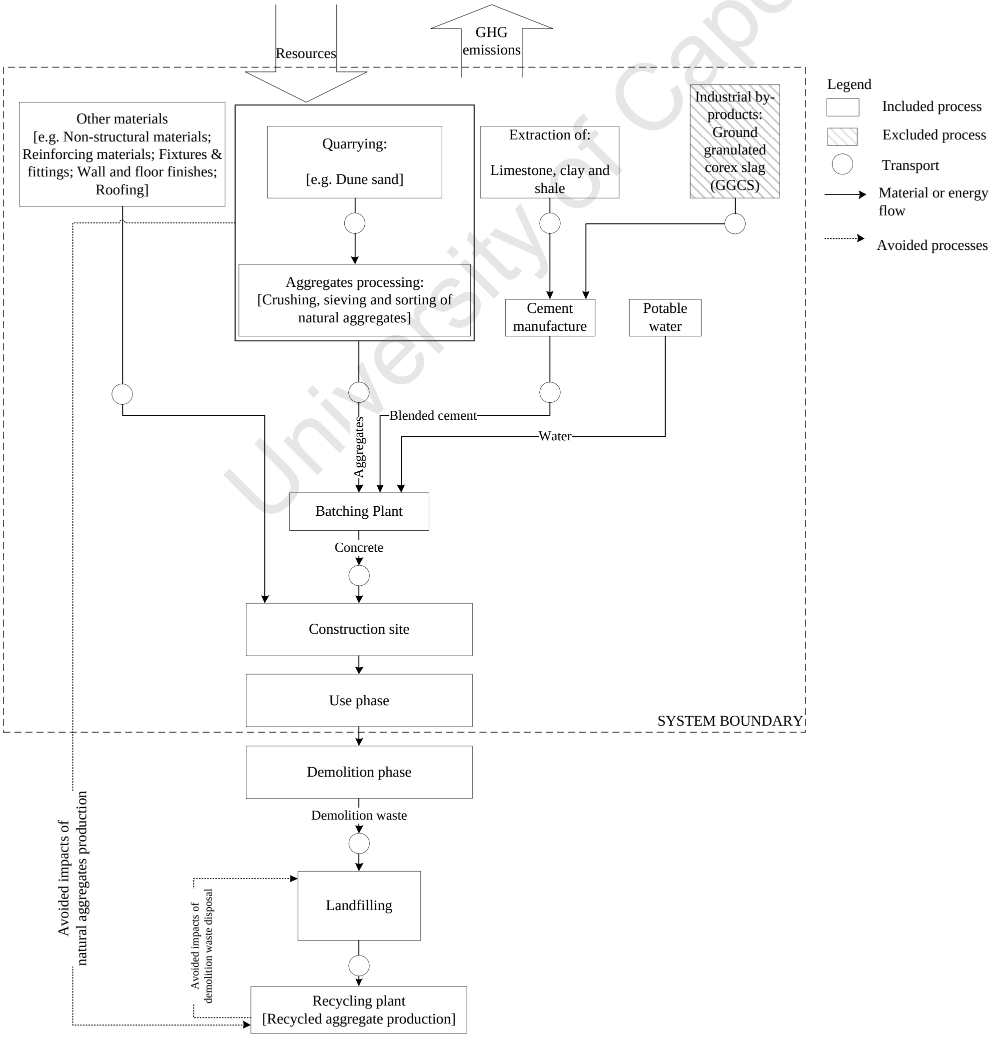

Figure 6-2: *Life-cycle phases of the new engineering building indicating the system boundary.*

The main life-cycle phases presented in ***Figure 6-2*** are described as follows:

(a) Raw material extraction and processing phase

The evaluation carried out during this phase involves the quantification of the environmental impacts related to the acquisition of materials and energy inputs in the quarrying of raw materials using e.g. blasting agents, their transportation to and within the processing facilities. The quantification process covers the extraction and processing of all building material components e.g. concrete, steel, glass etc.

The environmental impacts from the infrastructure (e.g. machinery in production plant) and the construction of the manufacturing facility are excluded as they would be negligible if allocated to a unit mass of product. In addition, the solid wastes generated by all manufacturing processes including ready-mix plant operations were not considered in the LCA.

(b) Transportation phase

This phase considers the quantification of the environmental impact related to the transportation of materials to the construction site and wastes from the construction site to a recycling facility. The data used for this include the mode of transport e.g. truck and actual transportation distances.

(c) Construction phase

This phase involves the quantification of the environmental impact related to site preparation and actual placement of materials in the construction site. The excavated materials during site clearance were considered in the assessment.

(d) Use phase

The building is assumed to have a service life of 50 years. In the use phase only the impacts related to the cooling and heating of the building are considered. The environmental impacts arising from lighting of the building, electronic equipment operation (e.g. desk top computers, laboratory equipment etc.), material replacements and repair activities have been left out of the analysis due to unavailability of data.

(e) Demolition/deconstruction phase

This phase involves the quantification of the environmental impact related to the end-of-life of the building. This includes the impacts from the energy used in demolishing the building and the transportation of the demolished material to the landfill site. This study did not consider the deconstruction/demolition phase of the building due to lack of data on machinery used in demolition processes and the working time for such machinery. Recycling processes were not considered since their related benefits are attributed to the recycled product (see Section 3.1.1.2 with reference to the allocation of material recycling processes).

The inventories of materials extracted and processed for construction and their transportation activities are detailed in sections 6.2.3.3 and 6.2.3.4, respectively. The environmental impact of construction activities, and use phase of the building are covered in sections 6.2.3.5 and 6.2.3.6, respectively.

6.2.3.3 Inventory of construction materials

The life-cycle inventory includes a record of material and energy flows of each life-cycle phase of the building. The building was principally constructed using reinforced concrete for the main structural frame, clay bricks for the walls and partitions and clay tiles for the roofing system. An inventory of all construction materials for the LCA was compiled using a Bill of Quantities (BOQ), supplied by LDM Quantity Surveyors (Pty). Additional specific information on each material in the BOQ was obtained through personal communication with the material suppliers.

6.2.3.3.1 Concrete

The concrete mix compositions for the building are given in ***Table 6.1***.

Table 6.1: *Mix-design for the reinforced and unreinforced concrete.*

Concrete mix-composition		***Units***	*Quantities of materials for 1m^3 of concrete*				
			***15 MPa** [a]*	***25 MPa***	***30 MPa** [a]*	***35 MPa***	***50 MPa***
Portland cement CEM I 52.5 N		kg/m^3	146	170	203	221	310
Corex slag		kg/m^3	49	57	68	74	103
Coarse aggregates	19 *mm*	kg/m^3	816	850	859	867	884
	9.5 *mm*	kg/m^3	144	150	152	153	156
Fine aggregates:	Dune sand	kg/m^3	495	467	445	431	370
	Crusher sand	kg/m^3	525	495	472	457	392
Water		L/m^3	175	172	172	172	175
Chemical admixture (superplasticizer)		L/m^3	1.165	1.362	1.623	1.767	2.476
Total		kg/m^3	2 350	2 361	2 371	2 375	2 390
w/b ratio		-	0.9	0.76	0.63	0.58	0.42
Hardened concrete properties (Design)							
Compressive strength, 28 days (f_{ck})		MPa	15	25	30	35	50

[a] : The 15 MPa and 30 MPa concrete mixes were applied for unreinforced concrete production such as in the unreinforced footings and cavity fills, whereas the remaining mixes were used in reinforced concrete applications such as reinforced footings, lift shaft, shear walls, retaining walls, columns and walls.
Mix-design composition data are supplied by Kleyn (2012) AfriSam (Pty), Personal communication.

All the concrete mixes consist of a blended mix of 75%: 25% (CEM I 52.5: Corex slag). A water-reducing admixture (superplasticizer) was used to improve the workability of the concrete mixes. The superplasticizer is sulphonated melamine formaldehyde.

The data sources used for the environmental impact of all concrete mix constituents, except for the superplasticizer (European Federation of Concrete Admixture Associations, 2006) were the Ecoinvent database 2.0 and the ELCD (European reference Life Cycle Database), in the SimaPro 7.1 software. In addition, the resources used in ready-mix production of the concrete are included in the LCA. The energy intensities of ready-mix plant operations vary widely depending on the state of the equipment and the type of fuel. Marceau *et al*. (2007)[49] give an average value of 43 MJ/m^3 (12 kWh/m^3) for the US ready-mix concrete industry, whereas the *fib* Bulletin no. 28 gives values of 75 MJ/m^3 and 272 MJ/m^3 for Japan and Canada ready-mix industries, respectively. This study adopted

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[49] Marceau *et al*. (2007) data are for the US ready-mix concrete industry. Local SA data are not available.

ready-mix plant operation data from Marceau *et al*. (2007) since local data for the same are not available.

6.2.3.3.2 Steel

The total amount of reinforcing steel and other steel used in the building is given in ***Table 6.2***.

Table 6.2: *Quantity of reinforcing steel used in the building.*

Type of steel	***Size*** *[mm]*	***Weight*** *[tons]*
High yield steel	10	44
	12	99
	16	135
	20	137
	25	162
	32	41
Mild steel	8	3
	10	4
	12	6
Fabric steel[a]	Type 245	2.9
	Type 395	3.6

[a] Fabric steel: Type 245: 2.45 kg/m^2; Type 395: 3.95 kg/m^2 (SANS 1024:2006). The fabric steel is used in the concrete floors.

Data are supplied by Allen (2012) LDM Quantity Surveyors (Pty).

6.2.3.3.3 Clay bricks

Clay bricks were used in the construction of the external walls, and partitions of the building. The amount of raw materials used in the production of a unit volume of bricks is given in ***Table 6.3***.

Table 6.3: *Constituent materials for the production of a unit volume of bricks.*

Mix-constituents	***Percentage composition*** *[%]*	***Mass*** *[kg/m^3]*
Clay	60.4	1 055
Waste coal (Fly ash)	7.2	126
Recycled brick waste	8.8	153
Recycled ceramic catalytic converter waste	3.6	64
Water (grey)	20	349
Total	**100**	**1 746**

Data are from: www.claytile.co.za (info@claytile.co.za); Forword (2012)

The bricks were manufactured using recycled waste and grey water was used in the production process. The total amounts of clay bricks used in construction of the building are computed in ***Table 6.4***.

Table 6.4: *Quantities of clay bricks.*

Mix-constituents	***Area*** [a] *[m^2]*	***Number of bricks*** *[52 bricks/m^2]* [b]	***Tonnage (t)*** *[2.3 kg per brick]*	***Volume*** *[m^3]* [e]
Half brick thick wall [c]	6 217	161 642	372	213
One brick thick wall [d]	1 946	101 192	233	133
280 *mm* cavity wall	6 013	625 352	1 438	824
Paving	612	31 824	73	42
Header	257	13 364	31	18
Total			**2 147**	**1 229**

[a] : Data are from the Bill of Quantities supplied by Allen (2012) LDM Quantity Surveyors, Personal communication

[b] : 52 bricks per m^2- reference: http://www.claytile.co.za/downloads/imperial_maxi_specs.pdf

[c] : Thickness of the wall is half a brick length

[d] : Thickness of the wall is a whole brick length

[e] : Volume [m3] calculated using the density of the brick mix (see Table 6.3) of 1746 kg/m^3

The energy used in the production of a single clay brick is given in ***Table 6.5***.

Table 6.5 : *Energy used in the production of a single clay brick (Forword, 2012).*

Energy	***Energy per brick***	***Energy per unit***
Carbon fuel	4 048 MJ	1.5 kWh/m^3 (5.33 MJ/m^3)
Electricity	55 kWh	0.07 kWh/m^3 (0.25 MJ/m^3)

6.2.3.3.4 Roofing tiles

The amount of resources used in the production of a single clay roofing tile is given in ***Table 6.6***.

Table 6.6 : *Resources for a single clay roofing tile.*

Mix-constituents	***Units***	***Amount***
Clay content	kg	3.4
Final clay product after processing	kg	3.1
Energy consumption		
Heating the clay briquette (5-15 kW)	MJ	6

Data are from www.claytile.co.za

6.2.3.3.5 Others

The materials that are indirectly related to the construction of the superstructure of the building are listed in ***Table 6.7***. These include fixtures and fittings, finishes and materials used in the construction of the foundation. For all these, the resources related to their production (including raw material extraction) and transportation processes to site are quantified.

Table 6.7 : *Inventory of other materials used in the building.*

Other materials	***Reference name in SimaPro***[c]	***Application***	***Units***	***Amount***
19 *mm* aggregate filling in foundation	Gravel 2/32, wet and dry quarry, production mix, at plant, undried RER S	Foundation	m^3	312
19 *mm* stone dressing on flat roof (50 *mm* thick) 925 m^2	Gravel 2/32, wet and dry quarry, production mix, at plant, undried RER S	Roof	m^3	46.25
Geotextile filter blanket under floor (assumed density of 175 g/m^2)	Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S	Roof	m^2	2 081
HDPE [a] resin dimpled drainage layer to roof garden	HDPE resin E	Roof	kg	26
3 *mm* reinforced bitumen waterproofing	Bitumen sealing, at plant/RER U	Roof, balconies and walls	kg	16 475
375 micron gundle dampproofing	Bitumen sealing, at plant/RER U	Walls and floors	kg	94.2
Floor insulation: Polystyrene	Polystyrene, extruded, at plant/ RER U	Foundation	m^2	3 932
Floor insulation: High Density Polystyrene	Expandable polystyrene (EPS) E	Floor insulation	kg	1 475
Epoxy resin	Epoxy resin, liquid, at plant/RER U	Floor waterproofing	kg	1 486
Granolithic screed	Cement cast plaster floor, at plant/CH U	Floor covering	kg	41 552
Sealant for cuts on floor: polysulphide	Polysulphide, sealing compound, at plant/RER U	Floors waterproofing	kg	148
Silicone sealant	Silicone product, at plant/RER U	Window	kg	227
Polyurethane sealant for construction joints	Polyurethane flexible foam E	Construction joints	kg	69
Plaster	Cement cast plaster floor, at plant/CH U	Wall finishing	kg	2 214 805
Paint	Cover coat, mineral, at plant/CH U	Finishing	kg	5 028
μPVC [b] drainage pipes (Ø160 *mm*) (assumed density of 1.23 Kg/m)	Polyvinylchloride, at regional storage/RER U	Foundation	m	120
μPVC [b] drainage pipes (Ø110 *mm*) (assumed density of 2.56 Kg/m)	Polyvinylchloride, at regional storage/RER U	Foundation	m	325
Fixtures and Fittings				
Wrought softwood	Sawn timber, softwood, planed, air dried, at plant/RER U	Skirtings'	m^3	5.2
Wood	Door, inner, wood, at plant/RER U	Door	m^2	563
Wood + Metal	Door, outer, wood-aluminium, at plant/RER U	Door	m^2	66.86
Carpet tiles	Yarn, cotton, at plant/GLO U	Floor covering	kg	2 323
Steel	Steel, low-alloyed, at plant/RER U	Door frame	kg	7 074
Wooden screed	Fibreboard soft, latex bonded, at plant (u=7%)/CH U	Floor covering	m^3	310
Porcelain	Sanitary ceramics, at regional storage/CH U	Wall tiles	kg	7 740
Porcelain	Ceramic tiles, at regional storage/CH U	Floor covering	kg	30 465
PVC [b] plastic pipe	PVC pipe E	Fittings	kg	2 528
Cast iron	Cast iron, at plant/RER U	Fittings	kg	0.036
Mirror	Flat glass, coated, at plant/RER U	Fittings	kg	235

[a] : HDPE – High-density polyethylene
[b] : PVC – Polyvinyl chloride
[c] : The processes include the whole manufacturing process for extracting the raw materials, internal processes (transport, etc.), and infrastructure for the operation (machinery)
U : Unit LCI processes (cradle-to-cradle)
S : System LCI that includes the subsystems of all inputs (from cradle-to-gate)
Data are supplied by Allen (2012) LDM Quantity surveyors (Pty)

6.2.3.4 *Transportation of materials*

An inventory of the transportation distances of materials to the processing plants and to site and their transportation mode is detailed in ***Table 6.8***.

Table 6.8 : *Transportation distances for main construction materials.*

Transported materials	***Source and destination***	***One-way transportation distance** [km]*	***Mode of transport***	***Source***
Concrete	Cement plant to ready-mix plant	131	Truck 35 t	Kleyn, 2012
	Corex slag to ready-mix plant	131	Truck 35 t	
	Coarse and fine aggregates from quarry to ready-mix plant	24	Truck 35 t	
	Superplasticizer: Chryso Omega 103 to ready-mix plant	10	Truck 3.5 t	https://maps.google.com/
	Ready-mix concrete: plant to site work	18	Truck 12 t	Kleyn, 2012
Clay roofing tiles	Raw materials to processing plant	10	Truck 32 t	Vardenega, 2012
	Finished product to site	12 336	Transoceanic freight ship	
		17.3	Truck 8 t	
Clay bricks	Clay to plant	0.4	Truck 34 t	Forword, 2012
	Waste coal to plant	132	Truck 34 t	
	Recycled material to plant	32	Truck 34 t	
	Finished clay bricks to site	35.7	Truck 34 t	
Steel	Reinforcement steel to site	1 452	Truck 28 t	Allen, 2012
	Steel formwork to site	10	Truck 17.3 t	Assumption
Crushed stone and excavated material	Crushed stone for backfill[a]	24	Truck 35 t	Assumption: Similar to coarse aggregates
	Surplus excavated material to dumpsite[b] (Vissershok Landfill site, Cape Town)	26.4	10 m^3 truck	Filcon contractors
Solid waste during site clearance	Solid waste to recycling plant (Vissershok Recycling facility, Cape Town)	26.4	Truck 28 t	https://maps.google.com/
Other materials listed in ***Table 6.7***	Finished product to site	10	Truck 17.3 t	Assumption

[a] : The quantity of backfilling material was supplied by the contractor and amounted to 709 m^3.
[b] : The surplus excavations dumped to a landfill were 1257 m^3.

Most of the construction materials were transported using 8 *t* –35 *t* trucks, except for the clay roofing tiles which were transported over water and land. The transportation distances by land varied from 18 to 1 452 km. Cement and steel travelled longer distances on land compared to other materials. During site clearance, the solid waste generated was transported approximately 26.4 *km* to the landfill/ recycling facility (Visserhok, Western Cape, South Africa) where a part of it was sorted and converted to recycled materials whereas the remaining was land-filled.

Within the ecoinvent database transportation is measured in reference units of one tonne kilometre (*tkm)* i.e. 1 tonne transported a distance of 1 *km*. The fuel consumption also depends on the type of vehicle as given in ***Table 6.8***.

6.2.3.5 Construction phase

This phase covers the energy used by equipment at the construction site for excavating the foundation, and material handling. Additionally, it includes materials such as the excavation of materials that do not constitute the final building material. The shuttering/scaffolding and the concrete handling in placement activities were excluded in this study. For the latter the following equipment was used: concrete buckets, spades, drive units, poker vibrators, steel trowels and timber floats. The duration of their use on site was not recorded, hence making it difficult for this to be included in the LCA.

The selected construction processes in ***Table 6.9*** relate to the building frame and form the major activities during construction and include the excavation of soil and rock and actual construction of the building. The equipment used in construction and the estimated duration of their use is also given in ***Table 6.9***. Further, the total hours of use for construction equipment, indicated in brackets, was estimated based on the assumption that the equipment was used for 6 hours per day and each week had 5 working days. This excludes the crane which was used for 2 hours daily. The environmental impacts related to the installation of the crane system on site have not been accounted for in this study.

Table 6.9 : *Construction equipment.*

Construction process	***Construction equipment***	***Materials [m³]***	***Total cumulative operation time***	***Reference name in SimaPro[b]***
Excavation for the foundation	30 ton excavator	147.8[a]	1 month (120 hours)	Excavation, hydraulic digger/RER U
	20 ton excavator	886.8[a]	6 weeks (180 hours)	Excavation, hydraulic digger/RER U
	3 ton machine	443.4	3 weeks (90 hours)	Excavation, skid-steer loader/RER U
	2 Tractor-Loaders-Backhoes (TLB)	1 478	13 weeks (390 hours)	Excavation, skid-steer loader/RER U
Back excavations of vertical sides for working space (battering)	20 ton excavator	4 577	1 week (30 hours)	Excavation, hydraulic digger/RER U
Earth filling supplied by contractor	Crane	709	4 weeks (40 hours)	Diesel[d] burned in machine/GLO
Excavation for the foundation	30 ton excavator	147.8[a]	1 month (120 hours)	Excavation, hydraulic digger/RER U
	20 ton excavator	886.8[a]	6 weeks (180 hours)	Excavation, hydraulic digger/RER U
	3 ton machine	443.4	3 weeks (90 hours)	Excavation, skid-steer loader/RER U
	2 Tractor-Loaders-Backhoes (TLB)	1 478	13 weeks (390 hours)	Excavation, skid-steer loader/RER U
Back excavations of vertical sides for working space (battering)	20 ton excavator	4 577	1 week (30 hours)	Excavation, hydraulic digger/RER U
Earth filling supplied by contractor	Crane	709	4 weeks (40 hours)	Diesel[d] burned in machine/GLO
Crushed stone for backfill	Crane	312	4 weeks (40 hours)	Diesel[d] burned in machine/GLO
Transport to site: crushed stone for backfill:	Transport: 10 m³ truck	312 [c1]	Refer to ***Table 6.8***	Transport, Truck >16t, fleet average/RER U
Waste management: Transport of surplus material to landfill	Transport: 10 m³ truck	1 257[c2]	Refer to ***Table 6.8***	Transport, Truck >16t, fleet average/RER U
Compaction of surfaces	Bomag rollers and plate compactors	312.15	7.5 weeks (225 hours)	Diesel[d] burned in machine/GLO
Transfer of construction materials within site[e]	Bobcat mini excavator	-	25.5 weeks (765 hours)	Diesel[d] burned in machine/GLO

[a] : The volume of materials excavated is apportioned depending on the number of weeks the machinery was in operation.

[b] : The process includes direct emissions as well as manufacturing of the entrepreneurial machine and the consumption of fuel and

lubricating oil

[c1] : The crushed stone for backfill is assumed to have a density of 2650 kg/m^3. Hence the tkm = $\left[\frac{2650 \times 312}{1000}\right] t \times 26.4 km = 21828 \ \ tkm$

[c2] : The waste material is assumed to have a density of 2400 kg/m^3. Hence the tkm = $\left[\frac{2400 \times 1257}{1000}\right] t \times 26.4 km = 79644 \ \ tkm$

[d] : Diesel used for excavation was estimated using the factor of 0.13 kg diesel per m^3 of excavation. Diesel has a net calorific value of 42.8 MJ/kg (Kellenberger *et al*., 2007) or 36 MJ/litre.

[e] : The bobcat was used for transferring materials on-site. The bobcat was estimated to have consumed 25 litres of diesel per fortnight (Filcon contractors (Pty)). Therefore, the amount of diesel used was: $\left[\frac{25.5 \times 25}{2}\right] \times 36 = 11.5 \ \ MJ$

Data are obtained from Filcon contractors (Pty)

From ***Table 6.9*** the volume of excavated materials amounted to 1478 m^3 and their transportation from site to the landfill is included in the LCA. The compaction quantity was 2081 m^2 for a depth of 150 *mm*. The assumed density of the excavated and backfill material is 2400 kg/m^3 and 2650 kg/m^3, respectively. The excavated material consists of reinforced concrete rubble whereas the backfill material consists of crushed aggregates. Data on the transportation distances for the excavated material were given in ***Table 6.8***.

6.2.3.6 Operational phase

The operational phase includes the energy that is used in the heating, cooling, and ventilation of the building. This amount was estimated using energy simulation software for buildings in a study documented in NEB-UCT Energy Report (2011). Energy modelling was used to make the most of the passive design concept which requires the layout of a building to be oriented such that it makes use of natural lighting and ventilation.

Since this is a new building there was no record/utility bill of the actual energy to be used in computing activities, lighting and in the operation of laboratory machinery.

Table 6.10 gives a summary of the operational energy requirements of the building.

Table 6.10: *Operational energy use in the building.*

Activity	***Amount***	
	[MWh]	[MJ]
Fans	30.4	109 584
Pumps	66.5	239 364
Heating	12.6	45 468
Cooling	239.5	862 164
Annual total	**349.1**	**1 256 580**

Based on the annual electricity consumption of the building given in ***Table 6.10***, the total electricity use over the life time of the building (taken as 50 years) is estimated as 17 456 MWh (62 829 GJ) or 1200 MWh/m^2 (4.32 GJ/m^2).

6.2.3.7 Life-cycle impact assessment

Based on the results of the inventory analysis, an impact assessment was carried out using the GWP_{100} [kg CO_2-eq] and the energy [MJ] metric. These metrics have been discussed previously in Chapter 3.

An example of a material assembly in SimaPro 7.1 for 30 MPa concrete is given in Appendix D. ***Figure 6-3*** shows the flow of materials and energy required in the production of 693 tonnes of the unreinforced concrete used in the building and the corresponding environmental impact of 7.13 x 10^4 kg CO_2-eq (5.33 x 10^4 MJ).

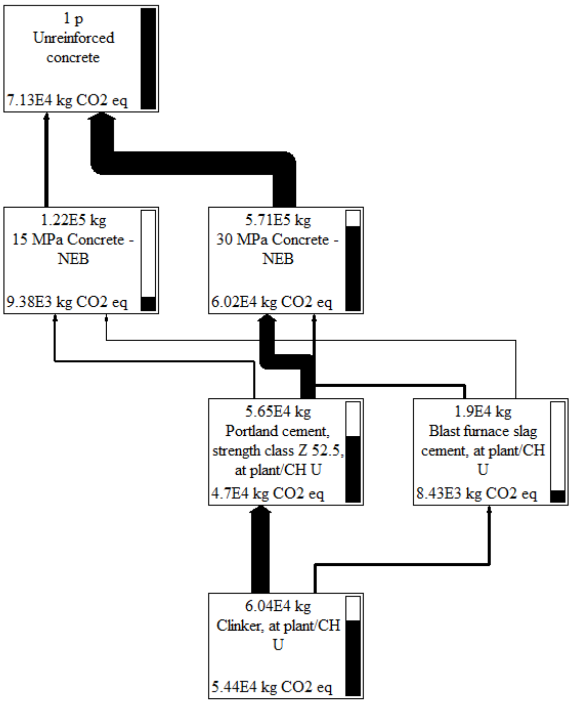

Figure 6-3: *Environmental impact flow for the production of unreinforced concrete (SimaPro 7.1: PRé Consultants, 2008).*

To allow for comparison of the results with other life-cycle phases and with other LCA studies on buildings, the environmental impact results are presented in terms of a functional unit (refer to section 6.2.3.1) as e.g. 0.1 kg CO_2-eq/m^2 (0.1 MJ/m^2) for the cradle-to-gate phase.

6.2.3.7.1 Environmental impact of construction materials

The environmental impact of all materials used in the building is summarized in ***Table 6.11***. For example, the total GHG emissions embodied in all materials amounted to 231 kg CO_2-eq/m^2 (2670 MJ/m^2). This amount constitutes:

- The manufacturing environmental impact of 219 kg CO_2-eq/m^2 (2450 MJ/m^2) that is generated during the manufacture of the materials and their transportation to and within the processing plants, and
- The transportation environmental impact of 12 kg CO_2-eq/m^2 (220 MJ/m^2) that is due to the transportation of the materials from the processing plant to site.

In addition, ***Table 6.11*** shows the percentage contribution of the various materials to the total environmental impact of the building. Concrete for use in reinforced structures and reinforcing steel were found to contribute to majority of the total 231 GWP_{100}/m^2 at 39.5% and 31.6%, respectively. The cement used to plaster the walls of the building also contributed to 11.3 % of the total GWP_{100}/m^2. The corresponding energy values are given in ***Table 6.11***.

6.2.3.7.2 Environmental impact of various concrete structural components

In addition, this study reviewed the contribution of the various concrete structural components (beams, columns, shear walls, slabs, staircase and foundation), as shown in ***Table 6.12***. The environmental impacts covers the manufacture and transportation of materials used in constructing the structural components. The environmental impacts arising from the surface finishing and construction of the structural components are not considered.

From ***Table 6.12***, the slab and beam structural components were found to have the highest (79%) contribution to the total environmental impact of all structural components.

6.2.3.7.3 Environmental impact of various life-cycle phases

In addition, this study reviewed the contribution of the various life-cycle phases of the NEB. The results are as follows:

(a) Raw material extraction and processing

The GWP_{100} and energy arising from the raw material extraction and processing phase as given in ***Table 6.11*** is 219 kg CO_2-eq emissions/m^2 and 2450 MJ/m^2, respectively. .

(b) Transportation phase

The GWP_{100} and energy arising from the transportation of materials and construction equipment amounts to approximately 12 kg CO_2-eq/m^2 emissions and 220 MJ/m^2, respectively.

(c) Construction phase

The GWP_{100} and energy arising from the construction of the building is given in ***Table 6.13*** and amounts to approximately 0.76 kg CO_2-eq/m^2 emissions and 12.2 MJ/m^2, respectively.

***Table 6.11** : Total energy and GWP$_{100}$ of materials used in the construction of the New Engineering Building.*

Material	***Description***	***Total mass^{a}***	***GWP$_{100}$***				***Energy***			
		[tons]	***Manufacture*** *[kg CO$_2$-eq]*	***Transportation to site*** *[kg CO$_2$-eq]*	***Total*** *[kg CO$_2$-eq]*	***%***	***Manufacture*** *[MJ]*	***Transportation to site*** *[MJ]*	***Total*** *[MJ]*	***%***
Reinforced concrete: (Concrete component only)	25 MPa	12820	1.17 x 10^{6}	3.07 x 10^{4}	1.20 x 10^{6}	39.49%	8.36 x 10^{6}	8.54 x 10^{5}	9.21 x 10^{6}	26.14%
	30 MPa	332	3.50 x 10^{4}	7.96 x 10^{2}	3.58 x 10^{4}		2.42 x 10^{5}	2.34 x 10^{4}	2.65 x 10^{5}	
	35 MPa	401	4.53 x 10^{4}	9.63 x 10^{2}	4.63 x 10^{4}		3.09 x 10^{5}	2.92 x 10^{4}	3.38 x 10^{5}	
	50 MPa	296	4.46 x 10^{4}	7.11 x 10^{2}	4.53 x 10^{4}		2.88 x 10^{5}	2.47 x 10^{4}	3.13 x 10^{5}	
Unreinforced concrete	30 MPa	571	6.02 x 10^{4}	1.37 x 10^{3}	6.16 x 10^{4}	2.12%	4.16 x 10^{5}	4.03 x 10^{4}	4.56 x 10^{5}	1.37%
	15 MPa	122	9.38 x 10^{3}	2.93 x 10^{2}	9.67 x 10^{3}		6.79 x 10^{4}	8.60 x 10^{3}	7.65 x 10^{4}	
Steel	Fabric steel	7	9.51 x 10^{3}	1.25 x 10^{3}	1.08 x 10^{4}	31.60%	1.31 x 10^{5}	1.99 x 10^{4}	1.51 x 10^{5}	38.40%
	Mild steel	14	2.06 x 10^{4}	2.70 x 10^{3}	2.33 x 10^{4}		2.83 x 10^{5}	4.29 x 10^{4}	3.26 x 10^{5}	
	High yield steel	619	9.10 x 10^{5}	1.19 x 10^{5}	1.03 x 10^{6}		1.25 x 10^{7}	1.90 x 10^{6}	1.44 x 10^{7}	
Clay bricks	Half brick wall	372	5.20 x 10^{4}	1.77 x 10^{3}	5.38 x 10^{4}	9.23%	7.64 x 10^{5}	3.00 x 10^{4}	7.94 x 10^{5}	11.82%
	One brick wall	233	3.26 x 10^{4}	1.11 x 10^{3}	3.37 x 10^{4}		4.78 x 10^{5}	1.88 x 10^{4}	4.97 x 10^{5}	
	280 *mm* cavity wall	1438	2.01 x 10^{5}	6.84 x 10^{3}	2.08 x 10^{5}		2.95 x 10^{6}	1.16 x 10^{5}	3.07 x 10^{6}	
	Bring paving	73	1.02 x 10^{4}	3.48 x 10^{2}	1.05 x 10^{4}		1.50x 10^{5}	5.91 x 10^{3}	1.56 x 10^{5}	
	Header	31	4.30 x 10^{3}	1.46 x 10^{2}	4.45 x 10^{3}		6.31 x 10^{4}	2.48 x 10^{3}	6.56 x 10^{4}	
Roofing tiles	Roof	4	1.13 x 10^{3}	2.80 x 10^{2}	1.41 x 10^{3}	0.04%	1.10 x 10^{4}	4.4 x 10^{3}	1.54 x 10^{4}	0.04%
19 *mm* aggregate filling in foundation	Foundation	811	2.75 x 10^{3}	1.08 x 10^{3}	3.83 x 10^{3}	0.11%	5.19 x 10^{4}	1.83 x 10^{4}	7.02 x 10^{4}	0.18%
Geotextile filter blanket under floor	Foundation	0.4	8.44 x 10^{2}	4.85 x 10^{-1}	8.44 x 10^{2}	0.03%	3.16 x 10^{4}	8.2 x 10^{0}	3.16 x 10^{4}	0.08%
µPVC drainage pipes (Ø160 *mm*)	Foundation	0.8	1.66 x 10^{3}	1.11 x 10^{0}	1.66 x 10^{3}	0.05%	5.07 x 10^{4}	1.88 x 10^{1}	5.07 x 10^{4}	0.13%
µPVC drainage pipes (Ø110 *mm*)	Foundation	0.2	2.95 x 10^{2}	1.96 x 10^{-1}	2.95 x 10^{2}	0.01%	9.00 x 10^{3}	3.30 x 10^{0}	9.00 x 10^{3}	0.02%
Floor insulation: Polystyrene	Foundation	0.6	6.56 x 10^{3}	7.85 x 10^{-1}	6.56 x 10^{3}	0.20%	5.94 x 10^{4}	1.33 x 10^{1}	5.94 x 10^{4}	0.15%
Floor insulation: High Density Polystyrene	Floor	1.5 x 10^{0}	4.99 x 10^{3}	1.97 x 10^{0}	4.99 x 10^{3}	0.15%	1.38 x 10^{5}	3.34 x 10^{1}	1.38 x 10^{5}	0.36%
375 micron gundle Dampproofing	Walls and floors	1.0 x 10^{-1}	1.03 x 10^{2}	1.25 x 10^{-1}	1.03 x 10^{2}	0.00%	4.77 x 10^{3}	2.13 x 10^{0}	4.77 x 10^{3}	0.01%
3 *mm* reinforced bitumen waterproofing	Roof, balconies and walls	1.65x 10^{1}	1.81 x 10^{4}	2.19 x 10^{1}	1.81 x 10^{4}	0.54%	8.34 x 10^{5}	3.73 x 10^{2}	8.34 x 10^{5}	2.15%
HDPE resin dimpled drainage layer to roof garden	Roof	2.6 x 10^{-2}	4.97 x 10^{1}	3.46 x 10^{-2}	4.97 x 10^{1}	0.00%	2.03 x 10^{3}	6.00 x 10^{-1}	2.03 x 10^{3}	0.01%
Polyurethane sealant for construction joints	Construction joints	6.9 x 10^{-2}	3.18 x 10^{2}	9.12 x 10^{-2}	3.18 x 10^{2}	0.01%	6.96 x 10^{3}	1.6 x 10^{0}	6.96 x 10^{3}	0.02%
Sealant for cuts on floor: polysulphide	Floors	1 x 10^{-1}	2.24 x 10^{2}	1.97 x 10^{-1}	2.24 x 10^{2}	0.01%	4.30 x 10^{3}	3.3 x 10^{0}	3.30 x 10^{0}	0.00%
Silicone sealant	Window	2 x 10^{-1}	6.10 x 10^{2}	3.02 x 10^{-1}	6.10 x 10^{2}	0.02%	1.42 x 10^{4}	5.13 x 10^{0}	1.42 x 10^{4}	0.04%
Epoxy resin	Floor	1.5 x 10^{0}	9.91 x 10^{3}	1.98 x 10^{1}	9.91 x 10^{3}	0.29%	2.01 x 10^{5}	3.36 x 10^{1}	2.01 x 10^{5}	0.52%
Paint	Finishing	5.0 x 10^{0}	4.03 x 10^{2}	6.69 x 10^{0}	4.10 x 10^{2}	0.01%	8.72 x 10^{3}	1.14 x 10^{2}	8.83 x 10^{3}	0.02%
Granolithic screed	Floor	4.16x 10^{1}	7.07 x 10^{3}	5.53 x 10^{1}	7.13 x 10^{3}	0.21%	4.79 x 10^{4}	9.40 x 10^{2}	4.88 x 10^{4}	0.13%
Plaster	Wall	2.2 x 10^{3}	3.77 x 10^{5}	2.95 x 10^{3}	3.77 x 10^{5}	11.30%	2.55 x 10^{6}	5.01 x 10^{4}	2.60 x 10^{6}	6.71%
Wrought softwood	Skirtings’	2.6 x 10^{-3}	4.51 x 10^{2}	3.47 x 10^{-3}	4.51 x 10^{2}	0.01%	5.6 x 10^{4}	5.86 x 10^{1}	5.61 x 10^{4}	0.14%
Wood	Door	1.55x 10^{1}	2.06 x 10^{4}	2.07 x 10^{1}	2.06 x 10^{4}	0.61%	1.01x 10^{6}	3.51 x 10^{2}	1.01 x 10^{6}	2.61%
Wood + Metal	Door	2.6 x 10^{0}	5.78 x 10^{3}	3.47 x 10^{0}	5.78 x 10^{3}	0.17%	1.27 x 10^{5}	5.87 x 10^{1}	1.27 x 10^{5}	0.33%
Carpet tiles	Floor	2.3 x 10^{0}	3.30 x 10^{4}	3.07 x 10^{0}	3.30 x 10^{4}	0.98%	4.18 x 10^{5}	5.25 x 10^{1}	4.18 x 10^{5}	1.08%
Steel door frame	Door frame	7.4 x 10^{0}	1.29 x 10^{4}	9.87 x 10^{0}	1.29 x 10^{4}	0.38%	1.97 x 10^{5}	1.60 x 10^{2}	1.97 x 10^{5}	0.51%
Wooden screed	Floor	7.44x 10^{1}	3.09 x 10^{4}	9.93 x 10^{1}	3.10 x 10^{4}	0.92%	1.76x 10^{6}	1.68 x 10^{3}	1.76 x 10^{6}	4.55%
Porcelain	Wall tiles	7.74x 10^{0}	1.80 x 10^{4}	1.03 x 10^{1}	1.80 x 10^{4}	0.54%	3.33 x 10^{5}	1.75 x 10^{2}	3.33 x 10^{5}	0.86%
Porcelain	Floor tiles	3.05x 10^{1}	2.37 x 10^{4}	4.07 x 10^{1}	2.37 x 10^{4}	0.71%	4.52 x 10^{5}	6.89 x 10^{2}	4.53 x 10^{5}	1.17%

*Continued…**Table 6.11** : Total energy and GWP100 of materials used in the construction of the New Engineering Building.*

Material	***Description***	***Total mass***[a]	***GWP$_{100}$***				***Energy***			
			Manufacture	***Transportation to site***	***Total***	***%***	***Manufacture***	***Transportation to site***	***Total***	***%***
		[tons]	*[kg CO_2-eq]*	*[kg CO_2-eq]*	*[kg CO_2-eq]*		*[MJ]*	*[MJ]*	*[MJ]*	
PVC plastic pipe	Fittings	2.5 x 10^{0}	8.04 x 10^{3}	3.34 x 10^{0}	8.04 x 10^{3}	0.24%	1.72 x 10^{5}	5.72 x 10^{1}	1.72 x 10^{5}	0.44%
Cast iron	Fittings	3.6 x 10^{-5}	5.42 x 10^{-2}	4.80 x 10^{-5}	5.42 x 10^{-2}	0.00%	0.9	0	9.00 x 10^{-1}	0.00%
Mirror	Fittings	2 x 10^{-1}	2.57 x 10^{2}	2.67 x 10^{-1}	2.57 x 10^{2}	0.01%	3.49 x 10^{3}	5.32 x 10^{0}	3.50 x 10^{3}	0.01%
Total			**3.19 x 10^{6}**	**1.73 x 10^{5}**	**3.36 x 10^{6}**	**100%**	**3.56 x 10^{7}**	**2.94 x 10^{6}**	**3.87 x 10^{7}**	**100%**
Total per m^2			**2.19 x 10^{2}**	**1.19 x 10^{1}**	**2.31 x 10^{2}**		**2.45 x 10^{3}**	**2.20x 10^{2}**	**2.67 x 10^{3}**	

[a] Data are obtained from the Bill of Quantities supplied by Allan (2012) LDM Quantity surveyors

Table 6.12 : *Environmental impact of main structural components of the New Engineering Building.*

Structural component		***Materials***	***Quantity***		***GWP$_{100}$***			***Energy***		
					[kg CO_2-eq]	***Total*** *[kg CO_2-eq]*	*Percentage contribution*	*[MJ]*	***Total*** *[MJ]*	*Percentage contribution*
Slabs and beams		25 MPa Concrete	4401	m^3	9.51 x 10^{5}	1.82 x 10^{6}	78.67%	7.46 x 10^{6}	2.14 x 10^{7}	78.55%
		Steel	528.12	t	8.66 x 10^{5}			1.39 x 10^{7}		
Columns		50 MPa Concrete	117	m^3	4.21 x 10^{4}	7.28 x 10^{4}	3.15%	4.94 x 10^{5}	7.89 x 10^{5}	2.90%
		Steel	18.72	t	3.07 x 10^{4}			2.95 x 10^{5}		
Staircases		35 MPa Concrete	32	m^3	8.60 x 10^{3}	8.60 x 10^{3}	0.37%	6.39 x 10^{4}	6.39 x 10^{4}	0.23%
Shear walls		25 MPa Concrete	217	m^3	4.69 x 10^{4}	1.18 x 10^{5}	5.10%	3.68 x 10^{5}	1.51 x 10^{6}	5.58%
		Steel	43.4	t	7.12 x 10^{4}			1.15 x 10^{6}		
Retaining walls		25 MPa Concrete	52	m^3	1.12 x 10^{4}	1.89 x 10^{4}	0.82%	8.82 x 10^{4}	2.12 x 10^{5}	0.78%
		Steel	4.68	t	7.67 x 10^{3}			1.24 x 10^{5}		
Foundations:	Strip footings	25 MPa Concrete	124	m^3	2.68 x 10^{4}	4.31 x 10^{4}	1.86%	2.10 x 10^{5}	4.72 x 10^{5}	1.74%
		Steel	9.92	t	1.63 x 10^{4}			2.62 x 10^{5}		
	Retaining walls	25 MPa Concrete	9	m^3	1.95 x 10^{3}	3.78 x 10^{3}	0.16%	1.53 x 10^{4}	4.48 x 10^{4}	0.17%
		Steel	1.12	t	1.84 x 10^{3}			2.96 x 10^{4}		
	Columns	25 MPa Concrete	7	m^3	1.51 x 10^{3}	2.84 x 10^{3}	0.12%	1.19 x 10^{4}	3.33 x 10^{4}	0.12%
		Steel	0.81	t	1.33 x 10^{3}			2.14 x 10^{4}		
Foundation bases:	Column bases	25 MPa Concrete	306	m^3	6.61 x 10^{4}	1.06 x 10^{5}	4.58%	5.19 x 10^{5}	1.17 x 10^{6}	4.28%
		Steel	24.48	t	4.01 x 10^{4}			6.46 x 10^{5}		
	Shear wall bases	25 MPa Concrete	217	m^3	4.69 x 10^{4}	1.18 x 10^{5}	5.10%	3.68 x 10^{5}	1.51 x 10^{6}	5.58%
		Steel	43.4	t	7.12 x 10^{4}			1.15 x 10^{5}		
Roofing		Roofing tiles	3.7	t	1.33 x 10^{3}	1.33 x 10^{3}	0.06%	1.54 x 10^{4}	1.54 x 10^{4}	0.06%
Total						**2.31 x 10^{6}**	**100**		**2.72 x 10^{7}**	**100**
Total per m^2						**159**			**1871**	

Table 6.13 *: Environmental impact of the construction phase.*

Construction activity	***Construction equipment***	***Reference name in SimaPro***	***GWP$_{100}$***			***Energy***		
			Construction	***Transportation to site***	***Total***	***Construction***	***Transportation to site***	***Total***
			[kg CO_2-eq]	*[kg CO_2-eq]*	*[kg CO_2-eq]*	*[MJ]*	*[MJ]*	*[MJ]*
Excavation for the foundation	30 ton excavator	Excavation, hydraulic digger/RER U	78.8	41	1.20 x 10^{2}	1.19 x 10^{3}	709	1.90 x 10^{3}
	20 ton excavator	Excavation, hydraulic digger/RER U	473	13.7	4.87 x 10^{2}	7.15 x 10^{3}	237	7.39 x 10^{3}
	3 ton machine	Excavation, skid-steer loader/RER U	230	4	2.34 x 10^{2}	3.44 x 10^{3}	67.8	3.51 x 10^{3}
	2 Tractor-Loaders-Backhoes (TLB)	Excavation, skid-steer loader/RER U	766	41	8.07 x 10^{2}	1.15 x 10^{4}	709	1.22 x 10^{4}
Back excavations of vertical sides for working space (battering)	20 ton excavator	Excavation, hydraulic digger/RER U	2440	13.7	2.45 x 10^{3}	3.69 x 10^{4}	237	3.71 x 10^{4}
Earth filling supplied by contractor	Crane	Diesel burned in machine/GLO	446	20	4.66 x 10^{2}	6.71 x 10^{3}	339	7.05 x 10^{3}
Crushed stone for backfill	Crane	Diesel burned in machine/GLO	160	20	1.80 x 10^{2}	2.40 x 10^{3}	339	2.74 x 10^{3}
Crushed stone for backfill: Transport to site	Transport: 10 m^3 truck	Transport, Truck >16t, fleet average/RER U	1100	26.6	1.13 x 10^{3}	1.87 x 10^{4}	452	1.92 x 10^{4}
Waste management: Transport of surplus material to landfill	Transport: 10 m^3 truck	Transport, Truck >16t, fleet average/RER U	4020	26.6	4.05 x 10^{3}	6.82 x 10^{4}	452	6.87 x 10^{4}
Compaction of surfaces	Bomag rollers and plate compactors	Diesel burned in machine/GLO	160	-	1.60 x 10^{2}	2.40 x 10^{3}		2.40 x 10^{3}
Transfer of construction materials within site	Bobcat mini excavator	Diesel burned in machine/GLO	1050	-	1.08 x 10^{3}	1.59 x 10^{4}		1.59 x 10^{4}
Total			**1.09 x 10^{4}**	**2.07 x 10^{2}**	**1.11 x 10^{4}**	**1.74 x 10^{5}**	**3.54 x 10^{3}**	**1.78 x 10^{5}**
Total per m^2			**0.75**	**0.01**	**0.76**	**12.00**	**0.24**	**12.24**

(d) Use phase

The environmental impacts arising from the use phase are 2.86 x 10^3 kg CO_2-eq emissions per year (1.38 x 10^6 MJ per year). This translates to 0.2 kg CO_2-eq/m^2 (0.1 GJ/m^2 per year).
This amount is below the average operational energy values of 0.3 to 1.8 GJ/m^2/year for commercial buildings that were reported previously in ***Figure 2-6***, Chapter 2.
However, it should be noted that the calculated value of 0.1 GJ/m^2/year does not include the actual energy to be used in the maintenance of structural components, computing activities by the building users, lighting of the building, and in the operation of laboratory machinery as there was no record/utility bill available during this study. This information if available would result in a higher operational phase environmental impact.

Due to this data limitation in the use phase, further comparisons of the LCA results will only be carried out for the manufacturing, transportation and construction phases. The initial embodied environmental impact from the manufacturing, transportation and construction phases is discussed in the next sub-section.

(e) Summary

Table 6.14 gives a summary of the various contributions of manufacturing, transportation and construction phases to the initial embodied[50] environmental impact of the building.

Table 6.14: *Contribution of the life-cycle phases to the embodied environmental impact of the building.*

Phase		***GWP$_{100}$***			***Energy***		
		[kg CO_2-eq]	*[kg CO_2-eq/ m^2]*	*% contribution to total emissions/m^2*	*[MJ]*	*[MJ/m^2]*	*% contribution to total energy/m^2*
Materials manufacture		3.19 x 10^6	2.19 x 10^2	94.54%	3.56 x 10^7	2.45 x 10^3	91.34%
Transportation	Materials	1.73 x 10^5	1.19 x 10^1	5.13%	3.19 x 10^6	2.20 x 10^2	8.20%
	Construction equipment	2.07 x 10^2	1.42 x 10^{-2}	0.01%	3.54 x 10^3	2.44 x 10^{-1}	0.01%
Construction		1.09 x 10^4	7.51 x 10^{-1}	0.32%	1.74 x 10^5	1.20 x 10^1	0.45%
Total		**3.37 x 10^6**	**2.32 x 10^2**	**100%**	**3.90 x 10^7**	**2.68 x 10^3**	**100%**

From ***Table 6.14***, the manufacturing phase accounts for 94.5% of the total 232 GWP_{100} per m^2 and 91.3% of the total energy 2.68 x 10^3 MJ/m^2 of the building.

6.2.3.8 *Discussion of the life-cycle impact assessment results*

From the results of the life-cycle impact assessment presented in section 6.2.3.7, the following was established:

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[50] The *initial embodied environmental impact* was defined in Chapter 2 as encompassing the impacts due to: *(i)* resource extraction, *(ii)* manufacturing of raw or recycled materials to produce construction materials, and transportation, and *(iii)* construction works.

(i) The New Engineering Building has an initital embodied environmental impact of 232 kg CO_2-eq/m^2 (2.68 GJ/m^2) as shown in ***Table 6.14***. This value is within the range of initial embodied energy of 1.25 to 16 GJ/m^2 for commercial buildings that was reported in Chapter 2 (***Figure 2-7***). The large variation in initial embodied energy of commercial buildings is due to the fact that different LCA studies include different processes in the LCA system boundary. In addition the unit environmental impact of construction products varies regionally and globally, and depends on e.g. the source of energy, production process implemented etc.

(ii) The manufacture of materials accounts for the majority (91.3%) of the initial embodied energy. Transportation of materials accounts for 8.2%, and the construction phase accounts for 0.46%.

(iii) The application of concrete in massive quantities (14 542 tonnes = 71 % of the total building material mass) results in it having a large share of the total environmental impact from manufacturing and transportation of materials. In ***Table 6.11*** concrete for reinforced and unreinforced concrete applications accounts for 27.5 % of the initial embodied energy, whereas reinforcing steel has the highest contribution at 38.4%. However the order of contribution is reversed with the GWP_{100} indicator. This is because in addition to the energy impact the carbon footprint also accounts for the carbon emissions from materials (e.g. calcination of limestone, which was shown to account for over half of the CO_2-eq emissions generated during cement production (see ***Figure 4-5***)). This difference in results between the two metrics has been previously discussed in Chapter 3.

(iv) The initial embodied environmental impact of the main structural elements (slabs and beams, columns, staircases, shear walls, roof, and foundation) of the building was given in ***Table 6.12***. The results show that the floor slab system contributes the highest value to the building's environmental impact representing 78.55% of the initial embodied energy.

Similar results were shown by Dimoudi and Tompa (2008) and Treloar *et al* (2001). Both studies (see ***Table 6.15***) show the floor slab system representing 27% to 77% of the initial embodied energy.

Table 6.15: *Embodied energy of structural components in the structural frame of concrete buildings.*

Structural component	***NEB (Current study)***		***Dimoudi & Tompa (2008)***				***Treloar et al. (2001)***					
	6 Storey		**5 Storey**		**3 Storey**		**3 Storey**		**7 Storey**		**15 Storey**	
	MJ/m^2	(%)	MJ/m^2	(%)	MJ/m^2	(%)	MJ/m^2	(%)	MJ/m^2	(%)	MJ/m^2	(%)
Beams	-	(-)	116	(6%)	196	(6%)	-	(-)	-	(-)	-	(-)
Columns	5.4	(2.90%)	135	(7%)	98	(3%)	614	(12.2%)	484	(6.9%)	1099	(11.1%)
Upper floors	1469	(78.55%)	675	(35%)	884	(27%)	3107	(61.5%)	5354	(76.7%)	4534	(45.8%)
Staircases	4.4	(0.23%)	19	(1%)	33	(1%)	110	(2.2%)	46.1	(0.7%)	133	(1.3%)
Shear walls	104	(5.58%)	347	(18%)	556	(17%)	-	(-)	-	(-)	-	(-)
External walls	-	(-)	231	(12%)	425	(13%)	785	(15.6%)	658	(9.4%)	2945	(29.8%)
Internal walls	-	(-)	58	(3%)	65	(2%)	432	(8.6%)	433	(6.2%)	1177	(11.9%)
Retaining walls	14.6	(0.78%)	-	(-)	-	(-)	-	(-)	-	(-)	-	(-)
Foundations	222	(11.89%)	212	(11%)	687	(21%)	-	(-)	-	(-)	-	(-)
Roof	1.1	(0.06%)	135	(7%)	327	(10%)	-	(-)	-	(-)	-	(-)
Total MJ/m^2 (%)	**1871**	**(100%)**	**1929**	**(100%)**	**3273**	**(100%)**	**5048**	**(100%)**	**6975**	**(100%)**	**9889**	**(100%)**

These results show the need for the designer to select suitable floor assemblies (e.g. ribbed slab or flat slab) that will reduce the volume of materials used and hence the *initial embodied energy* of the building. Further, according to the references presented in Table 6.15 it is clear that the floor slab system is the one that contributes the majority of environmental impacts, and therefore the calculation of the other components is of a much smaller importance. From practical consideration, it is impossible to ask the structural engineer to optimize each element in the building. Optimization of the slabs only can save a significant amount of environmental impact whereas the impact of the other components of the building is nearly negligible.

Further, the overall environmental impact of the NEB building can be minimized by simultaneously reducing the quantity of materials used in construction of concrete components and by specifying optimum cement system combinations for the different structural systems. This can be achieved by using the proposed framework for design as will be illustrated in the next section.

6.2.4 Optimized design of a 2-way spanning ribbed slab

A floor slab was selected for the optimization problem because the slabs have been shown to have the greatest environmental impact in the NEB. The aim of the optimization problem is to find the geometry and materials specifications for structural components that result in the lowest environmental impact while meeting design requirements for serviceability and safety. To demonstrate this, the study uses the floor slab of the 6th level of the New Engineering building (NEB) (floor plan is attached in Appendix D). The floor slab system utilizes both in-situ RC solid slabs and two–way spanning ribbed slabs supported directly by columns. The use of ribbed slabs in current practice has several sustainability advantages including the savings on the volume of materials used and hence costs in comparison to solid slabs (MacGinley and Choo, 2003). This study attempts to further specify the optimum structural geometry and materials for a ribbed slab in the case study.

The floor slab at level 6 of the building is continuous over 3 equal spans of 6 *m* each. An interior panel of the ribbed slab system is selected for the optimization problem. A plan view of the interior panel is shown in ***Figure 6-4***. The ribbed slab is 2-way spanning as the ratio of the longer side of the slab (l_y) to the shorter side (l_x) is equal to but not greater than 2. The loading on the slab is transferred to the supporting columns in two directions.

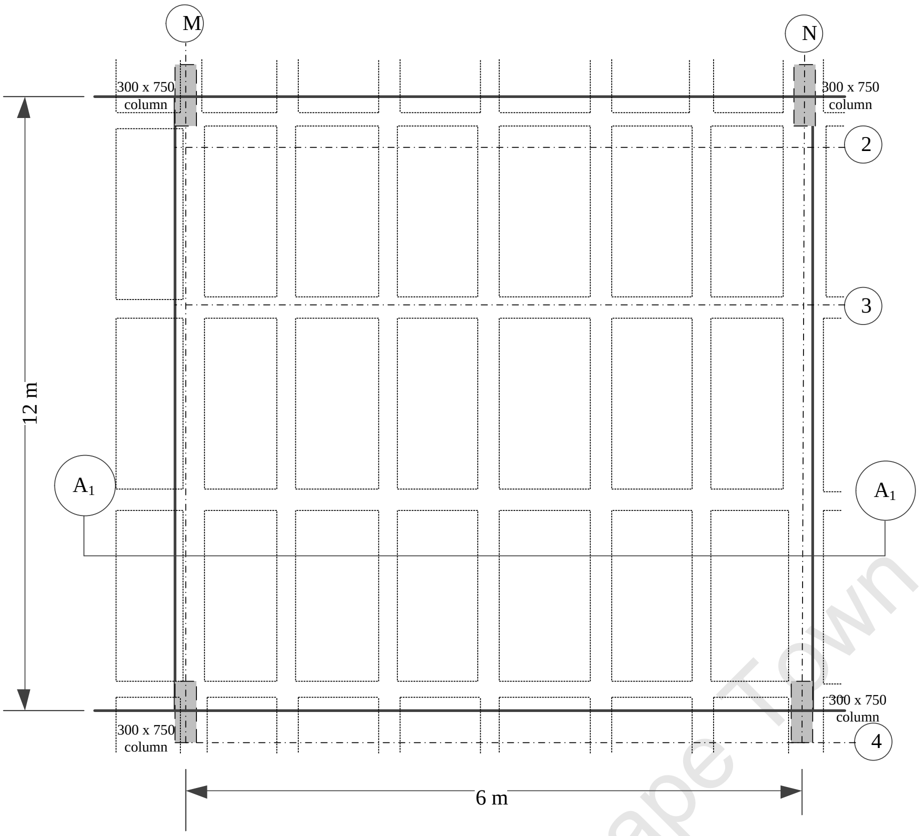

Figure 6-4: *Interior panel of the ribbed floor slab in level 6 of the New Engineering Building (Not to scale).*

A cross-section A_1-A_1 through the slab is given in ***Figure 6-5***. The figure also gives the structural design variables (X_1, X_2, X_3 and X_4) for the optimization problem.

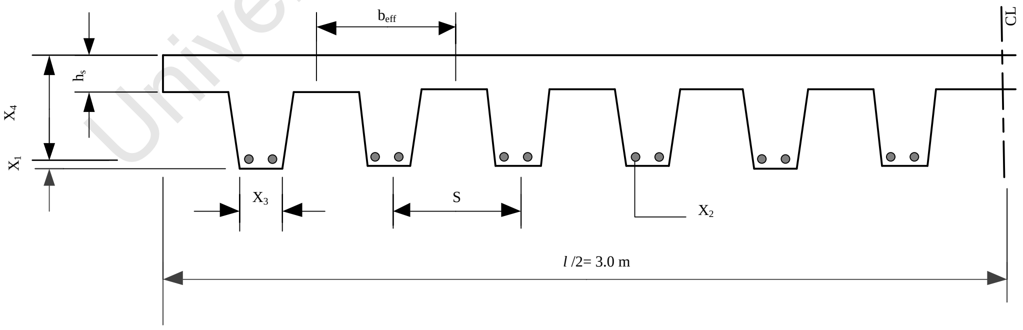

Figure 6-5: *Details of the ribbed slab cross-section A_1-A_1.*

where: X_1 *[mm] :– is the concrete depth (x) to reinforcing steel;* X_2 *[mm^2] :– is the area of compression and tension steel (*A_s*) reinforcement;* X_3 *[mm] :– rib thickness (*b_w*);* X_4 *[mm] :– is the effective depth (d) of the slab;* h_s *[mm] :– is the thickness of the flange;* b_{eff} *[mm] :– effective width of compressive flange (slab); S [mm] :– rib spacing; l [m] = 6 m :– is the effective span of the ribbed slab.*

6.2.5 Design variables

This study utilizes a vector of design variables [**X**] represented as:

$$[\mathrm{X}] = \{X_1, X_2, X_3, X_4, X_5\} = \{x, A_s, b_w, d, w/b,\} \tag{6-1}$$

where, *x* [*mm*] – is the concrete cover depth; A_s [mm^2] – is the area of tension and compression steel reinforcement; b_w [*mm*] – is the thickness of the rib; *d* [*mm*] – is the effective depth of the rib and; *w/b* [-] – is the water/binder ratio of the concrete design mix (which depends on the choice of the binder system). In addition, there are dependent variables describing the resultant material properties represented by vector [**Y**] as follows:

$$[\mathrm{Y}] = \{Y_1, Y_2\} = \{D_a, f_{ck}\} \tag{6-2}$$

where, D_a [m^2/s] – the diffusion coefficient of concrete; and f_{ck} [MPa] – the concrete characteristic compressive strength. The two variables are dependent on the binder system.

6.2.6 Design parameters

Other than the design variables, there are particular design parameters which have an influence on the sustainability of concrete. These design parameters are listed in ***Table 6.16***.

***Table 6.16**: Design parameters.*

Symbol	*Units*	*Name of parameter*	*Value*
b_{eff}	[*mm*]	: Effective width of compressive flange (slab)	see Equation (6-5)
S	[*mm*]	: Clear spacing between ribs	800

6.2.7 Objective function

The optimization problem in this study considers the non-linear objective function $f(X,Y)$ (see Equation (5-22) and Equation (5-23), in Chapter 5) that represents the life-cycle environmental impacts of the structural component. The aim is to select a vector of material variables, [**X**] and [**Y**] (see Equations (6-1) and (6-2), respectively) that gives the minimum environmental impact for the concrete section.

6.2.8 Design constraints

The design constraints relate to the ultimate limit states (ULS) and serviceability limit states (SLS) for reinforced concrete given in EN 1992-1-1: 2004. The constraints include: (i) the ultimate-limit state of bending resistance of the structural component due to gravity loads, (ii) the durability of the structural component in its service environment, (iii) deflection in the member due to service loads. In addition, the optimization problem includes three side constraints: (i) the upper and lower boundaries of the area of steel reinforcement, (ii) the upper and lower boundaries of the geometry of the cross-section of the structural member, and (iii) the upper and lower boundaries for the water content in order to achieve a desired slump in the concrete mix.

6.2.8.1 Bending moment constraint

Slabs are usually subjected to flexural moments and lower magnitudes of shear compared to beams. The flexural moment and shear strength in the 2-way ribbed slab are considered in this study. The study considers the bending moment due to gravity loads. Bending moments due to lateral loads e.g. wind loading, have not been considered in the analysis.

At ULS, the applied bending moment should be less than the yielding moment of the RC slab as expressed by the inequality constraint (C_1) in Equation (6-3).

$$\mathrm{C}_1 \equiv M_{Ed} - M_{Rd} \leq 0 \tag{6-3}$$

where, M_{Rd} [kNm/m] – is the design moment of resistance per rib, and M_{Ed} [kNm/m] – is the maximum bending moment of the ribbed section due to an applied dead load (g_k) and live load (q_k) on the slab.

The M_{Rd} for a ribbed slab section is regarded as that of a reinforced concrete T-section and is evaluated using simplified design formulations derived using the rectangular stress-block shown in *Appendix D*. The final expression for M_{Rd} is derived in *Appendix D* and is given by Equation (6-4).

$$M_{Rd} = 0.85\frac{f_{ck}}{\gamma_m}\left(b_{eff} - b_w\right)h_s\left(d - \frac{h_s}{2}\right) + \lambda_c\frac{0.85 f_{ck}}{\lambda_m}b_w d^2\alpha\left(1 - \frac{\lambda_c\alpha}{2}\right)S \tag{6-4}$$

where,

f_{ck}	[MPa]	:	characteristic compressive cylinder strength of concrete
b_w	[*mm*]	:	width of the web
b_{eff}	[*mm*]	:	effective width of the flange as expressed by Equation (6-5)
h_s	[*mm*]	:	thickness of the flange
α	[-]	:	internal force equilibrium as expressed by Equation (6-6)
λ_c	[-]	:	Relative depth of the compressive concrete zone = 0.8
γ_m	[-]	:	The partial material factor given as 1.5 for concrete
S	[mm]	:	Rib spacing

where,

$$\begin{gathered} b_{eff} \equiv b_w + b_{eff\,1} + b_{eff\,2} \\ b_{eff\,1} = b_{eff\,2} = 0.2\left(\frac{S - b_w}{2}\right) + 0.1(0.7l) \leq 0.2(0.7l) \leq \left(\frac{S - b_w}{2}\right) \end{gathered} \tag{6-5}$$

S, l and b_w are shown in ***Figure 6-5***. Whereas, b_{eff}, b_{eff1} and b_{eff2} are illustrated in ***Figure 4.2*** of *Appendix D*.

$$\alpha = \left(\frac{f_{yk}}{0.66 f_{ck}}\right)\left(\frac{A_s}{\lambda_c b_w d}\right) - \left(b_{eff} - b_w\right)\frac{h_s}{\lambda_c b_w d} \tag{6-6}$$

Detailed calculations of the ultimate design moment, M_{Ed} due to a uniformly distributed live load (q_k) and dead load (g_k) at mid-span of the RC slab are given in *Appendix D*.

6.2.8.2 Shear strength constraint

The shear constraint (C_2) of the slab is given as follows:

$$C_2 \equiv [V_{Rd}] - [V_{Rd,c}] \leq 0 \tag{6-7}$$

where, $V_{Rd,c}$ [kN] – is the design shear resistance;. V_{Rd} [kN] – is the ultimate shear force on a width of slab equal to the distance between ribs. Detailed calculations of $V_{Rd,c}$ and V_{Rd} are given in *Appendix D*.

6.2.8.3 Deflection constraint

For serviceability requirements, there is a need to verify that the slab deflection is within acceptable limits. For this, the span to depth ratio $\left(\frac{l_x}{d}\right)$ is limited as follows (EN 1992-1-1: 2004):

$$C_3 \equiv \frac{l_x}{d} - K\left[11 + 1.5\sqrt{f_{ck}}\,\frac{\sqrt{\rho_o}}{\rho} + 3.2\sqrt{f_{ck}}\left(\frac{\rho_o}{\rho} - 1\right)^{3/2}\right] \leq 0 \tag{6-8}$$

where,

f_{ck}	[MPa]	:	characteristic cylinder compressive strength
K	[-]	:	factor that accounts for support fixity e.g. cantilever, continuous slab etc. For this case $K = 0.104$ (EN 1992-1-1: 2004)
ρ	[-]	:	ratio of tension reinforcement at mid-span and supports to resist moments due to the design loads: $\rho = \frac{A_s}{b_w d}$
ρ_o	[-]		is the reference reinforcement ratio $\rho_0 = 10^{-3}\sqrt{f_{ck}}$
l_x	[m]	:	span of the RC slab in the shorter direction

6.2.8.4 Durability constraint

The reinforcing steel in the floor slab is exposed to a carbonating environment and thus the RC slab is susceptible to carbonation-induced corrosion. However, for illustration, a mild chloride exposure environment corresponding to the class XS1 in EN 206-1:2000 is adopted. The durability of the structural component should be maximized to avoid repair actions on the component during its service-life. This is ensured by applying the durability limit-state Equation (6-9).

$$C_4 \equiv C_{(x,t)} - C_{crit} \leq 0 \tag{6-9}$$

where,

C_{crit}	[% of chlorides by mass of cement]	:	is the threshold value of chloride concentration for corrosion initiation, and is taken as 0.4 % chlorides by mass of cement
$C_{(x,t)}$	[% of chlorides by mass of cement]	:	is the chloride concentration at depth *x* at a given time *t* , and is given by Equation (6-10) which is in turn derived from Fick's second law of diffusion (Collepardi *et al*., 1972).

$$C_{(x,t)} = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D_a t^{(1-m)}}}\right)\right] \tag{6-10}$$

where,

C_s	[% of chlorides by mass of cement]	:	is the chloride concentration at the concrete surface, and is dependent on the service environment
erf	[-]	:	is the mathematical error function
D_a	[m^2/s]	:	is the apparent chloride diffusion coefficient as previously given by Equation (5-9) in Chapter 5.
x	[*mm*]	:	cover to reinforcing steel
t	[years]	:	time of exposure
m	[-]	:	is a reduction factor for chloride diffusion due to chloride binding and is dependent on the type of binder used for the concrete. Based on the work of Mackechnie (1996), m is taken as 0.29 for CEM I and 0.68 for both CEM II and CEM III, assuming they incorporate slag and/or fly ash.

6.2.8.5 *Maximum and minimum bending reinforcement*

In addition, side constraints (C_5 and C_6) in Equation (6-11) and Equation (6-12), respectively, are applied to ensure that the value of A_s in a RC slab is within the minimum ($A_{s,min}$) and maximum area of steel ($A_{s,max}$), respectively, as specified by EN 1992-1-1:2004.

$$\mathrm{C}_5 \equiv A_{s,\min} - A_s \leq 0 \tag{6-11}$$

$$\mathrm{C}_6 \equiv A_s - A_{s,\max} \leq 0 \tag{6-12}$$

where, $A_{s,max}$ is given as 4 % $b_w d$ and $A_{s,min}$ is given as (EN 1992-1-1:2004):

$$\mathrm{A}_{s,\min} = \max\left\{0.26\frac{f_{ctm}}{f_{yk}}b_w d; 0.13\% b_w d\right\} \tag{6-13}$$

where, f_{ctm} [MPa] – is the characteristic mean value of the flexural tensile strength of concrete; f_{yk} [MPa] – is the characteristic strength of steel and; other variables are as previously defined. The design variables, A_s, d and b_w are as illustrated in ***Figure 6-5***;

$A_{s,min}$ minimizes thermal and shrinkage cracking whereas $A_{s,max}$ allows for adequate placing and compaction of concrete around the reinforcement.

6.2.8.6 Geometric constraints

To ensure that the continuous ribbed slab has sufficient torsional stiffness, a series of side constraints ($C_{7\text{-}9}$) are applied to the optimization problem that relate to the standard cross-sectional dimensions of a ribbed slab as expressed by Equations (6-14) (a) to (c). The geometric constraints are adopted from EN 1992-1-1:2004. In addition, the constraint C_{10} represented by Equation (6-14d) ensures that the rib depth is at least the depth of locally available construction moulds.

$$C_7 \equiv \left(\left(d + \frac{\phi}{2} + x\right) - h_s\right) - 4b_w \leq 0 \tag{6-14a}$$

$$C_8 \equiv 1 - \max\left\{\frac{h_s}{50}; \frac{S - b_w}{10}\right\} \leq 0 \tag{6-14b}$$

$$C_9 \equiv S - 1.5 \leq 0 \tag{6-14c}$$

$$C_{10} \equiv 525 - \left(\left(d + \frac{\phi}{2} + x\right) - h_s\right) \leq 0 \tag{6-14d}$$

6.2.9 Results and discussion

This study involves the selection of the optimum cross-section dimensions and concrete mix-design, for the interior panel of a two-way spanning ribbed slab. This involves the minimization of an objective function (see Equation (5-22) and (5-23), in Chapter 5) subject to a set of design constraints (see section 6.2.8) that relate to specific structural and material performance requirements. Due to the non-linear nature of the objective and constraint functions, the optimization problem is solved using a generalized reduced gradient method which is discussed in Appendix C.

Table 6.17 gives optimal values of the design variables at a specified concrete grade of C25/30 concrete made using different binder systems. Also given in ***Table 6.17*** are the design values of the slab using the current structural design procedure given in EN 1992-1-1:2004 and represent the existing design. The material specifications for the existing design of the slab are as previously given in ***Table 6.1*** and summarized again in ***Table 6.17***.

Table 6.17: *Comparison of existing and optimized design variables for the C25/30 RC ribbed slab.*

*Variables [**X**]and [**Y**]*		*Units*	***Existing design of the NEB***	***Optimized designs***			
			CEM I 42.5N: Corex slag (75%:25% PC: CS)	CEM III/A-S 42.5 N (50%:50% PC: GGBS)	CEM II/B-V 42.5 N (70%:30% PC:FA)	CEM II/A-V 52.5 N (80%:20% PC:FA)	CEM I 52.5 N (100% PC)
M_{binder}	Mass of binder	kg/m^3	227	360	377	350	308
M_{water}	Mass of water	L/m^3	172	180	170	175	185
M_a	Mass of aggregates	kg/m^3	1 962	1 856	1 845	1 869	1 906
M_{Ad}	Mass of superplasticizer	L/m^3	1.362	-	-	-	-
b_w	Rib width	mm	150	130	130	130	135
x	Cover depth	mm	30	35	25	30	70
A_c	Cross sectional area of ribbed slab section	m^2	0.15	0.14	0.14	0.14	0.14
A_s	Area of steel required	mm^2/rib	91	99	96	98	106
w/b	Water-to-binder ratio	-	0.76	0.50	0.45	0.50	0.57
f_{ck}	28-day cylinder compressive strength	MPa	25	25	25	26	25
f(X,Y)	**kg CO_2-eq/m^2**		**40**	**29**	**41**	**35**	**42**

The following can be deduced from the results of the optimization problem presented in ***Table 6.17***:

1. The cover depth of the existing design was provided using a ‘deemed-to-satisfy approach’ (see Section 5.2.1, Chapter 5) that requires a minimum cover depth to be provided for a specific exposure class. On the other hand, the optimized design applies a ‘partial safety factor approach’ (see Section 5.2.1, Chapter 5) that utilizes service-life models to specify the minimum cover depths to be provided for a service life of 30 years without repair. The service-life models take into consideration the service environment and the quality of the concrete. Concrete made using CEM I 52.5 N requires the highest cover depth provision of 70 *mm*. The use of fly ash in concrete allows for the provision of lower (~ 60%) cover depths which in turn results in a reduction in the volume of concrete and environmental impact.
2. Although CEM I 42.5N: Corex slag (75% PC: 25% CS) and CEM III/A-S 42.5 N (50% PC: 50% GGBS) have similar binder environmental impacts of 465 kg CO_2-eq/tonne, the latter results in a concrete section with a lower (28%) environmental impact using the proposed optimization process. The optimization process allows for a reduction in the cross-sectional area of structural components based on the strength performance of a binder. The use of the proposed optimization process can assist in selecting appropriate cross-sectional dimensions for a binder system.
3. For the optimized designs, the use of CEM III/A-S 42.5 N leads to the least environmental impact of 29 kg CO_2-eq/m^2 compared to other binder systems. If the proposed optimization process had been applied during the design of the floor slab of the New Engineering building it would have resulted in a 28% reduction in the embodied environmental impact of the building of 159 kg CO_2-eq/m^2 reported in ***Table 6.12***.

6.3 Case study II: Post-tensioned concrete box girder

6.3.1 General description of the highway switch ramp

The second case study is the Elands interchange, located at the N12/N17 intersection in Johannesburg, Gauteng Province, South Africa. The interchange starts at Latitude: 26°12' 47" South; Longitude: 28° 8' 10" East and has a 378 *m* radius horizontal curve. A layout plan of the Elands (N12/N17) interchange is shown in ***Figure 6-6***, and is indicated therein as Loop A.

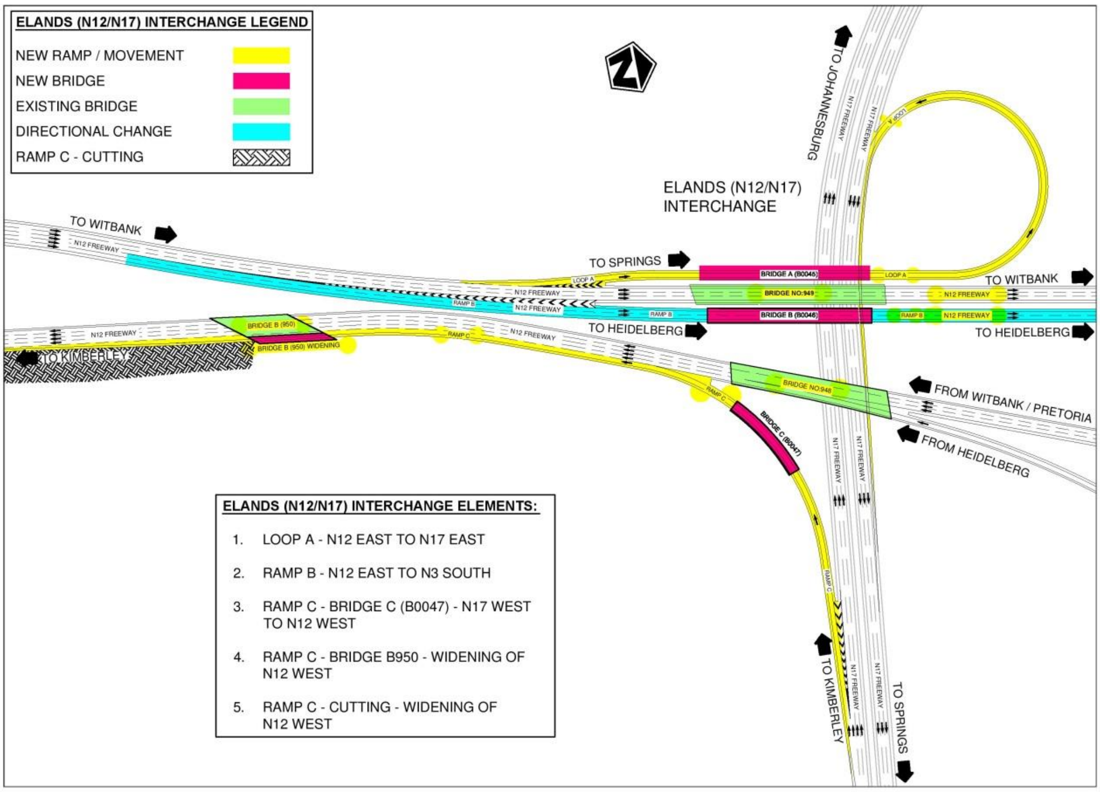

Figure 6-6: *Layout plan of the Elands (N12/N17) interchange (National Roads Authority, 2011).*

6.3.2 Objective of the case study II

The objective of the case study II will be twofold. First a LCA will be made on the overall structure to show the contribution of the various structural components to the overall environmental impact [kg CO_2-eq and MJ] of the highway switch ramp. Secondly, the use of the proposed framework for design of more sustainable concrete structures developed in Chapter 5 will be applied in the re-design of the deck.

6.3.3 Life-cycle assessment of the highway switch ramp

6.3.3.1 *Goal definition and functional unit*

The LCA is performed in accordance with ISO 14040:2006 standard for life-cycle assessment using SimaPro 7.1 LCA software (PRé Consultants, 2008). The scope of the LCA study includes investigating the material and energy resources used by the highway switch ramp over its life-cycle.

A life-cycle inventory of processes and material quantities used in the construction of the highway switch ramp were obtained from the project team[51]. Based on the results of the inventory analysis, an impact assessment was carried out using the GWP_{100} and the energy metric. These metrics have been discussed previously in Chapter 3.

In order to make a comparison between different construction components, a functional unit of 1 *m* of the structure in the longitudinal direction was selected.

6.3.3.2 *System boundary*

The study investigates the cradle-to-gate environmental impacts of the Elands switch ramp. The 'cradle-to-gate' encompasses the raw material extraction and processing phase, and the transportation of materials within the processing plants and to site.

(a) Raw material extraction and processing phase

This includes the quantity of CO_2-eq emissions and energy from: the quarrying of raw materials using e.g. blasting agents; their transportation to and within the processing facilities.

The amount of CO_2-eq emissions and energy from the infrastructure (e.g. machinery in processing plant) and the construction of the manufacturing facility are excluded as they are negligible if located to a unit mass of product.

(b) Transportation phase

An environmental assessment of the transportation phase involves aggregating the amount of CO_2-eq emissions and energy from transportation of raw materials to the construction site.

The inventories of materials used in the LCA are detailed in the following sections.

6.3.3.3 *Inventory of main construction materials and their corresponding environmental impact*

The life-cycle inventory gives a record of material and energy flows used in the highway switch ramp. These data are then used to compute the amount of CO_2-eq emissions and energy for each construction material. The highway switch ramp was principally constructed using post-tensioned concrete for the deck structure and reinforced concrete for the piers, abutments, and pile caps. An inventory of all construction materials was compiled using the Bill of Quantities, which was supplied by the project's quantity surveyors.

6.3.3.3.1 Concrete

The structure was constructed using 9 different mix-designs detailed in ***Table 6.18*** and ***Table 6.19***. From ***Table 6.18***, concrete Mix I and Mix III are used in the abutment and pier foundations and pile caps, whereas Mix II and IV are pump mixes used in piles (Mix II) and in the concrete deck (Mix IV).

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[51] The project team comprised of: (i) the client – SANRAL (South African National Roads Agency); (ii) the Contractors – Group 5 Pty; (iii) the Structural Engineers – Arcus Gibb (Pty); among other material suppliers and sub-contractors.

Table 6.18: *Concrete mix design used for the construction of Elands Interchange.*

Concrete mix-composition		***Units***	*Quantities of materials for 1 m^3 of concrete*			
			Mix I: 30MPa	***Mix II: 30 MPa***	***Mix III: 40 MPa***	***Mix IV: 40 MPa***
Portland cement CEM I 42.5 N		kg/m^3	271	293	331	357
Ground granulated blast furnace slag (GGBS)		kg/m^3	116	126	142	153
Coarse aggregates	19 *mm*	kg/m^3	1045	880	1065	900
Fine aggregates:	Crusher sand	kg/m^3	630	619	548	544
	Filler sand	kg/m^3	155	262	135	230
Water		L/m^3	186	201	189	204
Water reducers (Superplasticizer)		kg/m^3	1.16	1.26	1.42	1.53
Total		**kg/m^3**	**2 404**	**2 382**	**2 411**	**2 390**
w/b ratio		-	0.48	0.48	0.40	0.40
Slump		*mm*	75	90	75	90

CEM I : Portland cement from PPC (Pretoria Portland Cement);
GGBS : Ground granulated blast furnace slag supplied by Slagment (Pty) Ltd;
Coarse aggregates and crusher sand are supplied by Quarry Cats; Admixture supplied by Chryso (Pty) Ltd; Filler sand is a Vaal river sand.

The concrete mixes are CEM I 42.5N: GGBS (70%: 30%) with a maximum *w/b* ratio of 0.40. The fine aggregates are a mix of granite crusher sand and filler sand (Vaal river sand) whereas the ready-mix concrete is supplied by Johannesburg City Afrimix source plant. Additional concrete mixes used in the structure are given in ***Table 6.19***. In ***Table 6.19***, Mix V is used for mass concrete and concrete screed in the foundation.

Table 6.19: *Concrete mix design used for the construction of Elands Interchange.*

Concrete mix-composition		***Units***	*Quantities of materials for 1 m^3 of concrete*				
			Mix V: 15 MPa	***Mix VI: 20 MPa***	***Mix VII: 25 MPa***	***Mix VIII: 30 MPa***	***Mix IX: 35 MPa***
Portland cement CEM I 42.5 N		kg/m^3	170	192	218	244	267
Ground granulated blast furnace slag (GGBS)		kg/m^3	73	82	93	105	115
Coarse aggregates	19 *mm*	kg/m^3	1075	1085	1095	1105	1115
Fine aggregates:	Crusher sand	kg/m^3	711	685	654	621	590
	Filler sand	kg/m^3	174	168	160	152	145
Water		L/m^3	188	186	185	184	184
Water reducers (Superplasticizer)		kg/m^3	0.81	0.92	1.04	1.17	1.28
Total		**kg/m^3**	**2 392**	**2 399**	**2 406**	**2 412**	**2 417**
w/b ratio		-	0.77	0.68	0.60	0.53	0.48
Slump		*mm*	75	75	75	75	75

CEM I : Portland cement from PPC (Pretoria Portland Cement);
GGBS : Ground granulated blast furnace slag supplied by Slagment (Pty) Ltd;
Coarse aggregates and crusher sand are supplied by Quarry Cats; Admixture supplied by Chryso (Pty) Ltd; Filler sand is a Vaal river sand.

The quantity of concrete used in various structural components and its corresponding embodied GWP$_{100}$ and energy are summarized in ***Table 6.20***. Under the column 'Type of concrete', the prefix '*W*' denotes concrete achieving the durability criteria specified for a specific exposure class and using South African concrete durability index tests (Alexander *et al.*, 1999). The first figure after the '*W*' denotes the characteristic 28-day cube strength [MPa] and the second figure denotes the maximum aggregate size [*mm*].

Table 6.20: *Environmental impact of concrete used in structural components.*

Structural component	***Type of concrete*** *[MPa/mm]*		***Quantity*** *[m^3(tons)]*		***GWP$_{100}$*** *[kg CO$_2$-eq]*	***Energy*** *[MJ]*
Abutment and pier foundations and pile cap	W30/19	(Mix I)	792	(1904)	2.72 x 10^{5}	2.03 x 10^{6}
Abutment columns, earwings and approach slab	W30/19	(Mix I)	408	(975)	1.40 x 10^{5}	1.04 x 10^{6}
Piers	W30/19	(Mix I)	763	(1834)	2.64 x 10^{5}	1.96 x 10^{6}
Deck (Box girders)	W40/19	(Mix IV)	3659	(8745)	1.57 x 10^{6}	1.08 x 10^{7}
Prestressing anchor blocks in deck bottom and top slabs (Assumed thickness = 0.935 *m*)	W40/19	(Mix III)	56	(135)	2.27 x 10^{4}	1.61 x 10^{5}
End blocks (4 in number) (Assumed width = 9.63 *m*)	W30/19	(Mix I)	21	(50)	7.15 x 10^{3}	5.33 x 10^{4}
Piles (cast in-situ)	W30/19	(Mix II)	47	(113)	1.72 x 10^{4}	1.24 x 10^{5}
Foundations	15/38	(Mix V)	394	(943)	9.56 x 10^{4}	8.12 x 10^{5}
Foundation (concrete screed)	15/19	(Mix V)	6.62	(16)	1.61 x 10^{3}	1.36 x 10^{4}
Total			**6145**	**(14 715)**	**2.39 x 10^{6}**	**1.70 x 10^{7}**

6.3.3.3.2 *Prestressing steel*

The amount of CO$_2$-eq emissions generated and energy consumed as a result of raw materials extraction and processing of prestressing steel tendons are given in ***Table 6.21***. The prestressing steel used has a characteristic tensile strength of 1860 MPa.

Table 6.21: *Prestressing steel in superstructure.*

Material		***Tensioning force***	***Quantity*** *[tons]*	***Environmental impact***			
				Units	*Raw materials extraction and manufacturing*	*Transportation*	*Total*
Prestressing tendons	Longitudinal tendons in the deck	33 550 MN-m	142	***GWP$_{100}$*** *[kg CO$_2$-eq]*	2.44 x 10^{5}	970	2.45 x 10^{5}
				Energy *[MJ]*	3.96 x 10^{6}	1.68 x 10^{4}	3.98 x 10^{6}

MN-m : megaNewton-metre and is computed as: the product of the characteristic tensile strength in mega Pascal's (MPa) of the prestressing steel, the cross-sectional area of the tendon in square meters and the length of the tendon in meters

6.3.3.3.3 *Reinforcing steel*

The amount of CO$_2$-eq emissions and energy from raw materials extraction and processing of reinforcing steel are given in ***Table 6.22*** and ***Table 6.23***, respectively.

Table 6.22: *GWP$_{100}$ of reinforcing steel in the Elands switch ramp.*

Structural component	***Units***	***Quantity*** *[tons]*	***GWP$_{100}$*** *[kg CO$_2$-eq]*		
			Raw materials extraction and manufacturing	*Transportation*	*Total*
Abutment and pier foundations and pile caps	High yield steel	84	1.24 x 10^{5}	3.21x 10^{2}	1.24 x 10^{5}
Abutment columns, approach slabs and piers	High yield steel	121	1.78 x 10^{5}	4.64 x 10^{2}	1.78 x 10^{5}
Deck	High yield steel	360	5.31 x 10^{5}	1.38 x 10^{3}	5.32 x 10^{5}
Anchor blocks	Mild steel	0.1	1.47 x 10^{2}	0.38 x 10^{0}	1.47 x 10^{2}
	High yield steel	2.0	2.95 x 10^{3}	7.66 x 10^{0}	2.96 x 10^{3}
Piles (cast in-situ)	Mild steel	0.4	5.38 x 10^{2}	1.40 x 10^{0}	5.39 x 10^{2}
	High yield steel	4.2	6.14 x 10^{3}	1.60 x 10^{1}	6.16 x 10^{3}
Total		**572**	**8.42 x 10^{5}**	**1.41 x 10^{3}**	**8.44 x 10^{5}**

Table 6.23: *Energy of reinforcing steel in the Elands switch ramp.*

Structural component	***Units***	***Quantity*** *[tons]*	***Energy*** *[MJ]*		
			Raw materials extraction and manufacturing	*Transportation*	*Total*
Abutment and pier foundations and pile caps	High yield steel	84	1.94 x 10^6	5.55x 10^3	1.95 x 10^6
Abutment columns, approach slabs and piers	High yield steel	121	2.80 x 10^6	8.01 x 10^3	2.81 x 10^6
Deck	High yield steel	360	8.32 x 10^6	2.38 x 10^4	8.34 x 10^6
Anchor blocks	Mild steel	0.1	2.31 x 10^3	6.62 x 10^0	2.32 x 10^3
	High yield steel	2.0	4.62 x 10^4	1.32 x 10^2	4.63 x 10^4
Piles (cast in-situ)	Mild steel	0.4	8.44 x 10^3	2.41 x 10^1	8.46 x 10^3
	High yield steel	4.2	9.63 x 10^4	2.76 x 10^2	9.66 x 10^4
Total		**572**	**1.32 x 10^7**	**3.8 x 10^4**	**1.33 x 10^7**

6.3.3.4 *Inventory of other construction materials and their corresponding environmental impact*

6.3.3.4.1 Surface finish

A 50 *mm* asphalt surfacing was applied on the road pavement. Concrete screed surface finishing was also applied to the concrete structural components. The amount of CO_2-eq emissions and energy from raw materials extraction and processing of the surface finishes are summarized in ***Table 6.24***.

Table 6.24: *Surface finishing.*

Structural component	***Reference in SimaPro software***	***Quantity*** *[m^2 (kg)]*	***GWP_{100}*** *[kg CO_2-eq]*	***Energy*** *[MJ]*
Class F1 finishing				
Abutment and pier foundations	Cement mortar, at plant/CH U	513 (5.13 x 10^4)	9.76 x 10^3	7.85 x 10^4
Abutments columns	Cement mortar, at plant/CH U	441 (4.41 x 10^4)	8.40 x 10^3	6.75 x 10^4
Approach slabs	Cement mortar, at plant/CH U	11 (1.11 x 10^3)	2.10 x 10^2	1.69 x 10^3
Deck	Cement mortar, at plant/CH U	4 324 (4.32 x 10^5)	8.23 x 10^4	6.62 x 10^5
Anchor blocks	Cement mortar, at plant/CH U	60 (6.00 x 10^3)	1.14 x 10^3	9.18 x 10^3
Diaphragms	Cement mortar, at plant/CH U	430 (4.30 x 10^4)	8.18 x 10^3	6.58 x 10^4
Class F2 finishing:				
Piers and pier heads	Cement mortar, at plant/CH U	952 (9.52 x 10^3)	1.81 x 10^4	1.46 x 10^5
Deck sides	Cement mortar, at plant/CH U	2 459 (2.46 x 10^4)	4.68 x 10^4	3.76 x 10^5
Class F3 finishing				
Deck: 50 *mm* asphalt	Bitumen at refinery/ CH U	682 (5.97 x 10^4)	3.47 x 10^4	3.19 x 10^6
Deck: Concrete screed	Mix IX (***Table 6.19***)	682 (8.24 x 10^4)	1.16 x 10^4	8.74 x 10^4
Total			**2.21 x 10^5**	**4.68 x 10^6**

Environmental impact data on cement mortar includes the whole manufacturing process to produce cement mortar (raw material extraction, raw material mixing, packing, and storage), transports to plant and infrastructure.
Thickness of cement mortar is assumed to be 50 *mm*
Density of cement mortar = 2 000 kg/m^3; Density of Asphalt = 1 750 kg/m^3
Surface finishes: F1 – Unexposed surface; F2 – Exposed to view; F3 – End blocks

6.3.3.4.2 Bearings

Table 6.25 gives the embodied GWP_{100} and energy of bearings which are used in transferring the deck loading onto the pier structure while accommodating longitudinal movement of the deck due to thermal effects, creep, and shrinkage deformation.

Table 6.25: *Bearings.*

Component	***Working load capacity***	***Material***	***Reference in Simapro***	***Quantity***	***GWP_{100}*** *[kg CO_2-eq]*	***Energy*** *[MJ]*
Fixed bearing (Fixed pot bearing of 322 kg)	9 100 *kN* *(910 tons)*	Sliding plate	Steel, low-alloyed, at plant/RER	1	554	8.98 x 10^3
		Polytetrafluoro ethylene (PTFE)	Tetrafluoroethylene, at plant/RER U[a]	1	1.81 x 10^4	1.22 x 10^4
		Elastomeric pad	Synthetic rubber, at plant/RER U	1	2.47	85.3

*Continued…**Table 6.25:** Bearings.*

Component	***Working load capacity***	***Material***	***Reference in Simapro***	***Quantity***	***GWP$_{100}$** [kg CO_2-eq]*	***Energy** [MJ]*
Uni-directional bearing (Pot bearing of 1000 *kg*)	2 800 – 12 000 *kN* *(280 -1200 tons)*	Sliding plate	Steel, low-alloyed, at plant/RER	10	1.72×10^4	2.79×10^5
		Elastomeric pad	Synthetic rubber, at plant/RER U	10	1.81×10^3	1.22×10^3
		Polytetrafluoro ethylene (PTFE)	Tetrafluoroethylene, at plant/RER U [a]	10	24.7	853
Multi-directional bearing (Elastomeric bearing)	2 800 – 12 000 *kN* *(280 -1200 tons)*	Neoprene	Synthetic rubber, at plant/RER U	9	22.3	768
Bearing strips 200 *mm* wide		Mild steel (raw materials)	Synthetic rubber, at plant/RER U	5.05 m^2	3.29×10^3	1.13×10^5
Dowels 20 *mm* diameter, 500 *mm* long		Mild steel (manufacturing process)	Steel, low-alloyed, at plant/RER	50 No.	1.06×10^4	1.72×10^5
Plates (Assumed thickness 2 *mm*)		Mild steel	Steel, low-alloyed, at plant/RER	1 No.	14.4	234
Total					$\mathbf{5.17 \times 10^4}$	$\mathbf{5.89 \times 10^5}$

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[a] EcoInvent LCA database list PTFE to being synonymous to tetrafluoroethylene with a carbon footprint of 324 kgCO_2-eq/kg

6.3.3.4.3 Expansion joints

The GWP$_{100}$ and energy from quarrying and processing of raw materials used in the manufacture of expansion joints and filling materials for the deck is given in ***Table 6.26***.

***Table 6.26:** Expansion joints and filling material.*

Material			***Reference in Simapro***	***Quantity***	***GWP$_{100}$** [kg CO_2-eq]*	***Energy** [MJ]*
Modular expansion joint:	160 *mm* movement capacity	Steel	Steel, low-alloyed, at plant/RER/kg	9.6 m	2.61×10^3	4.23×10^4
	240 *mm* movement capacity	Steel	Steel, low-alloyed, at plant/RER/kg	9.6 m	5.87×10^3	9.52×10^4
12 *mm* fibre board filler (60 kg/m^3)		Creosite	Fibreboard hard, at plant/RER U	5.05 m^2	35.4	2.17×10^3
Bituminous sealing (12 *mm* wide x 20 *mm* deep)			Bitumen at refinery/ CH	16.82 m	5.65	509
Total					$\mathbf{8.52 \times 10^3}$	$\mathbf{1.40 \times 10^5}$

6.3.3.4.4 Drainage system

Table 6.27 gives the materials used in the construction of the drainage system, and their corresponding embodied GWP$_{100}$ and energy.

***Table 6.27:** Materials for the drainage system.*

Materials	***Reference in Simapro***	***Quantity***	***GWP$_{100}$** [kg CO_2-eq]*	***Energy** [MJ]*
Ø 100 *mm* pipes at 1000 *mm* c/c	PVC Pipe E	400 No.	3.37×10^3	6.96×10^4
Ø 75 *mm* uPVC[a] drain pipes	PVC Pipe E	7 m	57.9	1.22×10^3
300 *mm* thick concrete channelling total length and on both sides of the Elands switch ramp	Refer to ***Table 6.18*** Class W40/13 concrete	400 No.	778	5.50×10^3
Total			$\mathbf{4.15 \times 10^3}$	$\mathbf{7.63 \times 10^4}$

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[a] PVC: Polyvinyl chloride

6.3.3.4.5 Parapet and barriers

The parapets were constructed from precast concrete and delivered to the construction site where they were assembled. The amount of materials used in the construction of the parapets and barriers is given in ***Table 6.28***. The GWP_{100} and energy from the quarrying and processing of these materials is also given in ***Table 6.28***.

Table 6.28: *Parapets and barriers.*

Material	*Reference in Simapro*	*Quantity*	*GWP_{100} [kg CO_2-eq]*	*Energy [MJ]*
Type A, 2.75 *m* long, mass 2.5 *t*	Concrete block, at plant/DE U	288 No.	8.72×10^4	5.98×10^5
Type B, varying length 2.2. *m* to 3.0 *m*, mass 2.0 *t* to 2.75 *t*	Concrete block, at plant/DE U	4 No.	1.15×10^3	7.89×10^3
Total			$\mathbf{8.83 \times 10^4}$	$\mathbf{6.06 \times 10^5}$

6.3.3.4.6 Excavated material

The amounts of materials excavated from the construction site are given in ***Table 6.29***. The GWP_{100} and energy from their excavation and transportation is also given in ***Table 6.29***.

Table 6.29: *Excavated material.*

Material		*Reference in Simapro*	*Materials [m^3]*	*GWP_{100} [kg CO_2-eq]*	*Energy [MJ]*
Excavation of materials		Clay, at quarry/CH U	4281.36	2.12×10^4	3.21×10^5
Backfill to excavations utilization:	Material from excavation	Clay, at quarry/CH U	1147.85	5.70×10^3	8.60×10^4
	Imported material	Clay, at quarry/CH U	214.2	1.06×10^3	1.60×10^4
Concrete fill to foundation 15/38	(Refer to ***Table 6.19***)		394.2	9.57×10^4	8.12×10^5
Concrete screed filling 15/19	(Refer to ***Table 6.19***)		6.62	1.61×10^3	1.36×10^4
Total				$\mathbf{1.25 \times 10^5}$	$\mathbf{1.25 \times 10^6}$

The amount of energy used during piling and the materials used in piling are given in ***Table 6.30***. The GWP_{100} from their excavation and transportation is also given in ***Table 6.30***.

Table 6.30: *Piling materials.*

Material	*Reference in Simapro*	*Quantity*	*GWP_{100} [kg CO_2-eq]*	*Energy [MJ]*
Bored holes for 1200 *mm* diameter piles (4 No.)	Clay, at quarry/CH U	41.78 m	235	3.54×10^3
Bored piles through 600 *mm* boulders: 1200 *mm* diameter piles	Clay, at quarry/CH U	14.5 m	81.4	1.23×10^3
Socket piles through quartzite/sand rock: 1200 *mm* diameter piles	Sand, at quarry/CH U	4 No.	226	5.47×10^3
Ø 100 *mm* uPVC[a] pipes in bored piles	PVC Pipe E	48.92 m	405	8.51×10^3
Total			**947**	$\mathbf{1.88 \times 10^4}$

[a] PVC –Polyvinyl chloride

6.3.3.5 *Transportation distances*

Data on the transportation distances for materials to and from the construction site are important when considering the "*cradle-to-gate*" phase of the concrete structure. The transportation distances for the materials are given in ***Table 6.31***.

Table 6.31: *Transportation distances for construction materials.*

Transportation of materials		***From:***	***To:***	***One way transportation distance [km]***
(i)	Cement plant to ready-mix plant	Pretoria Portland Cement (PPC) (Pty) Ltd	Afrimix Readymix Concrete (Pty) Ltd	39
(ii)	Coarse aggregates: quarry to ready-mix plant	Quarry Cats (Pty)	Afrimix Readymix Concrete (Pty) Ltd	66
(iii)	Fine aggregates (crusher sand): quarry to ready-mix plant	Quarry Cats (Pty) Ltd.	Afrimix Readymix Concrete (Pty) Ltd	66
(iv)	Fine aggregates (Vaal river sand): gravel pit to ready-mix plant	Vaal river	Afrimix Readymix Concrete (Pty) Ltd	124
(v)	Blast furnace slag: to ready-mix plant	Slagment (Pty) Ltd, Alberton	Afrimix Readymix Concrete (Pty) Ltd	49
(vi)	Superpasticizer: to ready-mix plant	Chryso(Pty) Ltd.	Afrimix Readymix Concrete (Pty) Ltd	16
(vii)	Ready-mix concrete: to site	Afrimix Readymix Concrete (Pty) Ltd	Exits 108A-Geldenhuys	31
(viii)	Prestressing steel to site	Freyssinet Posten, Gauteng	Exits 108A-Geldenhuys	50
(ix)	Reinforcement steel to site	Barnes Reinforcing Industries (Pty) Ltd	Exits 108A-Geldenhuys	28
(x)	Asphalt: from plant to site	Much Asphalt (Pty) Ltd Benoni, Gauteng	Exits 108A-Geldenhuys	29
(xi)	Crushed stone for backfill: to site	-	Exits 108A-Geldenhuys	10
(xii)	Surplus excavated material: to landfill	-	Exits 108A-Geldenhuys	3
(xiii)	Parapet	Precast concrete producers	Exits 108A-Geldenhuys	10

The construction materials were transported using 3.5 – 16 ton trucks. The transportation distances varied between 3 and 124 *km*. Fine and coarse aggregates had the longest transportation distances.

6.3.3.6 Life-cycle assessment results and discussion

The LCA was carried out to show the contribution of various construction materials and structural components on the overall environmental impact of the Elands switch ramp.

6.3.3.6.1 Energy and GWP$_{100}$ for various construction materials

The "*cradle-to-gate*" energy and GWP$_{100}$ for all materials used in the switch ramp are summarized in ***Table 6.32***. In addition, ***Table 6.32*** shows the percentage contribution of the various materials to the total environmental impact.

Table 6.32 *: Total environmental impact of materials used in the construction of the Elands interchange.*

Material	***Description***	***Total mass***[a]	***GWP$_{100}$***		***Energy***	
		[tons]	*[kg CO$_2$-eq]*	*%*	*[MJ]*	*%*
Ready-mix concrete:	30 MPa	4763	6.83×10^5	17.35	5.08×10^6	12.59
	30 MPa (Pump mix)	113	1.72×10^4	0.44	1.24×10^5	0.31
	40 MPa	135	2.35×10^4	0.60	1.61×10^5	0.40
	40 MPa (Pump mix)	8 745	1.57×10^6	39.88	1.08×10^7	26.75
	15 MPa	1921	1.95×10^5	4.95	8.26×10^5	2.04
Precast concrete	Parapets and barriers	-	8.83 x 104	2.24	6.06 x 105	1.50
Cement mortar	Surface finishing	612 004	1.78 x 105	4.52	1.40 x 106	3.47
Asphalt	50 mm	59 679	3.54 x 104	0.90	3.19 x 106	7.90
Concrete screed	35 MPa	82 425	1.16 x 104	0.29	8.74 x 104	0.22

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[a] Data are obtained from the Bill of Quantities supplied by the contractors

*Continued…***Table 6.32** *: Total environmental impact of materials used in the construction of the Elands interchange.*

Material	***Description***	***Total mass[a]***	***GWP_{100}***		***Energy***	
		[tons]	*[kg CO_2-eq]*	*%*	*[MJ]*	*%*
Prestressing tendons	High yield steel	142	2.44 x 10^{5}	6.20	3.98 x 10^{6}	9.86
Reinforcing steel	High yield steel	572	8.26 x 10^{5}	20.98	1.33 x 10^{7}	32.94
Steel sliding bearing plate	Steel, low-alloyed, at plant/RER	0.32	5.54 x 10^{2}	0.01	8.98 x 10^{3}	0.02
Polytetrafluoro ethylene (PTFE)	Tetrafluoroethylene, at plant/RER U		1.81 x 10^{4}	0.46	1.22 x 10^{4}	0.03
Elastomeric pad	Synthetic rubber, at plant/RER U		2.47 x 10^{0}	0.0001	8.53 x 10^{1}	0.00
Steel sliding bearing plate	Steel, low-alloyed, at plant/RER	1000	1.72 x 10^{4}	0.44	2.79 x 10^{5}	0.69
Elastomeric pad	Synthetic rubber, at plant/RER U		1.81 x 10^{3}	0.05	1.22 x 10^{3}	0.00
Polytetrafluoro ethylene (PTFE)	Tetrafluoroethylene, at plant/RER U		2.47 x 10^{1}	0.0006	8.53 x 10^{2}	0.00
Neoprene	Synthetic rubber, at plant/RER U	322	2.23 x 10^{1}	0.0006	7.68 x 10^{2}	0.00
Mild steel	Bearing strips, Dowels and steel plates	-	1.39 x 10^{4}	0.35	2.85 x 10^{5}	0.71
Steel expansion joint	Expansion joint	-	8.48 x 10^{3}	0.22	1.38 x 10^{5}	0.34
Fibreboard	Creosite	-	3.54 x 10^{1}	0.00	2.17 x 10^{3}	0.01
Bituminous sealing	Expansion joint sealant	-	5.65 x 10^{0}	0.0001	5.09 x 10^{2}	0.00
µPVC	Drainage pipes (Ø100 *mm*)	-	3.72 x 10^{3}	0.09	7.81 x 10^{4}	0.19
µPVC	Drainage pipes (Ø75 *mm*)	-	5.79 x 10^{1}	0.0015	1.22 x 10^{3}	0.00
Clay	Excavated materials and Piles	-	3.16 x 10^{2}	0.01	4.77 x 10^{3}	0.01
Quartzite sand	Piles	-	2.26 x 10^{2}	0.01	5.47 x 10^{3}	0.01
Total	**[Environmental impact]**		**3.98 x10^{6}**	**100**	**4.16 x 10^{7}**	**100**
	[Environmental impact per m]		**1.05 x 10^{4}**		**1.20 x 10^{5}**	

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[a] Data are obtained from the Bill of Quantities supplied by the contractors

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Ready-mix concrete contributes to majority of the total 1.05 x 10^{4} GWP_{100}/m at 63%, and 1.20 x 10^{5} MJ/m at 42%.

6.3.3.6.2 *Environmental impact of the main concrete structural components*

The "*cradle-to-gate*" energy and GWP_{100} for the main structural components of the Elands switch ramp are summarized in ***Table 6.33***. The energy and GWP_{100} are for the manufacturing and transportation of the materials for each structural component.

Table 6.33: *Environmental impacts of the structural components.*

Structural component	***Material***	***Quantity*** *[t]*	***Total GWP_{100}*** *[kg CO_2-eq]*	***%***	***Total Energy*** *[MJ]*	***%***
Post-tensioned concrete box girders	Structural concrete	8745	1.57 x 10^{6}	39.46	1.08 x 10^{7}	25.96
	Reinforcing steel	360	5.32 x 10^{5}	13.37	8.34 x 10^{6}	20.05
	Prestressing steel	142	2.45 x 10^{5}	6.16	3.98 x 10^{6}	9.57
	Surface finishing	599	1.75 x 10^{5}	4.40	4.32 x 10^{6}	10.39
Abutment and pier foundations and pile cap	Structural concrete	1904	2.72 x 10^{5}	6.84	2.03 x 10^{6}	4.88
	Reinforcing steel	84	1.24x 10^{5}	3.12	1.95 x 10^{6}	4.69
	Surface finishing	51.3	9.76 x 10^{3}	0.25	7.85 x 10^{4}	0.19
Abutment columns, earwings and approach slab	Structural concrete	975	1.40 x 10^{5}	3.52	1.04 x 10^{6}	2.50
	Reinforcing steel	121	1.78 x 10^{5}	4.47	2.81 x 10^{6}	6.76
	Surface finishing	88.2	1.68 x 10^{4}	0.42	1.35 x 10^{5}	0.32
Piers	Structural concrete	1834	2.64 x 10^{5}	6.64	1.96 x 10^{6}	4.71
	Surface finishing	9.52	1.81 x 10^{4}	0.45	1.46 x 10^{5}	0.35
Anchorage blocks	Structural concrete	135	2.27 x 104	0.57	1.61 x 105	0.39
	Reinforcing steel –mild steel	0.1	1.47 x 102	0.00	2.32 x 103	0.01
	Reinforcing steel –high yield steel	2.0	2.96 x 103	0.07	4.63 x 104	0.11
	Surface finishing	6	1.14 x 103	0.03	9.18 x 103	0.02

*Continued… **Table 6.33:** Environmental impacts of the structural components.*

Structural component	***Material***	***Quantity*** *[t]*	***Total GWP$_{100}$*** *[kg CO$_2$-eq]*	***%***	***Total Energy*** *[MJ]*	***%***
Anchorage blocks	Structural concrete	135	2.27×10^4	0.57	1.61×10^5	0.39
	Reinforcing steel –mild steel	0.1	1.47×10^2	0.00	2.32×10^3	0.01
	Reinforcing steel –high yield steel	2.0	2.96×10^3	0.07	4.63×10^4	0.11
	Surface finishing	6	1.14×10^3	0.03	9.18×10^3	0.02
Piles (cast in-situ)	Structural concrete	113	1.72×10^4	0.43	1.24×10^5	0.30
	Reinforcing steel –mild steel	0.4	5.39×10^2	0.01	8.46×10^3	0.02
	Reinforcing steel –high yield steel	4.2	6.16×10^3	0.15	9.66×10^4	0.23
	Piling materials for excavation (see Table 6.30)	-	947	0.02	1.88×10^4	0.05
Foundations	Structural concrete	943	9.56×10^4	2.40	8.12×10^5	1.95
	Concrete screed	16	1.61×10^3	0.04	1.36×10^4	0.03
	Excavated materials and backfill	10552	1.25×10^5	3.14	1.25×10^6	3.01
Box girder equipment:	Bearings	17.9	5.17×10^4	1.30	5.89×10^5	1.42
	Expansion joints & filler	5	8.52×10^3	0.21	1.40×10^5	0.34
	Drainage system	5.7	4.15×10^3	0.10	7.63×10^4	0.18
	Parapets and barriers	730	8.83×10^4	2.22	6.06×10^5	1.46
	End blocks	50	7.15×10^3	0.18	5.33×10^4	0.13
Total	**[Environmental impact]**		**3.98×10^6**	**100**	**4.16×10^7**	**100**
	[Environmental impact per deck m]		**1.05×10^4**		**1.20×10^5**	

From ***Table 6.33***, the majority of the environmental impacts are from the concrete box girder which accounts for approximately 63 % of the overall cradle-to-gate environmental impacts of 1.05×10^4 kg CO$_2$-eq/m and 66 % of 1.20×10^5 MJ/m.

Using a functional unit of *weight (kg)* of a material, the ready-mix concrete for the box girders had an environment impact of 0.18 kg CO$_2$-eq/kg. These results are slightly lower than those of Dennison and Maddox (2002) (*as cited in* Martin (2004)) who carried out a comparative LCA of a steel-concrete composite, and a post-tensioned concrete box girder by considering the greenhouse gas emissions associated with the materials proposed for their construction. In their study, they found that the concrete component of the post-tensioned concrete deck, made using 100% Portland cement concrete, produced 0.22 kg CO$_2$-eq emissions/kg. In the same study by Dennison and Maddox (2002), the prestressing and reinforcement steel in a post-tensioned concrete box girder had an environmental impact of 2.82 kg CO$_2$-eq/kg. This value is also higher than that of this study which found the prestressing and reinforcing steel to have an environmental impact of 1.55 kg CO$_2$-eq/kg.

Since the LCA results in this study show that the concrete box girder has the highest environmental impact compared to other structural elements, the next section demonstrates a design optimization of the post-tensioned concrete box girder using the proposed design framework in Chapter 5.

6.3.4 Design optimization of the post-tensioned concrete box girder

6.3.4.1 Problem statement

The Elands switch ramp consists of nine spans with their lengths varying from 30 *m* (Span 1) to 70 *m* (Span 7). The entire switch ramp consists of 18 single-cell internally post-tensioned concrete box girders. The box girder in its entirety is considered an integral bridge component as it contributes to 63% of the overall cradle-to-gate environmental impacts (Section 6.3.3.6.2). The focus of the case study will be on the design optimization of the cross-sectional geometry and materials for the box girder in order to reduce the structure's environmental impact.

Each box girder comprises of the following distinct structural components (Shushkewich, 1988): (i) cantilevers, (ii) top flange between the webs, (iii) bottom flange, and (iv) web walls. Details of the existing design of a box girder cross-section in the mid-span of Span 1 are given in ***Table 6.34***.

Table 6.34: *Geometric properties of a box-girder cross-section as per existing design.*

Details of structural component	***Notation***	***Dimension in existing design***
Thickness of top flange	t_{tf}	$225^{\#}$ *mm*
Thickness of bottom flange	t_{bf}	200 *mm*
Thickness of web	t_w	500 *mm*
Width of top flange	b_{tf}	9630 *mm*
Exterior width of bottom flange	b_{bf}	4500 *mm*
Length of cantilever overhang	l_c	2215 *mm*
Overall depth of box girder	H	3545 *mm*
Cross-sectional area of concrete of the entire box girder	A_c	7.9×10^6 mm^2
Distance from the neutral axis to the bottom fibre	y_b	2324 *mm*
Distance from the neutral axis to the top fibre	y_t	1221 *mm*
Second moment of area about the neutral axis (Uncracked section)	I_{yy}	1.2×10^{13} mm^4
Section modulus of top fibre	Z_t	5.2×10^9 mm^3
Section modulus of bottom fibre	Z_b	9.8×10^9 mm^3

[#] The thickness of the deck varies from 225 *mm* to 480 *mm*, however for simplification in the optimization problem, the deck is assumed to be of uniform cross-section.
The equations used in calculating the cross-sectional properties of the box girder section are given in Appendix D

Further, the cross-section geometry of a typical concrete box girder is illustrated in ***Figure 6-7***. The notations used in ***Figure 6-7*** are defined in ***Table 6.34***.

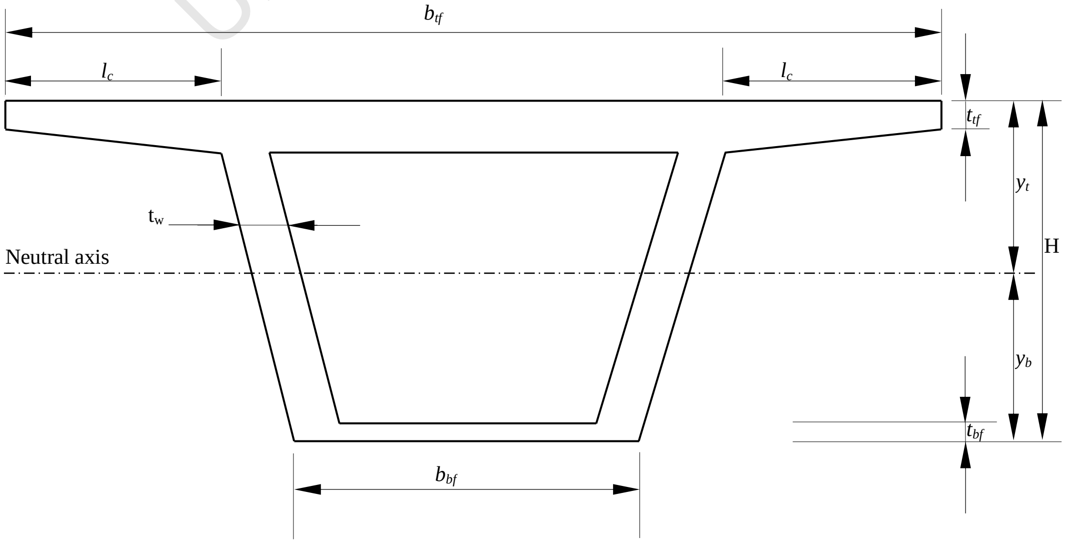

Figure 6-7: *Typical cross-section of a single-cell concrete box girder.*

For a transverse analysis, the box girder is idealized as a plane frame as shown in ***Figure 6-8***. The plane frame is assumed to be supported at the junction of the web walls and bottom slab. A unit length of the cross section is considered in the analysis of the loading on the box girder.

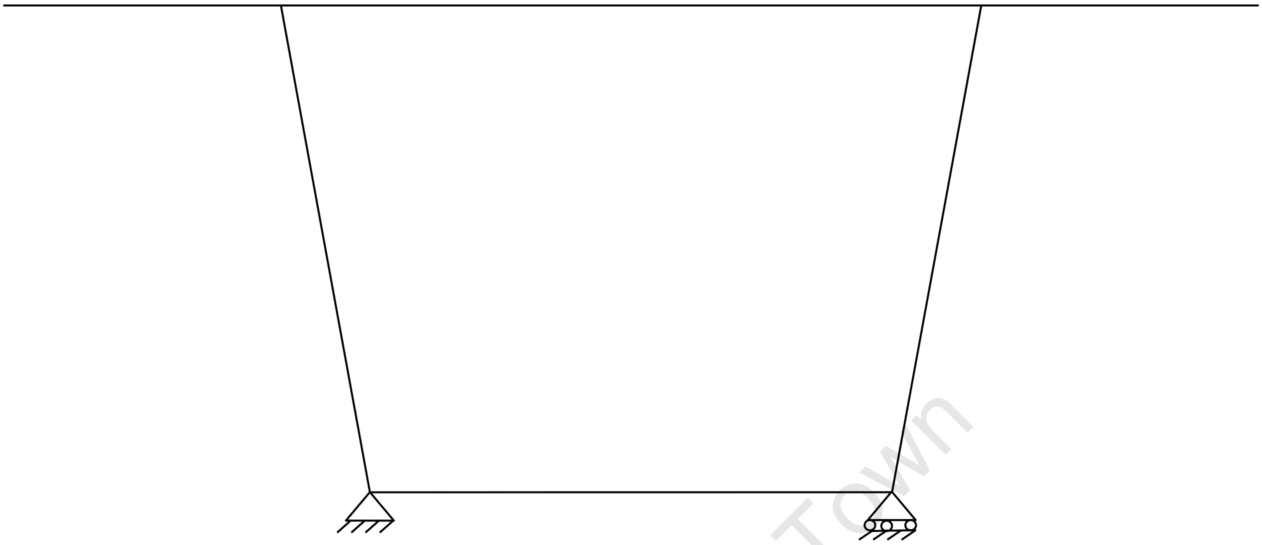

Figure 6-8: *One-dimension plane frame idealization of a box-girder.*

The maximum moments and shears due to traffic loading, dead weight and superimposed loading on the box girder are analysed in Appendix D. ***Figure 6-9*** gives a transverse section of the box girder as modelled using MIDAS/Civil (2014) software.

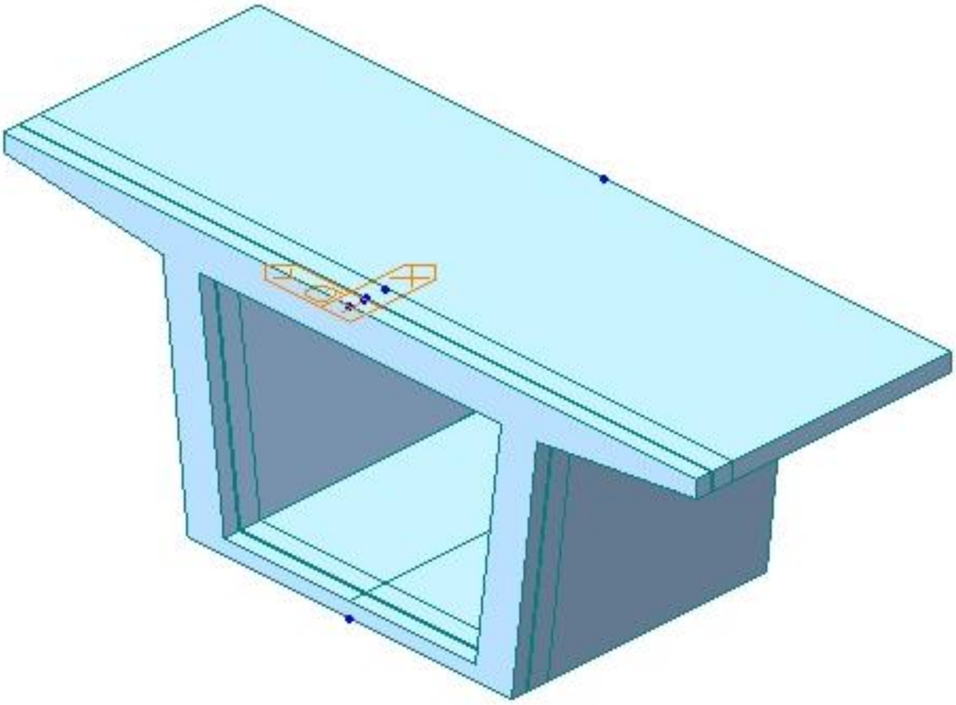

Figure 6-9: *Transverse section of a single segment of the box girder using MIDAS/Civil software.*

6.3.4.2 Design variables and parameters

(a) Design variables

The design variables [**X**] and response variables [**Y**] for the optimization problem are given in ***Table 6.35***. They include: concrete properties and composition (f_{ck}, water and binder content); the box girder geometry (t_{tf}, x); and the area of prestressing steel (A_p).

Table 6.35: *Design variables for the optimization problem.*

Symbol	***Notation***	***Units***	***Comment***
x	X_1	*mm*	Thickness of the concrete cover
A_p	X_2	-	Cross-sectional area of prestressing steel
t_{tf}	X_3	*mm*	Thickness of the upper flange (deck)
w/b	X_4	-	Water-to-binder ratio
f_{ck}	Y_1	MPa	Compressive cylinder strength at 28-days
f_{ci}	Y_2	MPa	Compressive cylinder strength at 7-days

(b) Design parameters

Table 6.36 lists the material and section properties that are included in the optimization problem for the box girder section.

Table 6.36*: Material and section properties of the post-tensioned box girder.*

Symbol	***Units***	***Name of parameter***	***Value***
f_{pu}	MPa	Ultimate tensile strength of prestressing steel (Low relaxation strands)	1 860
f_{py}	MPa	Yield strength of prestressing steel (0.9 f_{pu})	1 674
Ø	*mm*	Diameter of one strand	15.7
E_p	GPa	Modulus of elasticity of strands	195
γ_c	kg/m^3	Unit weight of concrete	varies with each mix-design composition
γ_p	kg/m^3	Unit weight of the steel tendons	7 850
A_p	*mm^2*	Cross-sectional area of a prestressing strand	150

6.3.4.3 Objective function

The objective function for the material and structural optimization of the deck of a post-tensioned concrete box girder, with respect to its life-cycle environmental impact, is defined by Equation (6-15). The Equation (6-15) gives the cradle-to-gate environmental impact of the deck as a function of structural materials (concrete and prestressing steel tendons).

$$\min\{f(X,Y)\} = \rho_{ps} A_p Env_p + A_c Env_{concrete} \tag{6-15}$$

where,

X, Y : vector of material design variables and response variables (in Equation (6-15) which optimize the value of the objective function

A_p [mm^2] : area of prestressing steel

A_c [mm^2] : total cross-sectional area of the box girder section

ρ_{ps}	[kg/m^3]	:	density of prestressing strand
Env_p	[kg CO$_2$-eq/kg]	:	unit environmental impacts of prestressing strand per unit weight
$Env_{Concrete}$	[kg CO$_2$-eq/m^3]	:	unit environmental impacts of concrete per unit volume as given by Equation (5-24) (Chapter 5).

6.3.4.4 Design constraints

The design constraints under consideration are given in ***Table 6.37*** and are formulated in accordance with the requirements of EN 1992-1-1:2004 with respect to the ultimate- and serviceability-limit-states of a RC structure. The first and second constraints in ***Table 6.37*** are limit-state equations for the bending moment, and shear strength, respectively. The third to sixth constraints in ***Table 6.37*** relate to the maximum permissible stresses in post-tensioned concrete at transfer and when in service. The last constraint relates to limits on the deflection in a box-girder section.

Table 6.37: *Main limit-state criteria for a post-tensioned concrete deck.*

	Constraint	***Limit-state function***
(i)	Bending moment	$M_{Rd} - M_{Ed} \leq 0$
(ii)	Shear strength	$V_{Rd} - V_{Ed} \leq 0$
(iii)	Permissible top fibre stress at transfer (f_{tt}) Stress in concrete due to applied loading ($f_{applied}$)	$f_{tt} - f_{applied} \leq 0$
(iv)	Permissible top fibre stress under service loads (f_{tw})	$f_{applied} - f_{tw} \leq 0$
(v)	Permissible bottom fibre stress at transfer (f_{bt})	$f_{applied} - f_{bt} \leq 0$
(vi)	Permissible bottom fibre stress under service loads (f_{bw})	$f_{bw} - f_{applied} \leq 0$
(vii)	Deflection limit	$\delta - \frac{l}{500} \leq 0$

6.3.4.4.1 Bending moment constraint

The direct loading of the deck slab during its design life, includes dead load, live (traffic) loading, environmental loads (wind, earthquake), and others (braking and accelerating load). This study only considers the dead and live loading on the deck slab. The loading on the deck causes bending moments (M_{Ed}). A bending moment constraint, C$_1$, represented by Equation (6-16) is applied to ensure that M_{Ed} is within the flexural capacity of the deck.

$$C_1 \equiv [M_{Ed}] - [M_{Rd}] \leq 0 \tag{6-16}$$

where, M_{Rd} [kNm/m] – is the resistance moment of the concrete section, and M_{Ed} [kNm/m] – is the bending moment due to the design dead load and live loading on the deck.

Detailed calculations of M_{Rd} and M_{Ed} are given in *Appendix D.*

6.3.4.4.2 Shear strength constraint

The design constraint (C$_2$) for shear strength of the deck is given as:

$$C_2 \equiv [V_{Rd}] - [V_{Rd,c}] \leq 0 \tag{6-17}$$

where, $V_{Rd,c}$ [kN/mm^2] – is the design shear resistance; V_{Rd} [kN] – is the applied shear. Detailed calculations of $V_{Rd,c}$ and V_{Rd} are given in *Appendix D.*

6.3.4.4.3 Concrete allowable stress

To control cracking in prestressed concrete, the net stress at the top and bottom concrete fibre should not exceed an allowable value at transfer of the prestress (f_{tt} and f_{bt}), and under service loads (f_{tw} and f_{bw}) as expressed by Equations (6-18) to (6-19), respectively (EN 1992-1-1:2004; Clause 5.10.2.2).

$$C_3 \equiv f_{tt} - \left[\frac{P_o}{A_c} - \frac{P_o e}{Z_t} - \frac{M_g}{Z_t}\right] \leq 0 \tag{6-18}$$

$$C_4 \equiv f_{bw} - \left[\frac{\eta P_o}{A_c} + \frac{\eta P_o e}{Z_t} - \frac{M_s}{Z_t}\right] \leq 0 \tag{6-19}$$

$$C_5 \equiv \left[\frac{P_o}{A_c} + \frac{P_o e}{Z_b} - \frac{M_g}{Z_b}\right] - f_{bt} \leq 0 \tag{6-20}$$

$$C_6 \equiv \left[\frac{\eta P_o}{A_c} - \frac{\eta P_o e}{Z_t} + \frac{M_s}{Z_t}\right] - f_{tw} \leq 0 \tag{6-21}$$

where, P_0 [kN] – is the initial prestress force ($0.7 f_{pu} A_{ps}$); A_c [mm^2] – is the cross-sectional area of the concrete section; e [mm] – is the eccentric distance between the prestressing tendons and a members' neutral axis; Z_b and Z_t are the section moduli; η [-] – is a loss factor that accounts for prestress losses, is taken here as 0.8 by assuming 20% losses (10% initial losses, 5% creep, 2% shrinkage, 3% prestressing steel relaxation) (*adopted from*: Mosley *et al.*, 2007); M_g [Nmm] – is the moment at transfer due to the self-weight of the concrete and superimposed loading on the structure (see Appendix D); M_s [Nmm] – is the total applied moment and is due to the self-weight of the concrete, the superimposed load, and live loading on the structure (see Appendix D).

6.3.4.5 *Durability constraint*

The post-tensioned box girder is located in a mild-exposure carbonating environment which corresponds to exposure class, XC1 in EN 206-1:2000 environmental exposure classifications. However, for illustration, a mild chloride exposure environment corresponding to the class XS1 in EN 206-1:2000 is adopted. As such the durability constraint (Equation (6-9)) that was used in the New Engineering building optimization problem, is applied for this case also.

6.3.4.6 Deflection constraint

For serviceability requirements, there is a need to verify that the deck deflection is within acceptable limits. For this, the span-to-depth ratio (δ) is limited as follows (EN 1992-1-1 Expression 7.16a):

$$\mathrm{C}_7 \equiv \delta - \frac{l}{500} \leq 0 \tag{6-22}$$

6.3.4.6.1 Geometric constraints

The side constraints (C_{11}) expressed by Equation (6-23), is applied to ensure that the deck thickness is in accordance with the design criteria given by EN 1992-1-1:2004. l_c is the length of the cantilever at the top flange of a box girder.

$$\mathrm{C}_8 \equiv t_{tf} = 0.1 l_c \leq 0 \tag{6-23a}$$

6.3.5 Results and discussion

This study aims at selecting the optimum binder type, thickness, and area of prestressing steel for the top deck of a post-tensioned box girder. This involves the minimization of an objective function (Equation (6-15)) subject to a set of design constraints (*see section 6.3.4.4*) that are formulated based on the design requirements of EN 1992-1-1. Due to the non-linear nature of the objective and constraint functions, the optimization problem is solved using a generalized reduced gradient method which is discussed in Appendix C.

Table 6.38 gives a comparison of the optimized design for different binder types that can be used in the production of grade C25/30 concrete for the deck of the box-girder.

Table 6.38: *Optimized design variables for the post-tensioned concrete deck.*

Variables [X]and [Y]		***Notation***	***Units***	***Optimized design variables***		
				CEM I 42.5 N (100 % PC)	CEM III/A-S 42.5 N (50%:50% PC:GGBS)	CEM II/B-V 52.5 N (70%:30% PC:FA)
x	Thickness of the concrete cover	X_1	*mm*	60	20	25
A_{ps}	Area of prestressing steel	X_2	*mm²*	8 518	7 163	7 937
t_{tf}	Thickness of the upper flange (deck)	X_3	*mm*	227	244	212
w/b	Water-to-binder ratio	X_4	-	0.5	0.4	0.45
f_{ck}	Compressive cylinder strength at 28-days	Y_1	MPa	32	32	30
f_{ci}	Compressive cylinder strength at 7-days	Y_2	MPa	25	25	25
M_{binder}	Mass of binder	-	*kg/m³*	360	335	356
M_{water}	Mass of water	-	*kg/m³*	180	135	160
M_a	Mass of aggregates	-	*kg/m³*	2 389	2 309	2 055
f(X,Y)		*[kg CO_2-eq/m]*		**896**	**652**	**714**

From the results of the optimization problem, it can be observed that the optimum top flange thicknesses and corresponding area of prestressing steel are different for the selected binder combinations. The optimum deck thickness ranges from 212 *mm* to 227 *mm* with concrete made using CEM III/A-S 42.5 N having the lowest value. Concrete made using the same binder also has the lowest cradle-to-gate environmental impact of 652 kg CO_2-eq/m. This indicates that it is necessary to select the appropriate binder combination that will lead to reduced cross-sections and volumes of concrete required and hence different environmental impacts per unit length of the box-girder. The use of CEM III/A-S 42.5 N for the construction of the box girder leads to a 27 % reduction in the environmental impact/m of the box girder compared to CEM I 42.5 N.

6.4 Summary

Firstly, this study carried out an LCA on two local (South African) case studies: the New Engineering building (NEB) at the University of Cape Town, and the Elands interchange in Gauteng province, South Africa. The LCA on both case studies considered the energy use and greenhouse gas emissions associated with the cradle-to-gate phases of the two structures.

The LCA results on the NEB, which is a reinforced concrete-framed building, showed the floor slab system to contribute the highest value to the building's environmental impact representing 78.55 % of the embodied environmental impact of 159 kg CO_2-eq/m^2. The LCA of the Elands interchange covered cradle-to-gate environmental impacts of all the structural components of the interchange, including the precast concrete box girders, prestressing anchor blocks, end blocks, and the substructure abutment, pier and foundation piles. The majority of the environmental impacts were from the concrete box girders which accounted for approximately 63 % of the overall cradle-to-gate environmental impacts of 1.09×10^3 kg CO_2-eq/m and 66 % of the 1.14×10^4 MJ/m.

Secondly, structural components contributing the highest to the overall environmental impact of the two case studies were selected for design using the proposed optimization procedure presented in Chapter 5. These were the RC ribbed concrete floor slab of a building and the post-tensioned concrete box girder. Using these two structural elements, this study investigated the optimum design variables that would lead to more sustainable concrete structures. The design variables included the cross-sectional geometry, area of steel and concrete properties such as diffusivity and compressive strength. An optimization algorithm was used to establish the global minimum of an objective function with several constraints. The influence of the use of different binder combinations was studied.

This study showed that if the proposed optimization process had been applied during the design of the floor slab of the New Engineering building it would have resulted in a 28% reduction in the embodied environmental impact of the building of 159 kg CO_2-eq/m^2 reported

The proposed optimization problem for both case studies showed the importance of selecting an appropriate binder combination, as it can lead to a reduction in cross-sectional geometry and hence reduced environmental impacts.

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The project team for case study I: New Engineering Building comprised of the following:

	Name	*Team*	*Affiliation*
1.	Charles Croeser	Project manager	Msingi Project Managers
2.	Louis Langenhoven	Site quantity surveyor	Filcon
3.	Michael Wentworth	Architects	SAOTA Architects
4.	Richard Klein	-	AfriSam Ready-mix lab
5.	Daniel Allen	Quantity surveyor	LDM Quantity Surveyors (Pty)
6.	Keith Forword	-	Clay tile
7.	Eder Vardenega	-	Cotto Possagno

The project team for case study II: Elands Interchange comprised of the following:

	Name	*Team*	*Affiliation*
1.	Toni Niemand and Dave Thurlow	Contractors	Group 5 Pty
2.	Arthur Vanderstraeten	Structural Engineer	Arcus Gibb Pty
3.	Dale Milner	Quantity surveyor	Group 5 Pty
4.	Nicola Ebersohn	Quality control	Group 5 Pty
5.	Phillip Louw	Project manager	
6.	Mandy Lukan	Materials procurement	
7.	Marianne Smit / Dave Thurlow	Construction equipment	

Chapter 7

7 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 Conclusions

The global demand for engineering materials[52] quadrupled between 1960 and 2005 (Allwood *et al*., 2011). This growing consumption of materials has been increasingly driven by population growth and the need for economic development, and has raised questions regarding the sustenance of the dynamic equilibrium within the ecosystems due to issues such as environmental degradation (resource depletion, deforestation, pollution) (Goodland, 1995). Sustainable development recognizes the need to preserve natural ecosystems that humanity is so dependent on by using natural resources with greater efficiency and controlling pollution. Through sustainable development, the promotion of human well-being does not have to depend on the destruction of nature but is carried out within the ecological capacity of the earth. This study developed a framework for design that aims to bring about energy and resource efficiency in the concrete construction industry and hence enable "sustainable development" within the industry. By applying the framework, the designer of a reinforced concrete (RC) structure can explicitly address rational, quantitative design considerations regarding the sustainability of a RC structure over its life-cycle.

In addition, the following work which was part of the objectives of this study was attained:

1) The study showed the adaptability of the novel framework to a range of infrastructure applications by testing it on two diverse case studies: (i) a highway switch ramp and (ii) a building structure.
2) A state-of-the-art literature review that: (i) gave a working definition of the term "sustainable concrete structure", and (ii) recommended suitable single-score metrics for measuring quantitatively the sustainability of concrete structures.
3) An environmental impact assessment of S.A's cement and concrete industry that established S.A's global ranking in the growing trends of environmental pressures due to increasing resource consumption and waste generation of the global construction industry. The output of this assessment was to show the main processes and/or products that label the concrete industry unsustainable. The study was able to determine the contribution of the key players in the cement and concrete industry in lowering its' environmental impact.

The following subsections (7.1.1 to 7.1.4) give a summary of the results of this study.

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[52] Engineering materials are those used to construct buildings, infrastructure and equipment such as cement, steel, aluminium and thermoplastics.

7.1.1 Suitable metric for environmental sustainability

The worldwide consumption of concrete has been estimated to be increasing gradually from 6.4 billion m^3 in 1997 (Aïtcin, 2000) to about 8 billion m^3 in 2009 (CEMBUREAU, 2009). The latter estimate translates to approximately 3 tonnes per capita making concrete the most widely used material on earth. There is an escalating burden on the environment associated with this massive use of concrete. This study found it essential to identify a suitable ‘single-score’ measure for evaluating the use of different non-renewable and renewable materials and energy resources by RC structures relative to the availability of these resources in the physical environment. A ‘single-score’ metric represents a variety of environmental impacts and eliminates the difficulty and complexity of combining a number of environmental impact categories such as ‘mineral resource depletion’ and ‘fossil fuel depletion’. A ‘single-score’ metric would be useful for decision making and allow for the selection of more sustainable concrete constituent materials and production processes. However, it should be noted that in the overall material selection process, other effects such as ecotoxicity should be checked.

It was mentioned in Chapter 3 that an appropriate metric[53] should be integrated into the existing life-cycle assessment procedure (ISO 14040: 2006; ISO 14044: 2006) for assessing environmental aspects of products and processes. In addition, the proposed metric should be founded on scientific principles. This means that the metric should quantify life-cycle environmental impacts of materials in physical units and should give consistent results, independent of time and place, i.e. it should not be prone to inflation or other factors. As such, this study used five concrete mix-designs to examine the applicability of three metrics: carbon footprint, energy and exergy, in decision making. A carbon footprint is a life-cyle assessment (LCA) with the analysis limited to emissions that have an effect on the global warming potential. It gives the amount of equivalent carbon dioxide emissions that is accumulated over the life stages of a product. Energy is a measure of the gross amount of energy requirements of a product, whereas exergy is a measure of the potential for carrying out work contained in a material (i.e. its potential to cause changes to the surrounding environment). The

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[53] This study notes that environmental impacts related to the use of concrete in construction are not limited to resource consumption and carbon emissions but may include acidification and loss of arable/forest land. For example, aggregate extraction and processing may lead to: (i) Loss of land used for other competing land uses such as human settlement and agriculture and; (ii) Environmental damage in the form of resource depletion and loss of bio-diversity due to the consumption of renewable and non-renewable resources e.g. water and minerals respectively. In addition, cement contains alkaline ingredients such as lime and trace constituents such as chromium, derived from the clay and shale, which cause ecotoxicity. However, for simplification in the optimization problem presented in Chapter 5, this study selected a single mid-point metric that is representative of a variety of environmental impacts of concrete that occur over its life-cycle.

exergy metric is interpreted as an assessment of the ‘quantity’ (energy and mass) and ‘quality’ (environmental impact due to use of energy and matter) of resources.

Using the three single-score metrics, the environmental impact of five concrete mixes were assessed and compared to show the effects of:

- replacing natural aggregates with recycled aggregates,
- using supplementary cementitious materials as partial replacements for Portland cement, and
- the use of chemical admixtures, in particular superplasticizers.

An environmental assessment of the five mix designs showed that the use of the energy metric leads to different decisions on concrete mix choices than those arrived at using the exergy and carbon footprint metrics. For the energy analysis, concrete mix designs containing recycled aggregates were preferred over those with 100% natural aggregates, whereas the converse was found to be true for the exergy metric and carbon footprint. The different outcomes arise from the fact that the exergy metric is more comprehensive and accounts for both energy and non-energy resources. The production of recycled aggregates results in the consumption of additional non-energy resources (e.g. additional water in the concrete mix-design). These additional non-energy resources are not accounted for by the energy metric hence its preference for the use of recycled aggregate concrete to natural aggregate concrete. Similarly, the carbon footprint and energy metric give different results. This is because in addition to the energy use the carbon footprint also accounts for the carbon emissions from materials e.g. calcination of limestone. Calcination refers to the decomposition of limestone ($CaCO_3$) to calcium oxide (CaO), in the process liberating CO_2. The calcination process was shown, in this study (Chapter 4), to account for over half of the CO_2-eq emissions generated during cement production.

The carbon footprint was shown to give similar results to the exergy metric. The practice of blending cements contributes to the conservation of natural resources and a reduction in the amount of CO_2-eq emissions. These two effects are captured by the exergy metric and carbon footprint, respectively. However, in a case where the amount of Portland cement is minimal for all concrete mixes under comparison e.g. such as with the use of geopolymer binders, then exergy would be the preferred metric as it is able to capture the effect of resource conservation due to the use of chemical admixtures and the use of recycled materials.

All the metrics captured the benefit of using superplasticizers in concrete mixes. Both the carbon footprint and exergy metric showed that the use of superplasticizers leads to a 12% reduction in the embodied impacts of concrete made using natural aggregates and Portland cement. The energy metric showed a 7% reduction for the same mix. The use of chemical admixtures is beneficial to the environment as it leads to resource conservation i.e. chemical admixtures lead to a reduction in the water content of the mix-design and hence its binder content.

Further, the three metrics (carbon footprint, exergy and energy) were evaluated using a number of criteria: (i) reliability, (ii) robustness, and (iii) support in decision making.

A statistical quantification of the input data was found to be important as it enabled a more meaningful assessment to be made on the suitability of the single-score metrics in terms of their '*reliability*', compared to the use of deterministic values. In addition, the probabilistic approach determined whether there were significant differences in the environmental performances of the different concrete mixes investigated. A qualitative uncertainty estimate for each data input was determined, using a 'pedigree matrix' uncertainty estimation approach described in Frischknecht and Jungbluth (2007). Since the carbon footprint and the exergy metric had been shown to give similar results, the study singled out the exergy and energy metrics for the reliability analysis. The variability in both the exergy and energy metrics were compared using the margin of error[54]. A confidence interval of 95% in the NAC embodied energy gave a margin of error of 9 MJ/m^3 whereas the respective spread for exergy in NAC was found to be 57 MJ/m^3. Hence, the exergy analysis is reported to have higher variability compared to energy analysis. However it should be noted that although similar standard deviations, measured using the square of the geometric standard deviation (SD_g^2) were assigned to the energy and exergy values of the input variables, the overall variability of the exergy values is higher than that of energy as the exergy data has higher mean values. Further studies are required to establish the actual standard deviation of the respective energy and exergy values. This should be arrived at by collecting energy and exergy datasets for each input variable and quantifying their respective uncertainty.

In terms of robustness, an energy analysis *per se* does not account for consumption of non-energy resources such as natural aggregates and water and only energy consumed in their transportation or processing is considered. Other complementary methods e.g. material flows [in kg] are usually applied to cover impacts due to consumption of non-fuel resources. However, the different units, *kg* vs. *MJ*, make them difficult to combine during decision making, and thus a comparison can only be done qualitatively or by weighting the results. Exergy forgoes this hindrance by accounting for both mineral and fuel resources in the same units, and hence is a more robust metric compared to energy. Also, the carbon footprint accounts for the CO_2-eq emissions from energy resources and cementitious materials used in concrete. Hence, it is also a more robust metric compared to energy.

All three metrics were found to be consistent in their methodology and give reliable results as they are based on sound scientific principles. However, this study showed that the exergy and carbon footprint

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[54] Margin of error is calculated as the confidence interval divided by 2

methods are more suitable metrics than energy for measuring resource consumption of concrete structures. Exergy is able to account for both mineral resources and energy in the same units, whereas the carbon footprint accounts for the carbon emissions from cementitious materials and energy sources. In future cases, where the amount of Portland cement use in concrete is much reduced, then it is foreseeable that exergy will be a more suitable metric. However, the exergy method is tedious in its computations and requires a consistent database of the exergy of resources, which is not yet complete. In conclusion, exergy metric and the carbon footprint were found to be the more appropriate metrics in assessing resource consumption of concrete structures compared to the energy metric. Notwithstanding, this study used only the carbon footprint in Chapter 4 as it required the use of case-specific environmental impact data on the local construction industry. The available data are presented in terms of the GWP_{100} potential. Again in Chapter 6, the LCA results of the two case studies were presented in terms of the GWP_{100} and energy metrics. This facilitated the comparison of the LCA results with other LCA studies in literature.

7.1.2 The environmental performance of South Africa's cement and concrete industry

There has been a 39% increase in global greenhouse gas (GHG) emissions from a pre-industrial level (1750) of 280 parts per million (ppm) CO_2, to the 2012 level of 393 ppm CO_2 (Blasing, 2012; http://www.esrl.noaa.gov/gmd/ccgg/trends). Further, by 2100 an increase of atmospheric concentration of CO_2 ranging to between 541 and 970 ppm is projected to occur (IPCC, 2007). This is an increase of 90 – 250% as compared to the year 1750.

The dependence on non-renewable energy resources (e.g. fossil fuels) in the processing of cementitious materials largely contributes to GHG emissions.

This study investigated the environmental performance of S.A's cement and concrete industry with a view to establishing where SA ranks in the growing global trends of environmental pressures due to increasing resource consumption and pollution. The study quantified the extent to resource use and GHG emissions associated with the production of concrete construction materials in SA. Six-year average (2005-2010) data were provided for resources consumed and wastes emitted to the air due to quarrying and processing of raw materials for concrete in S.A.

From the study, it is determined that on average, 9.1×10^9 kg CO_2-eq emissions per year were emitted in SA for the period 2005 to 2010. These CO_2-eq emissions per annum relate to the production activities for cement and aggregates used for concrete production. Cement is the main contributor of CO_2-eq emissions, contributing on average 98 % of the total carbon equivalent emissions by the concrete industry in SA. In addition, this study quantified the average amount of concrete produced per annum in SA for 2005-2010 as 27 million m^3 (65.2 Mt). The amount of concrete produced in SA relative to the size of its population[55] is relatively low in comparison to developed countries. SA produced approximately 1.4 metric tonnes of concrete per person. A similar study carried out by Woodward and Duffy (2011) on the cement and concrete flow analysis of the Republic of Ireland's concrete industry found that 32.8 Mt of concrete were consumed by the country (population approximately, 4.2 million) in 2007. On a per capita basis, Ireland produced 8 metric tonnes in 2007 (Woodward and Duffy, 2011).

Further, the study showed the need to include all the key players in the cement and concrete industry in order to further reduce the overall impacts of the industry. The study provided an insight on how the key players in the construction industry can contribute towards the environmental performance of the cement and concrete industry. In particular, the role of the concrete practitioner in designing for more sustainable concrete structures was viewed as a practicable means to drive the concrete construction industry in reducing its short- and long-term environmental impacts.

7.1.3 Sustainable concrete structures

Integrating the concept of sustainable development into the concrete industry requires a clear and definite understanding of the term: 'sustainable concrete' structures. However, the definition of 'sustainable concrete' remains elusive. Following a review of current definitions of the term, 'sustainable concrete structure', this study proposed the following comprehensive definition:

"…one that is designed to meet case-specific needs of the users of a concrete structure, that minimizes life-cycle costs and environmental impacts through (i) use of efficient production and construction technologies (ii) selection of materials that have a minimal negative environmental impact and which give optimized properties for long-term durability (iii) selection of an appropriate structural layout and optimized volume, and (iv) is designed for deconstruction and recycling"

According to this definition, sustainability takes precedence over all current design criteria such as structural performance and durability. This means that criteria (i) to (iv), in the definition, are selected in view of the structure's life-cycle environmental impact and cost.

The four criteria required to achieve a sustainable concrete structure are summarized as follows:

7.1.3.1.1 Use of efficient production and construction technologies

The use of efficient production and construction techniques for all concrete materials constituents which lead to minimal social impacts, reduced energy throughput and carbon emissions. For example:

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[55] South Africa's population in 2008 was around 48 million with a GDP of US$ 277 billion (GDP per capita= US$ 5 770) (World Development Indicators database, 2009)

(a) The thermodynamic improvement of production machinery and/or, the installation of carbon capture and storage (CCS)[56] systems in high carbon emitting production processes e.g. cement kilns.

(b) The use of self-compacting concrete in order to reduce construction noise when casting concrete.

(c) The use of pre-cast concrete technology which offers numerous advantages including: the utilization of alternative materials (e.g. site waste and industrial waste) which would have otherwise ended up in land-fill sites. In addition, a pre-cast structure offers better quality control and a reduction in site work and therefore results in minimal traffic disruption during construction.

7.1.3.1.2 Selection of optimized material properties

This refers to the selection of optimized material types and properties that not only meet the structural design requirements but also lead to minimized life-cycle environmental impacts.

7.1.3.1.3 Selection of an appropriate structural layout and optimized volume of a structural component

An appropriate structural layout for buildings in particular is important as it helps minimize the energy requirements during the use phase of a building. The layout of a building with respect to its location and orientation can be such that natural lighting and ventilation are provided to its users during its operational phase. This is also referred to as passive design.

For a civil engineering structure, an appropriate layout would enhance the aesthetic quality of the structure.

In addition, an optimized volume of materials in each of the structural components would lead to reduced quantities of materials needed for construction. This can also be achieved with the use of light-weight construction materials or through design optimization of the structure’s cross-sectional geometry.

7.1.3.1.4 Design for deconstruction and recycling

The design for deconstruction is a long-term approach perspective of the use of the structure after its useful service life. This requires the key players in construction to consider the end-of life phase of a structure and consider ways in which it can be adapted or recycled.

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[56] Carbon capture and storage (CCS) is a method of CO_2 sequestration whereby CO_2 emissions are captured at the source and transported to storage reservoirs.

The concept of ‘sustainable concrete structures’ in the context of this study, focused on the materials design aspect and was limited to the selection of optimum material properties and cross-sectional geometry of RC structural components based on their environmental performance.

7.1.4 Proposed framework towards the design of more sustainable concrete structures

From the definition of a ‘sustainable concrete structure’, it is clear that there are a number of options available over the life-cycle of the RC structure that can be used to ensure the construction of more sustainable RC structures.

(i) Firstly there is the use of best practice in manufacturing and construction of RC structures.
(ii) Secondly, there is the exploration of renewable resources and advanced material technology such as the use of chemical admixtures that facilitate the conservation of natural resources.
(iii) Thirdly, there is the optimization of the volume of materials that leads to reduced quantities of materials needed for construction.
(iv) Lastly, there is the development of substitutes for natural resources and increased recycling of demolition wastes.

The concept of ‘sustainable concrete structures’ in the context of this study, focuses on the materials design aspect and is limited to the selection of optimum material properties and quantities for concrete based on their environmental performance. The main contribution of this study was the development of a novel framework to support the design of more sustainable concrete structures.

The proposed framework was detailed in Chapter 5. The framework showed the important quantifiable variables and parameters that need to be considered in the design of concrete. The main design variables include the geometry of a structural component, concrete mix-design constituents and concrete hardened properties that have an influence on the life-cycle sustainability of concrete. The framework showed how optimum values for the design variables and parameters of a given structural element can be selected using a set of performance measures. The performance measures developed in this study relate to the environmental life-cycle material performance, whereby the environmental impact of different concretes of different concrete grades is represented as e.g. kg CO_2-eq/m^3 per MPa. In addition, the framework showed the need for a reliable and comprehensive database of the unit environmental impacts and costs of alternative materials for concrete, construction and repair methods and end-of-life strategies for concrete. Such a database is important to support design calculations.

Using this framework, the study developed an optimization model to optimize the concrete properties and cross-sectional dimensions of structural components. The optimization model was applied in Chapter 5 to find the geometry and materials specifications for a simplified RC beam that result in the lowest environmental impact while meeting design requirements for serviceability and safety.

A comparative analysis of the optimum design specifications for the RC beam was carried out for four different binder types: CEM I 52.5 N, CEM II/ B-V 42.5N, CEM II/ A-V 52.5 N, and CEM III/ A-S 42.5 N. The water and binder content was varied for the four binder types in order to achieve a common concrete grade of C30/37. It was shown that concrete made using CEM III/A-S 42.5N had the lowest environmental impact compared to other concrete types. This was followed by CEM II/B-V 42.5, CEM II/A-V 52.5, and finally CEM I 52.5 N.

Generally, the following deductions were made from the optimization problem of the RC beam:

(i) Even though a lower binder content (higher *w/b* ratio) results in a reduced environmental impact, it leads to a greater reduction in compressive strength, and a corresponding increase in cross-sectional dimensions, and hence for a particular concrete strength grade, there is a reported increase in the kg CO_2-eq/m with decrease in binder content (increase in the *w/b* ratio).
(ii) Specifying higher compressive strengths leads to a reduction in cross-sectional dimensions.
(iii) It is important to select an appropriate binder content for a binder system, and vice versa, as the choice of binder system is based on its environmental impact at a particular binder content.
(iv) The use of SCMs allows the designer to prescribe lower values of concrete cover and hence leads to reduced cross-sectional dimensions, which translates to reduced volume of materials.

In addition, the study implemented the framework and optimization model using two local (South African) case studies: the New Engineering building (NEB) at the University of Cape Town, and the Elands interchange in Gauteng province, South Africa. Both these structures have high embodied and operation energy requirements and also have a significant influence on their users. Firstly, an LCA on the two case studies was carried out. The LCA considered the energy use and greenhouse gas emissions associated with the cradle-to-gate phases of the two structures.

The LCA results on the NEB, which is a reinforced concrete-framed building, showed the floor slab system to contribute the highest value to the building's environmental impact representing 78.55 % of the embodied environmental impact of 159 kg CO_2-eq/m^2. The LCA of the Elands interchange covered cradle-to-gate environmental impacts of all the structural components of the interchange, including the precast concrete box girders, prestressing anchor blocks, end blocks, and the substructure abutment, pier and foundation piles. The majority of the environmental impacts were from the concrete box girders which accounted for approximately 63 % of the overall cradle-to-gate environmental impacts of 1.09×10^3 kg CO_2-eq/m and 66 % of the 1.14×10^4 MJ/m.

Secondly, structural components contributing the highest to the overall environmental impact of the two case studies were selected for design using the proposed optimization procedure presented in Chapter 5. These were the RC ribbed concrete floor slab of a building and the post-tensioned concrete box girder. Using these two structural elements, this study investigated the optimum design variables that would lead to more sustainable concrete structures. The design variables included the cross-sectional geometry, area of steel and concrete properties such as diffusivity and compressive strength. An optimization algorithm was used to establish the global minimum of an objective function with several constraints. The influence of the use of different binder combinations was studied.

It was shown that if the proposed optimization process had been applied during the design of the floor slab of the New Engineering building it would have resulted in a 28% reduction in the embodied environmental impact of the building of 159 kg CO_2-eq/m^2 reported

The proposed optimization problem for both case studies showed the importance of selecting an appropriate binder combination, as it can lead to a reduction in cross-sectional geometry and hence reduced environmental impacts.

7.2 Recommendations for further research

Based on the findings of this thesis the following recommendations are given for future research:

7.2.1 Comparative life-cycle assessment of RC repair methods

The LCA and subsequent design optimization carried out on the two case studies in this study assumed that both structures would last their full service life and hence replacement and repair activities of the structure were not considered. However, in reality this is not the case due to durability issues, further cradle-to-gate environmental assessment studies should be carried out to investigate the environmental impacts of alternative repair methods on RC structures.

The selection of an appropriate repair method for the optimization problem should be based on it feasibility in reducing repair time, improving the residual service life of a structure, reducing costs to the owner and user of a structure and minimizing environmental impacts. Local information on most of these factors is currently lacking. Thus, there is a need to carry out a comparative life-cycle assessment of various repair methods: (i) patch repairs, (ii) coating systems (iii) migrating corrosion inhibitors (iv) electrochemical techniques, (v) cathodic protection systems. From this study a database of unit environmental impacts of each repair method should be quantified. Such a database would enable the optimization procedure to cover the cradle-to-grave phase impacts during the analysis.

7.2.2 Life-cycle costs of RC structures

The proposed framework indicates that the RC design is an optimization process seeking to ensure that the selected design variables satisfy the design requirements and result in minimum life-cycle environmental/social/cost impact. However, the integration of life-cycle costs in the case studies used in this study was out of the scope of this study. A further study is required to show the multi-objective optimization of life-cycle social and financial costs and the life-cycle environmental impact of RC structures. For such a study, it would be necessary to first establish an appropriate method of quantifying social impacts as this is still under contention and a separate study is required to establish this.

7.2.3 Verification of empirical models for hardened concrete properties

Since the proposed design framework considers the influence of concrete mix proportions on hardened concrete properties, this study adopts physical prediction models from the ones already established in literature.Further, it should be noted that the framework can readily be generalized to any other representative relationship for concrete hardened properties which takes account of the important mix-design constituents.

The empirical models adopted in this study to predict hardened properties of concrete i.e. its compressive strength and diffusivity have been developed and verified using international data. Further studies are required to verify the models using local data. Alternatively, local models can be developed to allow the structural engineer to predict the properties of concrete and hence produce reliable results when using the proposed framework.

7.2.4 Environmental impact of aggregates mining in South Africa

The sand and aggregate sector in SA is one of the biggest (ranking 5th or 6th) in the mining industry (Pienaar, 2013), and hence its environmental performance has a large impact on the overall mining industry and also on the concrete industry since aggregates account for 65-80% of the volume of concrete.

In Chapter 4, an environmental assessment of South Africa's cement and concrete industry was carried out. However the aggregate mining data was not comprehensive as it did not include natural (pit-derived) fine aggregate data. The quantity produced and environmental impacts of the latter would be useful to investigate in a further research project and this would be compared to that of crushed fine aggregates and site-derived materials. Of importance in such a study would be a distinction to be made on the quantities of crushed and non-crushed aggregates produced in SA and their resultant environmental impact.

7.2.5 Uncertainty of design variables

The design variables have a degree of uncertainty that can potentially be quantified using a probabilistic approach. The first sources of uncertainties are termed as physical and relate to variations in material production processes, measurement errors, data handling and transcription errors depending on the quality assurance observed during the data collection, and geographical differences in data due to e.g. differences in the electrical energy mixes in different countries. The second source of uncertainty is associated with the use of simplified models or relationships between basic variables to represent actual physical phenomena. The physical uncertainty in datasets make it difficult if not impossible to say with conviction that there is a uniquely defined energy or exergy value for each material. Rather, there is a certain probability range of energy or exergy values. Thus, a probabilistic approach is a rational approach to dealing with data variability caused by physical and model uncertainties. The relevant statistical parameters (e.g. average (μ) and standard deviation (σ)), and probability distributions (e.g. normal, log-normal, uniform, triangular) for the design variables should be included to improve the reliability of the design decisions.

However, the probability distribution functions of the variables have not been quantified in this study, and are largely unavailable at this stage. Instead, the study considers deterministic values of all the design variables. The proposed framework in this study is however adaptable to the use of either a deterministic or probabilistic approach to design. Further research requires the statistical quantification of the uncertainty associated with design variables and parameters governing the design of sustainable concrete structures.

7.2.6 Other design parameters

The study focuses on materials selection and geometry optimization of a RC structure at the detailed design phase. It should be noted that design aspects such as the layout optimization of structural elements within RC structures contributes importantly towards the design of more sustainable concrete structures. However, these aspects are not explicitly included in the scope of this study and are recommended as part of a further study.

7.3 References

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Appendix

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APPENDIX PAGE

A-1. APPENDIX A: ADDITIONAL INFORMATION FOR CHAPTER 2 & 3

A.1 Types of life-cycle assessment methodologies

A life-cycle assessment (LCA) can be carried out using three distinct methodologies (Chapman, 1974; Bullard *et al.*, 1978): (i) Process analysis (ii) Input-Output analysis and (iii) Hybrid analysis. A description of the process analysis was given in *Chapter 3*. This section gives a brief description, strengths and limitations of each of the latter 2 methods.

A.1.1 Input-output analysis

Input-output (IO) energy analysis was first demonstrated by Bullard *et al*. (1978). The IO methodology was originally developed by Leontiff in 1932 (Leontief, 1936) to relate production of goods with the expense of producing them as shown by Equation (A.1) or Equation (A.2).

$$x = A \cdot x + f \qquad \text{(A.1)}$$

or

$$x = (I - A)^{-1} \cdot f \qquad \text{(A.2)}$$

where: x – production output; f – Final demand of the product; A – Matrix describing the amount of products needed from other sectors for the production of one unit of product (described in physical terms (e.g. *kg*) or in monetary units); I – Identity matrix and $(I - A)^{-1}$ – referred to as the Leontief inverse matrix.

If the energy consumption of economic sectors is known, Equation (A.3) can be extended into an energy I/O analysis by:

$$C = E(1 - A)^{-1} \cdot f \qquad \text{(A.3)}$$

where: C – overall energy produced; E – Matrix describing energy intensities of different economic sectors

I/O analysis uses input-output tables that show the transactions between different economic sectors in monetary units. Each sector constitutes industries with similar products and services. Additional data on the primary energy consumption (energy cost) of each industry are required and represented in a matrix format.

The energy intensity of each sector is calculated using data from the input-output table and data on the primary energy use of each sector. This energy intensity gives the total primary energy that a sector needs for the production of one financial unit of output.

Since the data available from input-output tables are more aggregated than data received from a process analysis, input-output analysis is less accurate than process analysis.

A.1.2 Hybrid Analysis

A hybrid analysis incorporates elements from both process-based and IO-based models.

A.2 Uncertainty analysis of life-cycle inventory data using the pedigree matrix

The pedigree matrix developed by Frischknecht and Jungbluth (2007) allows for an estimation of the uncertainty in input data sets based on a set of qualitative criteria: "reliability", "completeness", "temporal correlation", "geographic correlation", "further technological correlation" and "sample size". Each characteristic is divided into 5 quality levels as shown in ***Table A.1***. The data is then ranked 1-5 depending on its quality level for each criterion.

Table A.1*: Pedigree matrix used to assess the quality of data sources (Pedersen Weidema and Wesnaes as cited in Frischknecht and Jungbluth (2007))*

Indicator score	***1***	***2***	**3**	**4**	**5**
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy etc.)	Non-qualified estimate
Completeness	Representative data from all sites	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from <<50% of the sites relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a smaller number of sites AND from shorter periods.
Temporal correlation	< 3 years of difference to a reference year	< 6 years of difference to the reference year	< 10 years of difference to the reference year	< 15 years of difference to the reference year	age of data unknown or more than 15 years of difference to reference year
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from a smaller area, than the area under study, or from similar area		Data from unknown OR distinctly different area
Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials but same technology OR Data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
Sample size	>100, continuous measurements,	>20	>10	>=3	unknown

An uncertainty factor is assigned to each quality level for the different categories. Default uncertainty factors (based on expert panel judgments) are given in ***Table A.2***.

***Table A.2**: Default uncertainty factors (contributing to the square of the geometric standard deviation) applied together with the pedigree matrix (Frischknecht and Jungbluth, 2007)*

Indicator score	***1***	***2***	**3**	**4**	**5**
Reliability	1.00	1.05	1.10	1.20	1.50
Completeness	1.00	1.02	1.05	1.10	1.20
Temporal correlation	1.00	1.03	1.10	1.20	1.50
Geographical correlation	1.00	1.01	1.02		1.10
Further technological correlation	1.00		1.20	1.50	2.00
Sample size	1.00	1.02	1.05	1.10	1.20

The scores for each indicator are analyzed to compute the geometric standard deviation of the data as follows (Frischknecht and Jungbluth, 2007):

$$SD_{g,95} = \sigma_g^2 = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \qquad \text{(A.4)}$$

where,

U_1	:	Uncertainty factor of reliability
U_2	:	Uncertainty factor of completeness
U_3	:	Uncertainty factor of temporal correlation
U_4	:	Uncertainty factor of geographic correlation
U_5	:	Uncertainty factor of other technological correlation
U_6	:	Uncertainty factor of sample size
U_b	:	Basic uncertainty factor

Using the geometric standard deviation, the arithmetic mean (μ_{ar}) and arithmetic standard deviation are computed using Equation (A.5) and Equation (A.6), respectively.

$$\mu_{ar} = \mu_g \times e^{\frac{\log^2(\sigma_g)}{2}} \qquad \text{(A.5)}$$

$$\sigma_{ar} = \sqrt{e^{2\times\ln(\mu_g)+\ln^2(\sigma_g)} \times \left(e^{\ln^2(\sigma_g)} - 1\right)} \qquad \text{(A.6)}$$

Example on the calculation of the geometric standard deviation:

The computation of $SD_{g,95}$ for: *Portland cement, strength class CEM I 42.5, at plant/kg/CH U*, as given in Table 3.3; Chapter 3 is as follows:

Using the EcoInvent database, the environmental impact data for Portland cement manufactured in Switzerland has the following scores for: “reliability”, “completeness”, “temporal correlation”, “geographical correlation”, “further technological correlation”, and “sample size” , respectively: [4,2,1,1,1,5].

The corresponding uncertainty factors for the pedigree matrix in Table A2 are: U_1 = 1.20; U_2 = 1.02; U_3 = 1.0; U_4 = 1.0; U_5 =1.0; U_6 =1.20; and U_b = 1.

Hence,

$$SD_{g,95} = \sigma_g^2 = \exp^{\sqrt{[\ln(1.20)]^2+[\ln(1.02)]^2+[\ln(1.0)]^2+[\ln(1.0)]^2+[\ln(1.0)]^2+[\ln(1.20)]^2+[\ln(1)]^2}} = 1.30 \qquad \text{(A.7)}$$

A.3 Confidence interval on the mean

The confidence interval of the mean environmental impact using the energy and exergy metric as computed as detailed in Sub-sections A.3.1 to A.3.4.

A.3.1 Confidence interval of mix I using energy metric

$\bar{x}_{mixI}$ = 2 038; σ_{mixI} = 475 n = 10 000

The 95% confidence interval for α = 0.05, $z_{\alpha/2} = z_{0.025}$ = 1.96 is given as:

$$\begin{aligned} &\bar{x} - z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \le \mu \le \bar{x} + z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \\ &2038 - 1.96\left(\frac{475}{\sqrt{10000}}\right) \le \mu \le 2038 + 1.96\left(\frac{475}{\sqrt{10000}}\right) \\ &2029 \le \mu \le 2047 \end{aligned} \qquad \text{(A.8)}$$

A.3.2 Confidence interval of mix III using energy metric

$\bar{x}_{mixIII}$ = 2 034; σ_{mixI} = 444; n = 10 000

The 95% confidence interval for α = 0.05, $z_{\alpha/2,} = z_{0.025}$ = 2.064 is:

$$\begin{aligned} &\bar{x} - z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \le \mu \le \bar{x} + z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \\ &2034 - 1.96\left(\frac{444}{\sqrt{10000}}\right) \le \mu \le 2034 + 1.96\left(\frac{444}{\sqrt{10000}}\right) \\ &\mathbf{2025} \le \mu \le 2043 \end{aligned} \qquad \text{(A.9)}$$

A.3.3 Confidence interval of mix I using exergy metric

$\bar{x}_{mixI}$ = 28 589; s_{mixI} = 5 742 n = 10 000

The 95% confidence interval for α = 0.05, $z_{\alpha/2} = z_{0.025} = 1.96$ is given as:

$$\bar{x} - z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \leq \mu \leq \bar{x} + z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \tag{A.10}$$

$$28589 - 1.96\left(\frac{5742}{\sqrt{10000}}\right) \leq \mu \leq 28589 + 1.96\left(\frac{5742}{\sqrt{10000}}\right)$$

$$28476 \leq \mu \leq 28702$$

A.3.4 Confidence interval of mix III using exergy metric

$\bar{x}_{mixIII}$ = 29 058; s_{mixI} = 5 923 n = 10 000

The 95% confidence interval for α = 0.05, $z_{\alpha/2} = z_{0.025} = 1.96$ is given as:

$$\bar{x} - z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \leq \mu \leq \bar{x} + z_{0.025}\left(\frac{\sigma}{\sqrt{n}}\right) \tag{A.11}$$

$$29058 - 1.96\left(\frac{5923}{\sqrt{10000}}\right) \leq \mu \leq 29058 + 1.96\left(\frac{5923}{\sqrt{10000}}\right)$$

$$28941 \leq \mu \leq 29174$$

A.4 Review of life-cycle assessment studies on buildings

This study reviewed nineteen journal articles describing forty LCA studies on various concrete residential and commercial buildings. Details of these are listed in ***Table A.3***and

Table A.4 and include the building location and the life-cycle phases covered.

Table A.3: *Details of the life-cycle assessment studies on commercial concrete buildings*

	Reference	*Country*	*Building type* ^{a}	*Service life* *[Years]*	*LCA analysis type* ^{b}	*WBP/ BCMC* ^{c}	*Energy type* ^{d}	*Life-cycle phases*			
								Embodied	Operation	Recurring	Demolition
1.	Cole and Kernan (1996)	Canada	Com	50	P	WBP	-	×	×	×	-
	Cole and Kernan (1996)	Canada	Com	50	P	WBP	-	×	×	×	-
2.	Cole (1999)	Canada	Alternative structural systems	-	P	BCMC	-	×	-	-	-
3.	Dimoudi and Tompa (2008)	Greece	Com	50	P	BCMC and WBP	-	×	×	-	-
	Dimoudi and Tompa (2008)	Greece	Com	50	P	BCMC and WBP	-	×	×	-	-
4.	Guggemos and Horvath (2005)	Midwestern US	Com	50	H	WBP	-	×	×	×	×

Continued… Table A.3: *Details of the life-cycle assessment studies on commercial concrete buildings*

	Reference	***Country***	***Building type*** [a]	***Service life*** *[Years]*	***LCA analysis type*** [b]	***WBP/ BCMC*** [c]	***Energy type*** [d]	***Life-cycle phases***			
								Embodied	Operation	Recurring	Demolition
5.	Jönnson *et al*. (1998)	Sweden	Com	50	P	WBP	Primary	×	×	×	×
	Jönnson *et al*. (1998)	Sweden	Com	50	P	WBP	Primary	×	×	×	×
6.	Junilla *et al*. (2006)	Finland	Com	50	H	WBP	-	×	×	×	×
	Junilla *et al*. (2006)	Mid-Western US	Com	50	H	WBP	-	×	×	×	×
7.	Kofoworola and Gheewala (2009)	Thailand	Com	50	H	WBP	Primary	×	×	×	×
8.	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
	Suzuki & Oka (1998)	Japan	Com	40	I/O	WBP	Primary	×	×	×	×
9.	Treloar *et al*. (2001)	Australia	Com	-	H	-	-	×	-	-	-
	Treloar *et al*. (2001)	Australia	Com	-	H	-	-	×	-	-	-
	Treloar *et al*. (2001)	Australia	Com		H	-	-	×	-	-	-
10.	Xing *et al*. (2008)	China	Com	50	P			×	×	-	-
11.	Adalberth *et al*. (2001)	Sweden – Malmo	Res	50	-	WBP	End use	×	×	-	-
	Adalberth *et al*. (2001)	Sweden – Helsingborg	Res	50	-	WBP	End use	×	×	-	-
	Adalberth *et al*. (2001)	Sweden–Vaxjo	Res	50	-	WBP	End use	×	×	-	-
	Adalberth *et al*. (2001)	Sweden – Stockholm	Res	50	-	WBP	End use	×	×	-	-
12.	Blengini (2009)	Italy	Res	70	P	WBP	Primary	×	×	×	×
	Blengini (2009)	Italy	Res	70	P	WBP	Primary	×	×	×	×
13.	Kahhat *et al*. (2009)	US Phoenix	Res	50	P	WBP and BCMC	Primary	×	×	×	×
	Kahhat *et al*. (2009)	US-Phoenix	Res	50	P	WBP and BCMC	Primary	×	×	×	×
	Kahhat *et al*. (2009)	US-Phoenix	Res	50	P	WBP and BCMC	Primary	×	×	×	×
14.	Jönnson *et al*. (1998)	Sweden	Res	50	P	WBP	Primary	×	×	×	×
	Jönnson *et al*. (1998)	Sweden	Res	50	P	WBP	Primary	×	×	×	×
15.	Mithratne and Vale (2004)	New Zealand	Res: Standard	100	p	WBP and BCMC	Primary	×	×	-	-
16.	Thormark (2002)	Sweden Gothenburg	Res Low energy	50	P	WBP	Primary	×	×	×	-
17.	Asif *et al*. (2007)	Scotland	Res	-	P	BCMC	Primary	×	-	-	-
18.	Hammond and Jones (2008)	UK	BM	-	P	BCMC	Primary	×	-	-	-
19.	Reddy and Jagadish (2003)	India	BM	-	P	BCMC	Primary	×	-	-	-

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[a] Building type: Com –Commercial building; Res –Residential building; BM –Building material

[b] LCA Analysis type: P – Process analysis; I/O – Input /Output analysis; H – Hybrid analysis

[c] WBP – Whole building process

[c] BCMC – Building component and material combinations

[d] Energy type:

P.E – Primary energy defined as the theoretically usable energy content of fossil, nuclear, and renewable energy media as they occur in nature and have not yet been converted or prepared (Hegger *et al*., 2008);

D.E – Delivered energy the quantity of energy used for the energy service e.g. space heating (Hegger *et al*., 2008).

Table A.4*: Details of the life-cycle assessment studies on residential concrete buildings*

Reference	*Country*	*Service life* [Years]	*Type of concrete*	*Number of floors*	*Floor area [m^2]*	*Embodied Energy* [MJ/m^2]	*Operation energy* [MJ/m^2.year]
Adalberth *et al*. (2001)	Sweden–Malmo	50	Lightweight concrete	3	700	2 241	461
Adalberth *et al*. (2001)	Sweden –Helsingborg	50	Concrete	3.5	1160	2 510	533
Adalberth *et al*. (2001)	Sweden–Vaxjo	50	Concrete/Wood	4	1190	2 888	662
Adalberth *et a*l. (2001)	Sweden–Stockholm	50	Steel column and concrete	5	1520	2 158	518
Blengini (2009)	Italy	70	Low energy building[b]	2	250	9800	141
Blengini (2009)	Italy	70	Standard house	2	250	7630	515
Jonsson *et al*. (1998)	Sweden	50	Precast	1	2400	1111	527
Jonsson *et al*. (1998)	Sweden	50	In-situ	1	2400	1311	527
Kahhat *et al*. (2009)	US– Phoenix	50	Concrete block (200 x 200 x 400 mm)	1	200	3425	1311
Kahhat *et al*. (2009)	US–Phoenix	50	Cast-in-place concrete (200 mm thick) - 9% FA	1	200	3350	1319
Kahhat *et al*. (2009)	US–Phoenix	50	Insulated concrete (1500 mm thick) -9 % FA	1	200	3695	1262
Mithratne and Vale (2004)	New Zealand	100	Standard house[a]	1	94	4764	115
Thormark (2002)	Sweden– Gothenburg	50	Low energy building [b]	2	120	5526	164

A.5 Chemical exergy calculations

In Chapter 3, it was shown that the chemical exergy of a material is computed using the following equation (Szargut 1989):

$$E_x^{Chem} = \sum_i n_i\left(\mu_i - \mu_{i0}\right) + RT\sum_i n_i \ln\left(\frac{c_i}{c_{i0}}\right) \tag{A.12}$$

where: n_i – number of moles of the material *i*; μ_i – is the chemical potential for the material *i* in its present state [J/mol]; μ_{io} – is the chemical potential for the material *i* in the environment in relation to its standard state [J/mol]; R – is the universal gas constant, 8.314Jmol^{-1}k^{-1}; T – is the absolute temperature [K]; c_i – is the concentration for material *i* in its present state and; c_{io} – is the concentration for material *i* in the environment in relation to its standard state.

The first component of Equation (A.12) is also referred to as the Gibbs energy of formation (G_f^0) [kJ/mol] and can also be illustrated as follows:

$$\sum_i n_i \left(\mu_i - \mu_{i0}\right) = G_f^0 \qquad \text{(A.13)}$$

Also the second component of Equation (A.12) is summarized as follows:

$$RT \sum_i n_i \ln\left(\frac{c_i}{c_{i0}}\right) = \sum n_i E_{x,i}^{Chem} \qquad \text{(A.14)}$$

Where, n_i -number of moles in the chemical species'i' and; $E_{x,i}^{Chem}$ - chemical exergy of an element 'i' in the substance.

A simple illustrative example on the computation of chemical exergies is given next.

A.5.1 Example showing the calculation of chemical exergy

For the calcination of limestone to lime:

$$CaCO_{3(s)} \xleftrightarrow{Calcination} CaO_{(s)} + CO_{2(g)} \qquad \text{(A.15)}$$

The prevailing ambient conditions are estimated as:

$T = 25°C$, $[CaCO_3] = 1M$ $[CaO] = 1M$ $[CO_2] = 3.35 \times 10^{-2} M$

The different components of Equation (A.12) are computed as follows:

A.5.1.1 The Gibbs free energy for non-standard ambient conditions:

For a generalised reaction:

$$aA + bB \longrightarrow cC \qquad \text{(A.16)}$$

where: a, b and c are the number of moles of compound A,B and C respectively, then Gibbs free energy $\left(\Delta G^0\right)$ is given by (Mihelcic, 1999):

$$\Delta G^0 = c\Delta G^0_{f\,C} - \left(a\Delta G^0_{f\,A} + b\Delta G^0_{f\,B}\right) \qquad \text{(A.17)}$$

The Gibbs energy of formation is computed as:

$$\Delta G^0 = G^0_{Products} - G^0_{Reactants} = H_{Products} - H_{Reactants} - T_0\left(S_{Products} - S_{Reactants}\right) \qquad \text{(A.18)}$$

where: H - Heat of enthalpy (kJ/mol); S - Entropy (kJ/molK).

For example, the Gibbs energy of formation of CO$_2$ ($C_{(s)} + O_2 \longrightarrow CO_{2(g)}$) is calculated as shown in Equation (A.19). Values of enthalpy and entropy are given in standard textbooks.

$$\begin{aligned} &\Delta G^0_{CO_2} = G^0_{CO_2} - \left(G^0_{C_{(s)}} + G^0_{O_{2(g)}}\right) = H_{CO_2} - H_C - H_{O_2} - T_0\left(S_{CO_2} - S_C - S_{O_2}\right) \\ &G^0_{CO_2} - (0-0) = -393{,}500\,J/mol - (0) - (0) - 298K(213.7\,J/mol - 5.74\,J/mol - 205.033\,J/mol) \\ &G^0_{CO_2} = -394.4\,kJ/mol \end{aligned} \tag{A.19}$$

Hence, for the example in Equation (A.15), the Gibbs free energy is given as:

$$\begin{aligned} &\Delta G^0 = \Delta G^0{}_{f(CaO)} + \Delta G^0{}_{f(CO_{2(g)})} - \Delta G^0{}_{f(CaCO_3)} \\ &\Delta G^0 = -604.11 + (-394.4) - (-1128.9) \\ &\Delta G^0 = 130.4\,kJ/mol \end{aligned} \tag{A.20}$$

The Gibbs energy of formation values are given in standard chemistry text books e.g. Atkins (2001).

A.5.1.2 Total chemical exergy

Hence, the chemical exergy of lime is:

$$\begin{aligned} &E^{Chem}_{CaO} = \left[G^0_{CaCO_3} - G^0_{CaO} - G^0_{CO_2}\right] + \sum\left(E_{x,CaCO_3} - E_{x,CO_2}\right) \\ &E^{Chem}_{CaO} = \frac{130.4kJ}{mol} + (1 - 19.87)kJ/mol \\ &\qquad = 111.53\,kJ/mol \end{aligned} \tag{A.21}$$

A.5.2 Chemical exergy of raw materials for concrete

An exergy analysis of materials requires detailed knowledge of the chemical compositions of materials. Chemical exergy refers to the work necessary to produce one mol of an element in its standard state from the environment in a reversible way, heat being exchanged in the process only with the environment at standard temperature $\left(T^0\right)$ (Szargut, 1988).

To start an exergy analysis, a complete flow-sheet of the mass and energy flows of the different production processes is required. Knowledge of the chemical composition of the materials is important for the determination of exergy.

Table A.5 gives the standard chemical exergy of Portland cement.

For aggregates, the composition of the rock forming the aggregate is important. For sand it was assumed that 100% Quartz mineral and the granite chemical composition was obtained from Finneveden & Ostulund (1997). However, it should be noted that this composition is based on mineral ores located in Scandinavia and local petrographic examination of the mineral ores is required. ***Table A.6*** and ***Table A.7*** give the exergies of the fine and coarse aggregates respectively. ***Table A.8*** gives the exergy of portable water.

***Table A.5**: Standard chemical exergy of Portland cement*

Measurements	*Units*	*Composition of Portland cement (CEM I)*						
		$3CaO.SiO_{2(s)}$ *(60-73%)*	$2CaO.SiO_{2(s)}$ *(8-30%)*	$3CaO.Al_2O_{3(s)}$ *(5-12%)*	$4CaO.Al_2O_3.Fe_2O_{3(s)}$ *(8-16%)*	$MgO_{(s)}$ *(1.9-3.2%)*	$CaSO_{4(s)}$ *(4.4-6.7%)*	$CaO_{(s)}$ *(0.2-2.5%)*
Abbreviation		(C_3S)	(C_2S)	(C_3A)	(C_4AF)	M	*Gypsum*	*Free lime*
E_x^{Chem} (Morris & Szargut 1986)	kJ/mole	219.8	95.7	500.6	667	66.8	8.2	413.1
% mass by cement in example		64.2%	11.1%	5.62%	9.77%	2%	5%	2.31%
Moles in 1 kg of cement for the example	-	2.81	0.64	0.21	0.2	0.5	0.37	0.41
E_x^{Chem} in cement	MJ/ton	617.83	61.65	104.08	133.98	33.40	3.01	170.10
Total E_x^{Chem} *(MJ/ton)*								**1 124.05**

***Table A.6**: Standard chemical exergy of sand (100% Quartz) (T^o of 25°C and P^o of 101.325 kPa)*

Elements	*References*	*Units*	SiO_2
Moles in 1 kg of sand	Atkins(2001)	-	16.64
E_x^{Chem}	Finnveden & Ostlund (1997)	kJ/mole	1.9
E_x^{Chem}		kJ/kg	**31.61**

***Table A.7**: Standard chemical exergy of coarse aggregates (granite) (Finnveden & Ostlund, 1997).*

Elements	*Units*	*Albite* $NaAlSi_3O_8$	*Quartz* SiO_2	*Anorthite* $CaAl_2Si_2O_8$	*Biotite* $K(Mg_{2.5}Fe_{0.5})(Si_3Al)O_{10}(OH)_{1.75}F_{0.25}$	*Tremolite* $Ca_2Mg_5Si_8O_{22}(OH)_2$	*Total*
Average proportion (%) (Finnveden & Ostlund, 1997)	%	51	25	6	10	8	
Mass (g)	g	510	250	60	100	80	
Moles in 1 kg of granite	-	1.94	4.16	0.22	0.24	0.1	
E_x^{Chem}	kJ/mole	105.5	1.9	218.3	74.03	81.6	
E_x^{Chem}	kJ/kg	204.67	7.90	48.03	17.77	8.20	**286.6**

***Table A.8**: Inventory of standard chemical exergies of elements in water.*

Elements	*References*	*Units*	$H_2O_{(l)}$
Moles in 1 kg of water	Atkins(2001)	-	55.56
E_x^{Chem}	Bösch, Hellweg, Huijbregts and Frichknecht (2007)	kJ/mole	0.9
E_x^{Chem}		kJ/kg	50

A.6 References

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B-1. APPENDIX B: ADDITIONAL INFORMATION FOR CHAPTER 4

The following are the calculations for a typical housing unit given in Chapter 4.

B.1 Apportioning cement sales

B.1.1 Typical residential housing unit in South Africa

To apportion the amount of cement sales (in Chapter 4) to their respective uses, this study used a typical single-storey residential building constructed using bricks and approximated the percentage amount of cement used in plaster and mortar applications and that used in the construction of its reinforced concrete ground floor slab and strip foundations.

A typical single storey housing unit in South Africa is given in ***Figure B.1***. The housing unit has a floor area of 44 m^2.

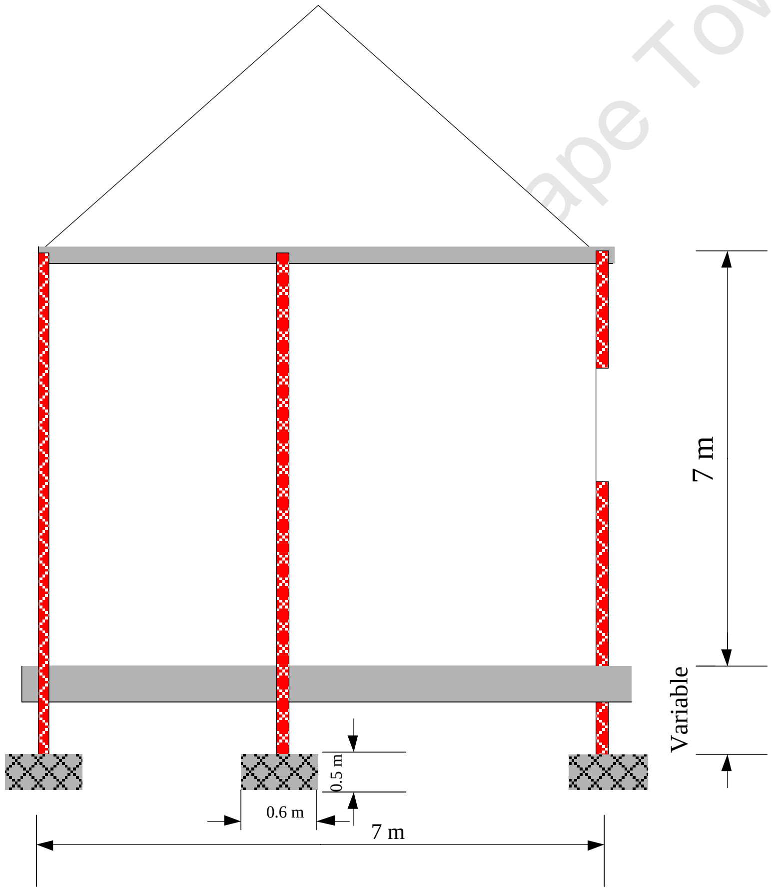

Figure B.1: *Typical single-storey residential building (NHBRC home building manual).*

The maximum dimensions for external and internal wall panels are given in ***Figure B.1*** and in ***Table B.1***. Calculations on the amount of cement used on the residential building are summarized in ***Table B.1***.

Table B.1: *Amount of cement used on a typical residential building in South Africa*

	Concrete element *References*	*Dimensions*	*Square meter*	*Mortar [9.11 x 10-3 m³/m²]** *Equation (B.5)*	*Plaster [0.036 m thick] Section B.1.3*	*Reinforced concrete volume*
1	2 Walls panels with no openings (North-South direction)	2 x (7.0 x 2.6).	36.4 m^2	0.33	1.31	-
2	Wall panel with openings less than 15 % (East direction)	6.2 x 2.6	16.12 m^2.	0.15	0.58	-
3	Wall panel with openings greater than 15 % (West direction)	6.2 x 2.6	16.12 m^2.	0.15	0.58	-
4	4 Internal wall panels	4 x (7.0 x 2.6)	= 36.4 m^2	0.33	2.62	-
5	Floor (300 *mm* thick)	7 x 6.2	= 44 m^2	-	1.584	13.2
6	3 Strip foundations	3 x (6.2 x 0.6)	= 11.16 m^2	0.1	-	5.58
	Total volume [m^3]			**1.06**	**6.67**	**18.78**
	Cement per m^3			290 kg	290 kg	360 kg
	Total amount [kg] **(%) cement**			**307** **(3 %)**	**1934** **(22 %)**	**6 761** **(75 %)**

Thus, from the computations in ***Table B.1*** the total percentages of cement used in mortar applications is 25% and that used in concrete applications is 75%.

B.1.2 Amount of mortar

Mortar per square metre of the walling is calculated as follows (Addis, 1998):

The height, length and width of the masonry unit and joint thickness are measured as illustrated in ***Figure B.2***.

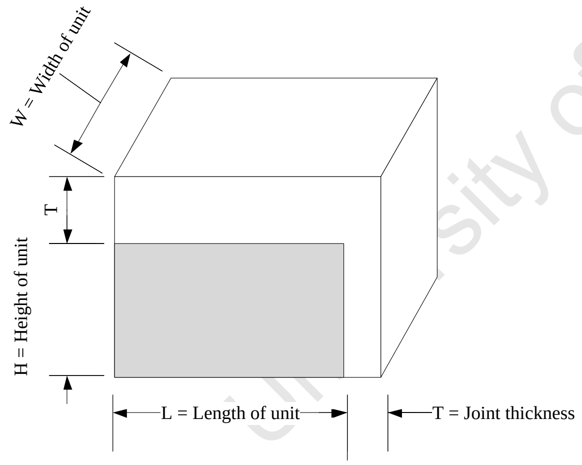

Figure B.2: *Dimensions of masonry unit and joint (Addis, 1998).*

For this study the dimensions of the masonry unit illustrated in ***Figure B.2*** are assumed as follows:

$$H = 140\ mm,\ L = 290\ mm,\ W = 90\ mm. \tag{B.1}$$

The joint thickness in this case is assumed to be 10 *mm*.

The gross face area (A_G) [m^2] of the masonry unit plus joint is computed as shown by Equation (B.2).

$$\begin{aligned} A_G &= (H+T)\times(L+T) \\ &= (0.14 \ + \ 0.01)\times(0.29 \ + \ 0.01) \\ &= 0.045 \ m^2 \end{aligned} \qquad \text{(B.2)}$$

The volume of mortar (V_1) [m^3] per masonry unit is computed as follows:

$$\begin{aligned} V_1 &= T \times W \times (L + H + T) \\ &= 0.01 \times 0.09 \times (0.29 + 0.14 + 0.01) \\ &= 3.96 \times 10^{-4} \ m^3 \end{aligned} \qquad \text{(B.3)}$$

The number of masonry units per square metre of walling, *N* is:

$$\begin{aligned} N &= \frac{1}{A_G} \\ &= \frac{1}{0.045} \\ &= 23 \end{aligned} \qquad \text{(B.4)}$$

The volume of mortar per square metre of walling, V is:

$$\begin{aligned} V &= V_1 \times N \\ &= 3.96 \times 10^{-4} \times 23 \\ &= 9.11 \times 10^{-3} \ m^3 \end{aligned} \qquad \text{(B.5)}$$

B.1.3 Amount of plaster

Plaster is used on walls and floors to produce a smooth surface (Addis, 1998). Three coatings of plaster are usually made. The first undercoat on 10 – 15 *mm* thick, the second undercoat is 5 – 10 *mm* thick and the finish coat is 5 – 10 *mm*. For this example an average figure of **36 *mm*** is assumed for the total plaster thickness. The assumed thickness accounts for a wastage value of up to 30 %.

B.1.4 Amount of concrete

The concrete will be used in the construction of the ground floor slab and strip foundations.

B.2 References

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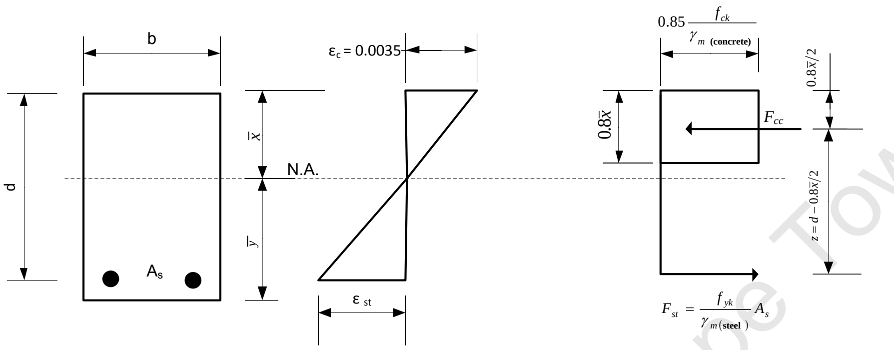
C-1. APPENDIX C: ADDITIONAL INFORMATION FOR CHAPTER 5

The following are the structural design calculations for the RC beam example given in Chapter 5.

C.1 Reinforced concrete beam design

C.1.1 Evaluating the bending moment constraint

The moment of resistances (M_{Rd}) for a reinforced concrete beam is evaluated using the rectangular stress diagram as shown in ***Figure C.1***.



(a) Cross section (b) Strains (c) Rectangular stress block and Forces

Figure C.1: *Assumed rectangular stress block of reinforced concrete members for up to class C50/60 (EN 1992-1-1: 2004).*

– A_s : Total cross-sectional area of steel reinforcement
– N.A : Neutral axis
– : The coefficient 0.85 in (c) takes into account the difference between laboratory and site strength of concrete.
– γ_m : The partial material factor given as 1.5 for concrete and 1.15 for steel and is used to account for the uncertainties in material strength properties at the ultimate limit state (EN 1992-1-1: 2004).
– f_{ck} : The characteristic compressive cylinder strength of concrete at 28 days
– f_{yk} : The characteristic yield strength of the longitudinal reinforcement
– F_{cc} : Resultant force from the compression zone (acting at the centre of that zone)
– F_{st} : Resultant force from the tension zone
– ε_c : Maximum compressive strain in concrete of class < C50/60 = 0.0035
– ε_{st} : Yield strain in steel = 0.00217 for f_{yk} = 500 MPa
– z : Lever arm
– d : Effective depth of the beam (from top of section to centre of reinforcement)
– b : Width of the beam cross-section
– $\bar{x}$: Depth of the neutral axis (from top of section)
– $\bar{y}$: Depth of the neutral axis (from bottom of section)

The following basic assumptions are made when formulating the rectangular stress-block (Mosley *et al*, 2007; Kong and Evans, 1998):

- Concrete cracks in the regions of the tensile strains and after cracking, all the tension is carried by reinforcement.

- Plane cross sections before loading remain plane after loading, giving a linear strain diagram as shown by ***Figure C.1*** (b).
- A perfect bond exists between steel and concrete such that the strain in concrete is the same as in reinforcing bars at the same level.
- The strain distribution in concrete and steel varies linearly with distance from the neutral axis as shown in ***Figure C.1*** (b).
- The ultimate compressive strain at the extreme compression fibre is assumed to be equal to 0.0035.
- The tensile stress of concrete is neglected.
- The stress and strain curves of steel and concrete are known.

From ***Figure C.1*** the concrete compression force is:

$$\left(\frac{0.85}{1.5} f_{ck}\right)(0.8\bar{x})b = 0.45 f_{ck} b\bar{x} \tag{C.1}$$

At equilibrium, the compression force (F_{cc}) is equal to tension force (F_{st}) as expressed by Equation (C.2).

$$0.45 f_{ck} b\bar{x} = A_s \frac{f_{yk}}{1.15} = 0.87 A_s f_{yk} \tag{C.2}$$

and dividing through by *d* and rearranging gives:

$$\frac{\bar{x}}{d} = 1.92 \frac{f_{yk}}{f_{ck}} \left(\frac{A_s}{bd}\right) \tag{C.3}$$

The moment corresponding to the forces in ***Figure C.1*** is either the concrete compression force or the steel tension multiplied by the lever arm (*z*), where *z* is given as:

$$z = d - \left(\frac{0.8\bar{x}}{2}\right) = d - 0.4\bar{x} \tag{C.4}$$

Thus, by taking the moments about the centre of the compression zone, the flexural strength of the RC member at equilibrium is given as:

$$M_{Rd} = 0.87 A_s f_{yk} \left(d - 0.4\bar{x}\right) \tag{C.5}$$

where,

f_{yk}	[MPa]	:	characteristic yield strength of steel

f_{ck}	[MPa]	:	characteristic compressive cylinder strength of concrete
A_s	[mm^2]	:	area of steel reinforcement
$\bar{x}$	[mm]	:	distance from the extreme compression fibre to the neutral axis
b	[mm]	:	width of the beam cross-section
d	[mm]	:	effective beam depth

C.1.2 Evaluating the shear strength constraint

The shear constraint of the beam is evaluated as follows:

$$\mathrm{C}_2 \equiv \frac{\mathrm{V}_{\mathrm{Rd}}}{bd} - \mathrm{V}_{\mathrm{Rd,c}} \leq 0 \tag{C.6}$$

where, $\mathrm{V}_{\mathrm{Rd,c}}$ [kN/mm^2] – is the design shear resistance; b and d [mm] – are the width and depth of the cross section, respectively; V_{Rd} [kN] – is the applied shear and is calculated as follows:

$$V_{Rd,x} = {wl}/{2} \tag{C.7}$$

where, w is the uniformly distributed load on the beam; l– is the effective span of the beam.

The design shear resistance ($\mathrm{V}_{\mathrm{Rd,c}}$) for RC beams is calculated using the following empirical formula (EN 1992-1-1:2004: Clause 6.2.1):

$$V_{Rd,c} = \left[\frac{0.18}{\gamma_c} \left(1 + \sqrt{\frac{200}{d}} \right) \left(100 \rho_1 f_{ck} \right)^{1/3} + k_1 \, \sigma_{cp} \right] b \; d \tag{C.8}$$

where,

γ_c	[-]	:	γ_c = 1.5 for permanent conditions, and γ_c = 1.2 for accidental conditions
d	[mm]	:	effective depth of the reinforcement
ρ_1	[-]	:	reinforcement ratio for longitudinal reinforcement $\rho_1 = \left(\frac{A_{st}}{bd} \right)$
A_{st}	[mm^2]	:	area of tension reinforcement
b	[mm]	:	width of the RC beam
k_1	[-]	:	coefficient of compressive stress = 0.15
σ_{cp}	[N/mm^2]	:	compressive stress of concrete due to direct loading $\sigma_{cp} = \frac{N_{Ed}}{A_c}$
N_{Ed}	[N]	:	axial force in the cross section of the RC beam
A_c	[mm^2]	:	cross-sectional area of the RC beam.

C.2 Deriving the unit environmental impact of concrete as a function of its compressive strength

The unit environmental impact ($Env_{concrete}$) of concrete is a function of the mass and environmental impact of the concrete constituents: aggregates, cement, SCM, water, and any chemical admixture used, as expressed by Equation (C.9).

$$Env_{concrete} = (M_c + M_P)Env_{binder} + M_a Env_a + M_w Env_w + M_{Ad} Env_{Ad} \tag{C.9}$$

where,

$E_{concrete}$: is the unit environmental impact of the concrete measured in exergy/energy/ equivalent carbon emissions or other suitable units.

M [kg/m^3] : is the mass of the constituents in concrete.

The subscripts '*c*', '*P*' '*a*', '*w*' and '*Ad*', refer to the cement, supplementary cementitious material (SCM), aggregates, water, and superplasticizer, respectively.

The total volume (for 1 m^3) of fully compacted concrete is equal to the sum of the absolute volumes of cement, aggregates and water as shown by Equation (C.10) (Addis and Goodman, 2009).

$$V = \frac{1}{1000}\left(\frac{M_c}{RD_c} + \frac{M_P}{RD_P} + \frac{M_a}{RD_a} + \frac{M_w}{RD_w} + w_a\right) = 1m^3 \tag{C.10}$$

where, M_c, M_P, M_a, and M_w [kg/m^3] refer to the mass quantities of cement, SCM, aggregates, water and admixture, respectively; RD are the respective relative densities of the concrete constituents; w_a is the air content of the fresh concrete [%]. The relative density of blends of different materials is calculated as follows (Addis and Goodman, 2009):

$$RD = \frac{100\%}{\frac{\%X}{RD_X} + \frac{Y\%}{RD_Y}} \tag{C.11}$$

where, X and Y are the percentage by mass of the materials X and Y respectively in the blend; and RD – is the relative density of the materials. The relative densities of different cementitious materials and aggregates are given in ***Table C.1***. The relative densities of factory blended cements can also be obtained from the manufacturer.

Table C.1: *Relative densities of concrete constituent materials (Addis and Goodman, 2009).*

Material	***Relative density***
Portland cement	3.14
Ground granulated blast furnace slag	2.90
Fly Ash	2.30

Silica fume	2.10
Natural aggregates	2.65
Recycled aggregates	2.40
Water	1.00

Using Equation (C.10), the aggregate content in concrete can be expressed in terms of binder and water content as follows:

$$M_a = 1000RD_a - \frac{RD_a}{RD_{binder}}\left(M_c + M_p\right) - RD_a M_w - RD_a w_a \qquad \text{(C.12)}$$

where, RD_{binder} is the relative density of the binder, and is calculated using Equation (C.11); and RD_a is the relative density of the aggregate.

Hence, by substituting Equation (C.12) into Equation (C.9), an expression for the unit environmental impacts of concrete as a function of cement, SCM and water content and unit environmental impacts of the concrete constituents is obtained follows:

$$\begin{aligned} &Env_{concrete} = \left(M_c + M_P\right)Env_{binder} + \\ &\left(1000RD_a Env_a - \frac{RD_a}{RD_{binder}}\left(M_c + M_P\right)Env_a - RD_a M_w Env_a - 2.65 w_a Env_a\right) \\ &+ M_w Env_w + M_{Ad} Env_{Ad} \end{aligned} \qquad \text{(C.13)}$$

Also the Bolomey strength equation is expressed as:

$$f_{ck} = K_B\left(\frac{1}{M_w/\left(M_c + kM_P\right)} - a\right) \qquad \text{(C.14)}$$

where, K_B [MPa] – is the Bolomey coefficient that depends on the aggregate type and cement strength, and is assumed to be 21.3 MPa for all concrete types; M_w [kg/m^3] – is the water content; M_c [kg/m^3] – is the cement content; M_P [kg/m^3]– is the content of the supplementary cementitious material (SCM) in concrete; M_{Ad} [mL/m^3] – is the superplasticizer content; k – cementing efficiency factor as given in *Table 5.5* (Chapter 5); and a [-] – depends on the time and curing of the concrete and is estimated as 0.5 for f_{ck} at 28 days (Papadakis and Tsimas, 2002);

From the Bolomey's strength model (Equation (C.14)), we can express the M_c, M_P, and M_w as follows:

$$M_c = \left[M_w \left(\frac{f_{ck}}{K_B} + a \right) - kM_p \right]$$

$$M_P = \left[M_w \left(\frac{f_{ck}}{K_B} + a \right) - M_c \right] \frac{1}{k} \tag{C.15}$$

$$M_w = \frac{M_c + kM_p}{\dfrac{f_{ck}}{K_B} + a}$$

where,

K_B	[MPa]	:	is the Bolomey coefficient that depends on the aggregate type and is assumed to be 21.3 MPa for all concrete types
k	[-]	:	is the efficiency factor of the respective supplementary cementitious material as given in *Table 5.5* (Chapter 5). The *k*-factor is used in this study to distinguish between the various types of binders.
a	[-]	:	is a parameter that depends on the time and curing of the concrete and is estimated as 0.5 for f_{ck} at 28 days (Papadakis and Tsimas, 2002)
f_{ck}	[MPa]	:	28-day cylinder compressive strength

The other parameters in Equation (C.15) are as defined previously.

By using Equation (C.15) we can express the environmental impacts of concrete as a function of the binder type (distinguished by the k factor); mass of binder (M_c and M_p); and the 28-day cylinder compressive strength of concrete (f_{ck}) as follows:

$$\begin{aligned} Env_{concrete} = {} & \left[M_w \left(\frac{f_{ck}}{K_B} + a \right) - kM_P \right] Env_{binder} + \left[M_w \left(\frac{f_{ck}}{K_B} + a \right) - M_c \right] \frac{Env_{binder}}{k} + 1000 RD_a Env_a - \\ & \frac{RD_a}{RD_{binder}} \left[M_w \left(\frac{f_{ck}}{K_B} + a \right) - kM_P \right] Env_a - \frac{RD_a}{RD_{binder}} \left[M_w \left(\frac{f_{ck}}{K_B} + a \right) - M_c \right] \frac{Env_a}{k} - \\ & RD_a \left[\frac{M_c + kM_P}{\left(\dfrac{f_{ck}}{K_B} + a \right)} \right] Env_a - RD_a w_a Env_a + \left[\frac{M_c + kM_P}{\left(\dfrac{f_{ck}}{K_B} + a \right)} \right] Env_w + M_{Ad} Env_{Ad} \end{aligned} \tag{C.16}$$

From Equation (C.16) one can compute the unit environmental impacts (kg CO_2-eq/m^3) of concrete based on the mix-composition of concrete and its characteristic compressive strength (f_{ck}) at 28-days.

C.3 Generalized reduced gradient optimization algorithm

Due to the non-linear nature of the objective and constraint functions, the optimization problems in Chapter 5 and 6 are solved using a non-linear programming technique based on the generalized reduced gradient (GRG) optimization algorithm.

The GRG algorithm was first introduced by Abadie and Carpentier (1969) and has been applied extensively in literature.

The GRG is an extension of the reduced gradient technique for linear constraints. The GRG is extended to cover both linear and non-linear constraints.

The general optimization problem described in Chapter 5 and 6 of this study is represented by a non-linear objective function and a mix of linear and non-linear constraint functions as follows:

$$\left.\begin{array}{llll} \text{Minimize } f(X) & & & \\ \text{Subject to} & & & \\ h_i(X)=0 & \text{i } = 1,\ldots,\text{J} & J & \text{Equality constraints} \\ 0 \le g_i(X) \le ub_{(n+i)} & \text{i } = 1,\ldots,\text{K} & K & \text{Inequality constraints} \\ lb_i \le x_i \le ub_i & \text{i } = 1,\ldots,\text{L} & L & \text{Side constraints} \end{array}\right\} \qquad \text{(C.17)}$$

where,

$f(X)$	:	the objective function in the present study is the life-cycle environmental impact
$X = \{x_1, x_2, .. x_N\}$	:	a vector of *n* design variables
$h_i(X) = 0$	:	J^{th} equality constraint function
$g_i(X) \le 0$	:	K^{th} inequality constraint function
lb_i, ub_i	:	are respectively the lower- and upper-bounds, of the design variables

The GRG algorithm begins by converting the non-linear equations by their linear Taylor approximation at the current value of [**X**]. This involves computing the partial derivative of each function with respect to each variable in the vector [**X**], following which the reduced gradient algorithm is applied to the result.

In the reduced gradient technique described in Drud (1994), the aim is to find a local minimum of the objective function using a gradient descent. Each step in the gradient descent is proportional to the negative of the gradient of the objective function at the current point X.

C.4 References

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D-1. APPENDIX D: ADDITIONAL INFORMATION FOR CHAPTER 6

This Section contains additional information for the case studies used in Chapter 6.

D.1 Reinforced concrete building

The floor area for the reinforced concrete (RC) framed, New Engineering Building (NEB) is computed in ***Table D.1***.

Table D.1: *Floor area for the New Engineering Building*

Level	*Area [m^2]*
1	3 144
2	3 263
3	2 469
4	2 118
5	2 010
6	1 536
Total floor area	***14 540***

D.2 Life-cycle inventory data

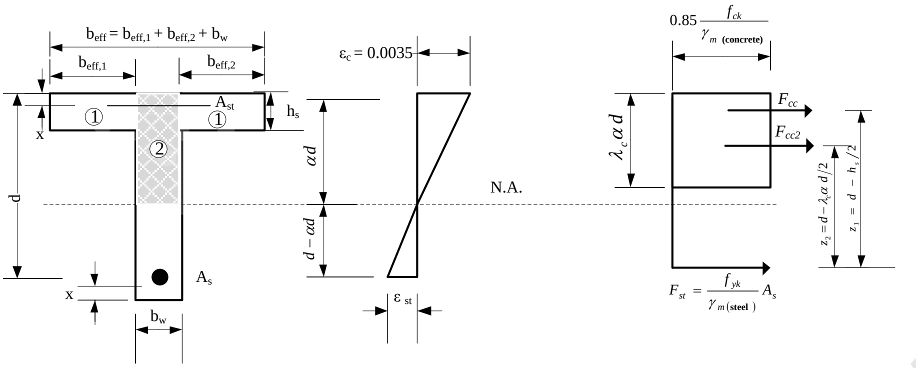
Table D.2 specifies the life-cycle inventory data in Simapro 7.1 software for the 30 MPa concrete used in the NEB. The data sources used for all concrete mix constituents, except for the superplasticizer (European Federation of Concrete Admixture Associations, 2006) were the Ecoinvent database 2.0 and the ELCD (European reference Life Cycle Database), in the SimaPro 7.1 software.

Table D.2: *Product assembly in SimaPro for 1 m^3 of 30 MPa concrete in the New Engineering Building.*

Name	**Corresponding name in SimaPro**	**Quantity**	**Units**
	Products		
30 MPa concrete	30 MPa Concrete - NEB	2371	kg
	Materials/fuels		
CEM I 52.5N	Portland cement, strength class Z 52.5, at plant/CH U	203	kg
Blast furnace slag	Blast furnace slag cement, at plant/CH U	68	kg
Coarse aggregates	Crushed stone 16/32, open pit mining, production mix, at plant, undried RER S	1011	kg
Fine aggregates - Crusher sand	Crushed stone 16/32, open pit mining, production mix, at plant, undried RER S	472	kg
Fine aggregates -Dune sand	Sand 0/2, wet and dry quarry, production mix are plant, RER S	445	kg
Water	Tap water, at user/CH U	172	kg
Superplasticizer	Input resources and emissions to air, land and water	1.623	kg
	Electricity/heat		
Cement and slag to ready mix	Transport, lorry >32t, EURO3/RER U	35.501	tkm
Aggregates	Transport, lorry >32t, EURO4/RER U	46.272	tkm
Concrete to site	Transport, lorry >16t, fleet average/RER U	42.678	tkm
Ready mix plant operations: Marceau *et al*. (2007)	Electricity, hard coal, at power plant/AT U	12	kWh
Superplasticizer transport to readymix plant	Transport, lorry 3.5-7.5t, EURO5/RER U	0.01623	tkm

D.3 Evaluating the flexural strength of a ribbed slab

The nominal yielding moment (M_{Rd}) for a ribbed slab section is similar to that of a reinforced concrete T-section and is evaluated using the rectangular stress diagram as shown in ***Figure D.1***.



(a) Cross section (b) Strains (c) Rectangular stress block and Internal forces

Figure D.1: *T-cross-section, strain, stress and internal forces, with neutral axis in the web (EN 1992-1-1: 2004).*

– A_s : Area of tension steel
– N.A : Neutral axis
– : The coefficient 0.85 in (c) takes into account the difference between laboratory and site strength of concrete.
– γ_m : The partial material factor given as 1.5 for concrete and 1.15 for steel and is used to account for the uncertainties in material strength properties at the ultimate limit state (EN 1992-1-1: 2004).
– f_{ck} : The characteristic compressive cylinder strength of concrete at 28 days
– f_{yk} : The characteristic yield strength of the longitudinal reinforcement
– F_{cc} : Resultant force from the compression zone (acting at the centre of that zone)
– F_{st} : Resultant force from the tension zone
– ε_c : Maximum compressive strain in concrete of class < C50/60 = 0.0035
– ε_{st} : Yield strain in steel = 0.00217 for f_{yk} = 500 MPa
– d : Effective depth of the concrete section(from top of section to centre of reinforcement)
– b_w : Width of the rib web
– b_{eff} : Effective width of the flange
– $b_{eff,1}$: $= 0.2l_o$
– $b_{eff,2}$: $= 0.2l_o$
– l_o : = Span distance between points of zero moments
– h_s : Flange thickness
– λ_c : Relative depth of the compressive concrete zone = 0.8

The following basic assumptions are made when formulating the rectangular stress-block (Mosley *et al*, 2007; Kong and Evans, 1998):

- Concrete cracks in the regions of the tensile strains and after cracking, all the tension is carried by reinforcement.
- Plane cross sections before loading remain plane after loading, giving a linear strain diagram as shown by ***Figure D.1***(*b*).
- A perfect bond exists between steel and concrete such that the strain in concrete is the same as in reinforcing bars at the same level.
- The strain distribution in concrete and steel varies linearly with distance from the neutral axis as shown in ***Figure D.1*** (*b*).

- The ultimate compressive strain at the extreme compression fibre is assumed to be equal to 0.0035.
- The tensile stress of concrete is neglected.
- The stress and strain curves of steel and concrete are known.

From ***Figure D.1*** the concrete compression forces F_{cc} and F_{cc2} are:

$$\begin{aligned}&\left(\frac{0.85}{1.5}f_{ck}\right)\left((\lambda_c \alpha d)b_w + h_s\left(b_{eff}-b_w\right)\right)\\&=0.57f_{ck}\left(\lambda_c \alpha d b_w + h_s\left(b_{eff}-b_w\right)\right)\end{aligned} \tag{D.1}$$

At equilibrium, the compression forces (F_{cc} and F_{cc2}) are equal to tension force (F_{st}) as expressed by Equation (D.2).

$$0.57f_{ck}\left(\lambda_c \alpha d b_w + h_s\left(b_{eff}-b_w\right)\right)=A_s\frac{f_{yk}}{1.15} \tag{D.2}$$

and dividing through by $\lambda_c b_w d$ and rearranging gives internal force equilibrium as follows:

$$\alpha=\left(\frac{f_{yk}}{0.66f_{ck}}\right)\left(\frac{A_s}{\lambda_c b_w d}\right)-\left(b_{eff}-b_w\right)\frac{h_s}{\lambda_c b_w d} \tag{D.3}$$

By taking moments about the tension zone, the flexural strength (M_{Rd}) of the RC member at equilibrium is given as:

$$M_{Rd}=0.85\frac{f_{ck}}{\gamma_m}\left(b_{eff}-b_w\right)\,h_s\left(d-\frac{h_s}{2}\right)+\lambda_c\frac{0.85f_{ck}}{\gamma_m}b_w d^2\alpha\left(1-\frac{\lambda_c\alpha}{2}\right) \tag{D.4}$$

where,

f_{ck}	[MPa]	:	characteristic compressive cylinder strength of concrete
b_w	[*mm*]	:	width of the web
b_{eff}	[*mm*]	:	effective width of the flange
h_s	[*mm*]	:	thickness of the flange
α	[-]	:	internal force equilibrium as expressed by Equation (D.3)

D.4 Evaluating the ultimate bending moment of ribbed slab

The ultimate design moment, due to a uniformly distributed live load (q_k) and dead load (g_k) at mid-span of the RC slab is calculated for the shorter span as follows:

$$M_{Edx} = \beta_{sx} w l_x^2 \tag{D.5}$$

where,

w	[kN/m]	:	ultimate design load as given by Equation (D.6)
l_x	[m]	:	shorter span
$ß_{sx}$	[-]	:	bending moment span coefficient in the directions of the shorter span, and is given in ***Table D.3***
M_{Edx}		:	ultimate design bending moments for the shorter span

Table D.3: *Bending moment coefficients for a reinforced concrete slab (EN 1991-1-1).*

Interior panel	*Bending moment coefficient in the shorter span ($ß_{sx}$)*
Negative moment at continuous support	-0.063*wl*
Positive moment at mid span	0.048*wl*

For simplification, it shall be assumed that the reinforcement provision in the longer span shall be similar to that of the shorter span.

Considering 1 *m* width of the floor is supported by each rib, then the ultimate design load is given as:

$$w = \gamma_g g_k + \gamma_q q_k \tag{D.6}$$

γ_g	[-]	:	partial load factor for the dead load and is given as: γ_g = 1.35, in EN 1992-1-1:2004
γ_q	[-]	:	partial load factor for the live load and is given as: γ_q = 1.5, in EN 1992-1-1:2004.
g_k	[kN/m^2]	:	permanent load including self-weight and finishes
q_k	[kN/m^2]	:	variable load

Equation (D.7) gives g_k as the sum of the slab's self-weight and a floor finishing load of 1.5 kN/m^2.

$$\mathrm{g_k} = \frac{\rho_c}{100}\left(\left[\begin{matrix}\left(\frac{b_{eff}}{1000}\times\frac{h_s}{1000}\right)+\left(\frac{b_w}{1000}\times\frac{(d+x+\phi/2-h_s)}{1000}\right)+ \\ \left(2\times{}^{1}\!/_{2}\times\frac{(d+x+\phi/2-h_s)}{1000}\times\frac{(d+x+\phi/2-h_s)}{10\times1000}\right)\end{matrix}\right]-\frac{A_s}{1000^{\,2}}\right)+\frac{\rho_s}{100}\frac{A_s}{1000^{\,2}}+1.5 \tag{D.7}$$

where, b_{eff} [mm] – is the effective flange (slab) width; h_s [mm] – slab thickness; d [mm] – effective depth of the slab; x [mm] – cover depth; $Ø$ [mm] – steel diameter; A_s [mm] – Area of steel; ρ_c [kg/m^3] – is the density of concrete; ρ_s [kg/m^3] – is the density of steel. In addition, the slope of the web is assumed to be ${}^{1}\!/_{10}$.

The 6-floor of the New Engineering Building office area for staff and students hence the characteristic uniformly distributed live load (q_k) on the RC waffle slab is taken as 5 kN/m^2 (EN 1991-1-1).

D.5 Evaluating the shear strength of the ribbed slab

The shear constraint of the slab is evaluated as follows:

$$C_2 \equiv \frac{V_{Rd}}{b_{eff}\ d} - V_{Rd,c} \le 0 \qquad \text{(D.8)}$$

where, $V_{Rd,c}$ [kN/mm^2] – is the design shear resistance; b_{eff} and d [mm] – are the effective width and depth of the cross section, respectively; V_{Rd} [kN] – is the applied shear and is calculated as follows for the shorter span:

$$V_{Rd,x} = \beta_{sx} w \, {}^{l_x}\!/_{2} \qquad \text{(D.9)}$$

where, w is as given previously by Equation (D.6); l_x and l_y– are the effective spans of the slab in the x- and y-direction respectively; $ß_{sx}$ is the shear coefficient in the direction of the shorter span, and is given in ***Table D.4***.

Table D.4: *Shear coefficients for slabs (EN 1992-1-1:2004).*

Interior panel	*Short span coefficients* *l_y/l_x=2.0*
Negative moment at continuous support	0.5w
Positive moment at mid span	-

The design shear resistance ($V_{Rd,c}$) for concrete slabs is calculated using the following empirical formula (EN 1992-1-1:2004: Clause 6.2.1):

$$V_{Rd,c} = \left[\frac{0.18}{\gamma_c} \left(1 + \sqrt{\frac{200}{d}} \right) \left(100 \rho_1 f_{ck} \right)^{1/3} + k_1 \, \sigma_{cp} \right] b_w \ d \qquad \text{(D.10)}$$

where,

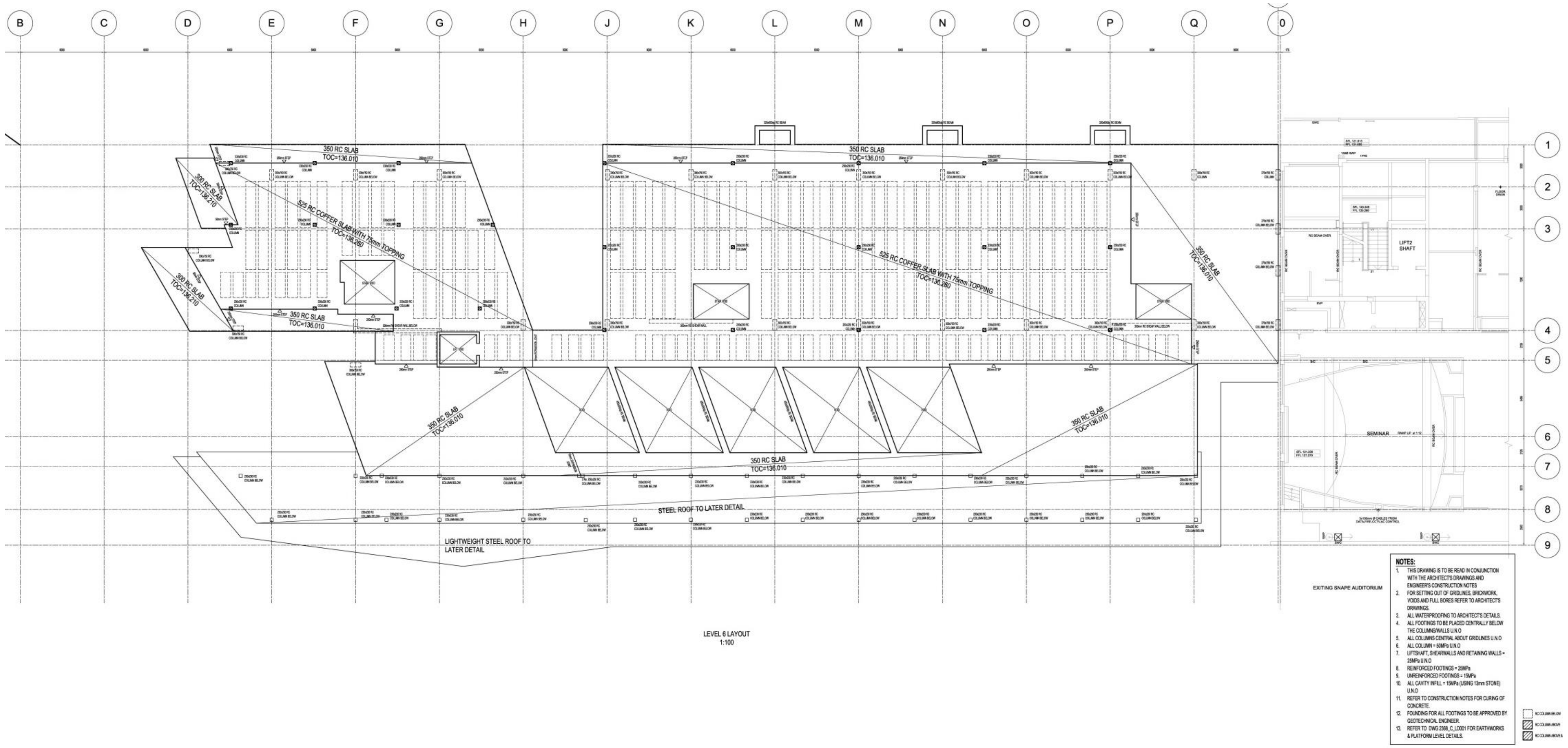
γ_c	[-]	:	γ_c = 1.5 for permanent conditions, and γ_c = 1.2 for accidental conditions
d	[mm]	:	effective depth of the reinforcement
ρ_1	[-]	:	reinforcement ratio for longitudinal reinforcement $\rho_1 = \left(\frac{A_{st}}{b_w d} \right)$
A_{st}	[mm^2]	:	area of tension reinforcement
b_w	[mm]	:	width of the slab = 1 m
k_1	[-]	:	coefficient of compressive stress = 0.15
σ_{cp}	[N/mm^2]	:	compressive stress of concrete due to direct loading

$$\sigma_{cp} = \frac{N_{Ed}}{A_c}$$

N_{Ed}	[N]	:	axial force in the cross section of the slab
A_c	[mm^2]	:	cross-sectional area of the concrete slab.

D.6 New Engineering Building Floor Plan

Figure D.2 shows the floor plan of the New Engineering Building.



NOTES:

1. THIS DRAWING IS TO BE READ IN CONJUNCTION WITH THE ARCHITECT'S DRAWINGS AND ENGINEER'S CONSTRUCTION NOTES
2. FOR SETTING OUT OF GRIDLINES, BRICKWORK, VOIDS AND FULL BORES REFER TO ARCHITECT'S DRAWINGS.
3. ALL WATERPROOFING TO ARCHITECT'S DETAILS.
4. ALL FOOTINGS TO BE PLACED CENTRALLY BELOW THE COLUMNS/WALLS U.N.O
5. ALL COLUMNS CENTRAL ABOUT GRIDLINES U.N.O
6. ALL COLUMN = 50MPa U.N.O
7. LIFTSHAFT, SHEARWALLS AND RETAINING WALLS = 25MPa U.N.O
8. REINFORCED FOOTINGS = 25MPa
9. UNREINFORCED FOOTINGS = 15MPa
10. ALL CAVITY INFILL = 15MPa (USING 13mm STONE) U.N.O
11. REFER TO CONSTRUCTION NOTES FOR CURING OF CONCRETE.
12. FOUNDING FOR ALL FOOTINGS TO BE APPROVED BY GEOTECHNICAL ENGINEER.
13. REFER TO DWG 2368_C_LD001 FOR EARTHWORKS & PLATFORM LEVEL DETAILS.

Figure D.2: *Level 6 floor plan of the New Engineering Building.*

D.7 Structural geometry of the cross-section of a box girder

The box girder cross-sectional geometry (A_c, y_b, y_t, I_{xx}, Z_t, Z_b) discussed in Chapter 6 (Case study II) are determined using the following equations:

The cross-sectional area (A_c) of the box girder is calculated as:

$$A_c = (b_{tf} \times t_{tf}) + (2 \times t_w \times (H - t_{tf} - t_{bf})) + (b_{bf} \times t_{bf}) \tag{D.11}$$

The distance from the neutral axis to the bottom fibre (y_b) is calculated as:

$$y_b = \frac{\left(\begin{array}{l} \left(b_{tf} \times t_{tf} \times \left(H - {t_{tf}}/{2}\right)\right) + (2 \times t_w \times (H - t_{tf} - t_{bf})) \times \\ \left(\dfrac{(H - t_{tf} - t_{bf})}{2} + t_{bf}\right) \\ + (b_{bf} \times t_{bf}) \times \left({t_{tf}}/{2}\right) \end{array}\right)}{A_c} \tag{D.12}$$

The distance from the neutral axis to the top fibre (y_t) is calculated as:

$$y_t = H - y_b \tag{D.13}$$

The second moment of area (I_x) about the box girder section is calculated as follows:

$$\begin{aligned} I_x = {} & \frac{1}{12}(b_{tf} \times t_{tf}^3) + \left(b_{tf} \times t_{tf} \times \left(y_t - {t_{tf}}/{2}\right)^2\right) + \\ & 2 \times \left(\frac{1}{12} t_w (H - t_{tf} - t_{bf})^3\right) + 2 \times \left(\begin{array}{l} t_w (H - t_{tf} - t_{bf}) \times \\ \left(y_b - \dfrac{(H - t_{tf} - t_{bf})}{2} - t_{bf}\right)^2 \end{array}\right) \\ & + \frac{1}{12}(b_{bf} \times t_{bf}^3) + b_{bf} \times t_{bf} \times \left(y_b - {t_{bf}}/{2}\right)^2 \end{aligned} \tag{D.14}$$

The section modulus at the top fibre (Z_t) and that at the bottom fibre (Z_b), are calculated as:

$$Z_t = {I_c}/{y_t} \tag{D.15}$$

$$Z_b = {}^{I_c}\!/_{y_b} \tag{D.16}$$

D.8 Evaluating the ultimate moment and shear capacity of the post-tensioned concrete box girder

The post-tensioned concrete box girder is subject to different types of loading during its design life, which includes dead load, live loading, environmental loads (wind, earthquake), and others (including braking load). This study only considers the dead and live loading on the structure. The ultimate moment and shear capacity of the box girder are computed by analyzing the loading on the structure in the transverse direction of the structure. The box-girder is modeled as a plane frame structure of unit length having pinned supports at the bottom of the web walls.

D.8.1 Dead load analysis

The dead load comprises of: (1) the self-weight of the box girder; and (2) the superimposed precast concrete parapet barriers and bituminous surface finishing on the deck. In the calculations, γ_g is the partial load factor for the dead load and superimposed dead load and is taken as follows at ULS: 1.15 for concrete; 1.75 for deck surfacing; and 1.20 for the parapet loading (EN 1991-2:2003). The total dead load per unit length [kN/m] is calculated as follows:

(1)	Self-weight of box girder	:	$\rho_c \times g \times A_c$	:	(24 kN/m^3 × A_c m^2) kN/m
			Factored self-weight	:	24 A_c kN/m × 1.15 × 1.15= 31.74 A_c kN/m
(2)	Superimposed load	:	50 *mm* thick bitumen wearing surface	:	21 kN/m^3 × 9 *m* × 0.05 *m* = 9.45 kN/m
			Factored load	:	(9.45 kN/m × 1.75 × 1.15) = 19 kN/m
		:	Parapet barrier (500 *mm* wide and 635 *mm* high)	:	24 kN/m^3 × 1.0 *m* × (0.5 *m* × (0.475 *m* + 0.16 *m*) = 7.62 kN/m
			Factored load	:	(7.62 kN/m × 1.20 × 1.15) = 10.52 kN

At the ultimate limit-state (ULS), the bending moment due to the dead loading (M_g) [kN-m] is calculated as a function of the cross-sectional area of the box girder (A_c) as follows:

$$M_{g,ULS} = \left(\frac{31.74 A_c \times 29^2}{8} + \frac{19 \times 29^2}{8} + \frac{10.52 \times 29}{4} \right) = 3337\, A_c + 2074 \tag{D.17}$$

Similarly at serviceability limit-state (SLS) the bending moment is given as:

$$M_{g,SLS} = \left(\frac{24A_c \times 29^2}{8} + \frac{9.45 \times 29^2}{8} + \frac{7.62 \times 29}{4} \right) = 2523\ A_c + 1049 \tag{D.18}$$

The shear force due to the dead load at SLS is calculated as follows:

(1) Shear force for UDL :

$$R_A = R_B = \frac{\left((24\ \ A_c) \times \left(\frac{29}{2} \right) \times 29 \right)}{29} = 348\ A_c\ \text{kN}$$

$$V_{UDL} = (348\ \ A_c) - (24A_c + 9.45) \times 1 = 324\ A_c - 9.45\ \text{kN}$$

(2) Shear force for Point loads : 7.62 kN × 2 = 15.24 kN

:

$$R_A = \frac{(15.24 \times (29-1))}{29} = 14.7\ \text{kN}$$

$$R_B = \frac{(15.24 \times 1)}{29} = 0.53\ \text{kN}$$

$$V_p = 14.7\ \text{kN}$$

Total : $V_p + V_{UDL} = 324\ \ A_c - 9.45 + 14.7 = 324\ A_c + 5.25\ \text{kN}$

Similarly, at ULS the maximum shear force one metre from the left support section due to the dead and superimposed dead load is calculated as follows:

(1) Shear force for UDL :

$$R_A = R_B = \frac{\left((31.74\ \ A_c) \times \left(\frac{29}{2} \right) \times 29 \right)}{29} = 460.23\ A_c\ \text{kN}$$

$$V_{UDL} = (460.23\ \ A_c) - (31.74A_c + 19) \times 1 = 428.49\ A_c\ \text{-}19\ \text{kN}$$

(2) Shear force for point loads : 7.62 kN × 2 × 1.20 × 1.15 = 21 kN

:

$$R_A = \frac{(21 \times (29-1))}{29} = 20.3\ \text{kN}$$

$$R_B = \frac{(21 \times 1)}{29} = 0.72\ \text{kN}$$

$$V_p = 20.3\ \text{kN}$$

Total : $V_p + V_{UDL} = 428.5\ A_c - 19 + 20.3 = 428.5\ A_c + 1.3$ kN

D.8.2 Live load analysis

In addition to the dead load, the box girder is designed to carry a normal traffic loading in accordance with Eurocode 1 (EN 1991-2:2003). The carriageway width is 9 *m* hence the deck has 3 notional lanes each having a width of 3 *m*. This study considers the sagging bending moments and shear force due to the extreme loading case on the deck.

D.8.2.1 Traffic load model 1 in Eurocode 1

The load model 1 in Eurocode 1 (EN 1991-2: 2003) consists of a pair of axles referred to as a tandem system (TS) superimposed over a uniformly distributed load (UDL) over the full width of a traffic lane. The carriageway has three notional lanes, each 3 *m* in width. The load model 1 is applied on each of the notional lanes and the remaining area of the carriageway as illustrated in ***Figure D.4***.

The contact surface of each wheel is a square of side 0.4 *m*.

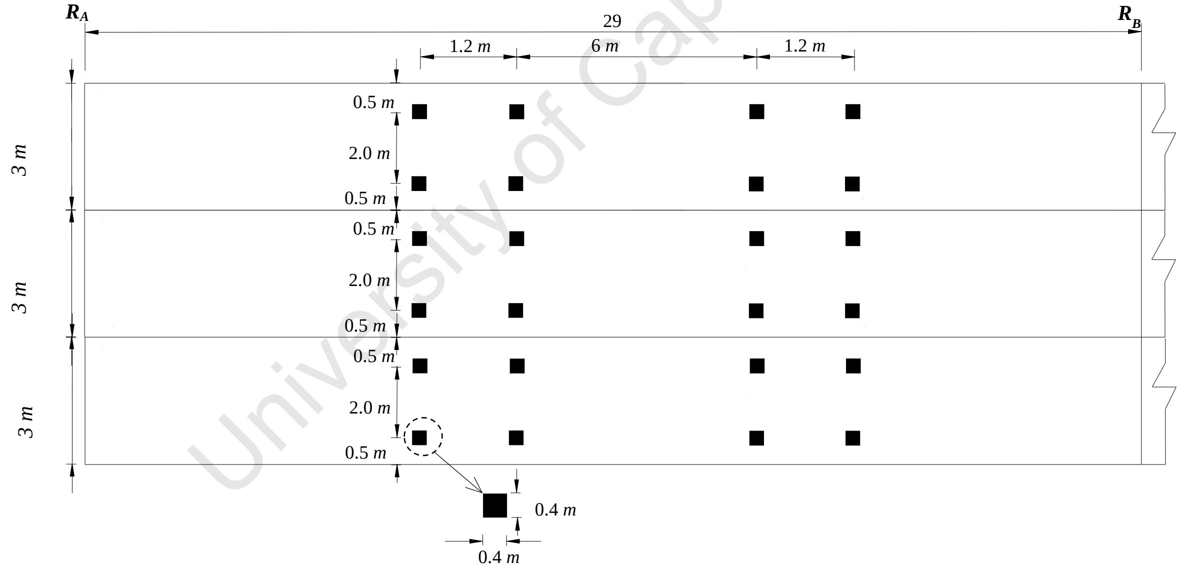


Figure D.3: *Plane view of Eurocode traffic load model 1 lane loading (EN 1991-2: 2003) on three notional lanes of the deck for the first span.*

Figure D.4 shows the transverse section of the traffic load model 1 on a unit length of the carriageway. The traffic loading is strategically placed in order to produce the maximum sagging moment in the bottom slab.

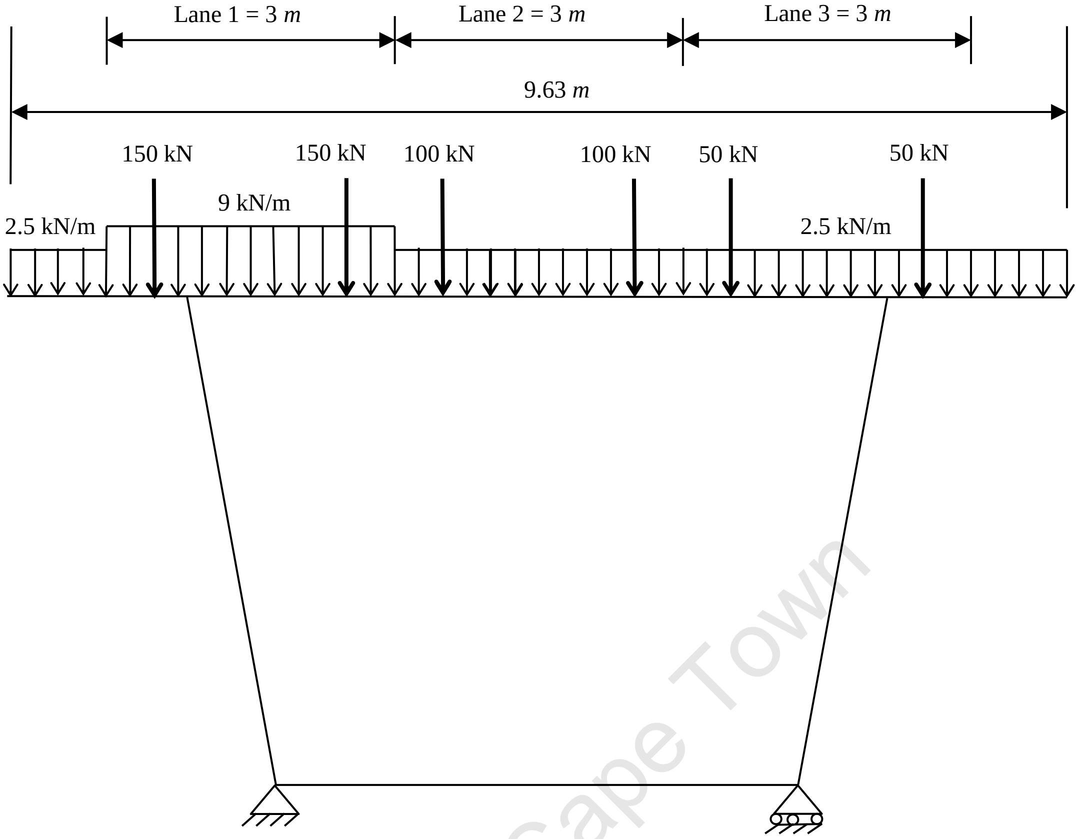


Figure D.4: *Transverse section of the concrete box girder showing the traffic loading per unit length.*

The resulting transverse bending moments in the box girder due to the traffic loads are approximated as follows:

(1) UDL : $2.5\ \text{kN/m}^2 \times 6.63\ \text{m} + 9\ \text{kN/m}^2 \times 3\ \text{m} = 43.6\ \text{kN/m}$

:

$$R_A = R_B = \frac{\left(43.6 \times \left(\frac{29}{2}\right) \times 29\right)}{29} = 632.2\ \text{kN}$$

$$M_{UDL} = \frac{\left(43.6 \times 29^2\right)}{8} = 4583\ \text{kNm}$$

(2) Tandem load : $(150\ \text{kN} \times 2) + (100\ \text{kN} \times 2) + (50\ \text{kN} \times 2) = 600\ \text{kN}$

:

$$R_A = \frac{\left(600 \times \left(\frac{29}{2} - 1.2\right) + 600 \times \left(\frac{29}{2}\right)\right)}{29} = 575\ \text{kN}$$

$$R_B = \frac{\left(600 \times \left(\frac{29}{2} + 1.2\right) + 600 \times \left(\frac{29}{2}\right)\right)}{29} = 625\ \text{kN}$$

			$M_{axle} = \frac{(575 \times 29)}{2}$ = 8340 kNm
	Total	:	$M_{axle} + M_{UDL} = 8340 + 4583 =$ 12923 kNm

The calculation of the maximum shear force one metre from the left support section due to the traffic loads is as follows:

(1)	Shear force for UDL	:	2.5 kN/m^2 × 6.63 m + 9 kN/m^2 × 3 m = 43.6 kN/m
		:	$R_A = R_B = \frac{\left(43.6 \times \left(\frac{29}{2}\right) \times 29\right)}{29}$ = 632.2 kN $V_{UDL} = 632.2 - 43.6 \times 1 =$ 589 kN
(2)	Shear force for tandem load	:	150 kN × 2 + 100 kN × 2 + 50 kN × 2 = 600 kN
		:	$R_A = \frac{(600 \times (29 - 1) + 600 \times (29 - 1 - 1.2))}{29}$ = 1134 kN $R_B = \frac{(600 \times (1 + 1.2) + 600 \times 1)}{29}$ = 66 kN V_{axle} = 1134 kN
	Total	:	$V_{axle} + V_{UDL} = 1134 + 589 =$ 1723 kN

D.8.3 Summary of ultimate moment and shear force on the concrete box girder

In summary, the maximum bending moment and shear force at ULS and SLS are given as follows:

(1)	Mid-span moment	SLS	12923 kNm + 2523 A_c+1049= 13972 + 2523 A_c
		ULS	17446 kNm + 3337 A_c +2074=19520 + 3337 A_c
(2)	Shear force at the supports	SLS	1723 kN +324 A_c +5.25 kN =1866 + 324 A_c
		ULS	2326 kN +428.5 A_c +1.3 kN = 2522 + 428.5 A_c

D.8.4 Load combinations

The load combination (E_d) consists of: (i) the tandem system (Q_k) and uniformly distributed load (q_k) of traffic load model 1 (EN 1991-2:2003), (ii) dead weight load (g_{k1}), (iii) superimposed dead load (g_{k2}), and (iv) prestressing load (with direct losses and time dependent losses) (Q_p).

At ULS E_d is evaluated as follows (EN 1990):

$$E_d = \gamma_{g1} g_{k1} + \gamma_{g2} g_{k2} + \gamma_q Q_k + \gamma_q q_k + \gamma_q Q_p \tag{D-19}$$

where, γ_{g1} – is the partial load factor of dead load and is taken as 1.20; γ_{g2} – is the partial load factor of 1.20 for superimposed load; γ_q – is the partial load factor of live loading and is taken as 1.5, and γ_q – is the partial load factor of prestressing loads and is taken as 1.0.

At SLS E_d is evaluated as follows (EN 1990):

$$E_d = \gamma_{g1} g_{k1} + \gamma_{g2} g_{k2} + \gamma_q Q_k + \gamma_q q_k + \gamma_q Q_p \tag{D-20}$$

where, γ_{g1} – is the partial load factor of dead load and is taken as 1.0; γ_{g2} – is the partial load factor of 1. 0 for superimposed load; γ_q – is the partial load factor of live loading and is taken as 1.0 at SLS, and γ_q – is the partial load factor of prestressing loads and is taken as 1.0.

D.9 Evaluating the post tensioning load on the box girder

The stress (σ_d) in prestressed concrete at the time of transfer is caused by: (i) the prestress force (P) acting on a cross sectional area (A_c) of the concrete component (ii) the self-weight of the concrete, and (iii) a bending moment (M_t) due to the self-weight of the concrete component. The stress distributions along the cross-section at the point of prestress transfer and during the service life are illustrated in ***Figure D.5*** and ***Figure D.6*** , respectively.

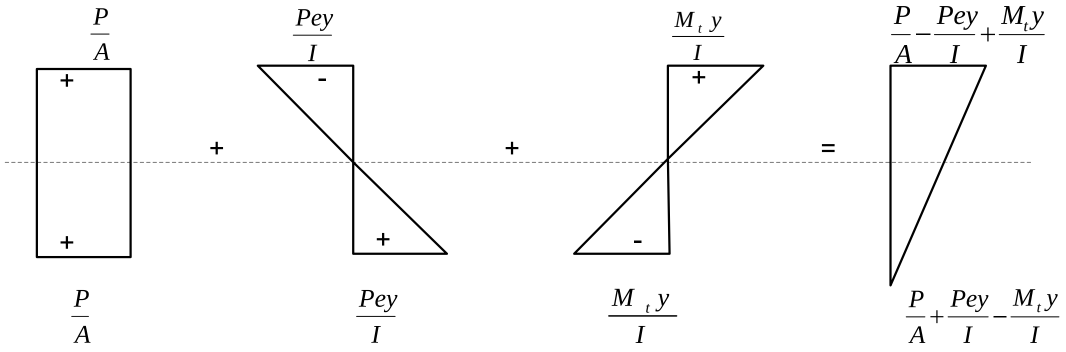


Figure D.5: *Illustration of the stress distribution at prestress at transfer.*

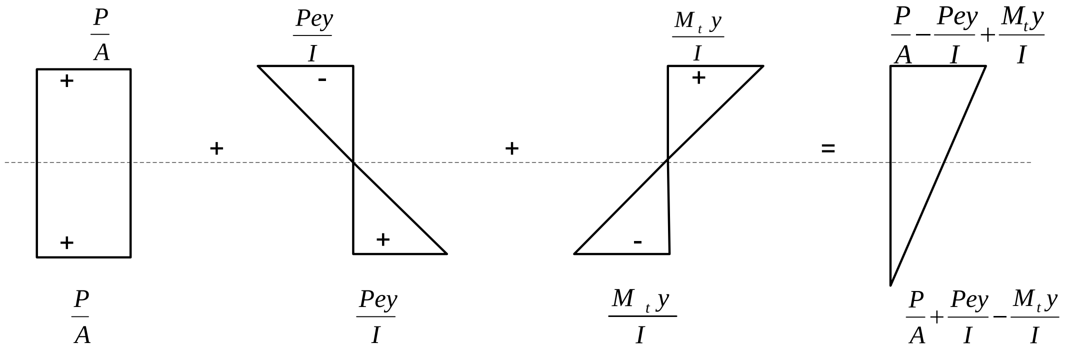


Figure D.6: *Illustration of the stress distribution at prestress at service.*

Thus, σ_d in concrete is computed as follows:

$$\sigma_d = \frac{P}{A_c} \pm \frac{Pe}{Z} \pm \frac{M_t}{Z} \tag{D.21}$$

where, A_c [mm^2] – is the cross-sectional area of the concrete section; e [mm] –is the eccentric distance between the prestressing tendons and a members' neutral axis; Z [mm^3] – is the section modulus of a structural component ; M_t [Nmm] – is the moment at transfer due to the self-weight of the concrete

To ensure that σ_d in concrete does not exceed an allowable (compressive and tensile) stress value, the limits to the design stress in concrete (σ_d) are given as (EN 1992-1-1:2004):

$$f_{tt} \leq \sigma_d \leq f_{bt} \tag{D.22}$$

where, f_{tt} [MPa] and f_{bt} [MPa] are the allowable top and bottom fibre stress at prestress at transfer, respectively.

Hence, the concrete stress limitations due to prestress transfer present two constraints: C_1 and C_2, given by Equation (D.23) and Equation (D.24), respectively.

$$C_1 \equiv f_{tt} - \left[\frac{P_o}{A_c} - \frac{P_o e}{Z_t} + \frac{M_g}{Z_t} \right] \leq 0 \tag{D.23}$$

$$C_2 \equiv \left[\frac{P_o}{A_c} + \frac{P_o e}{Z_b} - \frac{M_g}{Z_b} \right] - f_{bt} \leq 0 \tag{D.24}$$

Similarly during the service life of the structure, the design stress (σ_d) should not exceed the allowable compressive and tensile stress such that:

$$f_{bw} \leq \sigma_d \leq f_{tw} \tag{D.25}$$

where, f_{bw} [N/mm^2] and f_{tw} [N/mm^2] are the allowable compressive and tensile stress at full service loads, respectively.

Hence, the concrete stress limitations due to stress limitations at full service loads, present two additional constraints: C_3 and C_4, given by Equations (D.26) and (D.27), respectively.

$$C_3 \equiv f_{bw} - \left[\frac{\eta P_o}{A_c} + \frac{\eta P_o e}{Z_b} - \frac{M_s}{Z_b}\right] \leq 0 \tag{D.26}$$

$$C_4 \equiv \left[\frac{\eta P_o}{A_c} - \frac{\eta P_o}{Z_t} + \frac{M_s}{Z_t}\right] - f_{tw} \leq 0 \tag{D.27}$$

D.9.1 Evaluating the moment of resistance of a box girder

The moment of resistance (M_{Rd}) of a box girder section is evaluated using the stress distribution shown in ***Figure D.6***. At ULS the maximum compressive strain arises in the top flange.

Hence, at equilibrium, the sum of all internal compressive forces in the concrete sections (to flange, webs and bottom flange) is equal to the prestressing force (P_o).

By taking moments about the neutral axis, the ultimate moment of resistance of the box girder section (M_{Rd}) is calculated as the sum of the internal compressive forces in the structural components multiplied by their respective lever arm value, as shown by Equation (D.29).

$$M_{Rd} = \left\lfloor F_{ctf} \times y_{tf} + F_{cw} \times y_w + F_{cbf} \times y_{bf} \right\rfloor \tag{D-28}$$

where, F_{ctf}, F_{cw}, F_{cbf} [kN] – are the average internal compressive forces in the top flange, web and bottom flange, respectively; y_{tf}, y_w, y_{bf} [mm] – are the lever arms of the compressive force in the top flange, web and bottom flange, respectively.

The respective values of F_{ctf}, F_{cw}, and F_{cbf} are determined based on the strain distribution across the depth of the box section as follows (EN 1992-1-1:2004: Clause 6.2.1; Kenter, 2010):

$$F_{ctf} = \frac{\left(\varepsilon_{c\max} + \varepsilon_{ctf}\right)/2}{\varepsilon_{c3}} \times f_{cm} \times b_{tf} \times t_{tf}$$

$$F_{cw} = \frac{\left(\varepsilon_{ctf} + \varepsilon_{cbf}\right)/2}{\varepsilon_{c3}} \times f_{cm} \times 2t_w \times \left(H - t_{tf} - t_{bf}\right) \tag{D.29}$$

$$F_{cbf} = \frac{\left(\varepsilon_{cbf} + \varepsilon_{\min}\right)/2}{\varepsilon_{c3}} \times f_{cm} \times b_{bf} \times t_{bf}$$

The lever arms of the compressive forces are calculated as follows:

$$y_{tf} = y_t - \frac{1}{3}\left(\frac{\left(\frac{\varepsilon_{c\max} - \varepsilon_{ctf}}{2}\right)}{\left(\frac{\varepsilon_{c\max} - \varepsilon_{ctf}}{2} + \varepsilon_{ctf}\right)}\right)t_{tf} + \frac{1}{2}\left(\frac{\varepsilon_{ctf}}{\left(\frac{\varepsilon_{c\max} - \varepsilon_{ctf}}{2} + \varepsilon_{ctf}\right)}\right)t_{tf} \tag{D.30}$$

$$y_w = \frac{\left(\begin{array}{c}\left(\frac{\varepsilon_{ctf} - \varepsilon_{cbf}}{2}\right) \times \left(\frac{2\left(H - t_{tf} - t_{bf}\right)}{3} + t_{bf}\right) + \\ \varepsilon_{cbf} \times \left(\frac{\left(H - t_{tf} - t_{bf}\right)}{2} + t_{bf}\right)\end{array}\right)}{\left(\varepsilon_{cbf} + \frac{\varepsilon_{ctf} - \varepsilon_{cbf}}{2}\right)} - y_b \tag{D.31}$$

$$y_{bf} = \frac{2}{3}t_{bf} - y_b \tag{D.32}$$

In addition, the strains in the structural components (top flange and bottom flange) of the box girder are estimated as follows:

$$\varepsilon_{ctf} = \varepsilon_{c\max}\frac{\left(H - t_{tf}\right)}{H}$$

$$\varepsilon_{cbf} = \varepsilon_{c\max} \times \frac{t_{bf}}{H} \tag{D.33}$$

$$\varepsilon_{c\min} = 0\,;\varepsilon_{c\max} = 0$$

D.10 References

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