3

PERFORMANCE OF CONCRETE MADE WITH COMMERCIALLY PRODUCED RECYCLED COARSE AND FINE AGGREGATES IN THE CAPE PENINSULA

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DECLARATION

I, Benjamin Kutegeza, hereby declare that this dissertation is my own work. Where extracts, concepts and ideas have been borrowed from other sources and authors, they have been suitably referenced. It has not been submitted before for any degree or examination in any University.

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Date this___ day of ___, 2004

ABSTRACT

Properties and performance of concrete made with laboratory-crushed recycled aggregate have been extensively investigated and reported by various researchers. However, only limited data are available on commercially produced recycled aggregates (RA). In this study, the properties of RA and the performance of concrete made with RA were analysed and compared with the properties of natural aggregate and normal concrete respectively.

The results obtained from this study show the material to be within allowable limits suggested by various concrete Standards and specifications. Both recycled coarse aggregate (RCA) and fine aggregate (RFA) were continuously graded. Stone content was the main component in the RA, with mass fraction of about 58%. Stone/mortar conglomerate (concrete) comprised about 21%, mortar comprised 12% and bricks comprised 8%. Other impurities such as wood, chipboards, and tiles to mention a few totalled about 1 %.

Bulk density of RA was found to be between 1293 kg/m^3 and 1510 kg/m^3, lower than that of the NA which attained 1585 kg/m^3. RFA had 1533 kg/m^3 bulk density, while NFA attained bulk density of 1778 kg/m^3. Water absorption was found to be between 2.0% and 4.5% for RCA and between 7.5% and 10.4% for RFA. This is higher than that of NA which had water absorption of 0.4% for NCA and 1% for NFA. It was also observed that the water absorption increased with decrease in particle size. The 10% FACT results ranged between 175 kN and 188 kN for RCA. Inspection of the RA particles showed that they varied in shape, with a mixture of spherical, cubical/chunky and angular particles. The surface texture was of a rough nature and highly porous.

Properties of fresh recycled aggregate concrete made with SSD aggregates are also presented and discussed. These included water requirement, workability, cohesiveness, density of compacted freshly concrete, segregation (bleeding) and slump loss with time. The investigation of the fresh concrete properties revealed that SSD RA can produce concrete of good workability, cohesiveness and minimal bleeding.

Strength loss of 2% to 40% was observed for concrete containing RA. Maximum reduction of compressive strength occurred in concrete containing both RCA and RFA. For all water-binder ratios, the compressive strength difference between concrete mixes with only RCA and NFA was marginal. This shows that RCA can produce a range of concrete with acceptable compressive strength. Modulus of elasticity of RC was about 20 to 25% lower than that of normal concrete (NC) for all water-binder ratios. There was a marginal increase of elastic modulus with age. The flexural strength of RC was observed to be about 25% lower than that of NC. RC exhibited about 50% to 100% higher creep strain in an exposed condition than NC. In the case of sealed specimens, there was marginal difference between creep strain of RC and NC. Reserved moisture within RA pores might have attributed to lower the creep effect due to lower compressibility of confined water in the pores. There was a marginal difference of drying shrinkage between RC and NC containing corex slag. However, drying shrinkage of RC was higher than that of NC for concrete made with CEM I 42.5 at later age. A reversed trend was observed on sealed samples, whereby the autogenous shrinkage of RC was lower than that of NC. Reserved moisture in RA contributed to lower values of autogenous shrinkage in RC.

The overall results show that the RA reduced durability performance of concrete by 5% to 100%. The results show that concrete made with RA had lower oxygen permeability index (OPI) values than NC which implies that RC is more permeable. RC attained about 90% and 95% OPI values lower than NC made with corex slag and CEM I respectively at all water-binder ratios and curing regimes. The RC had higher water sorptivity values and porosity than NC. RC attained about 20% and 35% higher water sorptivity value than NC for 0.45 and 0.60 water-binder ratios respectively. Porosity values of RC were more than twice those of NC. It was found that RC had higher chloride conductivity values than NC. Chloride conductivity of RC was about 50% and 100% higher than that NC made with CEM I and corex slag respectively. This phenomenon can be explained by the fact that the porous nature of RA and inherent cracks render the concrete susceptible to ease of permeation, diffusion and absorption. OPI and water sorptivity of RC were improved when CEM I 42.5 was used while chloride conductivity improved when corex slag was used. Chloride conductivity values of RC improved by about 65% when corex slag was used. Durability index values generally improved with prolonged wet curing. Acceptable durability index values were however attained by RC made with both RCA and RFA.

It is concluded that concrete of acceptable strength and durability can be obtained using RCA and RFA. Finally, recommendations are made on the need to further characterise the properties of recycled aggregate.

DEDICATION

To my family

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CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

It is estimated that the South African construction industry generates between 5 and 8 millions tons of construction and demolition wastes (C&DW) per annum, most of it being concrete rubble. The sources of waste materials in the construction industry include waste from over production, rejects, repair and demolition to mention a few. If this huge volume of rubble could be recycled and reused as aggregates, the amount of land needed for disposal would be reduced and existing aggregate resources would not be depleted as quickly. Thus, large-scale recycling of demolished concrete could not only help conserve natural resources, but could also help solve a growing waste-disposal crisis.

The increasing charges for landfill on the one hand, and the scarcity of natural resources for virgin aggregates on the other, encourage the use of waste from construction and demolition as a source for aggregates. The usage of inferior materials for construction purposes is not acceptable, but changing the perception of what is an acceptable material for construction is important. Barriers to the use of recycled aggregate include those created by the use of specifications, which were originally based on the characteristics of natural aggregates. The changing of standards and specifications from being based on primary materials to being more performance-based needs to be considered.

The use of construction and demolition waste as a source of aggregates for the production of new concrete has become more common in recent decades. Test results by Chen et al (2003), show that building rubble can be transformed into useful recycled aggregate (RA) through proper processing. Performance tests that have been done by various researchers, as will be seen in chapter 2, show that the properties of fresh and hardened concrete made with RA are within manageable limits.

Very little is known in South Africa about the use of recycled aggregates in concrete production, possibly because natural aggregates are still readily available in urban areas, or engineers are not confident with the use of recycled aggregate materials due to lack of information on availability and suitability of recycled aggregates.

The production of concrete with recycled aggregate is the most desirable form of achieving a closed life cycle of concrete as a construction material. Concrete is a product which essentially consists of cement, aggregates, water and admixture(s). Among these, granular materials such as sand and gravel or crushed stone form the major part, which can be obtained through a proper recycling process of demolished old concrete structures. Traditionally natural aggregates have been readily available at economic prices and with qualities to suit all purposes. However, in recent years the trend of continuing extraction and use of aggregates from natural resources has been question at an international level (Limbachiya, 2002). This is mainly due to depletion of quality natural aggregate and greater awareness of environmental protection.

While the properties and performance of concrete made with laboratory-crushed recycled aggregate have been extensively investigated and reported by various researchers, only limited data are available on properties and performance of commercially produced recycled fine and coarse aggregates. Therefore there is a need to investigate and understand the behaviour of concrete made with aggregates from recycled C&DW rubble as such materials are likely to provide both environmental and economic advantages.

1.1 Background

The use of recycled construction and demolition waste (C&DW) as aggregates started as far back as the end of the Second World War when concrete rubble, bricks and other waste building materials recovered from the ruins of war were utilised for construction of new infrastructure (Olorunsogo et al, 2000). Since then, rubble obtained from demolition of concrete pavement, runways, foundations and building structures have been reused and recycled successfully around the world.

Various studies have generally found the construction industry to be a wasteful sector. A report by Vasquez and Barra (2000) shows that C&DW from the construction industry makes up about 40% of the total waste stream in many countries, with between 15 to 30% of this ending up in landfills. A large percentage of C&DW is composed of 'core' C&DW that has the quality to be recycled, and consequently could reduce the amount of primary (natural) aggregates extracted.

Shayan and Xu (2003) reported that countries such as Germany, UK, France, Denmark, the Netherlands, United States of America, Brazil, Australia, and Japan, have been researching the use of recycled C&DW aggregates for about the last twenty years. Vasquez and Barra (2000) reported that two-thirds of total demolished concrete produced in Japan is reused in road pavement construction projects and concrete rubble has been recycled as aggregate for new concrete.

Measures aimed at reducing the use of primary aggregates and increasing reuse of recycled C&DW have been introduced in various countries, where it is technically, economically or environmentally acceptable to do so. The usage has been constrained to low-level applications such as in road construction as a base and sub-base, but much research has been also done for higher levels of application such as in concrete works. The present challenge is how to improve the production of RA both qualitatively and quantitatively.

1.2 Aim of this Dissertation

The aim of this dissertation is to investigate the availability and suitability of both recycled fine and coarse aggregates as an alternative viable source of coarse and fine aggregates in making concrete in the Cape Peninsula. This will increase the use of recycled aggregates and their market demand will also be increased. This will encourage recycling of more C&DW rubble, and hence illegal dumping and C&DW in landfills will be reduced.

1.3 Objectives of this Dissertation

This investigation focuses on two main objectives. The first is a comprehensive literature review on recycled aggregates. Findings of other researchers on recycled aggregate materials and statistics of recycled aggregate production and application in the Cape Peninsula is reviewed and discussed. Secondly, the engineering properties of recycled aggregate (RA) and concrete made with recycled aggregate (RC) is investigated, presented and discussed. The specific objectives can be broken down into the following: -

- To provide a general literature review on the properties of recycled aggregate and concrete made with recycled aggregate.
- To characterize the physical, mechanical and other properties of recycled aggregates
- To assess the influence of recycled aggregates on fresh concrete
- To investigate the performance of hardened concrete made with recycled aggregates (strength, elastic modulus, creep and shrinkage, and durability).

1.4 Scope of this Dissertation

The scope of this study is to investigate the availability of RA in the Cape Peninsula, as well as properties of both coarse and fine RA and the performance of RC using available materials. Aggregate properties include composition, grading, fineness modulus, particle shape and texture, bulk and relative density, absorption and 10% FACT. Fresh concrete properties investigated include water requirement, workability, consistence and segregation (bleeding). The aspects which are investigated for hardened concrete include density of hardened concrete, compressive strength, flexural strength, creep and shrinkage, and durability monitored by durability index tests (oxygen permeability, water sorptivity and chloride conductivity). The results of RA and RC are compared with those of NA and NC and results of other researchers.

In the investigation of fresh and hardened concrete water-binder ratios of 0.45, 0.60, 0.75 and 0.90 were used. Greywacke stone and Klipheuwel sand which are natural aggregates widely found and used in the Cape Peninsula for concrete production were used in the control mixes. Ordinary Portland cement (CEM I 42.5) and Corex slag were used as binders. The production processes and chemical analysis of RA are not covered in this investigation.

1.5 Organization of this Dissertation

The literature review is presented in chapter 2. This includes the purpose of recycling and re-use of recycled aggregate, statistics of C&DW production, and recycling and application of recycled aggregates in the Cape Peninsula. Classifications of recycled aggregates using various codes are included in this chapter. Findings and reports of various researchers on properties of RA, and the influence of RA on fresh and hardened concrete are reported. Discussions and recommendations on the findings of other researchers are included in each section and a general discussion, recommendations and conclusions are included at the end of the chapter.

The experimental programme is presented in chapter 3. Characterisation of materials using various tests, equipment/apparatus and procedures are covered in this chapter.

Properties of RA are covered in chapter 4. These include grading, composition, dust content and contaminants, particle shape and surface texture of the RA. Bulk and relative densities, water absorption and crushing strength of the RA are also covered in chapter 4.

Chapter 5 covers the properties of fresh concrete. The workability, cohesiveness and bleeding behaviour of concrete containing RA are analysed and reported in this chapter.

Properties of hardened concrete are provided in chapter 6. These include compressive strength, modulus of elasticity, flexural strength, creep and shrinkage. The potential durability of recycled aggregate concrete, which includes permeability, sorptivity and the resistance to chloride ingress, are also investigated in chapter 6.

Finally, general conclusions and specific recommendations are summarised and reported in chapter 7. Results of particular investigations and discussions are included in each chapter.

1.6 Definition and terminologies

The following definitions, terminologies and abbreviations which partially resemble the terminologies defined by the Japanese proposed Standard on Recycled Aggregate and Recycled Concrete (Hansen 1992) are used in this work.

Recycling

The use of a waste material after it has been processed in such a way that it can be used substantially in the same way as originally, with no detrimental effects on the properties of a new product (s).

Construction and Demolition Waste (C&DW) rubble (debris or core)

This is non-hazardous waste resulting from the construction, remodelling, repair and demolition of structures. Structures include both residential and non-residential buildings, public works projects such as roads, bridges, piers and dams. C&DW includes but is not limited to concrete, bricks, masonry, excavation (rock type) materials and other contaminants such as ceramics, metals, plastics, paper, cardboard, timber and paints.

Recycled aggregates (RA)

Aggregates produced by the crushing of C&DW rubble (debris) after the removal of contaminants. These are sometimes referred to as C&DW-derived aggregates (Ayers 2002). When aggregates are obtained by crushing only old concrete rubble with or without minimal brick and masonry contaminants, they are referred to as recycled concrete aggregates (Hansen 1992). Such aggregates can be recycled fine aggregates (RFA) or recycled coarse aggregates (RCA). RFA contains particles less than or equal to 4.5 mm and RCA contains coarser particles greater than 4.5 mm.

Natural aggregates (NA)

Natural occurring sand (natural fine aggregate NFA), gravel and crushed natural rocks obtained by quarrying or marine dredging natural coarse aggregate (NCA). When no misunderstanding is possible, natural aggregates may also be referred to as virgin, original or conventional aggregates (Hansen 1992).

Recycled concrete (RC)

Concrete produced using recycled aggregates or combinations of recycled aggregates and other aggregates. RC sometimes referred as recycled aggregate concrete (RAC).

Normal concrete (NC)

Concrete produced with natural sand as fine aggregate and gravel or crushed rocks as coarse aggregate. Sometimes is referred as conventional concrete (CC).

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is a major construction material across the world and most widely used in all types of civil engineering and building works. Concrete is a product, consisting of cement, aggregates, water and admixture(s). Among these, granular materials such as sand and gravel or crushed stone form the major part. Traditionally natural aggregates have been readily available at economic prices and of qualities to suit all purposes.

However, in recent years the trend of continuing extraction and use of aggregates from natural resources have been questioned at an international level (Limbachiya, 2002). This is mainly due to depletion of quality natural aggregates and greater awareness of environmental protection. Failure to implement sustainable processes of utilizing these materials may lead South Africa to similar problems faced by many developed countries in near future, including lack of land for landfills.

Primary materials have traditionally been preferred over recycled materials due to the fact that the risk involved in using primary materials is generally well defined from the standards and specifications. The price difference between primary material and recycled materials in the Cape Peninsula has to date not been sufficient to persuade various authorities to use RA materials. Furthermore, the following aspects have played a part in hindering the development of RA materials generally in South Africa:

- Inadequate formal systems for measuring the properties and performance of recycled materials
- Inadequate promotion of recycled materials
- Lack of awareness of recycled materials
- Landfill taxes that are ineffective (enforcement)
- Inadequate initiative by clients and consultants to recommended use of recycled materials in projects.

2.1.1 Purpose of recycling and re-use

Waste arising from construction and demolition constitutes one of the largest waste streams in South Africa and many other countries. The results of a recent study undertaken by the CSIR (Council for Scientific and Industrial Research), Building and Construction Technology (Boutek), have revealed that nearly a million tons of C&DW end up in landfills in South Africa. The increasing charges for landfill on the one hand, and the scarcity of natural resources for virgin aggregates on the other, encourage the use of waste from construction and demolition sites as a source for aggregates. The factors which influence the use of aggregates from recycled C&DW in many countries are similar (Macozoma 2001). These include: -

- Increased shortage of primary (natural) aggregates leading to cost increase of primary aggregates
- The distance between deposits of natural aggregates and sites of new construction has increased and transportation costs have become correspondingly higher.
- Most natural aggregates are obtained by quarrying, which produces a number of environmental problems, such as soil degradation, soil erosion and water table pollution to mention a few
- Decreasing capacities of landfills to accommodate the amount of C&DW produced each year
- Increasing negative effects of C&DW on the environment
- An increasing awareness (in some countries) of the availability of C&DW suitable for processing to produce aggregates
- Greater sense of commitment for sustainable Construction and Development

2.1.2 Nature of recycled aggregates

Recycled aggregates (RA) are defined in chapter 1 as aggregates resulting from the reprocessing of mineral construction materials (composed predominantly of crushed old concrete, stones and brick masonry). Construction waste (new materials wasted during construction through over-ordering, breakage and rejection) or demolition waste may provide a source of materials. RA can contain in some circumstances significant quantities of natural aggregates; however, excessive quantities of other materials such as wood, metal and other contaminants need to be removed before the aggregate is fit for use in concrete production. Physical properties of RA are extensively covered in this chapter under section 2.4.

2.2 Statistics of C&DW production in the Cape Peninsula

2.2.1 Construction and Demolition Waste.

A report by Macozoma (2001) shows that the South African construction industry generates about 5 to 8 million tons of C&DW per annum. Over 1 million tons, mostly concrete rubble reaches landfill sites every year. More than 200 000 tons reach landfills in the Cape Peninsula, and the remainder is recycled or dumped illegally. Illegal dumping is becoming a serious problem in South African open space, as perpetrators try to avoid transport and disposal costs.

As landfills fill up and prices of raw materials begin to reflect the full cost of materials and processing, the construction industry has to change its disposal practices and think of recycling C&DW. Table 2.1 extracted from Macozoma (2001), shows some findings for each province and the situation regarding recycling and illegal dumping of C&DW. Poor record keeping, lack of site waste analysis, non-uniform waste classification in different regions and lack of weighing facilities at some landfills negatively affect the quantity of C&DW disposed of in landfill sites.

Table 2.1: Summary of C&DW disposal in SA landfills (Macozoma 2001)

Province	**Total C&DW received in landfills per annum (Tons)**	**Recycling activities**	**Illegal dumping**
Western Cape	**> 200 000**	**Extensive**	**Extensive**
Kwazulu-Natal	375 000	Minimal	Extensive
Gauteng	560 000	Minimal	Extensive
Eastern Cape	64 000	None	Extensive
Mpumalanga	Minimal	None	Extensive
North west	Minimal	None	Not available
Free State	Minimal	None	Not available
Northern Cape	Minimal	None	Not available
Limpopo Province	Minimal	None	Not available

Quantities of municipal solid waste MSW and C&DW 'core' (rubble) produced in the Cape Peninsula are shown in Table 2.2. The quantities of C&DW disposed at landfill sites within the Cape Peninsula are not known, owing to a lack of record keeping. The percentage of C&DW making up total Municipal solid waste is estimated at about 15% (Macozoma 2001).

Table 2.2: Landfill sites, quantities of solid waste and estimated C&DW rubble in Cape Peninsula (Macozoma 2001).

Regional Authority	**Landfill site**	**Total Solid waste/year (Tons)**	**Quantity of C&DW at 15% (Tons)**
Cape Metro	Coastal Park	221 796	33 269
	Swartklip	185 316	27 797
	Vissershok WMF*	327 687	49 153
	Bellville Park	329 344	49 402
	Vissershok CMC**	295 440	44 316
	Faure	165 568	24 835
	Brackenfell	78 743	11 811
Total		**1 603 894**	**240 583**

* Waste Management Facility
** Cape Metro Council

2.2.2 Sources of C&DW rubble for recycling

The sources of waste materials from Construction include waste from over production, rejects, repair or/and demolition to mention a few. The main suppliers of C&DW consist of large and medium contractors. The amount of C&DW materials supplied by these companies depends on the level of construction and demolition activities taking place within the region of the recycling plant. However the amount of recoverable C&DW supplied by these companies depends on the effective implementation of waste management plans on site. The amount of C&DW produced by small contractors is not commonly known. As the number of small contractors is greater than the number of medium and large contractors, the overall amount of recoverable waste collectively produced by this large number of small contractors would effectively assist in supplying recyclers on a continuous basis.

2.2.3 Amount of C&DW recycled, and typical applications

There are three types of companies involved in recycling and re-use of aggregates from C&DW in the Cape Peninsula. These include commercial crushing companies, Brick Manufacturers and Civil Engineering Contractors. Although recycling and use of recycled C&DW aggregates has been practised in the Cape Peninsula for more than seven years, there are few data showing how much C&DW materials are generated, recycled and re-used annually. The crushing of C&DW rubble to produce aggregates has been occurring in the Cape Peninsula from about 1996 (Ayers 2002).

The majority of construction companies apply RA materials in backfilling, landscaping, site levelling, landfill, road works as base and sub-base course, foundations as hard core and fill in building construction, construction of parking lots and brick/block manufacturing. This was confirmed by Macozoma (2001) report and the outcome of questionnaires. The main application of RA in the Western Cape is in road construction. Malans Quarries supplies more than 200 000 tons of RA annually and most of these aggregates are used in road works. Key barriers to wider acceptance of RA include lack of experience, lack of guidance and detailed case studies, as well as user resistance to 'second best' products.

Very little is known in South Africa about the use of RA in concrete production, possibly because natural aggregates are still readily available in urban areas, or engineers are not confident with the use of RA materials due to lack of information on availability and suitability of these materials. Bradis Recycling Company produces RA which has been used to produce concrete for light concrete structures. No much work has been done to analyse the properties and performance of this aggregates. Data in Table 2.3 obtained from questionnaires and Ayers (2001) report show the amount of RA produced in the Cape Peninsula by recycling companies, and their application. The questionnaire survey was conducted by sending questionnaires to major recycling companies, Malans Quarries Company and Bradis Crushing & Recycling (Pty) Ltd in the Cape Peninsula

Table 2.3: Recycling Companies, amount produced/year and application of RA in the Cape Peninsula

Company	**Production/Year (Tons)**	**Demand/Year (Tons)**	**Application**
Malans Quarries	> 150 000	> 200 000	• Road works • General site fill
Bradis (Pty) Ltd	> 55 000	> 100 000	• Road works • Concrete works • Brick manufacturing • General site fill
Ross & Sons Demolition	> 15 000	> 20 000	• Road works • General site fill
Cape-Brick (Pty) Ltd	> 2 000	> 2 000	• Brick manufacturing
Total	> 222 000	> 320 000	

2.2.4 Discussions and recommendations

Generally it is now accepted that there is a significant potential for reclaiming and recycling C&DW rubble for use in value-added applications to maximize economic and environmental benefits. Therefore, it is necessary to have an effective waste management plan on site so as to increase the supply of C&DW to the recycler, which will in turn assist in an increased supply of RA.

The quantity of RA used in the Cape Peninsula is small in comparison to natural aggregates, inadequate knowledge and experience about RA has played a vital role in less utilization of RA. Therefore more workshops on RA need to be conducted in order to increase awareness among various stakeholders.

Taxes on RA materials and recycling plants and companies which utilize RA should be reduced. Such incentives would encourage the production of RA as well as the use of these materials. Further research should be conducted on establishing effective secondary markets in South Africa construction industry, as well as ways of enforcing effective waste management practices in small, medium and large contractors.

While accepting the need to promote the use of RA in wider applications, it should be remembered that concrete aggregates must meet requirements set in relevant specifications for their particular use. The usage of inferior materials for construction purposes is not acceptable, but changing the perception of what is an acceptable material for construction is important. Barriers to the use of recycled aggregate include those created by specifications which were originally based on the characteristics of natural aggregates. The changing of standards and specifications from being based on primary materials to being more performance-based needs to be considered.

2.3 Classification of RA from C&DW

2.3.1 RILEM classification

A fundamental requirement in any specification for a material is to give a general description of its composition. For recycled C&DW, the relative proportion of concrete to brick masonry is the critical issue. RILEM TC 121-DRG (1994) and BRE[1] Digest 433 (1998) give the classification of RA and other specifications required for various applications. The documents classify different categories for the RA and indicate the field of application for concrete containing RA classes in terms of acceptable environmental exposure classes and concrete strength classes in accordance with Euro-code EN 206 (Design of concrete structures). RA are classified according to RILEM and BRE into three categories as follows:

- **Class I**: defines the lowest quality material. These have low strength and relatively high levels of impurity and mainly contain up to 100% of brick or block masonry. The strength as measured by 10% fines value test is usually in the region of 70 kN.

- **Class II**: defines a relatively high quality of materials with low content of impurities. It is mainly composed of concrete (stone/mortar conglomerate), stones (natural aggregates) and small percentage of bricks and other contaminant materials. The strength as measured by 10% fines value test is usually in excess of 100 kN.

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[1] Building Research establishment

- **Class III**: defines a mixture of natural aggregates (>80%) and rubble from the other two groups. Aggregates from this group can be used to produce all types of concrete, whereas restrictions limit the application of the other two groups.

According to the RILEM committee recommendations, RCA of class I, II and III can be used in plain and reinforced concrete under the provision that the mandatory requirements and restriction mentioned in table 2.4 and 2.5 respectively are satisfied.

2.3.2 South African (SA) Classification

The SA Classification of RCA by the CSIR resembles certain aspects of the RILEM Classification, but details on sizes, strength of RCA and areas of application are not well covered in the CSIR classification (Ayers 2002). RCA are classified in four categories as follows:

1. **Crushed Demolition Debris**: which is described as mixed crushed concrete, hand sorted to remove excessive contamination, but still containing a proportion of wood or other impurities

2. **Cleaned graded mixed debris**: which is described as a mixture of crushed concrete and bricks that is graded and contains less or no contaminants.

3. **Clean graded concrete**: is described as a crushed and graded concrete containing less than 5% brick and little or no contaminants

4. **Clean graded brick**: is described as crushed and graded clean brick and masonry containing less than 5% of stony materials and little or no contaminants. (Stony materials means, concrete, natural stone and Ceramic materials)

The South African classification resembles the RILEM and BRE classification as stated above. Amount of brick and contaminants are both used to classify RCA in RILEM/BRE as well as in SA classification. Class I from RILEM and BRE can be compared with category 1 for SA classification and class II with category 3. Category 4 for SA classification is the reverse of class III in RILEM/BRE classification. In general, RILEM and BRE classifications are based more on *recycled concrete aggregate* and SA classification is based on general RA.

2.3.3 Recommendations on the use of RA from various codes and standards

The main features of RA reported in RILEM and BRE publications show that RA has higher variability due to the variability of C&DW. This variability increases the risk of using these materials, which may require a much higher safety margin. There is also possibility of presence of a wide range of contaminants, some of which are harmful to human beings and some deleterious for concrete. RA are recommended not to contain any material or other substances which retard the setting of the concrete by more than 15%, compared with the setting of the identical composition with natural aggregates, or which are detrimental to human beings or concrete, such as heavy metals or radioactive materials.

RILEM TC 121-DRG gives the following reasons why the use of RFA should be limited:

- High content of different contaminants
- The influence of recycled fine materials on concrete strength and durability is not well documented
- A relevant test method for the determination of the strength of fine recycled aggregates is not available
- A reliable test method for the determination of residual alkali reactivity of fine recycled aggregates is not available and
- Use of recycled fine aggregates has been reported to lead to concrete production problems, for instance in the control of water demand and in the flow of materials during production.

The RILEM and BRE recommendations set a maximum allowable class depending on the type of RA. Usage of RA in certain exposure classes is restricted; additional testing, such as alkali-silica reaction expansion test, chloride content test etc. is required, when durability performance is of concern as shown in table 2.4 and table 2.5. The properties of sand obtained through recycling of C&DW have to be investigated to check its suitability as fine aggregate in concrete production.

Table 2.4: Mandatory requirements of RCA to be used in concrete production (RILEM TC 121-DRG)

	Type			
Requirements	I	II	III	Test Method
Min. dry density (kg/m^3)	1500	2000	2400	ISO 6783 & 7033
Max. water absorption (% m/m)	20	10	3	ISO 6783 & 7033
Max. content of material with SSD < 2200 kg/m^3 (% m/m)	-	10	10	ASTM C 123
Max. content of material with SSD < 1800 kg/m^3 (% m/m)	10	1	1	ASTM C 123
Max. content of material with SSD < 1000 kg/m^3 (% m/m and % v/v)	1	0.5	0.5	ASTM C 123
Max. content of foreign material (metal, glass, soft, bitumen) (% m/m)	5	1	1	prEN 933-1
Max. content of metals (% m/m)	1	1	1	prEN 933-1
Max. content of organic materials (% m/m)	1	0.5	0.5	NEN 5933
Max. content of filler (< 0.063 mm) (% m/m)	3	2	2	prEN 933-1
Max. content of sand (< 4 mm) (% m/m)	5	5	5	prEN 933-1
Max. content of sulfate (%m/m)	1	1	1	BS 812 part 118

Table 2.5: Provisions for the use of recycled concrete (RC) (RILEM TC 121-DRG)

RA	Type I	Type II	Type III
Maximum allowable strength class	C16/20	C50/60	No limit
Additional testing required when used in exposure class 1	None	None	None
Additional testing required when used in exposure classes 2A, 4A	ASR expansion test Use in class 4A not allowed	ASR expansion test	ASR expansion test
Additional testing required when used in exposure class 2B, 4B	Use in class 2B, 4B not allowed	ASR expansion test Bulk freeze-thaw test	ASR expansion test Bulk freeze-thaw test
Additional testing required when used in exposure class 3	Use in class 3 not allowed	ASR expansion test Bulk freeze-thaw test	ASR expansion test Bulk freeze-thaw test

The exposure classes according to prEN 206 (1997) are summarized below. There are 23 exposure classes in total, split into six groups covering:

1. No risk of corrosion
2. Carbonation-induced corrosion
3. Chloride-induced corrosion resulting primarily from de-icing salts
4. Chloride-induced corrosion resulting from seawater exposure
5. Freeze-thaw attack and
6. Chemical attack

According to the Japanese proposed Standard TR[2] - A0006 (2000) for RA and RC, as quoted by Kasai (2004), RA should not be used for concrete production when water absorption is more than 7% for coarse aggregates and 13% for fine aggregates, tables 2.6 and 2.7. Tables 2.8 and 2.9, show the type of RC and the maximum design strength which can be achieved by using RA, and the areas which RC can be applied respectively.

Hansen (1992) also reported that the presence of asphalts in aggregates seriously reduces the concrete strength. Additional of 30 % by volume of asphalt to RA, reduces compressive strength of the RC by approximately 30%.

Table 2.6: Quality requirement of RA by Japanese standards (Kasai, 2004)

Test item	**RCA**	**RFA**
Oven-dry specific gravity	Not less than 2200 kg/m^3	Not less than 2000kg/m^3
Percent of water absorption	Not more than 7%	Not more than 13%
Substance lost in washing test	Not more than 1%	Not more than 8%
Percentage of solid volume	Not less than 53%	-

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[2] Technical Report issued in 2000 assuming that it will become a Japanese Standard specification for RA in future.

Table 2.7: Quality of RA (Kasai 2004)

	Recycled Coarse Aggregate				Recycled Fine Aggregate	
	1st Class	2nd Class		3rd Class	1st Class	2nd Class
Water absorption (%)	< 3	< 3	< 5	< 7	< 5	< 10
Loss of soundness	< 12	< 40	< 12	-	< 10	-

Table 2.8: Type of RC and maximum values of compressive strength (Kasai 2004)

Class of RC	**Type of Aggregate**		**Design strength**
	Coarse Aggregates	Fine Aggregates	(MPa)
I	Recycled aggregate 1st class	Conventional aggregates	> 20 (reinforced concrete)
II	Recycled aggregate 2nd class	Conventional aggregate or recycled aggregate	> 16 (plain)
III	Recycled aggregate 3rd class	Recycled aggregate	< 16

NB: Japanese classification of RA could not be found in Hansen (1992) and Kasai (2004) references. Because Kasai was involved in the preparation and the final emendation of the RILEM specifications, was assumed to resemble RILEM classifications.

Table 2.9: Suggested uses of RC according to Japanese standards (Kasai, 2004)

Class of RC	**Principal object of use**
I	Low-rise buildings in general, low-rise apartment buildings, single family houses, single story commercial building, heavy foundations, etc.
II	Foundations for pre-cast concrete block construction, machinery foundations, etc.
III	Foundations for wooden buildings, gates, fences, simple machinery foundations, slabs on grade, etc.

Although the Japanese standard is not different from other codes and standards for conventional concrete in other countries, there are a number of requirements, which are specific to RA; some of these are quoted below from Hansen (1992).

- Original concrete shall be sound, hard, normal-weight concrete
- Concrete of distinctly different qualities shall be used separately
- Recycled concrete shall be classified according to types of aggregate used, as shown in table 2.8
- Required slump of RC shall not exceed 21 cm
- Water – binder ratio shall not exceed 0.70
- Cement content shall not be less than 250 kg/m^3

Maximum allowable contents of water-soluble chlorides (Cl^-) in recycled aggregates are shown in table 2.10 according to a proposed Dutch product standard for RA for production of plain, reinforced and pre-stressed concrete as quoted by Hansen (1992). Other recommendation and specifications from various codes can be found in RILEM Report 6, (Recycling of Demolished Concrete and Masonry) edited by Hansen (1992).

Table 2.10: Maximum allowable Chloride ion content (Hansen, 1992)

Fraction mm	**Plan concrete**	**Reinforced concrete**	**Pre-stressed concrete**
0 - 4	-	0.1%	0.015%
>4	-	0.05%	0.007%

2.3.4 Discussions on the specification and recommendations

These specifications classify different categories for RCA and indicate the field of application for concrete containing these RCA classes in terms of acceptable environmental exposure and strength. The use of RFA is limited because there is no operational testing procedure and acceptance criterion available. Further research in this field is recommended and since there are no specifications and guidelines in South Africa which show how this material can be used in concrete, RILEM/BRE specifications and guidelines can be used.

2.4 Properties of RA.

The properties and composition of RA vary depending on source, geographical location (climatic differences), and on the material available in that region (Vasquez and Barra, 2000). For example it is likely that RA in the Cape Peninsula will contain brick particles, as most old structures were built using brick materials.

Most common tests used to determine the properties of aggregates for use in concrete are grading and composition, dust content, bulk and relative density, moisture content, absorption, impurity content, chloride content, aggregate strength test (10%FACT or Aggregate Crushing Value test ACV). The particle shape and texture are also as they may have an influence on workability of fresh concrete (Addis, 1998).

2.4.1 Sampling of RA

Sampling is a very important step in the testing sequence (Edward et al, 1978) as any good product is only possible through proper sampling. Since RA has greater variability, sampling procedures and techniques need to be considered before any test is attempted. Sampling procedures of RA have not been reported by most researchers, and this may be due to the fact that most materials used for research are produced in small quantities in the laboratory. Some researchers such as Sagoe-Crentsil et al (2001), Shayan et al (2003) and Chen et al (2003) who have reported on the use of commercially produced recycled aggregates in manufacturing of new concrete did not include the sampling techniques in their reports.

Edward et al (1978) define *Sampling* as the process of obtaining samples from a large population. A sample as a small portion of a large population of a material (such as a lot, stockpile, batch, carload, truckload or continuous production stream) about which information is desired. The characteristics of the sample are presented as representative of the properties of the large population from which it is taken.

When the population is perfectly homogeneous, sampling becomes simple and in this case any sample can truly represent the larger homogeneous whole. Unfortunately, nature in general rarely if ever presents us with a homogeneous population of any materials, and this is true of concrete also. The more heterogeneous the population such as RA in particular, the more time it takes to develop a reliable estimate of its characteristics. A proper sampling procedure is therefore important for RA required for concrete production.

Duncan (1975) says that sampling is much more than the physical act of taking a sample from the lot as evidence of the properties of the latter. A sampling plan needs to be formulated to reflect the variability characteristics of the population. Edward et al (1978) suggest that the sampling plan should include information on the number, sizes and location or timing (if from production stream), and procedures for reduction of the gross sample to a laboratory sample should also be included. If a stockpile of aggregates is variable as is the case for RA, and if one has no knowledge of such unpredictable variation, it is suggested that samples be taken randomly in space and time.

Sampling techniques and procedures for normal aggregates are well documented by Edward et al (1978), Duncan (1975a, b), and various Standards such as SANS 195:1994 and ASTM Designation D 75 – 82. These procedures can be applied in sampling RA for concrete provide extra care is taken during sampling. SANS 195:1994 gives various procedures for sampling aggregates at various locations such as from stockpiles, moving conveyer belt and filled vehicles as summarized below.

Sampling from completely built-up stockpiles: Divide the stockpile or part thereof as appropriate into number of sections and take sample increment from each section. By using a shovel or mechanical means (example a front-end loader) take the sample from the bottom upwards to the top of the stockpile; in the case of a flat-topped stockpile, take the sample from the outer edges to the centre. It is advised to avoid sampling from segregated areas or from the surface only. Segregation is expected to be high in RA because of its graded nature. When sampling from stockpiles being built-up, follow the same procedures as above for every increment added to the stockpile. This sampling technique was used to get the RA material used in this project (refer chapter 3).

Sampling from vehicles: Divide the load into equal number of section and provide a trench of at least 300 mm across each section. Take sub-increment making sure that the shovel is pushed down into the aggregate and not horizontally along the surface. Combine the sub-increments taken from each trench to form a sample increment. If sampling is done on a vehicle being loaded or unloaded, the rate of loading /unloading should be established. Calculate the time intervals at which the sample increments have to be taken. At the appropriate times, stop the loading/unloading and take the sample using suitable appliance across the full width of the moving stream of aggregates.

Sampling from a continuous conveyer belt: Establish the rate of delivery of aggregate by the belt and calculate the time intervals at which the sample increments have to be taken. Stop the belt at appropriate times and at a fixed position along the traverse length of the belt take the sample increment using a suitable appliance. Make sure the fines that have segregated from the aggregates are also included in the sample increment. If the sample increment is taken at the end of the conveyer belt, make sure the samples are taken across the full width of the conveyer belt.

Making up laboratory samples: - Place all random sample increments taken from a stockpile, vehicles or conveyer belt, carefully onto a clean and non-absorbent surface. If the sample increment is too dry so that fines could be lost, moisten the sample increment slightly. Thoroughly mix the aggregate by any suitable means ensuring that all fines are included in the mixing process. By means of a sample splitter, or by coning and quartering, obtain a sample of sufficient quantity to enable all envisaged tests to be conducted and place the sample in clean, dust-tight plastic, metal or tightly woven canvas containers and mark each container for later identification.

A good sampling plan, methods and procedures are not sufficient to ensure suitable samples reach the laboratory for the preparation of specimens for testing, if they are not stored in proper containers. Edward et al (1978) have shown the undesirable effects on concrete properties due to the use of bags contaminated with sugar, flour or preservative chemicals for storing samples.

2.4.2 Composition and grading of RA

Olorunsogo (1999) reported that the RA obtained from local suppliers in Clairwood, Durban, was composed of stone/mortar conglomerate, brick, mortar and dust in percentages as shown in figure 2.1. The dust constituted the lowest percentage (1.9%)

and stone/ mortar conglomerate constituted the highest percentage (84.6%). RA was found to be graded containing particles ranging from coarser particles to finer particles.

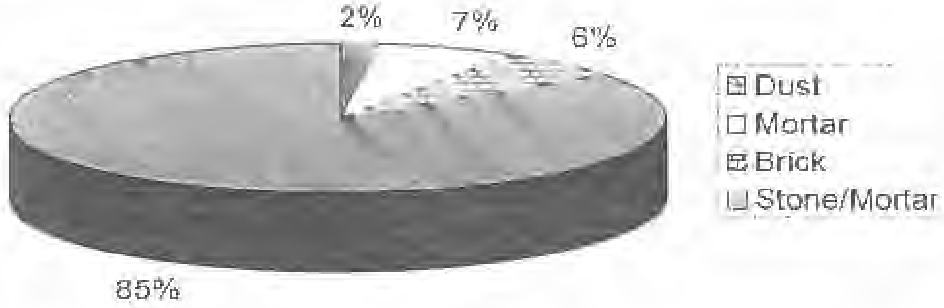


Figure 2.1 Composition of RA in Durban (Olorunsogo 1999)

Vasquez and Barra (2000) reported that the typical composition of RA used for road application in Catalonia, Spain was composed of concrete (65-80%), stone (16-25%), ceramic (1-3%) and others (0-5%).

Alexander et al (2002) reported similar composition but included also the natural stone component that was found in the RA. The RA, which was obtained from local supplier in the Cape Peninsula, consisted of 65% stone/mortar conglomerates, 25% stone, 8% mortar, 1% brick and 1% dust as shown in figure 2.2. The grading as shown figure 2.3 is a continuous graded materials containing both coarse and fine materials. Continuous grading has a number of advantages including less segregation of wetter mixes, less sensitive to slight in water content being advantage where uniform workability is important.

On the other hand Chen et al (2003) found that RA obtained from different regions in Taiwan on average was composed of 66.6 to 75.4% concrete (Stone/mortar conglomerate), Bricks (18.7 to19.9%), tiles (4.3 to13.3%) and others (0.4 to 1%).

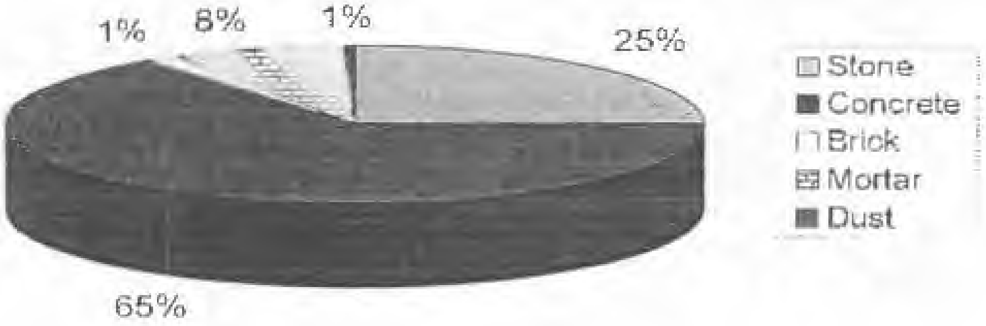


Figure 2.2: Composition of RA % from Cape Peninsula (Alexander et al 2002)

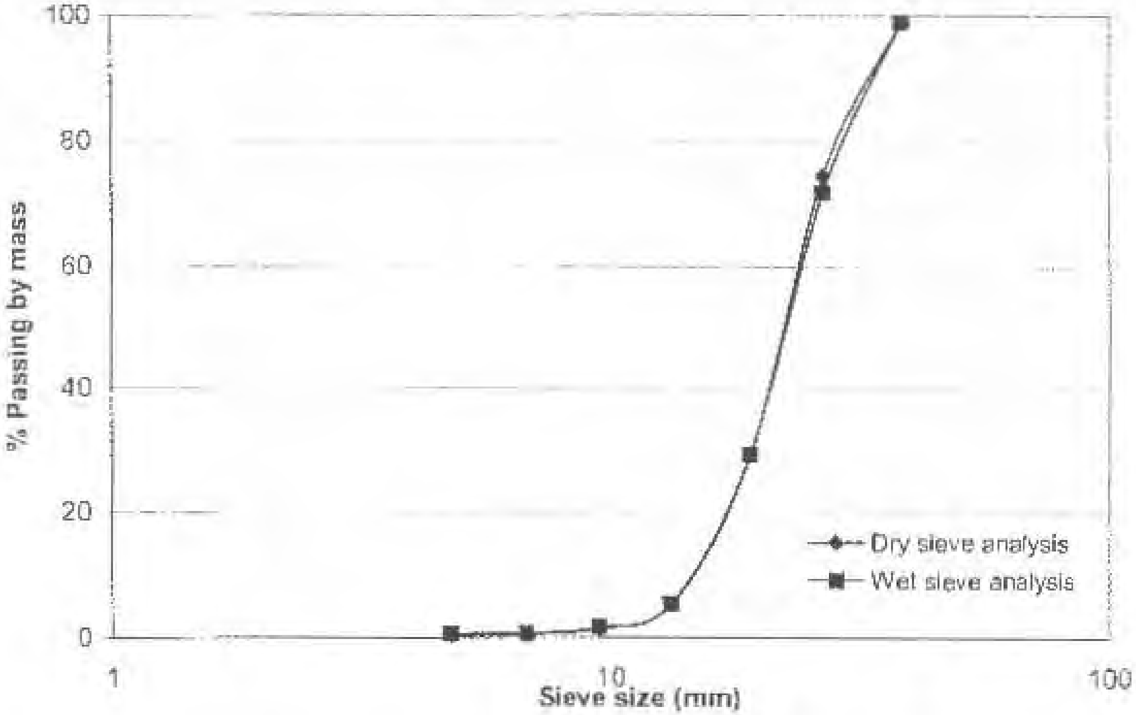


Figure 2.3: Grading curves for recycled coarse aggregate, wet and dry sieving (Alexander et al 2002)

Shayan et al (2003), in their analysis of commercially produced RA in Melbourne Australia, found that the RA was composed of: -

- 83% of relative clean coarse natural aggregate (NA) with amount of adhering mortar on one side or covering the whole particle (stone/ mortar conglomerate)
- 15% Particles made entirely of old mortar; and
- Very few contaminants such as brick pieces, timber and ceramics up to 2 %. They said that the RA had few contaminants due to the fact that the RA produced in Melbourne is manufactured after the removal of contaminants such as bricks, ceramics, plaster, metal, plastics and wood from the demolished rubble before recycling process.

Table 2.11 shows the percentage by weight the materials used in the laboratory experiment by Pedrozo et al (2000). These materials were collected from the landfill in Porto Alegre, Brazil. It was reported that the predominance of mortar and ceramic materials is because most construction technology available in Brazil is housing made of masonry with brick components. They said these aggregate are very porous and have higher water absorption.

Table 2.11: Composition of RA in percentage by Pedrozo et al (2000)

Material components	Percentage by weight
Mortar	29.5
Concrete	18.2
Porous ceramic material	25.9
Dense ceramic material	0.7
Natural stone	11.5
Sandstone	14.2
Others	0.1

2.4.3 Bulk and relative density

Alexander et al (2002) reported that the relative density and bulk density of recycled aggregates was 2.57 and 1392 kg/m^3 respectively, being lower than those of other natural aggregates (granite, greywacke and quartzite) as shown in table 2.12.

Table 2.12: Comparative densities of Western Cape aggregates (Alexander et al 2002)

Rock type	Source	RD	Loose BD (kg/m^3)	Compacted BD (kg/m^3)
Granite	Rheebok quarry Malmesbury	2.63	1365	1460
Greywacke (Malmesbury shale)	Peninsula quarry (Contermanskloof)	2.65	1400	1525
Quartzite	Mossel Bay quarry	2.65	-	1480
Recycled aggregate	**Malans Quarry**	**2.57**	**1257**	**1392**

Olorunsogo et al (2002) found the relative and bulk density differences between NCA (crushed granite) and RCA to be small as shown in table 2.13. The relative density of NCA and RCA was found to be 2.61 and 2.60 respectively while the compacted bulk density of NCA was 1458 kg/m^3 against 1397kg/m^3 for RCA. The loose bulk density of RCA was found to be higher than that of NCA due to the graded nature of RCA which influence good packing of particles.

Table 2.13 Properties of RA and crushed granite aggregates (Olorunsogo et al 2002)

Properties	NCA	RCA
Relative density	2.61	2.60
Compacted bulk density (kg/m^3)	1458	1397
Loose bulk density (kg/m^3)	1344	1362
Moisture content (%)*	5.13**	5.32
Fineness modulus (FM)	-	-

*Moisture content (%) does not give a proper meaning of aggregate properties, may be it was supposed to read water absorption (%)

**This figure obtained form the reference appears to be too high for NCA absorption; it is assumed to be a typing error.

Sagoe-Crentsil (2001) reported marginally lower bulk density of RA, as a result of residual mortar attached to the commercially produced RA in comparison with the basalt according to Australian standards as shown in table 2.14

Table 2.14 Properties of RA and basalt coarse aggregates (Sagoe-Crentsil et al 2003)

Property	RA	Basalt
Absolute density (kg/m^3) (AS 1141.6)	2394	2890
Water absorption (%) (AS 1141.6)	5.6	1.0
Aggregate crushing value (%) (AS 1141.21)	23.1	15.7
Impurity level (%) (AS 1141.32)	0.6	<0.1

Katz (2003) analyzed the properties of aggregates crushed from partially hydrated old concrete. Results of relative density, bulk density, absorption, crushing value and cement content in the RA of the different sizes and crushing ages are presented in table 2.15. The relative density of the RA ranged from 2.23 to 2.60 for the fine to the coarse fractions respectively while the relative density of NA was approximately 2.70. The bulk density of the RA ranged between1220kg/m^3 and 1462 kg/m^3. The bulk density of medium-size aggregate was lower than that of fine aggregate possibly because of better grading of the fine aggregate, leading to a denser packing of the particles. However, lager particles achieved higher bulk density than medium and fine aggregate; this could be contributed to less mortar content attached to the coarser aggregate.

Table 2.15 Properties of RA from partially hydrated concrete (Katz 2003)

Concrete crushing age	Size of crushed materials	Relative density	Bulk density (kg/m^3)	Absorption (%)	Crushing value (%)	Cement content (%)
1 day	Coarse	2.59	1462	3.2	25.4	6.9
	Medium	2.35	1220	9.7	-	15.8
	Fine	2.23	1324	11.2	-	26.6
3 days	Coarse	2.60	1433	3.4	25.3	6.1
	Medium	2.38	1234	8.1	-	15.2
	Fine	2.25	1342	11.4	-	25.4
28 days	Coarse	2.55	1433	3.3	24.3	6.8
	Medium	2.32	1278	8.0	-	13.2
	Fine	2.23	1321	12.7	-	24.5

Pedrozo et al (2000) reported that both RCA and RFA had lower bulk density and relative density than NCA and NFA as shown in table 2.16. RCA and RFA was about 30% and 25% lower than NCA and NFA respectively. The water absorption of RA was extremely higher than NA. Lower bulk density and relative density values were contributed by the porous nature of RA. High porosity also influenced higher water absorption of RA. NA was basalt and NFA was river sand. Both RCA and RFA were obtained from recycled C&DW materials.

Table 2.16: Properties of RA and NA by Pedrozo et al (2000)

Type of aggregate	Natural		Recycled	
Aggregate properties	Coarse	Fine	Coarse	Fine
Max. grain size (mm)	19	4.8	19	4.8
Bulk density kg/m^3	1610	1540	1120	1210
Relative density	3.09	2.62	2.51	2.53
Water absorption (%)	0.3	2.1	4.9	8.6
Fineness modulus	6.9	2.3	5.3	3.0

2.4.4 Particle shape and surface texture

Particle shape and texture affect the workability of concrete (Addis 1998). Rounded particles make concrete with good workability; flat and elongated particles tend to make harsh concrete, smooth surface reduces water requirement and improves workability. Particle shape and texture of fine aggregate has a greater effect than that of coarse aggregate (Addis 1998).

Based on visual inspection, Sagoe-Crentsil et al (2001) reported that the surface texture of the plant-crushed RA was rough and grainy in comparison with basalt aggregates.

Alexander et al (2002) reported that RA particles varied in shape, with a mixture of cubical and sub-angular particles. The surface texture was of a rough nature and highly porous as seen in figure 2.4.

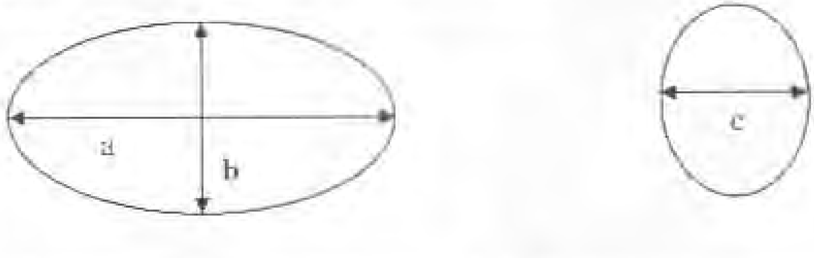
Figure 2.4: RA showing rough and porous surface texture (Alexander et al 2002)

Chen et al (2003) reported that RA had similar particle shape as the crushed rock used in normal concrete as shown in table 2.17. The surface texture of aggregate from concrete and bricks was found to be rough as expected due to mortar attached to the aggregates.

Table 2.17 Particle shape analysis for RA by Chen et al (2003)

Aggregate type		a/c	ab/c*	a/b
Waste concrete	A	2.26	36.0	1.41
	B	2.25	34.5	1.40
Brick	A	2.32	43.2	1.42
	B	2.29	42.3	1.38
Tile	A	2.87	54.1	1.50
	B	2.45	53.4	1.51
Gravel		2.28	45.9	1.47
Crushed rock		2.80	56.0	1.57

* Reference gives no unit for this ratio. (Assumed mm)



a: long axis of aggregate, b: the medium axis and, c: the short axis of aggregate

Tavakoli and Soroushian (1996) reported that the strength characteristics of RC are influenced by key factors such as the strength of the original concrete, the ratio of coarse to fine aggregate in the original concrete, the ratio of maximum size of aggregate in the original concrete to that of the RA, Los Angeles abrasion loss and water absorption of the recycled aggregate. It generally accepted that the cement paste from the original concrete that adhered to the recycled aggregate, and contaminants such as bricks, wood, plastics, paper, dust, bitumen and other impurities, play an important role in the performance of hardened RC.

2.7.2 Compressive strength

Results from laboratory experiment conducted by Pedrozo et al (2000) show that RC performed better than NC as shown in figure 2.9. Using the mix proportions as shown in table 2.27 and 0.60 w/c ratio, they found that RC made with both RCA and RFA had higher compressive strength than NC. RCA and RFA had different influence on concrete compressive strength. The substitution of NFA with RFA had a positive influence on mechanical performance. Increase of RFA content in the mixes increased the compressive strength of RC. They said that this improvement was due to the presence of higher percentage of fine particle and porosity in RA than in NA. This was said to improve the crystallization of cement composites in the surface aggregate pores which increased the compressive strength of RC. However, by using less water than the actual amount that to be absorbed and by use of superplasticizer to maintain good workability, reduced w/c ratio in the mixes containing RA because more free water was absorbed by RA. The amount of RCA and RFA used in the mix was also little in comparison with NCA and NFA because of the factor used to adjust the quantity of RA (equation 3). This also increased the amount of cement per cubic metre of the concrete containing RA. These two factors also played a big roll on increasing the compressive strength of RC.

On the other hand, the substation of NCA with RCA decreased the concrete compressive strength especially at higher substitution level. This was said to be attributed to high internal porosity and low grain strength of RCA. Despite the better bond between aggregate and cement paste, the grain structure of RCA was reported to be weak, mainly with an increase in aggregate grain size. As a result these feature lowered the compressive strength of RC.

approximately 2400 kg/m^3, whereas the concrete made with RA had approximately 2150 kg/m^3. The lower density was the result of lower relative density of the aggregate and also increased air content, leading to an additional reduction in the density of the fresh concrete.

Sagoe-Crentsil et al (2001) reported that the difference between NC and RC wet density was found to be significant. The wet-density of NC was found to be 2466 kg/m^3 while RC had 2335 kg/m^3. This could be attributed to the presence of lower-density residual cement mortar attached to aggregate particles.

2.6.5 Discussions and recommendations

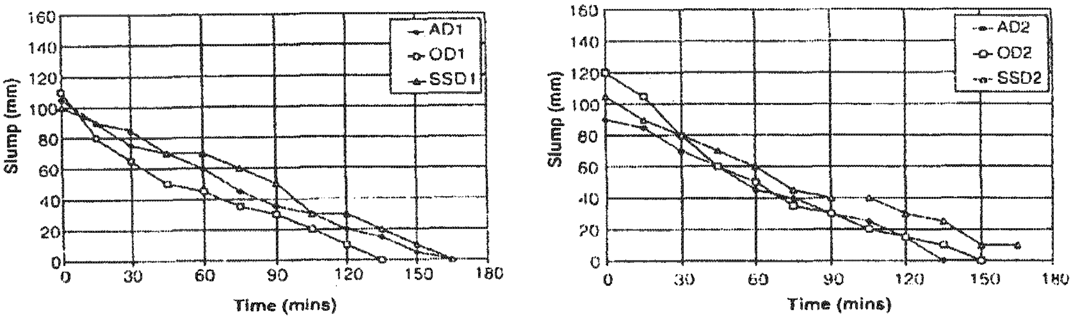
The properties of fresh concrete are important because they influence the handling of concrete, the degree to which the concrete can be compacted, and the uniformity of distribution of constituents within concrete. Handling of concrete has practical implications for construction while compaction and uniformity affects the properties of hardened concrete.

The results presented above from different research reports, show that when RA are used in dry state and no extra water is added to overcome absorption effect, the workability of fresh concrete is affected. Because of high water absorption of RA due to presence of brick particles or mortar attached to RA particles, pre-wetting and use of saturated surface dry RA is recommended in order to prevent a rapid decrease in concrete workability. To maintain mix proportions unchanged, amount of free water and aggregates used in the mix should be adjusted according to the actual moisture contents of the aggregates.

2.7 Influence of RA on hardened concrete

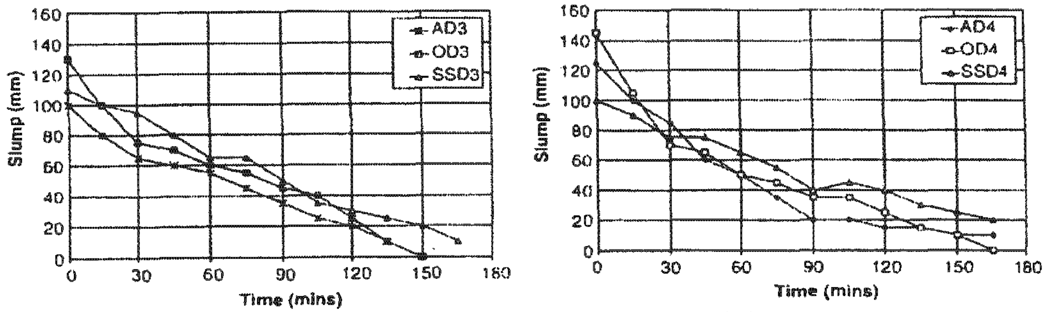
2.7.1 Introduction

It is well known that the strength of concrete depends on the strength of aggregates, cement matrix and the interfacial bond between cement matrix and the aggregates. Researchers (Hansen 1986) have tried to relate the quality of RC to the properties of the original concrete and paste, deterioration condition of the old concrete, crushing procedure, and the new mix composition.



(a) 100% crushed granite

(b) 80% crushed granite + 20% recycled aggregate



(c) 50% crushed granite + 50% recycled aggregate

(d) 100% recycled aggregate

Note: AD – air dry, OD – oven dry and SSD – saturated surface-dry

Figure 2.8: Changes of slump of concrete mixes with different types of coarse aggregates and at different moisture states (Poon et al 2004)

Generally it can be concluded that the workability of concrete containing oven or air-dry RA is less than that containing NA because of their absorption effect and roughness on their surface. Adding water may increase workability, but is advised against because of the adverse influence on the strength and durability of the resulting concrete if water added is more than the absorption capacity of the RA. Increasing both water and cement when using air-dry RA does not keeping w/c ratio constant because some of the water will be absorbed thus reducing water-cement ratio. The use of SSD RA and use of superplasticiser is advised to increase workability without affecting the concrete strength and durability in the hardened state. Use of fine materials in the concrete mix containing RA will reduce bleeding and improve cohesiveness.

2.6.4 Density of fresh RC

Katz (2003) reported that the bulk density of fresh concrete made from RA lower than that made with NA. The bulk density of fresh concrete made with NA was recycled aggregates, some quantity of natural sand was still needed in order to maintain proper workability and cohesiveness.

Hansen (1992) reported that while concrete mixes containing coarse RA and NFA produced desirable characteristics, concrete mixes which are made exclusively with coarse and fine RA tend to be very harsh and not suitable for placing with a slip-form paving machine. Salem et al (2003) reported that mixtures containing RA were found to be harsher and stiffer than mixtures that contained natural aggregates. To achieve the same level of slump for both mixtures, high range water-reducing admixture was used in the RA concrete mixture.

Wegen and Haverkort (1998) reported that the quality of RFA was found to be inferior in comparison with that of river sand. However, they reported that good quality concrete could be produced even at full replacement of the river sand by recycled sand when contaminants were reduced during the recycling process by washing.

Results by Poon et al (2004) in figure 2.8 show a minor difference in slump loss between concrete made with NA and RA at all moisture states. In comparison, the mixes prepared by 20-100% RA in oven-dry (OD) state showed a faster loss of slump than the mixes prepared with RA in SSD state. This may be attributed to the absorption of water by dry aggregates, which rapidly reduces the amount of water in the mixture.

The initial slump of concrete containing OD aggregates was higher as a result of increased amount of initial free water added to the mix. This high initial slump is undesirable in practice because it can lead to segregation of concrete during casting, although the slump may decrease more quickly if RA are used due to its absorption capacity. Generally the mixes prepared with SSD aggregates showed a slower rate of slump loss and the slump did not reach zero during the test period of 165 minutes.

reported that plant processing of RA produces relatively smoother and rounder particles, which leads to improved concrete workability in comparison with natural basalt aggregate with equivalent grading and ratio of the fine to coarse aggregate.

Alexander et al 2002 reported on the effect of dry batched concrete in comparison with SSD batched concrete containing RA as shown in figure 2.7. They found that the slump loss was rapid within 15 minutes for concrete with dry aggregates despite the additional 32 L/m^3 water in the mix. This was due the absorption of unsaturated aggregates. By visual inspection, Alexander et al (2002) reported minimal bleeding of fresh RC. However, no comparison between RC and NC was made.

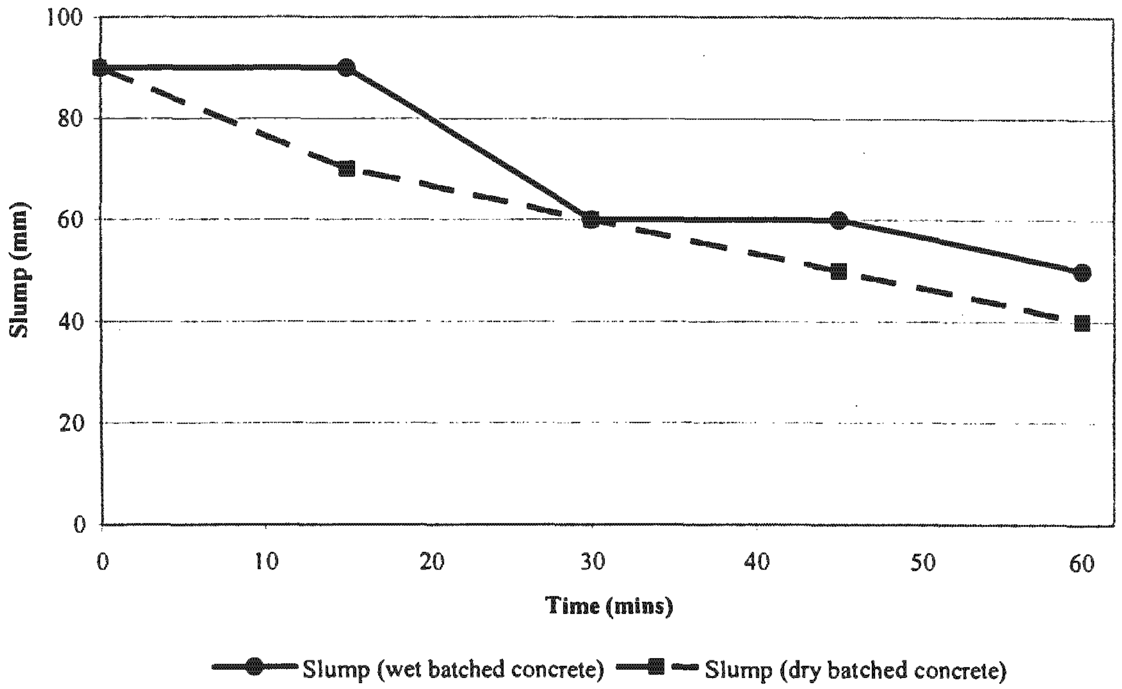


Figure 2.7: Graph showing the slump loss with time (Alexander et al 2002)

Salem et al [2003] on the other hand found that the loss of workability occurred at a faster rate for RA concrete than for NA concrete after the first five to ten minutes. They said that the highly absorbent mortar attached to the recycled aggregate contributed to this effect.

Katz (2003), using aggregates from partially hydrated old concrete, found that workability of fresh concrete was good, but noted that due to insufficient fine in the remains as to the effects of the water in the voids and on the aggregate surface on the hardened properties of the concrete.

The water that is absorbed by RA (pre-wetted) is free water and can be mobilized towards the paste depending on the types of pores within the aggregate. Barra et al (1998) indicated there are two possibilities of what can happen when this free water migrates towards the surface. The first possibility was that the water migrates towards the paste after the end of setting, thus providing an internal curing that will improve the microstructure. The other possibility is that the displacement of the water takes place before final setting, with the paste in a plastic state (partially in the case of delay hydration or retarding admixture being used). In such condition the release of water will increase the water-cement ratio in the interface zone, thus reducing the bonding effect. However several studies (Poon et al 2004) have concluded that there is no obvious impact of pre-wetted RA on the mechanical properties of hardened concrete.

2.6.3 Workability, consistence, cohesiveness and bleeding.

The absorption of RA due to porosity does not affect only the workability of fresh concrete but also the density and the final properties of hardened concrete, including strength and durability (Hansen 1992).

A study by Limbachiya (1998) showed a reduction of workability with increase of RA in the mix at constant water content, but the slump remained within the tolerance of ± 25 mm. The water absorption of RCA was found to be 3-5 times higher the corresponding NA concrete. The mixes were harsh, less cohesive and high bleeding in comparison with the mix with natural aggregates. However, separate work undertaken by Limbachiya (2002) clearly showed that these problems could be overcome by using fine materials.

In contrast, results from experiments carried out by Olorunsogo (1999) on recycled concrete aggregate with Ordinary Portland cement and 0.5 water/cement ratio show that the workability was improved with the increase of recycled aggregate in the mixes. Reasons for this were attributed to the relatively round shape and higher percentage of fine particles in the RA compared to crushed NCA. Sagoe-Crentsil et al (2001) also

2.4.5 Contaminants

One of the problems inherent in use of RA for manufacture of new concrete (Hansen 1992) is the possibility of contaminants in original demolished debris passing into new concrete. Contaminants may be clay balls, bitumen joint seal, gypsum, bricks, tiles, chlorides, organic materials (wood, paper, textile fabric, and other polymeric materials), plastics, industrial chemicals and radioactive substances, tramp steel and other metal particles, glass and weathered or fire damaged particles to mentioned a few.

In order to produce good quality recycled aggregate, Collins (1994), suggests that it is important to separate out different types of materials from the debris before it enters the crusher. He adds that the best place to start separation is on the demolition site itself. It is also important to exclude materials which could be contaminated, e.g. chimneys, furnaces and concrete that could be contaminated with chemicals.

Alexander et al (2002) found the chloride content for unwashed RCA to be higher (0.152% by mass of aggregate) than allowable (0.03%), but reduced to 0.042% when soaked in water for seven days, and subsequently drained.

A study by B.C.S.J[3] (1978) and reported by Hansen (1992), shows that impurities in the form of tiles and window glass have little influence on the compressive strength of RC. However, blast furnace slag aggregate may lower slightly concrete strength. Concrete with 3% of gypsum plaster was found to have 15% reduction in strength when concrete was dry-cured and 50% when concrete was wet cured. This is because gypsum plaster is soften and weakened by immersion (Hansen 1992).

Contaminants in the latest research information are not well covered. This may be due to the fact that most of the researchers have been using laboratory prepared RA or due to increase awareness of cleaning C&DW debris for being recycled. However, different type of contaminants in RA and their effects in concrete have been extensively covered by Hansen (1992). To overcome excessive amount of impurities, Japanese standards have set the requirements for RA to be used in concrete as shown in table 2.18.

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[3] Building Contractors Society of Japan

Table 2.18: Allowable amounts of impurities (Hansen, 1992)

Type of Aggregate	Impurity I*	Impurity II*
Recycled coarse aggregates	10 kg/m^3	2 kg/m^3
Recycled fine aggregates	10 kg/m^3	2 kg/m^3

I* - Gypsum plaster and other plaster materials, clay lumps < 1.950 kg/m3, II* - Asphalt, plastic, paint, cloth, paper, wood having density less than 1200 kg/m3 and similar material particles which can be retained on 1.2 mm sieve.

2.4.6 Water absorption

Hansen (1992) suggested that water absorption of RCA and RFA should be determined in the laboratory before any mix design of RC is attempted. He mentioned that it is difficult to determine the water absorption capacity and water content of RFA than of RCA because RFA particles are more cohesive. The use of ASTM C 128 (standard test methods for specific gravity and absorption of fine aggregate) was inappropriate and inaccurate when used to assess when RFA are in a saturated surface-dry condition. He suggested that other methods should be investigated for more accuracy and consistency.

Chen et al (2003) reported that absorption ranged from 5 % to 7.5 % for RCA and up to 10.4% for RFA, being higher than that of NA, table 2.19. This was attributed to the higher porosity of recycled concrete aggregate. Limbachiya et al (1998) also reported RA to have water absorption 3 to 6 times higher than that of natural aggregate for RCA and RFA respectively. This was mainly due to the porosity of mortar present in RA.

Table 2.19: Comparative physical properties of NA and RA by Chen et al (2003)

Properties	NCA	RCA	NFA	RFA
SSD specific gravity	2.63	2.28	2.62	2.19
SSD absorption capacity (%) by weight	1.17	7.54	1.04	10.37
Dry-bulk density (kg/m^3)	1533	1241	-	-
FM	-	-	2.95	2.68

Results in table 2.20 by Barra and Vasquez (1998) show water absorption of concrete and brick RA to be higher than that of limestone. Limestone had water 0.5% to 0.8 % water absorption. RA from concrete and bricks had 6.9 – 7.5% and 14.0 – 14.5 % water absorption respectively. Absorption in RA increased with the decrease of particle size. Results in table 2.20 also show that the porosity of aggregates is approximately twice the water absorption value and directly proportional to water absorption of RA.

Table 2.20: Physical properties of coarse NA and RA (Barra and Vasquez 1998)

Properties	Natural aggregate		Recycled aggregate			
	(Limestone)		(Concrete)		(Brick)	
Size range (mm)	Gravel (12-20)	Gravel (6-12)	Gravel (12-20)	Gravel (6-12)	Gravel (12-20)	Gravel (6-12)
R.D ASTM C642 (4) dry	2.680	2.660	2.270	2.238	1.870	1.866
SSD	2.694	2.682	2.427	2.406	2.141	2.135
Porosity (%) ASTM C642 (4)	1.4	2.2	15.6	16.8	27.1	27.1
Abs. (%) ASTMC642 (4)	0.50	0.80	6.85	7.49	14.5	14.4
L.A. (%) UNE 83-116 (5)	24.7	20.4	31.0	29.5	26.9	23.9
Size distribution UNE 7-139 (6)	19.0	12.5	19.0	12.0	19.0	12.0
Fineness modulus	7.10	6.00	6.97	6.15	7.10	6.00

Shayan et al (2003) reported the water absorption of RCA to be 4.7% in saturated surface dry condition, higher than that of NA (usually < 1%). The water absorption of RFA was found to be 6.3%, which is higher than that of NFA (1%). It was also reported that this value was lower than values of 9 to 12% obtained by the recycling company involved. This variability can be expected in mass production of RA.

Hansen and Narud (1983) reported that regardless of the quality of original concrete, the water absorption of RCA ranged from 8.7% for 4-8 mm material to 3.7% for 16-32 mm materials. The strength of the original concrete in commercial production of RA cannot be assessed due to the fact that the processed rubbles are a mixture of different concrete grades and types. However, Hansen (1992) said the properties such as density and water absorption might provide information on the effects of the old mortar on the properties of aggregates.

According to the Japanese proposed standard for the use of RA as quoted by Hansen (1992), RA should not be used for concrete production when water absorption is more than 7% and 13% for RCA and RFA respectively. Due to higher water absorption of RA, it is sometimes suggested to use pre-wetted aggregates for production of RC in order to maintain uniform quality during concrete production

A method to estimate water absorption has been suggested by Japanese researchers (Kasai 2004). This test method makes use of the relation between the rate of water absorption and the amount of mortar attached to the original aggregate. After determining the 100 kN crushing value by the BS 812 method, the water absorption Q in percent can be estimated by using the following formula

$$Q = 0.85\ Cg + 1.50 \qquad 2.1$$

Where Cg is the 100 kN crushing value, in percent. The loss of soundness P, of RCA also in percentage can be estimated by the following formula

$$P = 8 \times Q \qquad 2.2$$

Thus, for a Q-value of 3%, the soundness value P becomes 24%. According to table 2.7 in section 2.33, the durability of 1st and 2nd class RCA may be insufficient, but definite conclusion can be drawn only after further evaluation.

2.4.7 Crushing strength of RA

Alexander et al (2002) found that the 10% FACT values of 150 kN for wet and 190 kN for dry samples respectively as shown in table 2.21 and figure 2.5 were greater than the 110 kN recommended by SABS 1083:1994 for the concrete subjected to surface abrasion.

Table 2.21: 10% FACT of RA and Western Cape materials (Alexander et al 2002)

Rock type	Source	10% FACT dry (kN)
Granite	Rheebok Quarry	280
Greywacke (Malmesbury shale)	Peninsula quarry	299
Quartzite (Ortho-Quartzite)	Mossel bay Quarry	244
Recycled aggregate	**Malans Quarry**	**190**

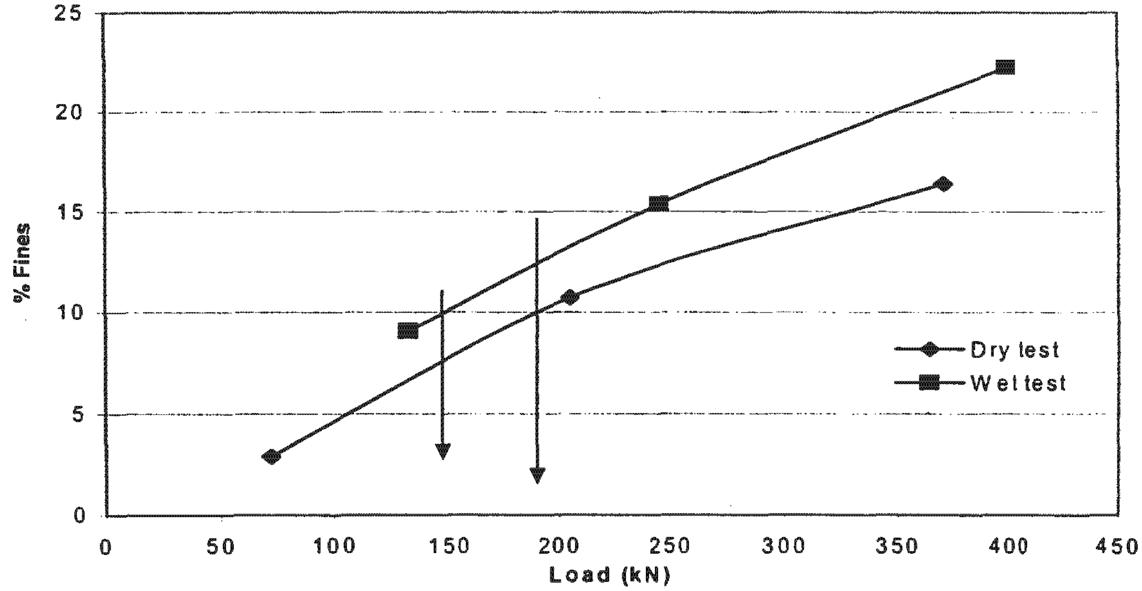


Figure 2.5: 10% FACT results of wet and dry RA (Alexander et al 2002)

Sagoe-Crentsil (2001) confirmed that the cement mortar attached to the aggregate particles primarily determines the physical properties and performance of concrete made with RA. In his experiment he found that the aggregate crushing value of the RCA was higher than that of natural aggregate (23.1% v/s 15.7%) as shown in table 2.13. This may be due to breakup of the weaker layer of mortar attached to the natural aggregates.

Results in table 2.20 by Barra and Vasquez (1998), shows that L.A. Abrasion of 'concrete' (stone/mortar conglomerate) to be higher than that of natural aggregate (limestone). There was also a substantial difference between NA and 'brick' aggregate (RA with brick content) abrasion value. On average NA had 22.5%, 'concrete' 30% and 'Brick' 25% abrasion value. There is no explanation of why brick materials had low abrasion value, but this may be due to plasticity of clay materials.

2.4.8 Discussions and recommendations

Properties of RA have been covered in this section. It has been observed that generally RA composed of stone/mortar conglomerate and stone in higher percentage, and lower percentage of masonry (brick/block) and others materials such as tiles, glasses, and wood depending on the source of recycled rubble.

Bulk density and relative density of RA have been reported to be lower than NA and water absorption RCA and RFA to be as higher as 3 and 10 times than NCA and NFA respectively. Since the quality of RA fluctuates considerably, quick test methods are required. It is believed that the rate of water absorption of aggregate is an indicator of quality. RA with large amount of mortar or bricks exhibits a higher water absorption, which points to low quality. It is therefore important that density, relative density and water absorption of RA are determined carefully prior to their use in concrete production. This should be done in order to achieve concrete of adequate workability, stability and cohesiveness; also to avoid large variations in properties of hardened concrete.

The use of RFA is not recommended for general use in concrete because it usually has an adverse effect on water demand and may contain increased level of contamination. However, where there is a high degree of control, RFA can be used to replace NFA in small scale concrete work.

2.5 Concrete mix design

2.5.1 Introduction

Because of variations in RA physical properties, Hansen (1992) suggests trial mix design be made in order to adjust free water content necessary to obtain the required slump, the water-cement ratio necessary to obtain the required strength, and the ratio between fine and coarse aggregate necessary to achieve an economical mix with good workability in the fresh state. Due to uncertainties in free water and absorbed water when using RA, De Pauw et al (1998) found that it was impossible to determine accurately the amount of water that had to be added to a mix to obtain the required workability. To overcome this, they tried several mixes to find the relationship between the amount of water in the concrete and its workability.

2.5.2 Concrete mix design

Alexander et al (2002) used the method proposed by the Cement and Concrete Institute (Addis, 1998) as guidance to estimate mix proportions. The method is for nominally single sized natural aggregates while the RA used for their study was partially graded aggregates. They carried out various trial mix designs until they got a mix with required workability and cohesiveness as shown in table 2.22. The table shows that an extra 32 L/m^3 of water was added to a dry mix to cover for water to be absorbed by aggregate. However, the aggregate content was not reduced by the same amount. That is, the mix with dry aggregate had higher content of RA than SSD mix.

Table 2.22 Mix proportions for wet and dry batched mix (Alexander et al 2002)

	SSD-batch	Dry-batch
Materials	Qty/m^3	Qty/ m^3
Free w/c	0,72	0,72
Water (L/m^3)	165	197
50/50 CEM I/GGCS (kg/m^3)	229	229
Recycled coarse aggregate (kg/m^3)	1009	1009
Natural fine aggregate (kg/m^3)	888	888
Slump (mm)	90	80

Olorunsogo et al (2002) also used the same method (C&CI method). The mix was design to have a 28-day target compressive strength of 30 MPa. Water-cement ratio was kept constant at 0.5. 198 litres of water and 395 kg of cement per cubic meter were used in the mixes as shown in table 2.23. All samples (NA and RA) were pre-saturated and had moisture content of 4.53%, 5.13% and 5.32% for NFA, NCA and RCA respectively.

Table 2.23 Mixing proportions by Olorunsogo et al (2002)

Mix type	Cement (kg/m^3)	% of RA	NFA (kg/m^3)	RCA (kg/m^3)	NCA (kg/m^3)	Water L/m^3
1	395	0	563	0	1196	198
2	395	50	563	598	598	198
3	395	100	563	1196	0	198

Poon et al (2004) designed mix proportions using the absolute volume method assuming that the aggregates were in a saturated surface-dry (SSD) condition. To maintain the design mix proportions unchanged, the amount of water and aggregate used in mixing were adjusted according to the actual moisture contents of the aggregates. Free water content up to 205 L/m^3 was used. Water-cement ratio (w/c) of 0.57 and fine aggregate to total aggregate ratio of 0.375 was kept constant. Due to difference in densities of NA and RCA the actual amounts of fine and coarse aggregate in the mixes were slightly different as shown in table 2.24.

Table 2.24: Actual water and materials used in different mixes (Poon et al 2004)

Mix	Aggregate combination	Moisture State		Proportions in (kg/m^3)					
			W	C	Sand	Crushed granite		RA	
						10 mm	20 mm	10 mm	20 mm
AD1	100% NCA	AD	214	353	667	362	724	-	-
OD1		OD	221	353	667	360	720	-	-
SSD1		SSD	209	353	666	364	729	-	-
AD2	80% NCA 20% RCA	AD	217	353	660	287	574	70	139
OD2		OD	230	353	661	284	569	67	135
SSD2		SSD	206	353	661	288	576	72	144
AD3	50% NCA 50% RCA	AD	229	353	647	176	351	170	343
OD3		OD	247	353	647	175	349	164	332
SSD3		SSD	207	353	649	177	354	177	354
AD4	100% RCA	AD	241	353	625	-	-	330	663
OD4		OD	271	353	625	-	-	317	642
SSD4		SSD	209	353	625	-	-	342	684

AD – air dry
OD – oven dry
SSD – saturated surface-dry

Barra et al (1998) on the other hand suggested a special mix design procedureswhich takes account of the influence of RA. They used the mix design diagram shown in figure 2.6 to design a concrete mix. The mix proportions for RC (R_r, R_n, R_p) were prepared with the relation of w/c ratio, compressive strength (f_{c28}), the aggregate content of the mix (m) and cement/m^3 (c). The mix proportions for normal concrete (H) were prepared with the data H_r, H_n, and H_p on the same axis as for RC in order to establish a comparison. Initially the strength level was estimated and then the quantity of cement calculated as shown in table 2.25 and then the mix proportions derived as shown in table 2.26.

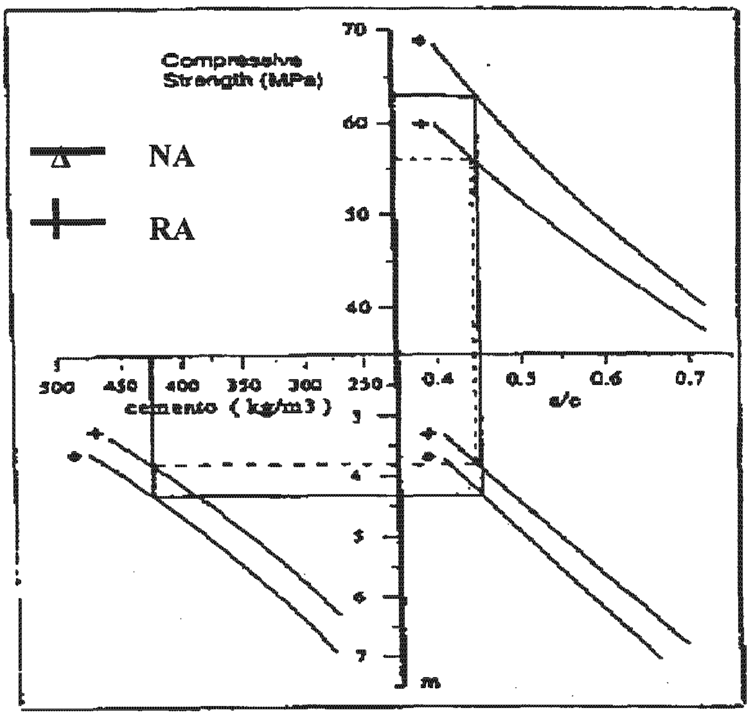


Figure 2.6 Mix design diagram (Barra et al 1998)

Table 2.25: Cement content for a given strength (Barra et al 1998)

		NA			RA		
Case	$F_{C,28}$ (MPa)	a/c	m	C (kg/m^3)	a/c	m	C (kg/m^3)
I	45.0	0.66	7.0	278	0.60	5.8	298
II	57.5	0.51	5.0	375	0.43	3.6	440

Table 2.26: Concrete mix proportions (Barra et al 1998)

Mix type	Mix proportions (weight)				
	Cement	Sand	Agg. (6-12)	Agg. (12-20)	w/c
Hr	1	1.05	1.05	1.57	0.40
Hn	1	1.94	1.39	2.09	0.53
Hp	1	2.68	1.74	2.60	0.66
Rr	1	1.21	0.92	1.37	0.42
Rn	1	1.94	1.22	1.84	0.54
Rp	1	2.68	1.53	2.29	0.67

H – normal concrete, R – recycled concrete, r – mix with high (rich) cement

n – mix with normal cement, p – mix with little cement

Pedrozo et al (2000) used a method proposed by Brazilian standards IPT/EPUSP, to determine mix proportions. For the w/c ratio of 0.60, cement content of 299 kg/m^3 was obtained. Six different mixture proportions prepared for this w/c ratio are presented in table 2.27. The aggregates volume content was compensated due to the influence of RA lower density. This adjustment was done by using the equation 3 below.

$$W_{RA} = W_{NA} \times (\gamma_{RA} / \gamma_{NA}) \tag{2.3}$$

Where, γ is the specific gravity value (relative density) of RA and NA.

Absorption water for RA was considered separately. 40% and 50% of RCA and RFA water absorption respectively was used to pre-saturate RCA and RFA for 1o minutes, prior to mixing. It is not explained why 40% and 50% of water absorption value for RCA and RFA was used. They said that the values were chosen based on the aggregate water absorption curves which demonstrate that RA absorb more than 50% of the total water absorption within ten minutes.

Table 2.27: Concrete mix proportions Pedrozo et al (2000)

Replacement (%)		Composition (kg/m^3)						
			Fine aggregate		Coarse aggregate		Free water	Added abs. water RCA/RFA
RCA	RFA	Cement	Natural	Recy.	Natural	Recy.		
0	0	299	1216.2	0.0	869.3	0.0	179.5	0.0
50	0	299	1216.2	0.0	434.7	417.6	179.5	9.8/0.0
50	50	299	608.1	493.5	434.7	417.6	179.5	9.8/18.0
0	50	299	608.1	493.5	869.3	0.0	179.5	0.0/18.0
100	50	299	608.1	493.5	0.0	835.3	179.5	19.5/18.0
50	100	299	0.0	986.9	434.7	417.6	179.5	9.8/35.9

From the different mix designs deployed above, it can be concluded that normal mix deign methods used to design proportions of normal concrete can be used to design concrete containing RA provided some modifications are used to allow for the water absorption problem of RA.

2.6 Influence of RA on fresh concrete

2.6.1 Introduction

In concrete production using RA, the amount of water that the aggregate will absorb in the mix depends on the porosity of RA (Poon et al 2004), which is not consistent at all. Hendricks and Pietersen (1998) reported also that the angularity of the crushed materials contributes to a higher water requirement as well. Because of these properties, concrete with RA absorbs a higher amount of moisture than concrete with NA.

Due to the high water absorption of RA, the influence of the moisture states of RA on the properties of fresh and hardened RC has received some research interest. Pre-wetted and saturated RA has been used in several studies (Hansen 1992) Sagoe-Crentsil et al (2001) in order to prevent a rapid decrease in concrete workability.

2.6.2 Water requirement

Due to the uncertainties in free water and absorption water, De Pauw et al (1998) found that it was impossible to determine accurately the amount of water that had to be added to the mix to obtain the required workability. To overcome this, various trial mixes were performed to find relationship between the amount of water needed in the mix and its workability.

Hansen (1992) reported that most researches have found that, approximately 10 L/m^3 or 5% more free water was required when only RCA were used in concrete production; when both RFA and RCA were used, 25 L/m^3 or 15% more water was needed. Barra et al (1998) reported that, when recycled aggregates are mixed directly with water, the amount of water absorbed is higher than if the aggregates are mixed with cement paste or previously prepared mortar. They found that by mixing the aggregates first with water and cement, the pores/voids of the aggregates are coated with cement paste and absorption is therefore reduced.

The influence of moisture state of RA on the properties of fresh and hardened RC has received some research interest. Researchers such as Hansen (1992), Sagoe-Crentsil et al (2001) and Poon et al (2004) have found that by pre-wetting or partially saturating the RA prior to concrete mixing, a decrease in concrete workability is prevented. Doubt

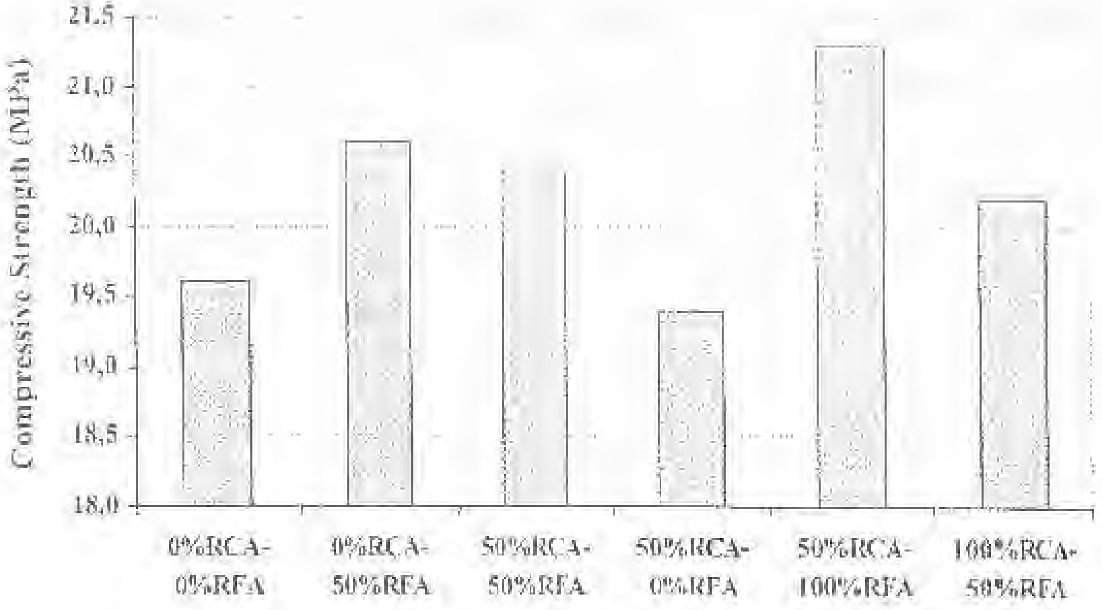


Figure 2.9: Influence of RA in compressive strength of concrete (Pedrozo et al, 2000)

Laboratory experiments by Katz (2003) on concrete made with RA from partially hydrated concrete showed that compressive strength of the RC made with White Portland cement (WPC) was 30-40% lower than the normal concrete. The maximum reduction was observed in concrete made with RA obtained from partially hydrated old concrete crushed after 1 day as shown in Table 2.28 and figure 2.9. Crushing age was seen to have a significant effect on the compressive strength of RC made with WPC. This might be attributed to the type of cement used in the previous old concrete. RA was from crushed concrete that was made with OPC. The effect of crushing age was much smaller on RC made with OPC. The difference between the lower and the higher compressive strengths were 7% and 13% at testing age of 7 days and 90 days respectively. Contrary to WPC RC, a higher compressive strength was observed on OPC RC made with RA crushed from 1-day-old concrete. This would be attributed to the presence of unhydrated cement that may have increased cement content in the new mix. There was no significant difference between RC made with RA crushed from 3 day and 28 day old concrete.

Generally the compressive strength of concrete (normal and RC) made with ordinary Portland cement was found to be lower than that made with White Portland cement for all mixes. However, when relative strength is compared as shown in figure 2.10, RC made with OPC was found to be higher than that made with WPC for all mixes, this due is due to higher compressive strength of NC made with WPC in comparison with NC made with OPC.

Table 2.28: Properties of hardened RC (Katz 2003)

Properties	WPC				OPC			
	Ref. concrete	1 d*	3 d*	28 d*	Ref. concrete	1 d*	3 d*	28 d*
Comp. strength (MPa)								
7 days	36.8	19.0	23.4	20.0	21.6	18.3	17.0	17.1
28 days	42.1	24.1	30.5	29.1	34.6	26.6	25.8	26.8
90 days	58.9	28.9	38.7	35.2	40.6	33.0	28.7	30.6
Flexural strength (MPa)	6.7	4.7	5.3	4.60	6.10	6.1	5.4	5.4
Splitting strength (MPa)	5.0	3.1	3.6	2.7	3.3	3.4	2.9	3.1
Modulus of elasticity (GPa)	23.1	11.4	13.7	11.5	22.7	14.2	13.3	11.3

d* – Crushing age (days) of old concrete

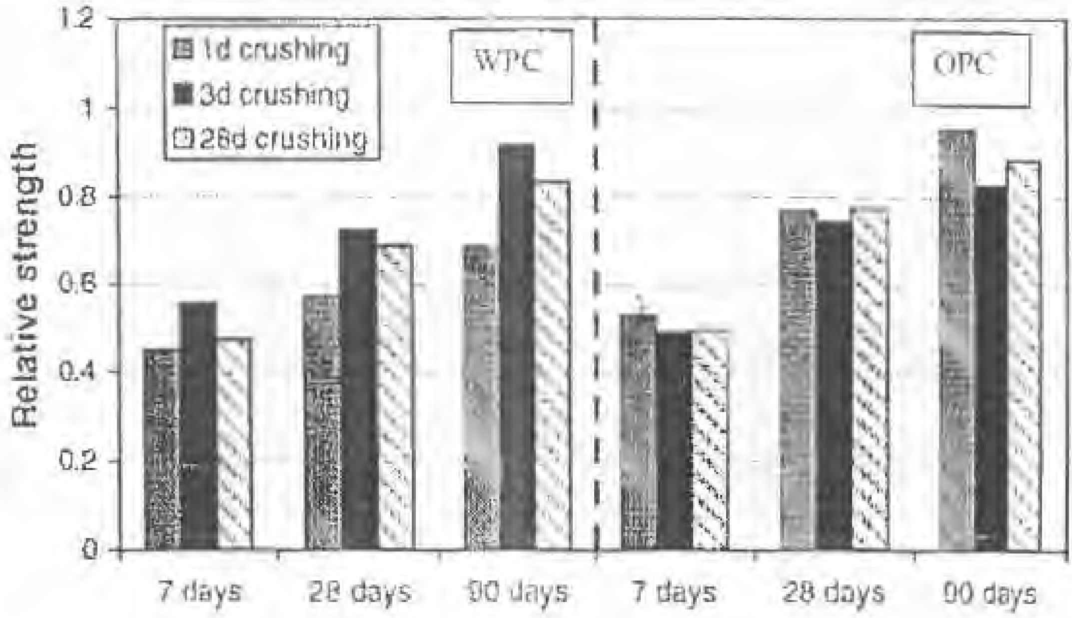


Figure 2.10: Relative compressive strength of RC to the reference concrete crushed at different age (Kratz 2003)

A study by Poon et al (2004) on the influence of moisture state of NA and RA on the compressive strength of NC and RC showed that RC had higher compressive strength than normal concrete when oven-dry NA and RA were used as shown in table 2.29 and figure 2.11. RC attained 97% and 85% of compressive strength of NC when air-dry and SSD RA was used respectively. Bleeding observed during compaction might have contributed to the lower compressive strength of SSD RA concrete.

Movement of moisture within the RA particles might have been another cause of lowering compressive strength of RC made with SSD RA. Sometimes it is difficult to judge SSD state of RA especially when contain smaller particles. Extra water around the RA may relatively increase water-binder ratio around the RA particles. This may weaken the bond between RA particles and the mortar.

On the other hand, when oven-dry RA is used, water may move from the mortar towards the "water-hungry" RA and water-binder ratio around the RA particles is reduced even when extra water is added to compensate for absorption effects. As a result, a strong bond may be formed between the RA particles and mortar especially at early age leading to higher strength.

Table 2.29 Influence of moisture state of RA on compressive strength (Poon et al 2004)

% of RA in the mix	Compressive strength at the age of 28 days (MPA)		
	OD	AD	SSD
0	40.2	48.3	46.0
20	43.2	44.9	43.0
50	39.7	44.7	38.1
100	43.3	46.8	39.1

Moisture state: OD – oven-dry, AD – air- dry and SSD – saturated surface dry

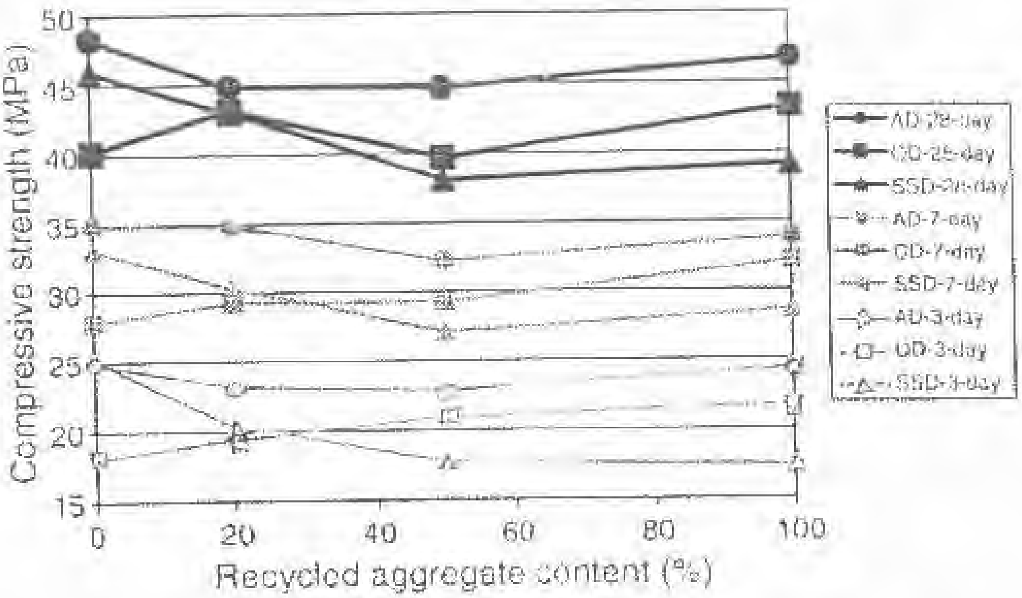


Figure 2.11: Effect of RA content on concrete compressive strength (Poon et al 2004)

Shayan et al (2003) determined the effect of improved surface of RA on properties of RC. It was found that concrete with RA treated with dilute sodium silicate and silica fume slurry (mix 3 and 4) developed higher compressive strength than untreated RA concrete as shown in table 2.30.

Table 2.30: Properties of concrete made with treated RA (Shayan et al 2003)

Mix No.	Mixture and (treatment)	W/C	Density (kg/m^3)	Compressive strength (MPa) 7 days	Compressive strength (MPa) 28 days
1	RA (N42)	0.36	2330	41.3	48.0
2	RA (N42) + lime	0.35	2325	39.9	44.6
3	RA (N42) + silica fume	0.35	2330	46.1	55.4
4	RA (silica fume slurry)	0.35	2330	46.6	60.3
5	RA (N42) + lime + silica fume	0.35	2290	41.0	50.8
6	Basalt + silica fume	0.34	2455	51.5	68.1
7	Basalt	0.35	2464	51.1	58.3
8	RA + silica fume	0.35	2376	46.7	49.3

This shows that silica fume and sodium silicate solution treatment on RA likely increases the interfacial bond in concrete by reducing the pores on the RA surface.

Strength values of 50 and 60 MPa were obtained on 28-day old concrete cylinders under moist curing conditions, which indicate that RA can be used to produce high-grade concrete. Though high compressive strength was achieved, applicability in real life especially on site work may be difficult and expensive.

Alexander et al (2002) reported that the target compressive strength of 30 MPa was achieved by using 100% of RCA in both dry and saturated surface-dry (SSD) conditions. Contrary to Poon et al (2004) results, they found that the compressive strength of concrete made with SSD RA was higher than that of dry aggregates after 28 days, refer Figure 2.12.

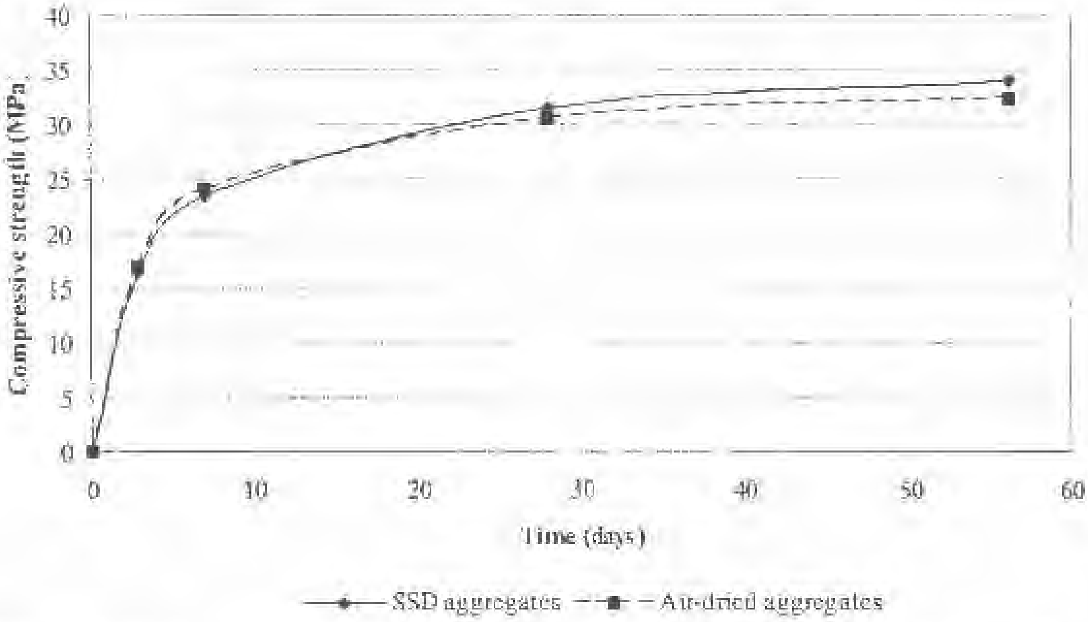


Figure 2.12: Compressive strengths for SSD RA and air-dried RA concrete mix (Alexander et al 2002)

A study by Olorunsogo et al (2001) showed that by using recycled concrete coarse aggregate the design compressive strength of concrete with the same binder type and w/c ratio was attained, but less than that of the concrete made with natural aggregates.

On the other hand Barra et al (1998) found that concrete with RA need higher cement content when designed for a given strength. They found that for 45 MPa concrete, the required cement content was increased by 7.2%. To obtain higher strength in RC, the cement content was increased progressively up to 17.3% to produce a 57.5 MPa concrete.

Results in figure 2.13 by Sagoe-Crentsil et al (2001) using Ordinary Portland cement (OPC) and ground granulated slag (GGS) show that concrete made with 100% RA attained a higher compressive and tensile strength than concrete made with NA (basalt) at later age. Compressive strengths were determined on concrete cylinders continuously stored under moist conditions for up to 365 days. The higher compressive strength of RC might be attributed to differences in water-binder ratios. Normal concrete made with basalt had absorption capacity of 1.0% and water-binder ratio of 0.76 while RA had high absorption capacity of up to 5.6% and water-binder ratio of 0.70 to 0.74.

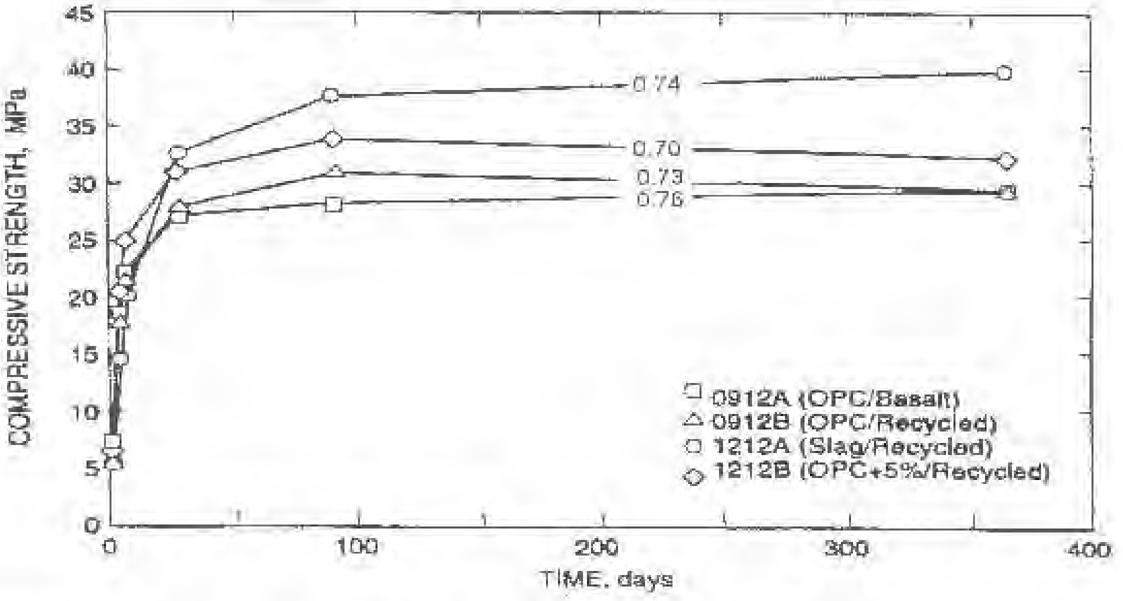


Figure 2.13: Concrete compressive strength with age (Sagoe-Crentsil et al 2001)

Although the RA were pre-saturated for 10 minutes before mixing, this period may have not allowed full saturation of RA leading to more absorption after mixing. Later absorption might have reduced free water in the mix, hence reducing water-binder ratio leading to higher compressive strength of RC. As expected, the RC with cement/slag (65/35) binder achieved higher later-age strength than OPC RC at similar water-binder ratio. This is due to the hydraulic properties of the slag.

Salem et al (2003) carried out an experiment to determine the strength properties of hardened RC. Three cases were considered for both RC and NA. Case 1 consisted of using a medium water-cement ratio of 0.47. Case 2 using 0.29 water cement ratio (high-performance concrete) and Case 3 consisted of varying the base mixture by entraining with an air content of 5%. They found that compressive strength of RC was higher than NC in Case I and case II and only lower for Case II after 28 days, figure 2.14. Reduction in the w/c ratio from 0.47 to 0.29 in Case I and Case II respectively, increased compressive strength as expected for both the RC and NA.

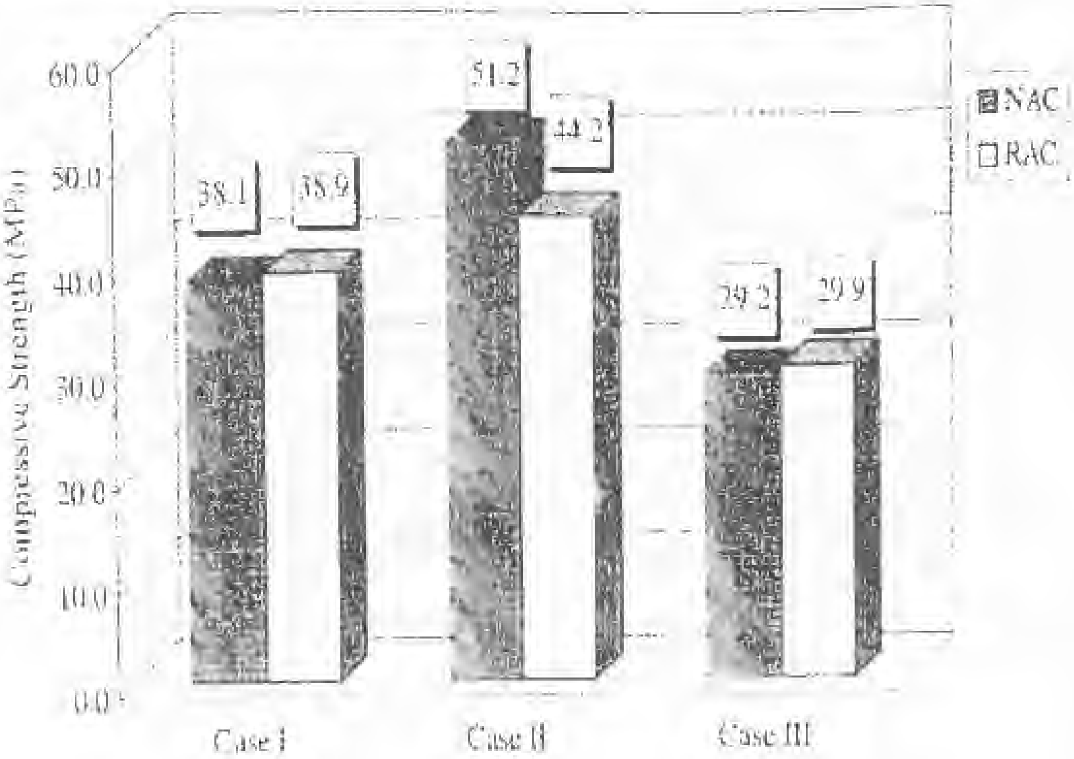


Figure 2.14: Compressive strength of RC and NC at 28 days (Salem et al 2003)

However, the rate of increase of compressive strength of RC was not equal to that of NA. Compressive strength of NA increased by 34% from 38.1 to 51.2 MPa, while compressive strength of RC increased only by 14% from 38.9 to 44.2 MPa. It was reported that RC failure in lower w/c ratio was caused by RA failure, while failure of NC was due to cement paste failure. This concludes that the RA can produce concrete with similar strength at higher w/c ration. Comparing the effect of air entrainment on the strength of RC and NC shows that 5% air entrainment, 25% and 23% reductions in compressive strengths of both NA and RC occurred, respectively.

Chen et al (2003) in their study found that the compressive strength of concrete made with washed and cleaned RA (without any RFA, wood, plastic, paper and other visible impurities), but containing variable brick and tile particle composition and 0.5 water-cement ratio was found to be 75-85% that of normal concrete as shown in figure 2.15. Cylindrical specimens with 100 diameter and 200 mm long were used for compressive strength test. They found that the compressive strength was reduced as the brick and tile content increased in the mix. At 67% brick and tile content in the mix, the RC attained 75% of compressive strength of normal concrete.

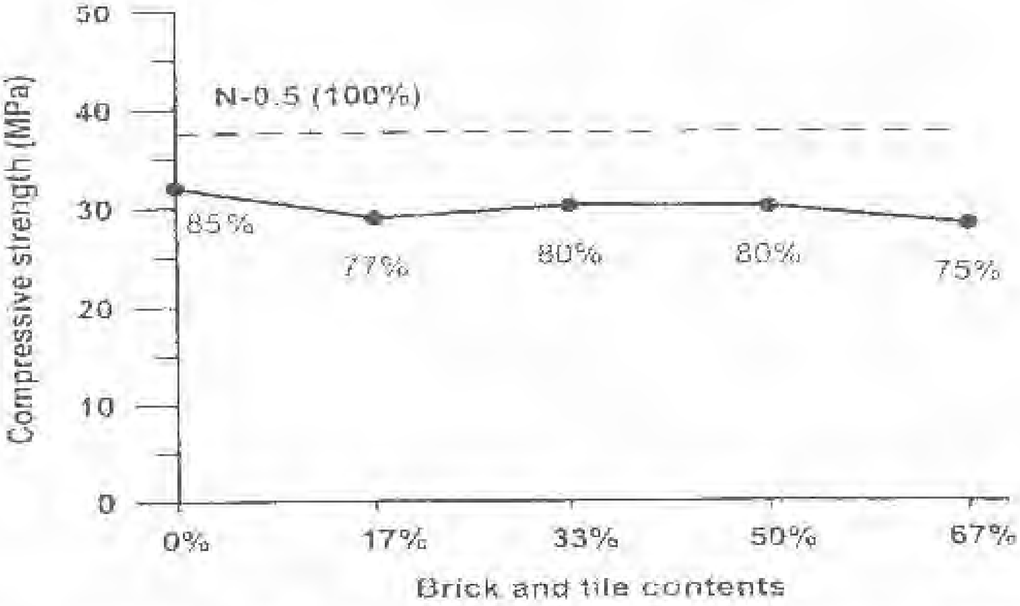
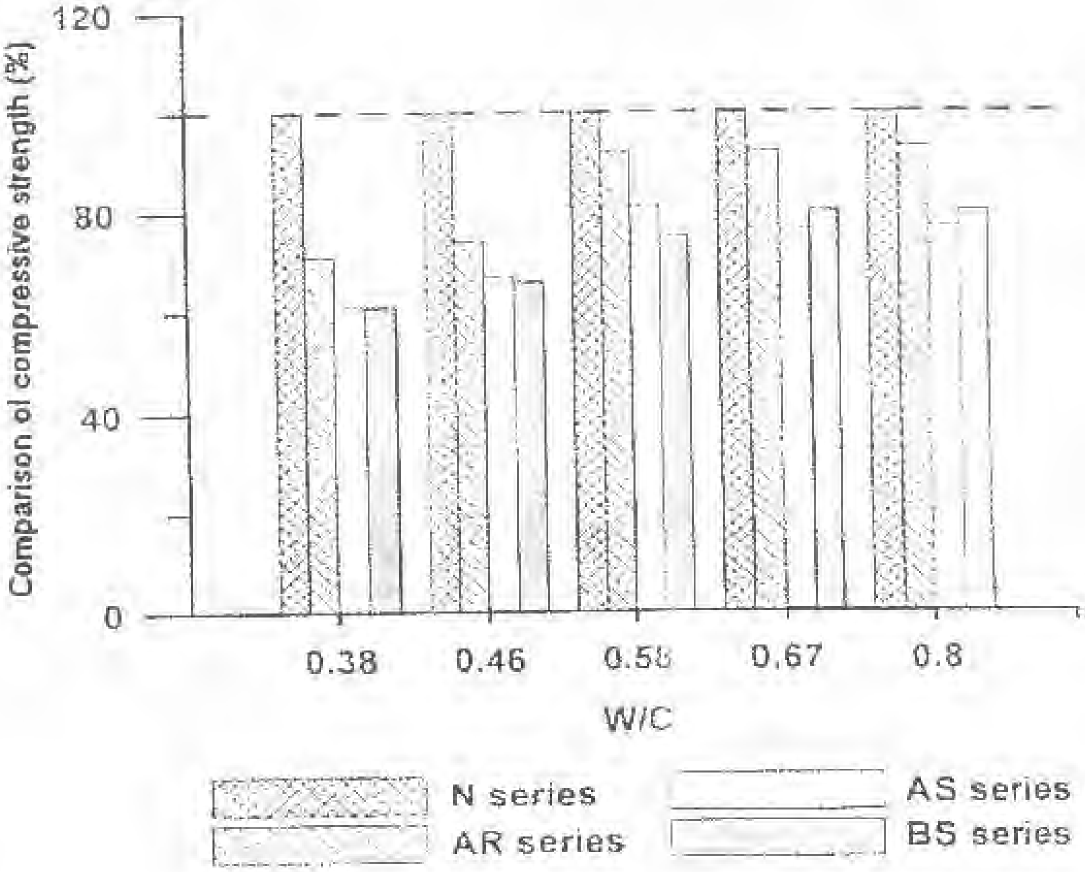


Figure 2.15: Compressive strength of RC containing up to 67% brick and tile contents with 0.5-water/cement ratios (Chen et al 2003)

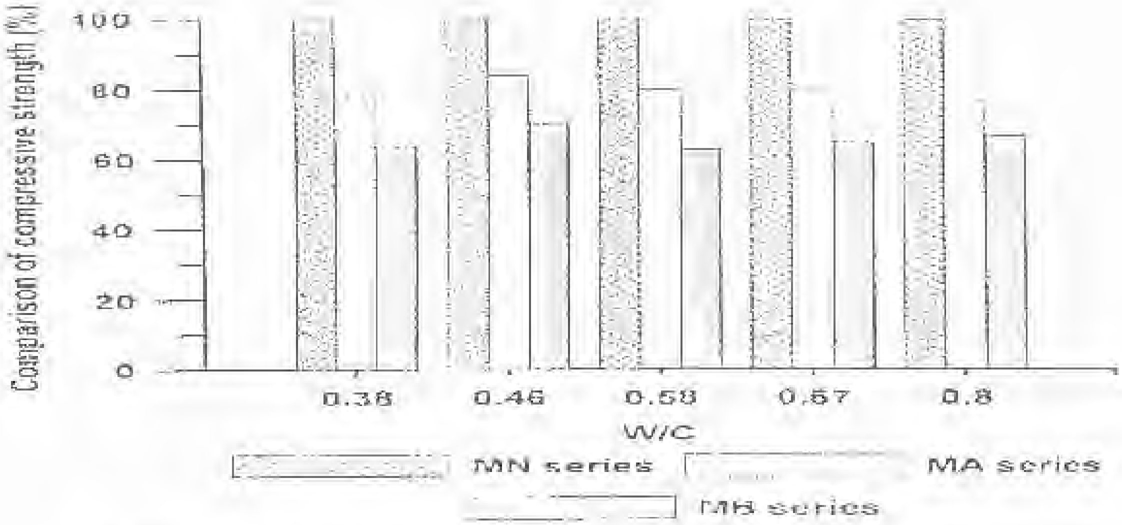
Comparing the effect of washed and unwashed RA on the new concrete at different water-binder ratios, they found that washed RA can attain 85% at lower water-binder ratio and up to 90% at higher water-binder ratio of normal concrete while the RC made with unwashed RA can reach only 60% compressive strength of normal concrete, see figure 2.16. This is due to the effect of impurities, powder (very fine materials) and other harmful materials on the aggregate surface. Using washed RA, impurities and other harmful materials are washed from aggregate surface creating better bonding between RA and paste.



N – Natural aggregate concrete, AR – washed RA from source A, AS and BS – unwashed RA from source A and B respectively

Figure 2.16: Comparison of concrete compressive strength (Chen et al 2003)

The effect of RFA on the properties of hardened mortar has also been reported. Figure 2.17 shows that with the same water-cement ratio, the strength of the MA (mortar containing 30% RFA) and MB (mortar containing 65% RFA) series was lower than that of the MN (normal mortar) series. The strength of MA and MB recycled mortar was about 80% and 65% that of MN series respectively at water-cement ratio ranging between 0.3 and 0.8. This shows that percentage reduction does not depend on water-cement ratio; rather the quantity of RFA in the mix governs the reduction in mortar strength. As the RFA content is increased, the percent reduction in mortar strength increases.



MN – Normal mortar, MA – Mortar with 30% RFA, MB – Mortar with 65% RFA

Figure 2.17: Comparison of recycled mortar compressive strength (Chen et al 2003)

It can be concluded that the brick and tile particles have some impact upon the compressive strength of RC, but using unwashed RA has comparatively greater effect on the mechanical properties of hardened concrete. However concrete of acceptable quality can be produced with recycled aggregate containing up to 67% of brick and tiles. Since mortar controls the failure mode of concrete, using RFA in concrete production might have a large effect on the hardened properties of concrete.

Hendricks and Pietersen (1998) reported that full replacement of the coarse and fine aggregate fraction in concrete by RA generally lowers the compressive strength by about 20%. They also found that, when only the fraction larger than 4 mm is used the decrease in strength could be limited to about 10%. They also found that the tensile splitting strength is only marginally lower compared to concrete with natural aggregates. However, when recycled aggregates are used the bending strength can amount to 50-60% of the value in ordinary concrete.

2.7.3 Splitting tensile and flexural strength

Sagoe-Crentsil et al (2001) found that generally the trend in the tensile strength development depends mainly on binder type rather than aggregate type as shown in figure 2.18. Tensile strength of the slag cement concrete improved with curing, while tensile strength of ordinary Portland cement concrete was partially reduced beyond 28 days. In contrast, the tensile resistance was found to increase as the cement content of the concrete increased. The increase on RC tensile strength is partly indicative of good bond characteristics between RA and mortar matrix.

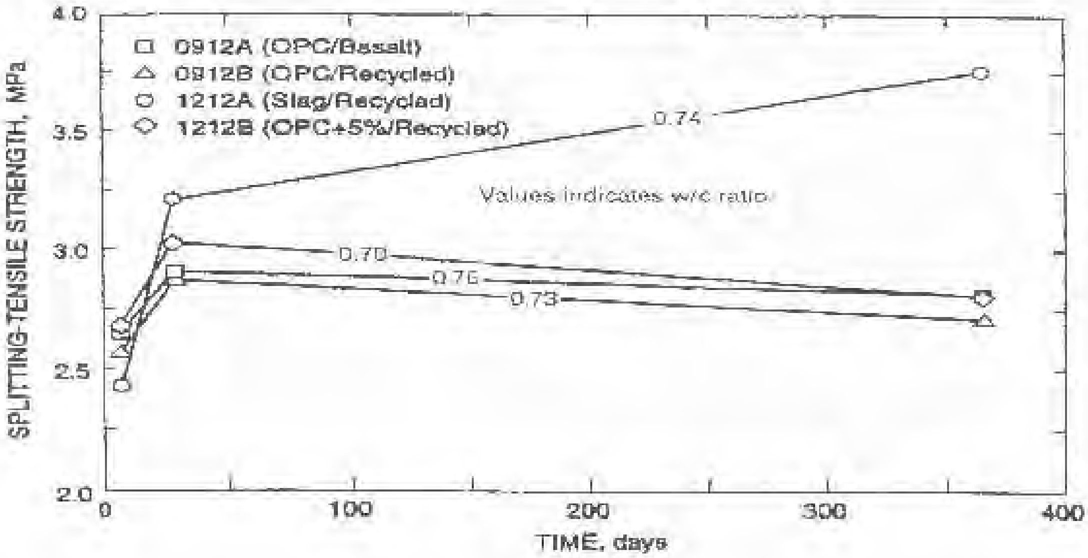


Figure 2.18: Relationship between splitting tensile strength of RC and NC with time (Sagoe-Crentsil et al 2001)

Olorunsogo (1999) found that all mixes with RA attained a minimum flexural strength of 7 MPa at 28 days. There was no specific trend in the relationship between the proportion of recycled aggregate included in the concrete mix and flexural strength. Alexander et al (2002) reported that the value obtained for flexural strength (6.4 MPa) was sufficient for flexural use.

On the other hand, Chen et al 2003 using RA containing variable brick content found no major differences between flexural strength of RC and NC as shown in figure 2.19. As the brick and tile content was increased up to 50%, the flexural strength obtained increased to about 91% that of normal concrete. They concluded that the content of bricks and tiles in the concrete mix had minor effects on the flexural strength of the RA concrete.

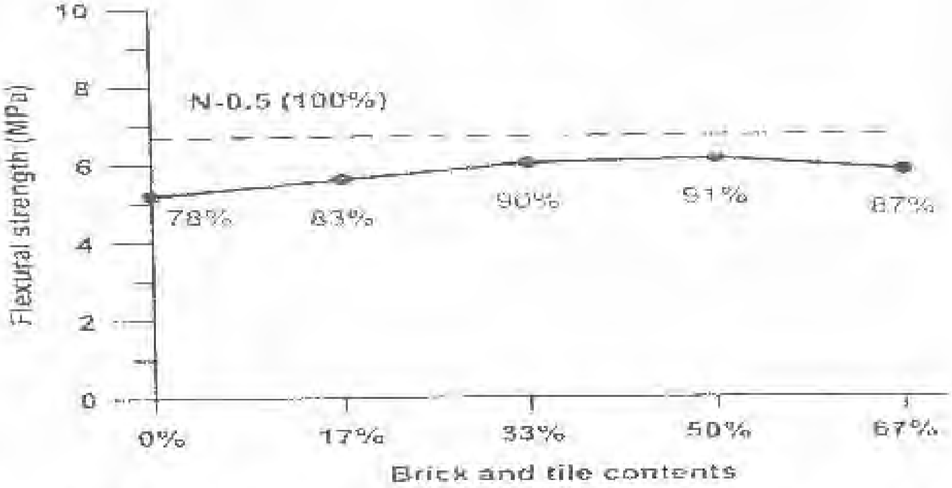


Figure 2.19: Flexural tensile strength of RC containing up to 67 % brick and tile content with 0.5-w/c ratio (Chen et al 2003)

2.7.4 Modulus of elasticity

Similar to the previous compressive and flexural strength results, Chen et al (2003) also found the modulus of elasticity for RC containing 67% brick content to be about 70 % that of natural aggregate concrete, figure 2.20. Brick and tile particles will have some negative effect upon the mechanical properties of recycled aggregate concrete.

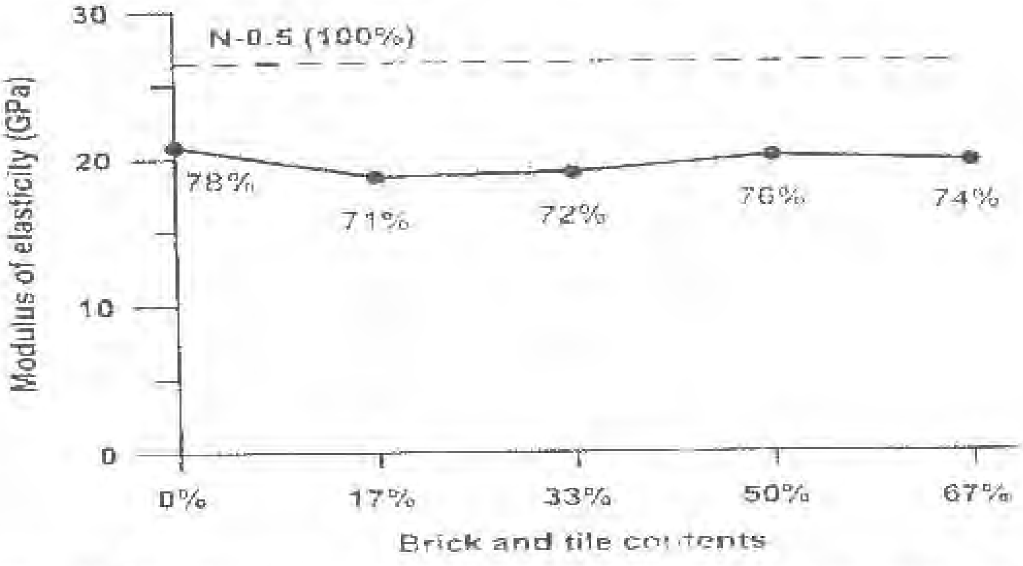


Figure 2.20: Modulus of elasticity of RC containing up to 67% brick and tile content with 0.5-w/c ratio (Chen et al 2003)

On the other hand, Salem et al (2003) carried out an experiment to determine the strength properties of hardened RC. Three cases were considered for both RC and NA.

Case 1 consisted of using a medium water-cement ratio of 0.47, Case 2 using 0.29 water cement ratio (high-performance concrete) and Case 3 consisted of varying the base mixture by entraining with an air content of 5%. In their experiment, they found RC to have lower elastic modulus than NA as shown in figure 2.21.

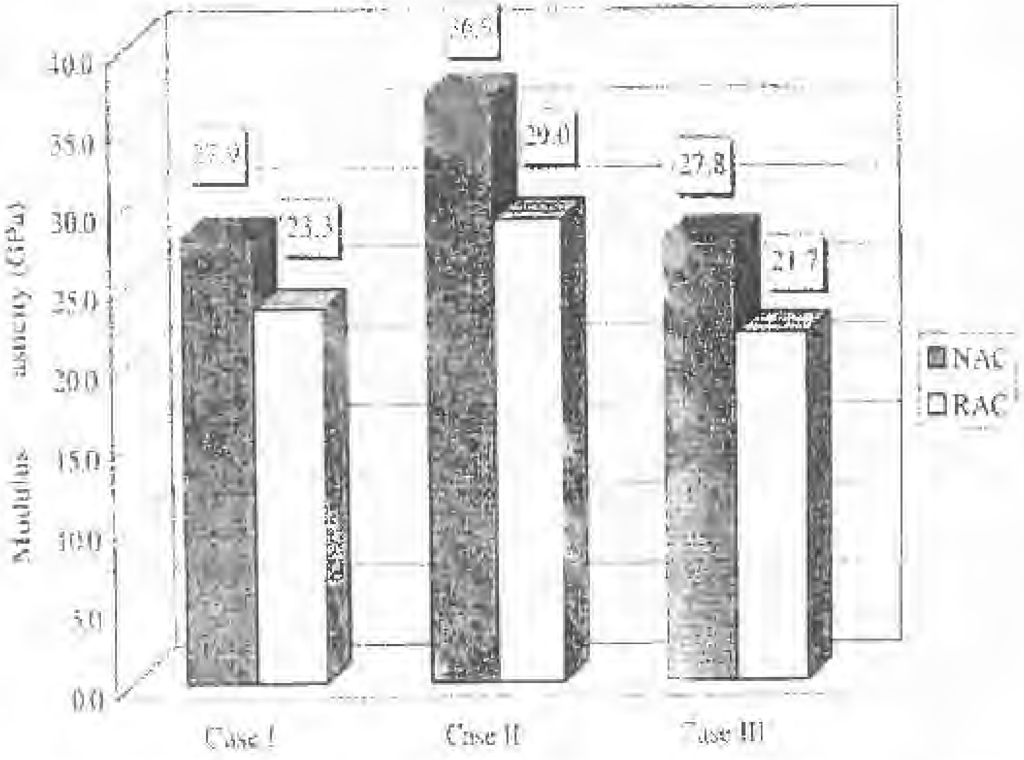


Figure 2.21: Modulus of elasticity of RC and NA at 28 days by Salem et al (2003)

Results in Figure 2.22 from a laboratory experiment conducted by Pedrozo et al (2000) show the influence of substitution proportion level of RA no modulus of elasticity of hardened concrete. Results show that when 50% of RFA was used with 100% NA, concrete attained the highest modulus of elasticity. Replacement of NCA with RCA reduced the modulus of elasticity. This was believed to be due porous nature of RCA. The results RC with 50% RCA and 100% RFA contradict the compressive strength results. It was expected that high compressive strength concrete could give high elastic modulus because for a given aggregate, the elastic modulus increases with the strength of concrete (Alexander 2001)

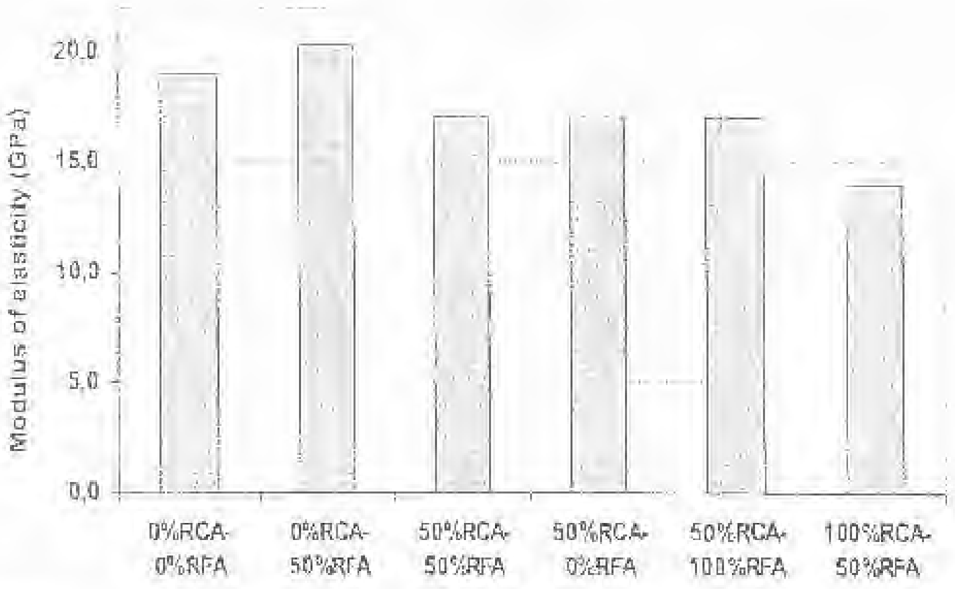


Figure 2.22: Influence of RA on modulus of elasticity (Pedrozo et al 2000)

Reports from various researchers show that the modulus of elasticity of RC is always lower than that of corresponding control concrete made with natural aggregates due to amount of old mortar attached to original aggregates which has comparatively low modulus of elasticity. Values from 15% to 40% lower are reported. However, comparatively high values are reported for RC made with RCA and NFA, and lower values when both RCA and RFA are used (Hansen 1992).

2.7.5 Creep and shrinkage

The relatively high water demand of RA will have an impact on shrinkage. However, due moisture absorption in RA, concrete made with these aggregates may display an even lower shrinkage in the initial stage of hydration (Hendricks and Pietersen 1998). Hansen (1992) reported that the drying shrinkage increases with time and stabilizes at about 91 days, following similar trends reported by several researchers.

From experimental results of Sagoe-Crentsil et al (2001) as shown in figure 2.23, RC display higher drying shrinkage values compared to the reference normal concrete mixture made with basalt aggregates, possibly due to the lower restraining capacity of RA particles compared to basalt.

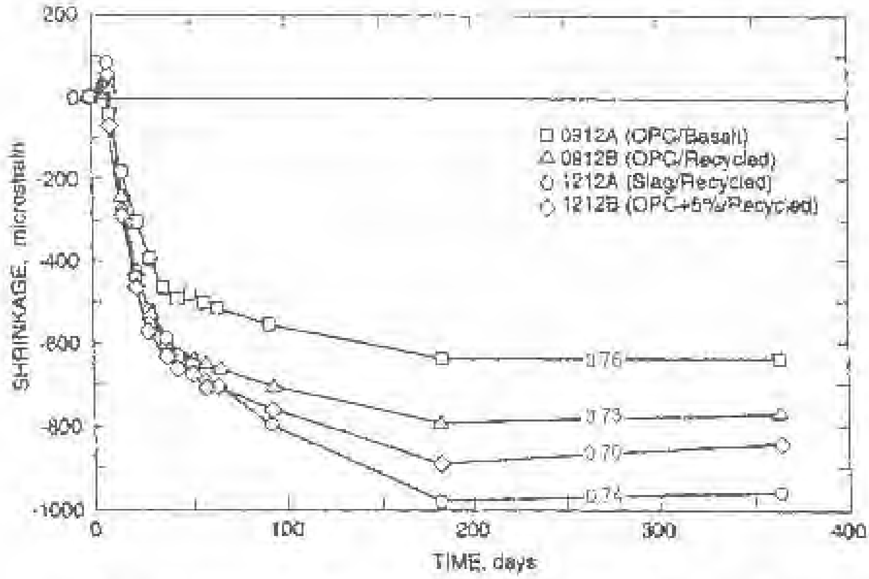


Figure 2.23: Drying shrinkage strain (Sagoe-Crentsil et al 2001)

The results of drying shrinkage test by Katz (2003) in figure 2.24, shows the drying shrinkage of RC made with OPC at the age of 90 days to be between 700 and 800 micro-strain and between 550 and 650 micro-strains for RC made with WPC. The reference concrete at the same age attained much lower shrinkage of 270 and 320 micro-strains for OPC and WPC concrete respectively. This is due to large amount of mortar attached to natural aggregate and mortar particle in the RA.

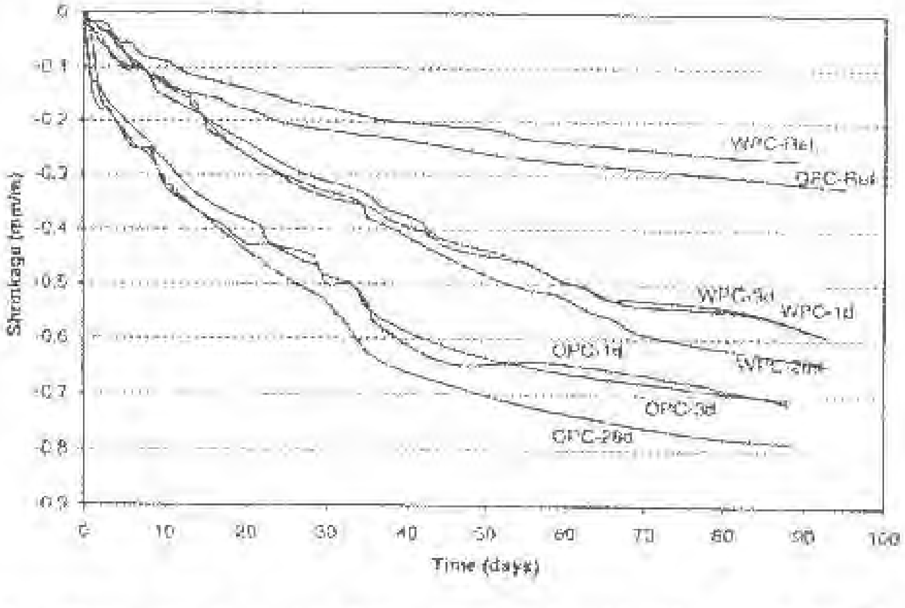


Figure 2.24: Drying shrinkage of RC and NC made with OPC and WPC (Katz 2003)

2.7.6 Durability

Durability of concrete may be defined as its ability to resist the damaging actions inherent in the environment in which it is employed. Factors influencing durability is the ability of concrete to resist flow of fluid through it, i.e. its penetrability. Other factors are ability to resist carbonation, sulphate attack, abrasion and freezing and thawing actions.

It is believed that deterioration of concrete begins almost immediately after casting as the hardened properties are influenced by the phenomena which occur at an early stage, such as plastic cracking, bleeding, segregation and thermal effects (Alexander et al, 1999a). In the hardened state, concrete can be affected by a variety of internal and external factors such as abrasion, freezing and thawing, carbonation, rusting to mention a few which may cause damage by physical and/or chemical mechanisms.

There is an increasing awareness that many of the problems experienced in structures made with concrete are due to lack of an adequate knowledge concerning factors affecting durability of concrete as a material and inability to apply effectively the knowledge already gained. To control the rate of deterioration in concrete, it is essential to design for durability by restricting deterioration mechanisms near the concrete surface as many deterioration mechanisms involve ingress of harmful substance from the environment into the concrete. Therefore, it is important to understand the nature of the intrinsic characteristics of concrete, such as permeability and diffusivity (which is the ease with which dissolved solids and ions are transported through a saturated or partially saturated porous material.

There are a number of tests, based on a variety of mechanisms which can b used to measure the rate of fluid transportation through concrete. Highly sophisticated equipment, complex monitoring and lengthy testing periods are however required to accurately model these mechanisms. Therefore, in response to the need for more practical durability tests, three durability index tests have been developed by Alexander et al (1999) in order to characterise fluid and ions transport mechanisms in concrete. These are oxygen permeability index (OPI) for permeation, chloride conductivity for diffusion and sorptivity for water absorption. Each test measures a different transport property of fluids or ions through the cover layer of concrete.

The resistance of cover concrete to these transport process governs the deterioration of concrete and embedded steel and may therefore define the potential durability of concrete. The tests have proved sensitive to durability-related aspects of concrete construction, such as materials, compaction and curing. The philosophy of durability index technique is extensively covered in chapter 6. Suggested ranges of index values for concrete durability are shown in table 2.31.

Table 2.31: Suggested range of durability index values (Alexander et al 2004)

Durability class and application	OPI (Log scale)	Sorptivity ($mm/h^{1/2}$)	Chloride conductivity (mS/cm)
High durability requirement – where durability is of paramount importance	> 10	< 6.0	< 0.75
Durability requirement in most conditions – where durability requirement is of some concern	9.5 - 10.0	6.0 – 10.0	0.75 - 1.50
Durability in mild condition where durability requirement is of less concern	9.0 – 9.5	10.0 – 15.0	1.50 – 2.50
Durability in non-aggressive condition – where durability is of no concern	< 9.0	> 15.0	> 2.50

Many research studies carried out on the use of RA in concrete in an attempt to understand the properties of RC, most of these studies focused on the mechanical properties of the RC. Few research works which have been done to assess the durability performance of RC are included herein.

Oxygen permeability:

Experimental work done by Olorunsogo et al (2002) using CEM I at 0.5 w/c ratio for grade 30 concrete after 28 days, showed that the OPI decreased with increases in the proportion of RCA included in the concrete mix. However, OPI was increased with increase of curing duration. Concrete with 100% RCA attained a 'poor' durability classification (9.0<OPI<9.5), while control mix (100% natural coarse aggregates) attained a 'good' durability classification (9.5<OPI<10.0) as shown in figure 2.25 at 28 day

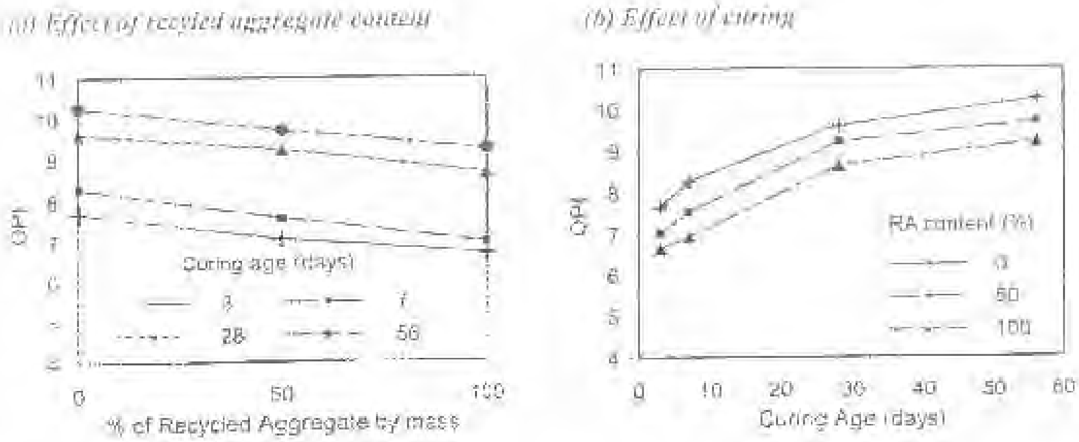
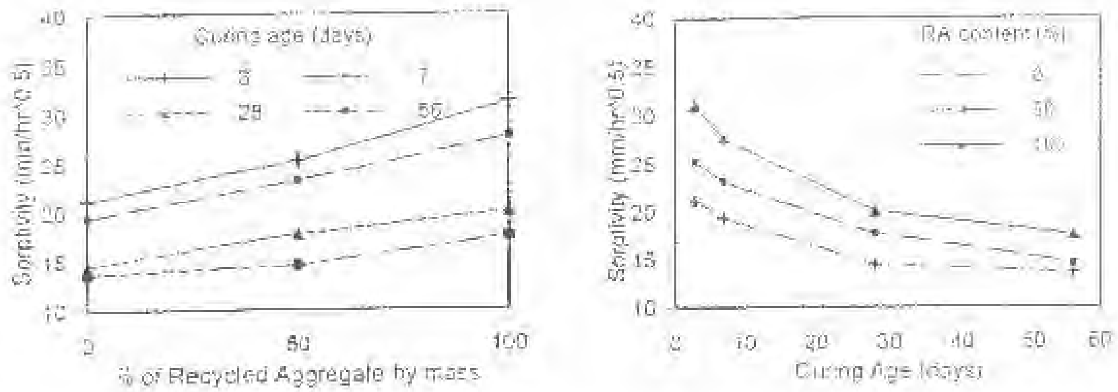


Figure 2.25: OPI results with 0.5-w/c ratios (Olorunsogo et al 2002)

Alexander et al (2002) using 100% RCA, 50/50 CEM I/Corex slag and 0.72 water-cement ratio for grade 25 concrete reported similar results. They found that, concrete with 100% of RCA had less than 9.5 OPI values, which falls into the range of 'poor' concrete classification. Curing improved the OPI value, whereby OPI increased from 8.5 to 9.5 after 28 day of curing. However, none of the concrete mixes including concrete made with natural aggregates achieved a 'good' durability classification. This may be caused not only by the effects of aggregates in the mixes but also higher water-cement ratio (0.72).

Water sorptivity

Olorunsogo et al (2002) using CEM 1 at 0.5 w/c ratio for grade 30 concrete after 28 days reported that water sorptivity decreased for longer curing age of concrete mixes. None of the concrete mixes achieved a 'good' or better durability classification for all ages of curing, Figure 2.26. However, none of the concrete mixes including concrete made with natural aggregates achieved a 'good' durability classification, which implies that generally the mixing proportions were not properly done or the concrete for all mixes was of low quality.


(a) Effect of recycled aggregate content

(b) Effect of curing

Figure 2.26: Sorptivity results with 0.5-water/cement ratios (Olorunsogo et al 2002)

Sagoe-Crentsil et al (2001) found that RC had higher water absorption than normal concrete, Figure 2.27. They reported that the lower porosity of the basalt aggregates in the normal concrete mixture restricts the rate of water absorption compared to the recycled concrete mixtures that have an average of 25% higher absorption. The residual mortar attached to recycled aggregate concrete was found to serve as conduits for moisture transportation, especially under limited curing conditions.

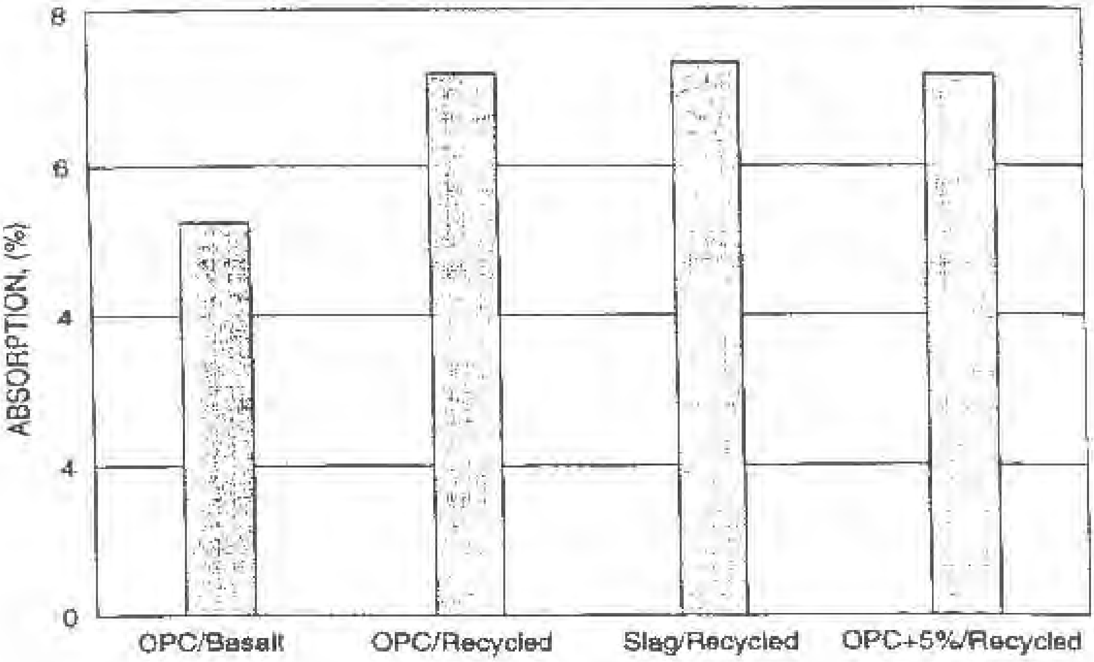


Figure 2.27: Comparison of water absorption (Sagoe-Crentsil et al 2001)

Alexander et al (2002) using 100% RCA, 50/50 CEM I/Corex slag and 0.72 water-cement ratio for grade 25 concrete found that water sorptivity attained 8.5 mm/√h, a 'good' durability classification after 28 day of curing. Water sorptivity improved with curing age, it improved from 12.2 mm/√h for 1 day curing to 8.5 mm/√h after 28 day of wet curing. They concluded that poor performance in durability indexes could be attributed to the porous nature of RCA. Cracks and fissures which might be created during RA processing could also contribute to ease permeation, absorption and diffusion of RC.

Katz (2003) reported similar findings using aggregates from partially hydrated old concrete. He found that the absorption was approximately 3.8% for reference concrete and 7.2% for the recycled concrete, Figure 2.28. He also commented that the high porosity of the recycled concrete is a result of the higher porosity of the recycled aggregates.

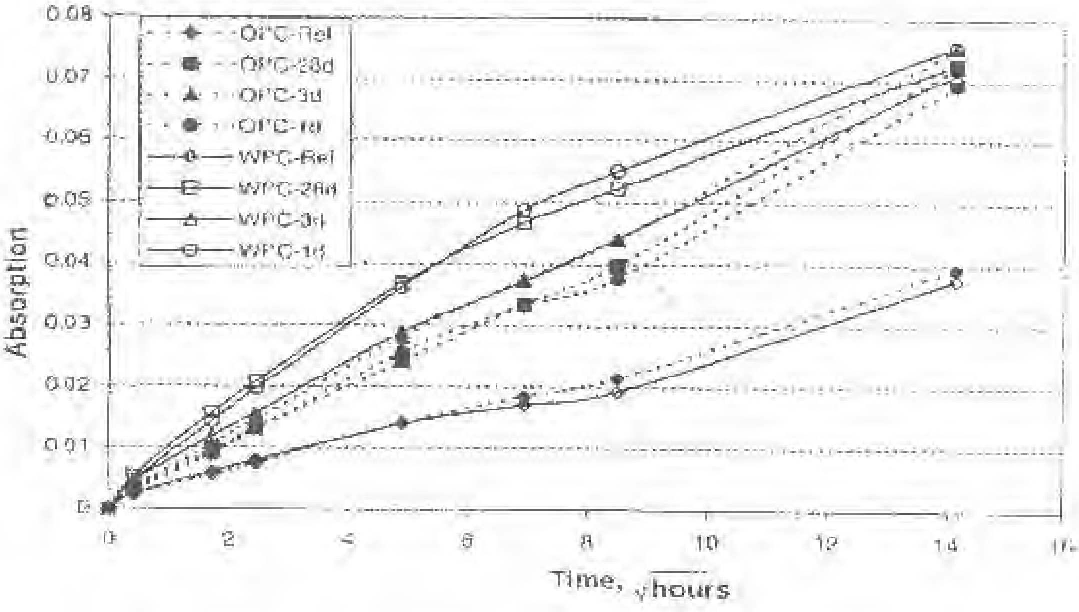
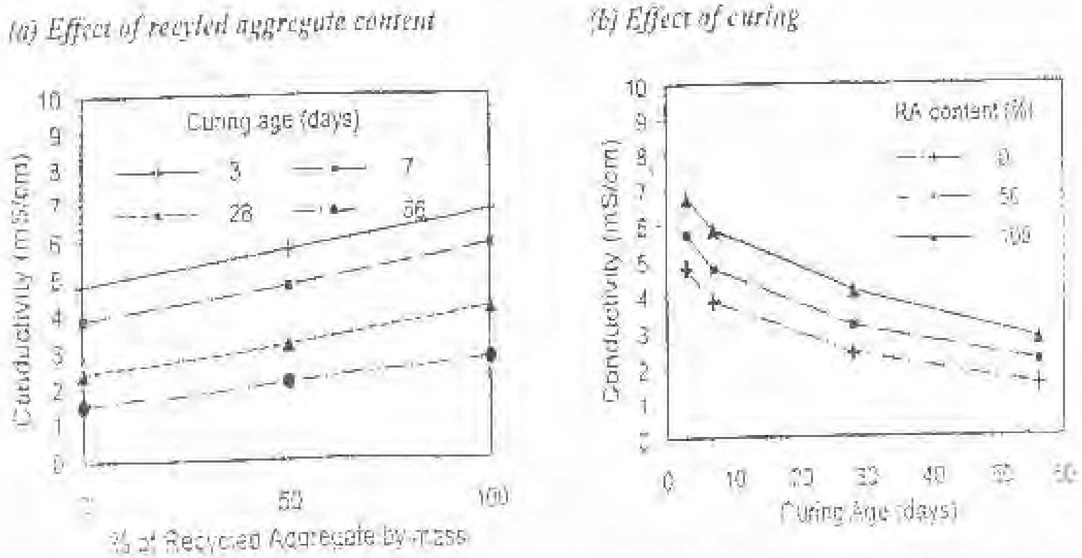


Figure 2.28: Absorption rate of RC and NC (Katz 2003)

Chloride conductivity:

Olorunsogo et al (2002) using CEM I at 0.5 w/c ratio for grade 30 concrete after 28 days found that chloride conductivity was increasing with the increase in the replacement level of RA for a given curing duration of concrete mixes. Considering the effect of curing age on the chloride conductivity of RA concrete, they found that the longer the duration of curing, the lower the conductivity of the concrete mix at a particular replacement level of RA, Figure 2.29. In comparison with the recommended values of chloride conductivity for concrete durability classification presented in Table 2.28, only the natural aggregate concrete attained a 'good' classification at the curing age of 56 days. All other fell into the 'poor' classification. They concluded that the weaker nature and formation of cracks and fissures in the recycled aggregates was the cause for easy diffusion of chloride ions.


(a) Effect of recyled aggregate content

(b) Effect of curing

Figure 2.29 Chloride conductivity results with 0.5-w/c ratio (Olorunsogo et al 2002)

Resistance of RC to Carbonation

Sagoe-Crentsil et al (2001) reported that the rate of carbonation of slag cement RC was found to be lower than the equivalent strength-grade concretes containing only ordinary Portland cement. In this case, slag improved carbonation resistance of RC. Other RC containing only ordinary Portland cement carbonation was 10% higher than normal concrete.

Katz (2003) reported that the carbonation of RC was 1.3 to 2.5 times greater than that of reference concrete. Higher rates were observed in concrete made with Ordinary Portland cement in comparison to that made with White Portland Cement.

Contrary to Katz (2003), Limbachiya (2002) reported that the carbonation depth measured at age of 20 weeks showed improved performance in concrete containing greater than 30% RA. He said the improvement may have been attributed to a number of factors, such as the quantity of calcium hydroxide in recycled aggregate which increased with the increase in attached cement paste; the cement content was also increased during mixing to adjust the water - cement ratio to achieve the intended strength at 28 days, and as a result there was an overall increase in alkalinity in the hardened concrete.

Resistance of RC to abrasion effects

Olorunsogo (1999) quoted the definition of abrasion resistance by Prior (1969), as the ability of a concrete element to resist wear that may arise as a consequence of attrition by sliding, scraping or percussion. He added that the evaluation of concrete resistance to abrasion is somewhat difficult since the destructive action differs depending on the nature of the actual cause(s). In his research, he found that there was no relationship between abrasion resistance and proportion of recycled aggregate included in the mixes. He found that mixes containing 50% and 70% of recycled aggregates performed better than concrete which contained 30% of recycled aggregate.

Sagoe-Crentsil et al (2001) also assessed the durability of concrete made by RA regarding abrasion resistance. The abrasion resistance of RC was compared with the abrasion resistance of concrete made with NA (basalt). They found that the abrasion resistance of RC was about 12% less than that of normal concrete. However abrasion resistance of recycled aggregate concrete containing 5% OPC more and that which contained slag increased, Figure 2.30.

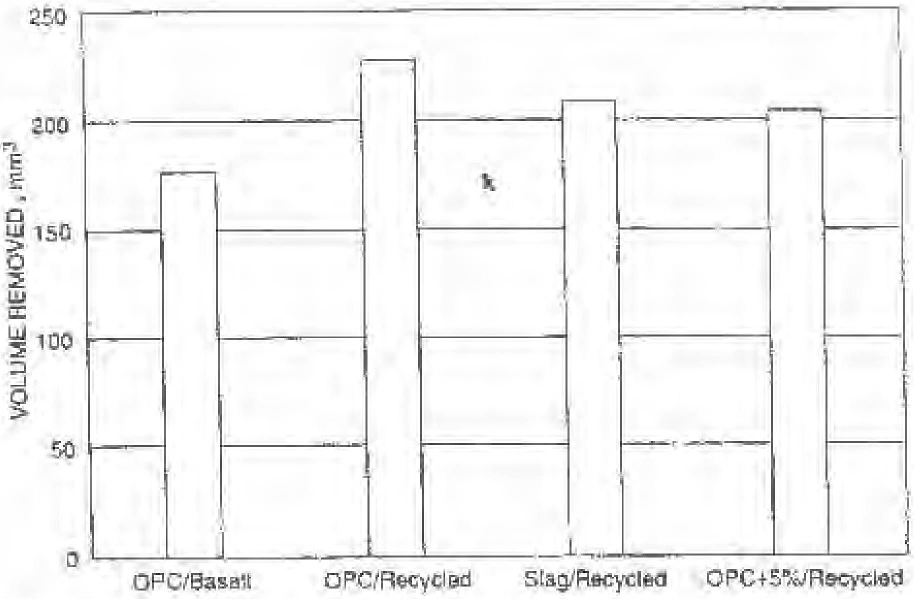


Figure 2.30: Abrasion resistance of RC and NC (Sagoe-Crentsil et al 2001)

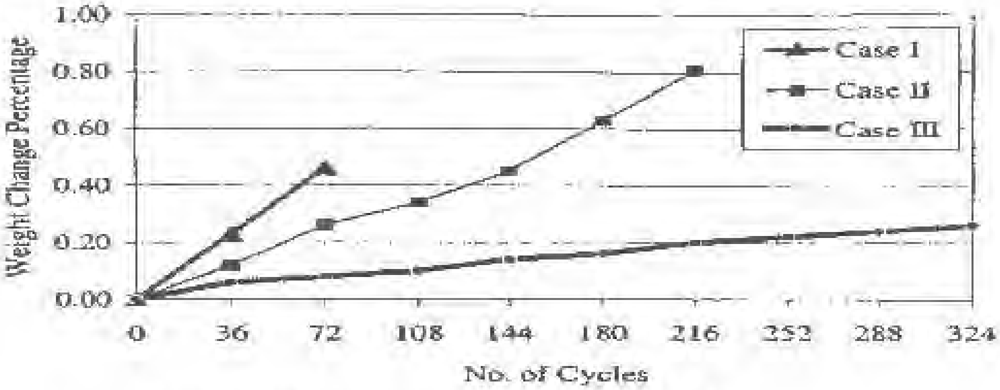
Resistance of RC to Freezing and thawing

Salem et al (2003) carried out an experiment to determine the resistance of RC to freezing and thawing. Three cases were considered for both recycled and natural aggregate concrete. Case 1 consisted of using a medium water-cement ratio of 0.47, Case 2 using 0.29 water cement ratio (high-performance concrete) and Case 3 consisted of varying the base mixture by entraining with an air content of 5%.

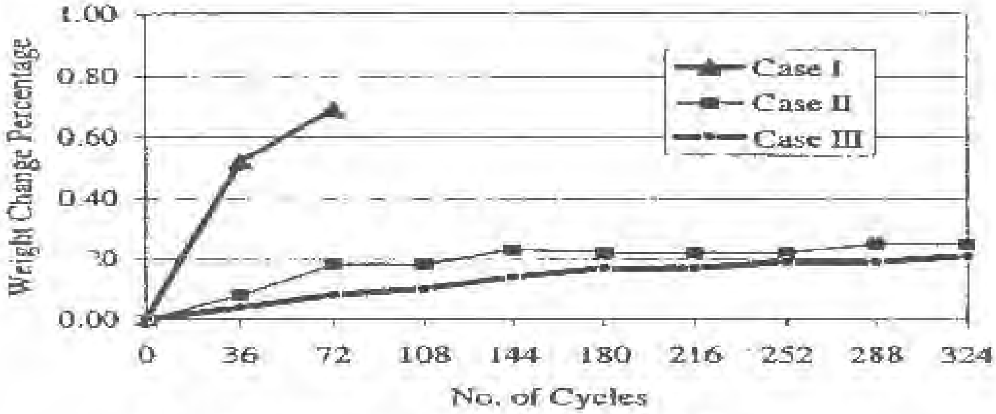
Relative dynamic modulus and weight change of concrete were used to determine the frost resistance because such measurements are nondestructive to concrete specimens. The variation in the value of the modulus over the entire duration of freezing and thawing cycles provides a good indication of the variation in the strength of the concrete specimen, which in turn reflects the degree of resistance to freezing and thawing.

On other hand, weight changes of the concrete specimen over the freezing and thawing cycles provides an indication of the deterioration of the concrete. Weight change provides an idea of the amount of moisture absorbed due to cracking of the specimen caused by the expansion of the cement paste. The durability performance of the RC in

Case 1 and 2 was negatively affected, while NC achieved free-thaw durability. However by use of entrained air (Case 3), RC was found to be as durable as natural aggregate concrete, refer Figure 2.31. This significant improvement was attributed to the entrained air bubbles in the concrete, which serves as reservoirs to receive water as it flows from the freezing site; as a result, the internal hydraulic pressure within the cement paste is relieved.



Weight change percentage for RAC.



Weight change percentage for NAC.

Figure 2.31: Weight change percentage for RC and NA by Salem et al (2003)

Malheron and O'Mahony (1988) reported that concrete made with laboratory RA has better or similar resistance to freezing and thawing as an equivalent concrete mixture made with conventional aggregates. Contrary to Malheron and O'Mahony, Nishibayashi and Yahura (1988) reported that the resistance of freezing and thawing of RA concrete is considerable inferior to that of normal concrete and can not even be improved by air entrainment. This difference might be attributed to the different type of RA used in their research.

No studies have been reported on the susceptibility to alkali reactions of RC produced from RA which originated from concrete that has been damaged by alkali reactions. Greywacke aggregates have been identified as potentially alkali reactive aggregates, both through service record and by laboratory testing (Oberholster, 2001). Therefore, there is a possibility that RC made with RA in the Western Cape will be susceptible to alkali-silica reaction

2.8 Discussion, recommendations and conclusion

It is now recognized that one of the most environmentally responsible and economically viable ways of meeting challenges of sustainability within the construction industry is the use of recycled C&DW as aggregate in new concrete production. However, there still numbers of practical problems that have to be addressed before construction industry will have confidence to accept the recycling and re-use of C&DW at larger scale.

Recycling of C&DW as aggregate offers a solution to the problems encountered with the quarrying of natural aggregates and the disposal of old concrete. With the growing production rate of C&DW in the Cape Peninsula, and the increasing difficulties in obtaining NA, recycling of C&DW and use of RA should be the step taken forward. Ongoing research to analyse properties of RA and performance of concrete made with RA should be encouraged.

The primary requirement for provision of good quality product is input control for materials received at the recycling plants. Each load of unprocessed C&DW material received at the plant should be inspected and, if accepted, be placed on a stockpile designated for the quality of aggregate to be produced. The frequency of testing of the RA produced should depend on the quality of output required, but it should also depend on the quality of information on the input. Higher quality materials can be obtained by inspecting demolition site and preparation of demolition plans to maximize the usefulness of recovered materials.

To increase awareness among various stakeholders, more workshops, seminars on RA materials and application need to be conducted. Taxes on recycled materials should be reduced as such incentives will encourage the use as well as the production of RA. New Standards and guidance especially in South African need to be set to accommodate the use of RA materials as such materials are likely to provide both environmental and economic advantages.

Properties of RA and possible effects of RA upon concrete properties such as workability, strength and durability were discussed in several papers. In most of these literatures the main concern was the variations of RA properties caused by native cement paste and the source of C&DW. Composition of RA reported by most research shows that RA contains old concrete particles, stones, brick, tiles, wood, plastic and other substances. Among these, wood, plastic, paper and other impurities, seriously affects the strength and durability of RC. However, if proper treatment is done on C&DW prior to recycling, only RA with old concrete, stone, bricks, tile particles and few impurities can be obtained.

Bulk density and relative density of RA have been reported to be lower than NA and water absorption RCA and RFA to be as higher as 3 and 10 times than NCA and NFA respectively. Since the quality of RA fluctuates considerably, quick test methods are required. It is believed that the rate of water absorption of aggregate is an indicator of quality. RA with large amount of mortar or bricks exhibits a higher water absorption, which points to low quality. It is therefore important that density, relative density and water absorption of RA are determined carefully prior to their use in concrete production. This should be done in order to achieve concrete of adequate workability, stability and cohesiveness; also to avoid large variations in properties of hardened concrete.

Practical experience has shown that RC is as easy to batch, mix, transport, place, compact and finish as NC. However, because of the relative high water absorption of RA, it is generally recommended to batch RA in a pre-soaked condition or SSD condition. Alternatively is by adding extra water in the mix to counterbalance absorption effect of RA.

Due to the old mortar attached to aggregate particles, bricks and mortar particles in the RA, creep and drying shrinkage of RC was reported to be higher from 40% to 80% than that of NC. Comparatively higher shrinkage is reported when both RCA and RFA are used. However, lower drying shrinkage is reported for concrete made with only RCA and NFA.

Durability quality of RC has been reported to reduce with increasing of RA quantity in the mixes. This phenomenon can be explained by the fact that, when RA materials are increased in the mix, week materials such as brick and mortar are also increased. Cracks and fissures created in RA during RA processing render the RC susceptible to ease of permeation, diffusion and absorption of fluid.

Data obtained from different researchers generally show that when RA are well processed and by using appropriate binders and binder water ratios, concrete of good quality and durability can be obtained. Although much is known about the physical, mechanical and durability properties of RA and RC, contradictory results have also been reported by different researchers. Due to these contradictions among these findings, more research is needed to better understanding the primary factors that affect the performance of RC.

While the engineering properties of laboratory -crushed RA and concrete made with these materials have been extensively covered, limited data are available on commercially produced RA, including mixture proportions, properties of fresh RC and performance of hardened RC including durability. In the following chapters, properties of commercially produced RCA and RFA as well as properties of fresh and hardened concrete are investigated.

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CHAPTER 3

EXPERIMENTAL PROGRAMME

The use of material derived from the demolition of structures and other construction is restricted because of lack of scientific data. There is not yet sufficient information available in South Africa to show that RA meets standard criteria for use in concrete production. This work describes an experimental investigation carried out to study the characteristics and potential use of RA in the manufacture of new concrete (RC). The purpose of the investigation is to explore the viability of the use of this material to produce ordinary concrete that can be used in the Cape Peninsula.

The overall experimental programme consisted of three phases: Phase one covered the characterisation of the physical properties of both RFA and RCA. Various tests were performed and results compared with the properties of natural aggregates and findings from other researchers. Mix design and mixing are covered in phase two, whereby properties of fresh RC, which included workability, consistence, cohesiveness and bleeding, were investigated. Phase three covers the properties of hardened concrete. These included compressive strength, flexural strength, elastic modulus, creep and shrinkage, and durability monitored by durability index parameters. A summary schedule of the entire testing programme is included at the end of this chapter.

3.1 Materials

3.1.1 Recycled Aggregate (RA)

Both recycled coarse aggregate (RCA) and recycled fine aggregate (RFA), were obtained from Bradis Crushing and Recycling (Pty) Ltd. The Bradis crushing plant is involved with extracting C&DW rubble that has been deposited at their site over many years, and processing them on site to produce RCA and RFA of various sizes. The RA was used as taken from the supplier without further beneficiation. The size ranged from 19 mm down to fine material. RFA had approximately 30% of its particles greater than 4.5 mm, which was taken into consideration during mix proportioning. RA from one batch and the same source were used to minimize variations. Sampling procedures suggested by South African National Standards

(SANS Method 195:1994 – sampling from completely built-up stockpile) was used to obtain materials used. The properties of these materials are covered in chapter 4.

3.1.2 Natural Aggregate (NA)

Natural coarse aggregate (NCA) used was a 19 mm crushed greywacke, which is a fined-grained stone consisting of quartz, feldspar, mica and iron oxides developed by thermal metamorphism of argillaceous rocks of the Malmesbury group (Brink, 1985). The rock does not crush to a good cubical particle shape and tends to be elongated and flaky as shown in Figure 3.1, thus negatively affecting the workability of concrete.

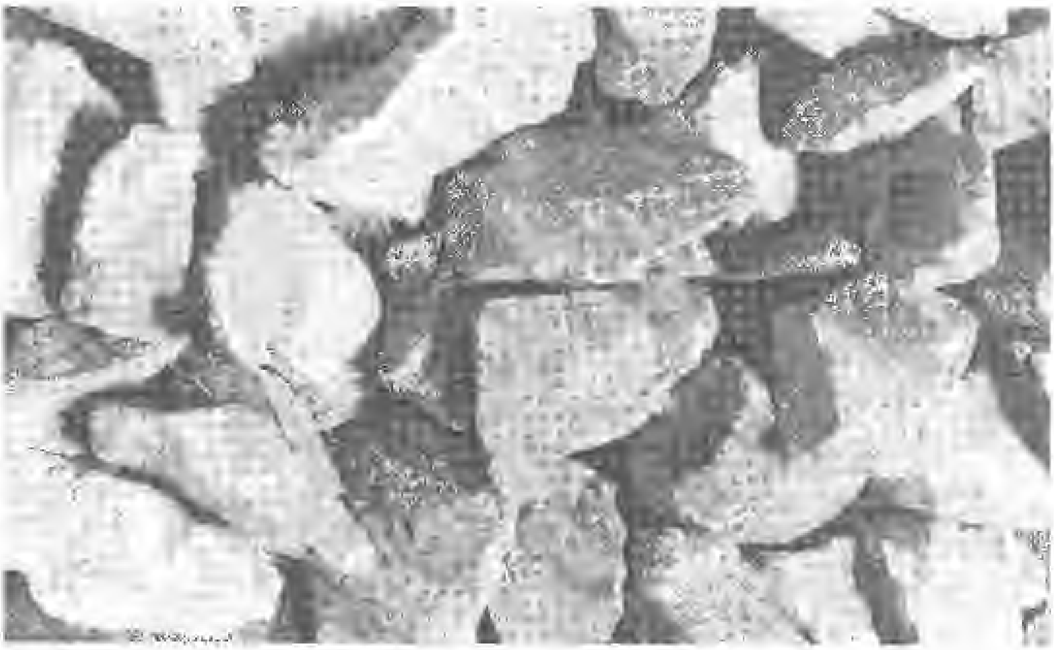

Figure 3.1: Particle shape of Greywacke coarse aggregates 19 mm.

The natural fine aggregate (NFA) used was a Klipheuwel sand, which is a siliceous pit sand having rounded particle shape. Although Klipheuwel is natural (pit) sand obtained broadly from the same area, it also occurs in different grain sizes. According to Grieve (2001), Klipheuwel sand has a high percentage of fines but this has no detrimental effect on shrinkage. To minimize variation, Klipheuwel sand of relatively fine grain size was used throughout. Figure 3.2 shows the grading curve of Klipheuwel sand. Both the crushed greywacke stone and the Klipheuwel sand, which are widely used in concrete production in the Cape Peninsula, were used as reference aggregates.

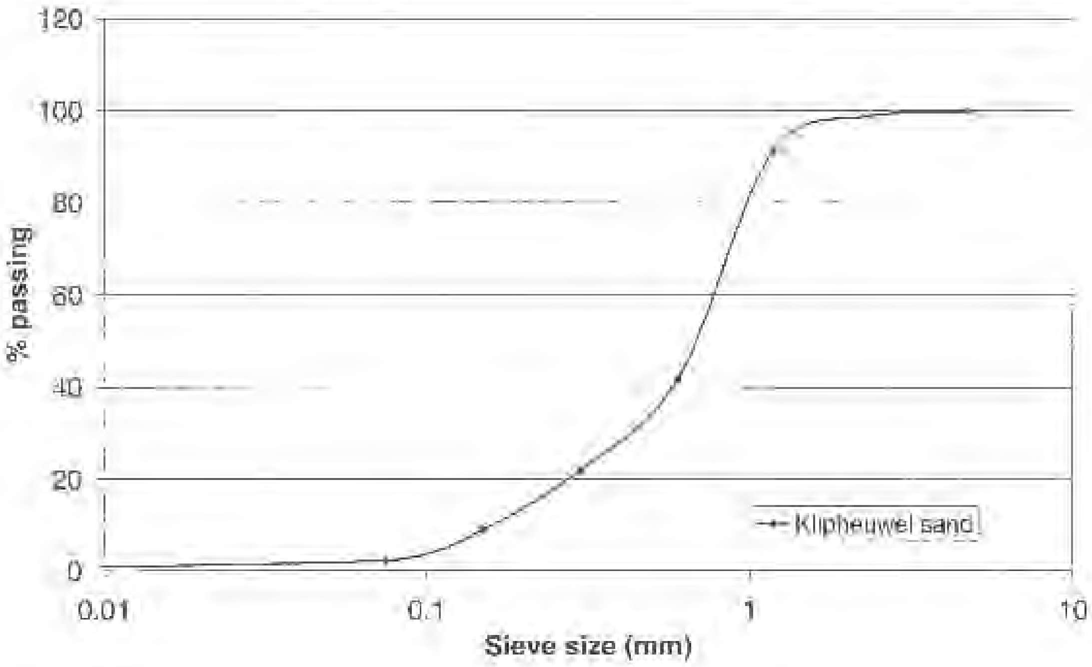

Figure 3.2: Grading curve of fine aggregate (Klipheuwel sand)

3.1.3 Binders

The binders used were Ordinary Portland Cement (CEM I 42.5) and Corex slag from Saldanha steel plant. Corex slag is a by-product of the reduction of iron ore to metallic iron. It is a new product, but has been widely used as binder material in the Western Cape for the past several years. The mineralogy of corex slag is similar to that of ordinary Portland cement (Jaufeerally 2001) containing the same cementitious minerals but in different proportions. To avoid variability, the cement and corex slag used for this work were obtained from one batch and stored in air tight drums at the UCT laboratory. The cement and slag were kept in such a way that they could not deteriorate within the experimental period.

3.1.4 Water

Ordinary tap water was used in this research for concrete production.

3.2 Tests conducted and standards used

3.2.1 Aggregates

The properties of recycled and natural aggregates assessed included composition, grading, fineness modulus, particle shape and texture, bulk and relative density, absorption and 10% FACT. The procedures and test methods were in accordance with South African National Standards (SANS), British Standards (BS) or ASTM

Standards. Detailed procedures, Standards methods used, results and discussions are covered in chapter 4 and summarised in table A1 of Appendix A.

3.2.2 Fresh concrete

Fresh concrete was tested for water requirement, workability, consistence, slump loss with time, segregation (bleeding), and density. The procedures and test methods were in accordance with South African National Standards (SANS 5862:1994). Water requirement was assessed using methods suggested by Cement and concrete Institute (C&CI) and by various trial mixes. By using SANS 5862-1 test method, the slump of the fresh concrete was determined using a standard slump cone apparatus to determine the consistence (workability) of freshly mixed concrete and 75 ± 25 mm slump was aimed for. A modified version of the ASTM standard C 232-92 was used to determine the bleeding potential of the concrete. A rigid steel cylindrical container with inside dimension of 155 mm diameter and 165 mm height was used instead of the prescribed container which has inside dimension of 254 ± 6.4 mm diameter and 279 ± 6.4 mm height. SANS 6250:1994 was used to determine the density of compacted freshly mixed concrete. The same cylindrical container used for the bleeding experiment was used for the determination of density of fresh concrete before bleeding measurement proceeded. Detailed procedures used are covered in chapter 5 and summarised in table B2 of Appendix B.

3.2.3 Hardened concrete

Seven tests were performed to determine the performance of hardened concrete. These were density of concrete at the age of 28 days, compressive strength, flexural strength, creep and shrinkage, and potential durability monitored by durability index tests (oxygen permeability, water sorptivity and chloride conductivity). Compressive strength of hardened concrete was determined on 100 mm concrete cubes which were cast and water-cured before being tested at ages of 3, 7, 28, 56 and 120 days. Concrete beams of 100 x 100 x 500 mm were used to determine the flexural strength of the hardened concrete. From each mix, 3 beams were prepared and cured in water for 28 days before being tested. The properties of hardened concrete tested and type of specimens, size and quantity are summarised in Table 3.1. Standard methods suggested by SANS 5863 and 5864: 1994 were used to determine the compressive and flexural strength of hardened concrete respectively.

Table 3.1: Type, size and quantity of specimens used to test properties of hardened concrete

Test	Type of specimen	Size (mm)	Quantity	W/C ratio
Density (28 days)	Cubes	100	360	0.45, 0.60 0.75, 0.90
Compressive strength	Cubes	100	360	0.45, 0.60 0.75, 0.90
Shrinkage (sealed & exposed)	Cylinders	100Φ x 300	24	0.60
Creep (sealed & exposed)	cylinders	100Φ x 300	16	0.60
Elastic modulus	Prisms	100 x 100 x 200	72	0.45, 0.60 0.75
Flexural strength	Beams	100 x 100 x 500	24	0.60, 0.75
Durability (68Φx25mm) discs	Cubes	100	32	0.45, 0.60

Static elastic modulus was determined on 100 x 100 x 200 mm concrete prisms at the ages of 28 days and 120 days using method proposed by BS 1881: Part 121: 1983. A stress equivalent to one-third of the cube ultimate compressive strength was applied. Two pairs of samples with 100 mm diameter and 300 mm long sealed and exposed for creep and shrinkage measurement were prepared from each mix with 0.60 water-binder ratios. All samples were cast in two layers and water cured for 28 days before being tested. The samples were sealed using bitumen emulsion and aluminum foils Creep cylinders had their faces grounded before loading to ensure plane-bearing surface.

Three tests to assess potential durability were performed. These included oxygen permeability index (OPI), water sorptivity, and chloride conductivity tests. Standard procedures given in the UCT Manual for Durability Index Testing (Alexander et al, 2004) were used. For all tests, specimens of 25 ± 2 mm thick concrete discs and 68 ± 2 mm diameter cored from 100 mm cubes were used. Test methods (standards) and equipment/apparatus used are summarized in Table 3.1 and detailed procedures and results of all experiments are covered in chapters 6 and Table C1 of Appendix C.

3.3 Mix design (mixture proportions)

Since there is no method existing in South Africa for designing concrete mixes containing recycled aggregates, the Cement and Concrete Institute (C&CI) method (Addis, 1998) was used as a guide to design the concrete mixes. This method is normally used for single sized natural stone while the recycled aggregates used were graded.

To overcome high absorption properties of RA and to prevent rapid decrease of concrete workability, both coarse and fine recycled aggregate were pre-saturated to saturated surface dry (SSD) condition prior to mixing. To maintain the designed mix proportions, the amount of water and aggregate used in the mixes were adjusted according to the actual saturated moisture contents of the aggregates. This method of pre-wetting and saturating RA before mixing has been used in several studies noted in chapter 2 to prevent a rapid decrease in concrete workability.

The binder content was calculated by using water-binder ratios and initially estimated mix water. The stone content was calculated by using the equation specified by the C&CI (Addis, 1998) and fineness modulus of the NFA and RFA. The NFA and RFA content was then determined, on the basis of the difference required to make up 1 m^3 of concrete. Various trial mixes were performed until concrete of good workability and appropriate consistence was obtained. Free mixing water of 180 liters per cubic meter of concrete was considered in all mixes and no other admixtures were used.

Six mixes, namely Mixes XNA, XRF, XRC, XRA, CNA and CRA as shown in table 2 were prepared. Mixes XNA and CNA were control mixes containing natural coarse and fine aggregate, 50% CEM I 42.5 and 50% corex slag for mix XNA and 100% CEM I 42.5 for mix CNA. The 30% fraction of coarse particles greater than 4.5 mm was considered in all mixes containing RFA. For detailed calculations refer Table B1 of Appendix B. Four water-binder ratios, 0.45, 0.60, 0.75 and 0.90, were considered. The compositions of all mixes are shown in Table 3.2

Note: 'X' denotes corex slag and 'C' denotes CEM I 42.5

Table 3.2: Composition of mixes

Mix	Coarse aggregate	Fine aggregate	Binder
X NA	Crushed-greywacke (NA)	Klipheuwel (NA)	50/50% CEM I /Corex
X RF	Crushed-greywacke (NA)	Recycled aggregate (RFA)	50/50% CEM I/Corex
X RC	Recycled aggregate (RCA)	Klipheuwel (NA)	50/50% CEM I/Corex
X RA	Recycled aggregate (RCA)	Recycled aggregate (RFA)	50/50% CEM I/Corex
C NA	Crushed-greywacke (NA)	Klipheuwel (NA)	100% CEM I
C RA	Recycled aggregate (RCA)	Recycled aggregate (RFA)	100% CEM I

3.4 Mixing procedure and concrete production

3.4.1 Mixing and production

RA were pre-saturated for one week and kept covered to allow absorption and avoid any loss of moisture before mixing. Prior to mixing, small samples of about 200 g each were taken from the materials prepared for the mix and put into the oven overnight at 100 ^{0}C to determine the actual moisture content of the materials. Free water and amount of materials to be used in the mix were determined thereafter. Free water of 180 liters per cubic meter of concrete was maintained for all mixes. Table 3.3 shows the mix proportions of each mix type.

All dry ingredients were mixed for two minutes before mix water was added and three minutes thereafter until a uniform and homogeneous mix was obtained. The mixing was done in a pan concrete mixer in the laboratory. A concrete sample from each mix was taken for bleeding and consistence tests. Then concrete was placed in the required moulds and compacted by using a vibrating table until concrete appeared to be fully compacted. During compaction it was observed that the lighter materials such as timber, chipboard, plastics and fire damaged particles were moving up to the concrete surface.

3.4.2 Curing

After specimens were removed from the moulds, they were cured in water tanks by immersion under controlled temperature of 23 ± 1 ^{0}C.

Table 3.3: Mix proportions (kg/m^3)

Mix type	W/C ratio	Cement	Slag	Coarse aggregate		Fine aggregate		Water
		CEM I 42.5	Corex	NCA	RCA	NFA	RFA*	
XNA	0.45	200	200	1100	-	725	-	180
	0.60	150	150	1100	-	810	-	180
	0.75	120	120	1000	-	965	-	180
	0.90	100	100	1000	-	1000	-	180
XRF	0.45	200	200	610	345	-	800	180
	0.60	150	150	610	370	-	855	180
	0.75	120	120	610	380	-	895	180
	0.90	100	100	610	395	-	915	180
XRC	0.45	200	200	-	1060	700	-	180
	0.60	150	150	-	1060	785	-	180
	0.75	120	120	-	1060	840	-	180
	0.90	100	100	-	1060	875	-	180
XRA	0.45	200	200	-	1055	-	665	180
	0.60	150	150	-	1080	-	720	180
	0.75	120	120	-	1095	-	755	180
	0.90	100	100	-	1105	-	785	180
CNA	0.45	400	-	1100	-	736	-	180
	0.60	300	-	1100	-	820	-	180
	0.75	240	-	1000	-	970	-	180
	0.90	200	-	1000	-	1000	-	180
CRA	0.45	400	-	-	1060	-	670	180
	0.60	300	-	-	1080	-	730	180
	0.75	240	-	-	1095	-	765	180
	0.90	200	-	-	1105	-	785	180

*RFA less than 4.5 mm

3.5 Summary of Testing programme

The summary schedules of the entire testing programme on aggregates, fresh concrete and hardened is given in Table 3.4

Table 3.4: Summary of test performed on aggregates and concrete

Test/experiment	**Type of aggregate tested**	
Composition	RCA and RFA	
Grading	RCA, RFA and NFA	
Particle shape and texture	RCA, RFA, NCA and NFA	
Relative density	RCA, RFA, NCA and NFA	
Bulk density	RCA, RFA, NCA and NFA	
Absorption	RCA, RFA, NCA and NFA	
10% FACT	RCA and NCA	
Fresh concrete	**Mix type**	**Water-binder ratios**
Water requirement	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60, 0.75, 0.90
Workability	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60, 0.75, 0.90
Consistence and slump loss with time	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60,
Bleeding	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60, 0.75, 0.90
Density	XNA, XRF, XRC, XRA, CAN, CRA	0.60, 0.75, 0.90
Hardened concrete		
Density (28 days)	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60, 0.75, 0.90
Compressive strength (100 mm cubes) (3,7,28,56 and 120 days)	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60, 0.75, 0.90
Flexural strength (28 days) (100 x 100 x 500 mm beams)	XNA, XRA, CAN, CRA	0.60, 0.75
Elastic Modulus (28 and 120 days) (100 x 200 mm Prisms)	XNA, XRA, CAN, CRA	0.45, 0.60, 0.75
Shrinkage (after 28 days wet curing) (Exposed and Sealed 100Φ x 300 mm)	XNA, XRF, XRC, XRA, CAN, CRA	0.60
Creep (after 28 days wet curing) (Exposed and Sealed 100Φ x 300 mm)	XNA, XRA, CAN, CRA	0.60
Durability after 28 days cured for (3,7,28 days)	XNA, XRF, XRC, XRA, CAN, CRA	0.45, 0.60,

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CHAPTER 4

PROPERTIES OF AGGREGATES

Aggregates make up about 70% of the volume and about 80% of the mass of concrete. Their properties therefore have a significant effect on the properties of fresh and hardened concrete. Aggregates should have properties that produce economical concrete that fulfills design requirements. In the fresh state concrete should be workable and in the hardened state concrete should be strong, durable and dimensionally stable. The properties and composition of RA vary widely, mainly depending on its source, geographical location, climate differences, the nature of construction/building, and on the material available in a specific region. For example it is likely that the RA in the Cape Peninsula will contain brick particles, as older structures were built using brick materials.

In this work properties of aggregates for use in concrete that were assessed included grading, fineness modulus, dust content, composition, bulk and relative density, water absorption, impurity content, and aggregate strength test (10% FACT). The particle shape and texture of aggregate were also assessed as these may have an influence on workability of fresh concrete. The results given are the average of three tests performed on each property during the experimental work. The aggregate properties were assessed at three different times: firstly, prior to mix design, secondly, during the mixing period and lastly before batching the last mix.

Separate investigations were conducted to monitor variability of RCA from the source. Three samples of materials were taken at 2 month intervals from the crushing plant. Tests and assessment performed to determine the properties of these materials were composition, density, relative density, water absorption and 10% FACT. Summary of the results obtained are given at the end of this chapter.

4.1 Grading, fineness modulus and dust content

Grading of aggregates refer to the distribution of particles of various sizes, and is determined by passing a representative sample through a nest of standard sieves with square openings. The grading of both stone and sand has an influence on the workability, cohesiveness and bleeding properties of concrete, with sand generally having a greater influence. The grading analysis of the aggregates provides information that can be used for determining the proportions of the materials in a concrete mix and may be further used to ensure that materials delivered on site have consistent properties.

Fineness modulus (FM) is a measure of the average fineness or coarseness of aggregates. It is used in most cases for sand but may be applied to stone as well (Addis 1998). According to Addis, FM does not describe the grading or distribution of particle size in a unique way. Nevertheless, it is a useful index of particle size. Low FM values indicate sand consisting of fine material while higher values indicate sand containing a high proportion of coarse particles. Very fine sand have FM value ranging from 0.5 to 2.3. Medium sands have FM values ranging between 2.4 and 2.9 while FM of coarse sands ranges from 3.0 to 3.5 (Addis 1998). In SABS 1083: 1994 a range from 1.2 to 3.5 of FM for sand is permitted for normal concrete and a range of FM from 2.0 to 3.0 is preferable for sand used for the manufacture of high-quality concrete.

Dust is defined as the material that passes a square apertures sieve of nominal size 75 μm. Dust content has an influence on water demand, workability, cohesiveness and bleeding properties of fresh concrete and may improve compressive strength of hardened concrete if of the right type and quality (Grieve, 2001).

4.1.1 Test Procedure

The aggregates were graded according to the method suggested by SANS 201:2002. Five samples of approximately 2 kg each were taken randomly from the material brought to the laboratory for the purpose of this research. By means of a shovel, samples were mixed thoroughly on a clean non-absorbent surface. Coning and quartering were used to obtain representative samples of sufficient quantity (1-2 kg). Due to the continuously graded nature of the RA, the sieve sizes for both coarse and fine aggregates were used, i.e. 26,5 mm; 19,0 mm; 13,2 mm; 9,5 mm; 6,7 mm; 4,75 mm; 2,36 mm; 1,18 mm; 0,6 mm; 0,3 mm; 0,15 mm and 0,075 mm. Grading analysis was performed frequently during the work to monitor the consistency of the materials.

4.1.2 Results and discussion

The sieve analysis results for RCA and RFA are shown in Figure 4.1. The grading curves for all three tests done at three different times show similar trends. This implies that sampling and mixing of materials was done properly. Both RCA and RFA show continuous grading, that is, all sizes are present, which can also be seen in Figure 4.2 and 4.3. RFA had 30% of its particles greater than 4.75 mm. Continuous grading has a number of advantages (Grieve 2001): it results in less segregation of wetter mixes, it is also less sensitive to slight changes in water content, which is an advantage where uniform workability is important, and at high pressure it improves pumpability of concrete. Continuously graded stone also improves flexural strength due to the increased surface area of the graded stone.

The fineness modulus of the fine material only (i.e. material of size 4.75 mm or less) present in the RFA was calculated to be 3.0, which corresponds to a relatively high value indicating the relative coarseness of the fine material present in the RFA. RCA overall fineness modulus was 6.9 and dust content in RFA was found to be 3.2 %, which is higher than the 2.2 % found in NFA as shown in the summary of aggregate properties, Table 4.5. Excessive quantities of minus 75 μm material may increase water requirement of the mix with a consequent increase in drying shrinkage, particularly if natural sands with possible clay content are used (Grieve 2001).

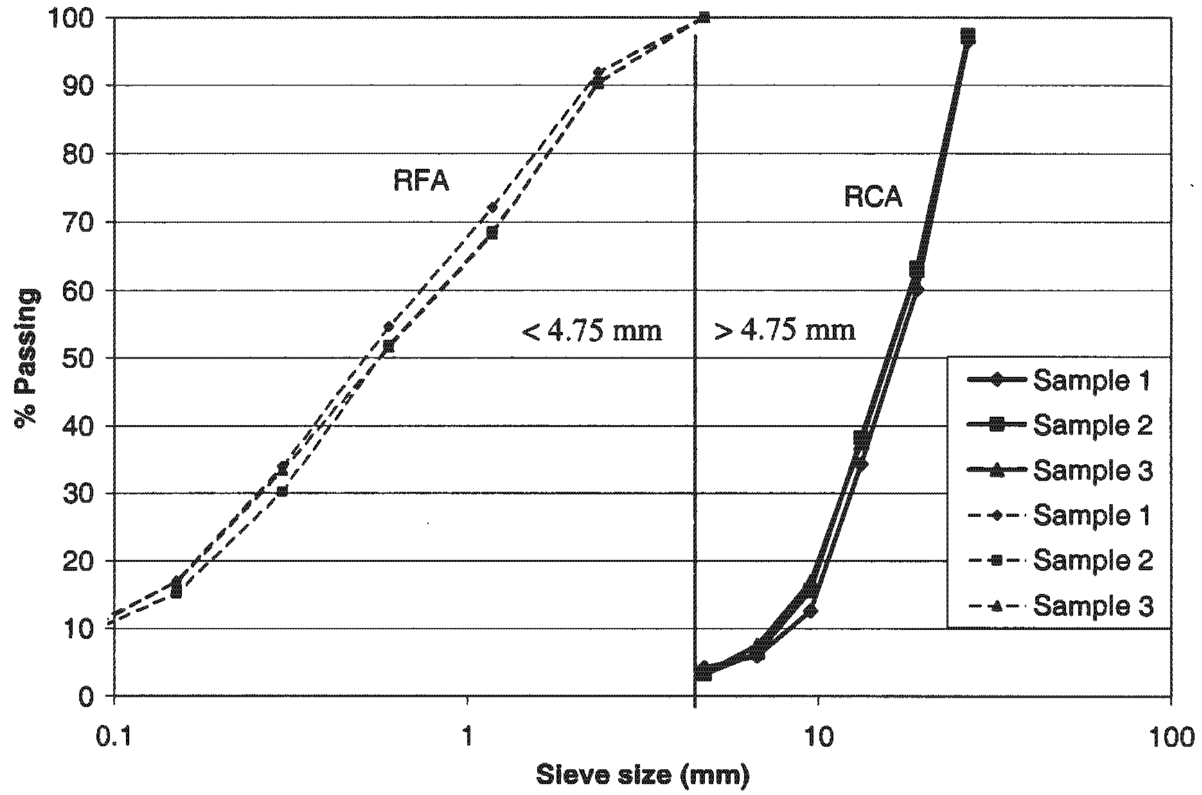
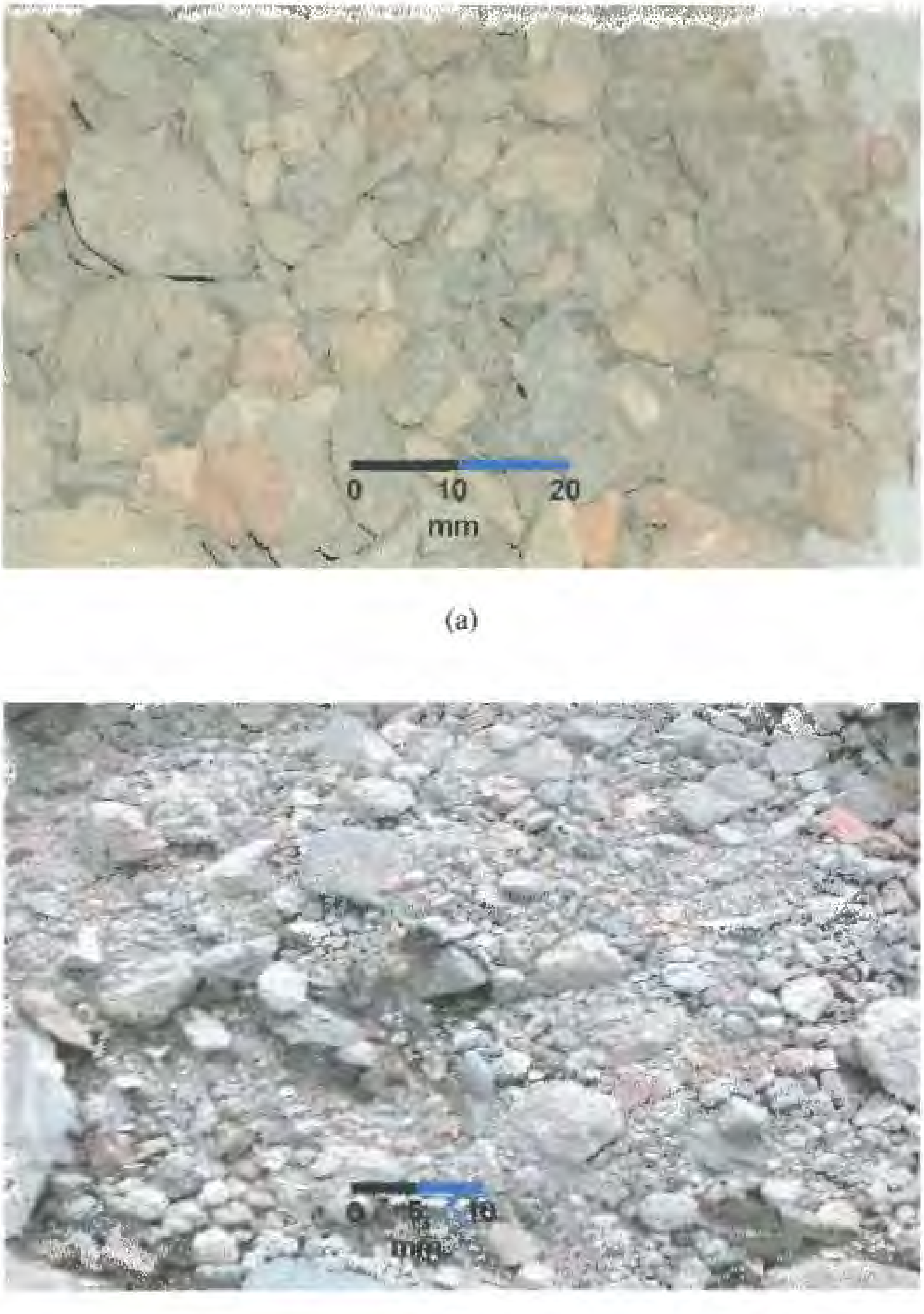


Figure 4.1 Grading curves from RFA and RCA sieve analyses



(a)

(b)

Figure 4.2 Particles sizes of RA (a) RCA (b) Blended RFA

4.2 Composition of RA

4.2.1 Testing Procedure

The same sampling procedure for obtaining the sample for grading analysis was used to obtain the samples to analyze the composition. Only materials retained on 4.75 mm sieve were used to determine the composition of RCA, while materials finer than 4.75 mm sieve were used to assess the composition of RFA. Sorting of RCA constituents was done by hand and the mass determined separately for each size. Composition of materials retained on each sieve was determined first and thereafter all materials were combined to calculate the average fraction percentage of each constituent. Guidelines procedure given by BS 8500-2:2002 was used to assess the composition of RCA. Composition of RFA was assessed by visual inspection.

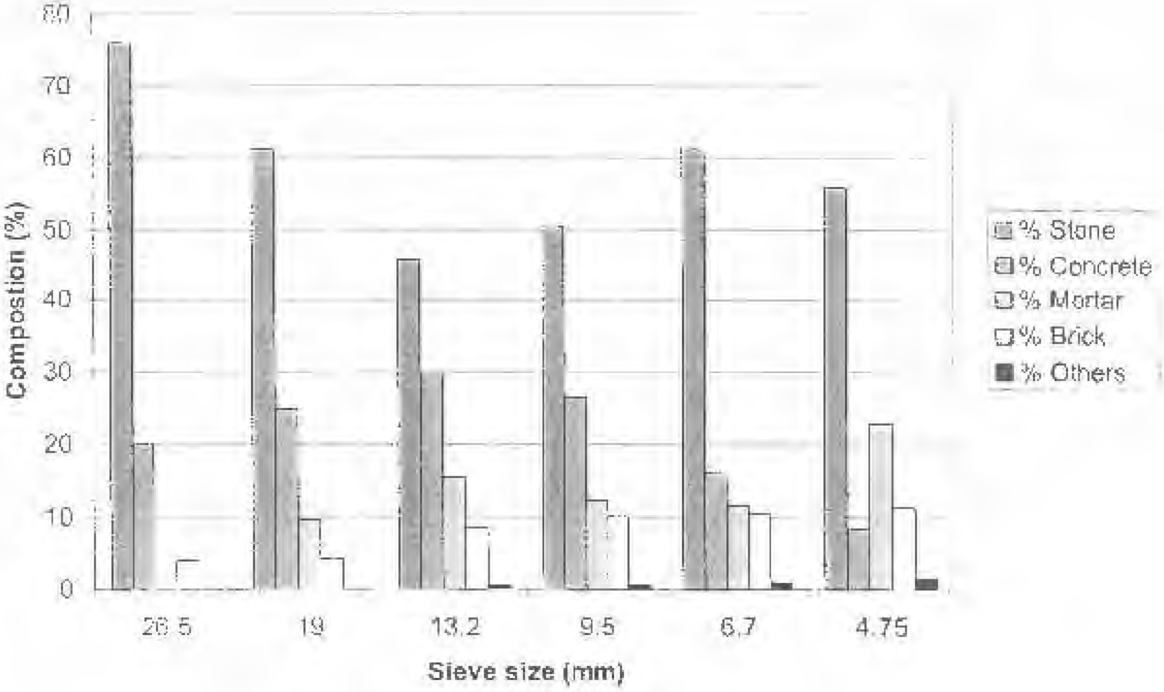
4.2.2 Results and discussion

Figures 4.3a-b show the results for the RCA composition. Stone content was the main component with an average mass fraction of about 58 %. Concrete comprised an average of about 21%, mortar comprised 12% and bricks comprised 8%. Other impurities such as wood, chipboards, and tiles totaled about 1 %.

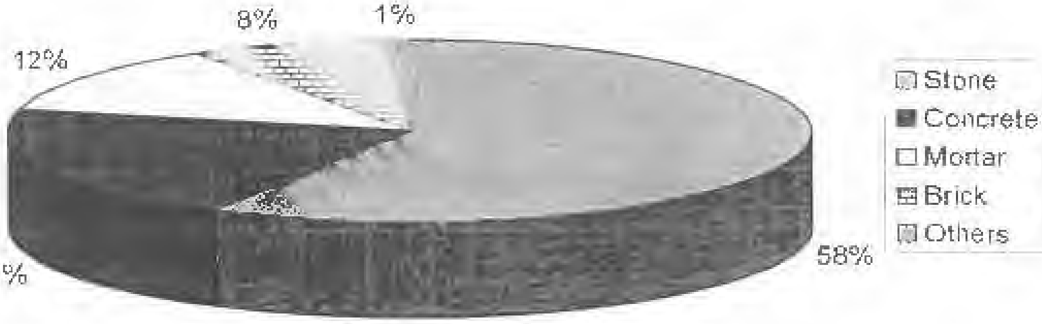
Contrary to the findings of other researchers such as Olorunsogo (1999), Alexander et al (2002) and Chen et al (2003), the stone content was found to be higher than the other constituents, which implies that the aggregates may be quite suitable for concrete production. The stone fraction constituted mainly greywacke natural coarse aggregate. The brick fractions were remnants of clay brick, which may have been used in the original structures. Mortar fractions were made up of cement and fine aggregate and were of a porous nature. It was observed that the amount of mortar and brick content increased as sieve size decreased as shown in Figure 4.3a.

On the other hand, RFA contained greater percentages of mortar and brick particles than stone particles. From visual inspection, it was found that RFA contained about 40%, 35% and 20% of mortar, brick and stone particles respectively. The remainder, 5% was of very fine particles (dust) and contaminants such as timber, glass, charcoal and plastic particles.

The crushing process and softness and friability of the different constituents contributed to this distribution. These results cannot be used to conclude that the RA produced by Bradis or from other recyclers possess the same composition, as aggregates may vary depending on the source of C & DW.



(a)



(b)

Figure 4.3: Composition of RCA from one batch (Bradis in Cape Peninsula).

(a) Composition in each sieve size (%) (b) Overall percentage

4.3 Contaminants

One of the problems inherent in use of RA for new concrete production is the possibility of contaminants in the original demolition debris passing into new concrete. Contaminants may be bricks, clay balls, bitumen joint seals, expansion joint fillers, gypsum, chlorides, organic materials, chemical admixtures, metals, glass, and fire damaged particles among others. If not taken into consideration, these contaminants may cause detrimental effects on the properties of fresh and hardened concrete.

4.3.1 Test procedure

South African standards for aggregates describe methods which can be used to determine contaminants such as chloride, organic impurities, sugar, and soluble deleterious impurities in the aggregates. In this work only visible contaminants were considered and were determined by visual inspection.

4.3.2 Results and discussions

Contaminants found in RA included fragments of brick, plastic, timber, asbestos, tile, bitumen, fire damaged materials (e.g. charcoal), and chipboard. However, contaminants other than brick constituted a very small percentage of about 1 % by mass. These contaminants are within the range of contaminants allowed in RA as per BS 8500: Part 2: 2002 and RILEM Specifications. Maximum content of foreign material such as metal, glass, bitumen and others is specified to be not more than 5% (m/m) (Table 2.4 in chapter 2, section 2.3.3).

4.4 Particle shape and surface texture

4.4.1 Test method

Particle shape and surface texture classifications suggested by BS 812: Part 102: 1989 as shown in Tables 4.1 and 4.2 were used as a guide to classify the RCA. This was done by visual inspection and by rubbing between the fingers. Particle shape cannot be easily quantified but can be assessed by eye and described. The shape of aggregate particles is an important factor that determines the performance of the aggregate in fresh concrete. The particle shape of aggregate depends largely on the crushing process that was used.

Table 4.1: Particle shape classification according to BS 812: Part 102: 1989

Classification	Description	Examples
Rounded	Fully water-worn or completely shaped by attrition	Gravel and sands derived from marine, alluvial, or windblown source
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges	Other gravel typically dug from the pits
Angular	Possessing well defined edges formed at the intersection of roughly planar faces	Crushed rocks of natural or artificial origin; talus rocks
Flaky	Material of which the thickness is small relative to the other two dimensions	Poorly crushed rocks, particularly if derived from laminated or bedded rocks
Elongated	Material, usually angular, in which the length is considerably larger than the other two dimensions	Poorly crushed rocks as above. Poor processing techniques can exacerbate the undesirable shape, and vice versa.
Flaky and elongated	Materials having the length considerably large than the width, and the width considerably larger than the thickness	

Table 4.2: Surface texture of aggregates according to BS 812: Part 102: 1989

Surface Texture	Characteristics	Examples
Glassy	Conchoidal (i.e. curved) fracture	Glassy or vitreous materials such as slag or certain volcanics
Smooth	Water-worn, or smooth due to fracture of laminated or fine-grained rock	Alluvial, glacial or windblown gravels and sands; fine grained crushed rocks such as quartzite, dolomite etc.
Granular	Fracture showing more or less uniform size rounded grains	Sandstone, coarse grained rocks such as certain granites etc.
Rough	Rough fracture of fine or medium-grained rock containing no easily visible crystalline constituents	Andesite, basalt, dolerite, felsites, greywacke
Crystalline	Containing easily visible crystalline constituents	Granite, gabbro, gneiss
Honeycombed	With visible pores and cavities	Brick, pumice, foamed slag, clinker, expanded clay

4.4.2 Results and discussion

Inspection of the RA particles showed that they varied in shape, with a mixture of rounded, irregular, angular and flaky particles as shown in Table 4.3, and Figures 4.4 and 4.5. The surface texture was of a rough nature and highly porous. Both these factors are influenced a greatly deal by the source and production process of the aggregate. The RA tested in this case was crushed in a jaw-crusher.

The rough surface texture and non-spherical particle shape may increase mix water requirements due to an increase in total surface area of the aggregate. However, a rough texture can also lead to a better bonding between the aggregates and the paste, thus improving the mechanical properties of the concrete. The aggregate shape influences water requirement of the concrete mix. Spherical, cubical or chunky shapes produce mixes having lower water requirement than particles that are elongated or flaky. Surface texture of the aggregate also has an effect on the water requirement. Rough textures increase the water requirement due to increased surface area and increased friction and mechanical interlock of the particles (Addis 1998).

Table 4.3: Particle shape and texture of different composition of RCA

Composition	Particle shape	Particle surface texture
Stone	Angular/flaky	Rough
Concrete	Angular	Granular
Brick	Irregular	Honeycombed
Mortar	Irregular	Honeycombed
Fines	Irregular/rounded	Rough

Figure 4.4 Rough surface texture of RCA particle (concrete)

Figure 4.5: Particle shape and texture of the 19 mm RCA

4.5 Bulk and relative density

Relative density (RD) is defined as the density of a particle, relative to the density of water at standard temperature. Relative density is used in calculations for mixes, batching and yields. Bulk density (BD) is the mass of granular aggregate that would fill a container of known volume. 'Loose bulk density' refers to aggregate that is placed without being compacted, while 'compacted bulk density' refers to aggregate that is compacted in the container.

4.5.1 Test Procedures

Procedures described by SANS 5844: 1994 and SANS 5845:1994 methods were followed to determine the RD and the BD of the aggregate respectively. To determine the compacted bulk density and the loose bulk density the SANS Standard specifies that a container of approximate capacity 15 dm^3 be used. In this work a rigid circular container with 150 mm and 155 mm internal diameter and depth respectively was used to determine the compacted and loose BD

A test sample of 25 kg was dried to constant mass at a temperature of 100 °C in a well ventilated oven and air cooled to room temperature before the tests were carried out. By cone and quartering, four samples were obtained. Each sample was tested and an average value calculated to determine the loose and compacted BD. The Pycnometer method and hydrostatic balance method were used to determine RD of fine and coarse aggregates respectively.

4.5.2 Results and discussion

Compacted and loose BD of RCA was found to be 1510 kg/m^3 and 1330 kg/m^3 respectively which were marginally lower than those of NA which attained 1585 kg/m^3 and 1388 kg/m^3 for compacted and loose BD respectively. Compacted and loose BD of RFA was much lower than compacted and loose BD of NFA. RFA had 1533 kg/m^3 and 1430 kg/m^3 compacted and loose BD respectively, while NFA attained compacted BD of 1778 kg/m^3 and loose BD of 1608 kg/m^3. Presence of higher content of stone (NA) in RCA might have contributed to the high value of RD and BD in RCA. Densities and other properties tested in this work are summarized in Tables 4.4.

Since aggregates makes up about 80% of the mass of concrete, RD of aggregates significantly affects the density of the concrete and by doing so the engineering properties of hardened concrete may be affected. On the other hand BD does not have a direct effect on engineering properties of hardened concrete (Addis 1998) but has indirect effect on drying shrinkage. BD is an indicator of packing capacity, which influences water requirement, which in turn influences drying shrinkage of hardened concrete. It is therefore important that the relevant densities of RA be determined prior to their use in concrete production. This should be done in order to avoid large variations in hardened properties of RC.

Table 4.4: Summary of aggregate properties (average values)

Property	RCA	RFA*	NCA	NFA
Compacted bulk density kg/m^3	1510	1533	1585	1778
Loose bulk density kg/m^3	1330	1430	1388	1608
Average Relative density	2.51	2.53	2.65	2.65
Fineness modulus	6.9	3.0	7.0	2.4
Dust content % (by mass)	1.0	3.2	0.4	2.2
Absorption % (by mass)	3.0	8.9	0.4	0.7
10 % FACT (kN)	175-188	-	285	-

* Less than 4.75 mm fraction

4.6 Water absorption

Due to high water absorption of RA as seen from the literature review, water absorption of coarse and fine RA was determined before attempting any mix design. Water absorption is an important indication of the porosity of the RA. The major difference between RA and NA is the porosity of the former. The overall porosity of the RA is mainly due to the adhering mortar fraction, or brick and mortar particles which are present in the RA.

4.6.1 Test procedures

Test procedures in SANS 5843:2002 were followed to determine water absorption of both coarse and fine RA. This standard specifies a method for determining the water absorption of fine and coarse aggregate by saturation in water, and for determining the difference in percentage by mass between an oven-dry and a saturated-surface-dry (SSD) sample. The value of the water absorption is directly related to the porosity of the aggregate. To determine water absorption of RA, three representative samples were tested for RFA and RCA, and an average value was obtained.

4.6.2 Results and discussion

Water absorption (absorption coefficient) was found to be between 2.0% and 4.5% for RCA and between 7.5% and 10.4% for RFA which is higher than that of NA with water absorption of 0.4% for NCA and 1% for NFA. This indicates that the RA has higher porosity than NA. It was also observed that the water absorption increased with decrease in particle size as shown in Table 4.5 and Figure 4.6. The increasing presence of brick and mortar content in RA as the aggregate particle size decreased and difficulties in judging the SSD condition of RFA due to stickiness of very fine materials present in RFA contributed to these results.

Table 4.5: Variation of water absorption with RA particle size

		Absorption (%)							
Sieve size (mm)		26.5	19.0	13.2	9.5	6.7	4.75	2.36	<2.36
Sample	1	1.87	2.46	3.09	3.31	3.72	4.38	7.48	10.10
	2	1.38	2.37	3.42	3.40	3.52	4.41	8.42	10.40
	3	1.60	2.63	3.12	3.27	4.00	4.56	8.77	9.85

mm required for this test was obtained by sieving the samples. Loose and dust particles were removed by washing the aggregate on the 9.5 mm sieve until adhering dust was removed. The aggregates were placed in a shallow try and dried to constant mass in the oven at 100 ^{0}C and cooled to room temperature before being tested.

A sample of known mass was placed in the prescribed metal cylinder and compacted using a tamping rod. The final pieces were hand packed so that the rod could roll freely over the top of the cylinder. A heavy piston was then placed over the sample and the apparatus was positioned in a compression-testing machine. The piston was then forced down onto the aggregate at a uniform rate such that the distance the plunger was forced down in the cylinder in 10 minutes was approximately 20 mm, and maximum applied load was recorded. All material was removed from the cylinder and sieved on a 2.36 mm sieve.

The percentage of fines was calculated by taking the mass of fines (particles less than 2.36 mm) as a fraction of the total mass of the sample. This procedure was repeated three times in the same manner, also over a period of 10 minutes, but at a different rate of application of force, so as to achieve different values of the crushing force, and of fines. The data were then analyzed to determine the value of the force producing 10% fines. The test was performed three times: during characterization of physical properties of RCA; during concrete mix design, mixing and production; and after concrete production to monitor the consistence of the material in the batch.

4.7.2 Results and discussion

Three results obtained from the 10% FACT test which was done at two month intervals are presented in Table 4.6 and Figure 4.7. The results show that the load required to produce 10 % of fine materials ranged between 175 kN and 188 kN which is greater than the 110 kN value recommended by SABS 1083: 1994. It is recommended that 10% FACT should be greater than 110 kN for concrete exposed to abrasion and 170 kN for concrete of high-grade. There was a variation of the load required to produce 10% fines as expected due to the fact that each sample tested would have contained different proportions of different particle types (stone, concrete, brick and mortar).

Table 4.6: 10% FACT results from three different tests

Test 1		Test 2		Test 3	
Load (kN)	% Fines	Load (kN)	% Fines	Load (kN)	% Fines
90	3.4	100	4.0	100	3.8
180	9.5	150	8.8	150	8.2
250	14.3	250	13.8	250	14.5

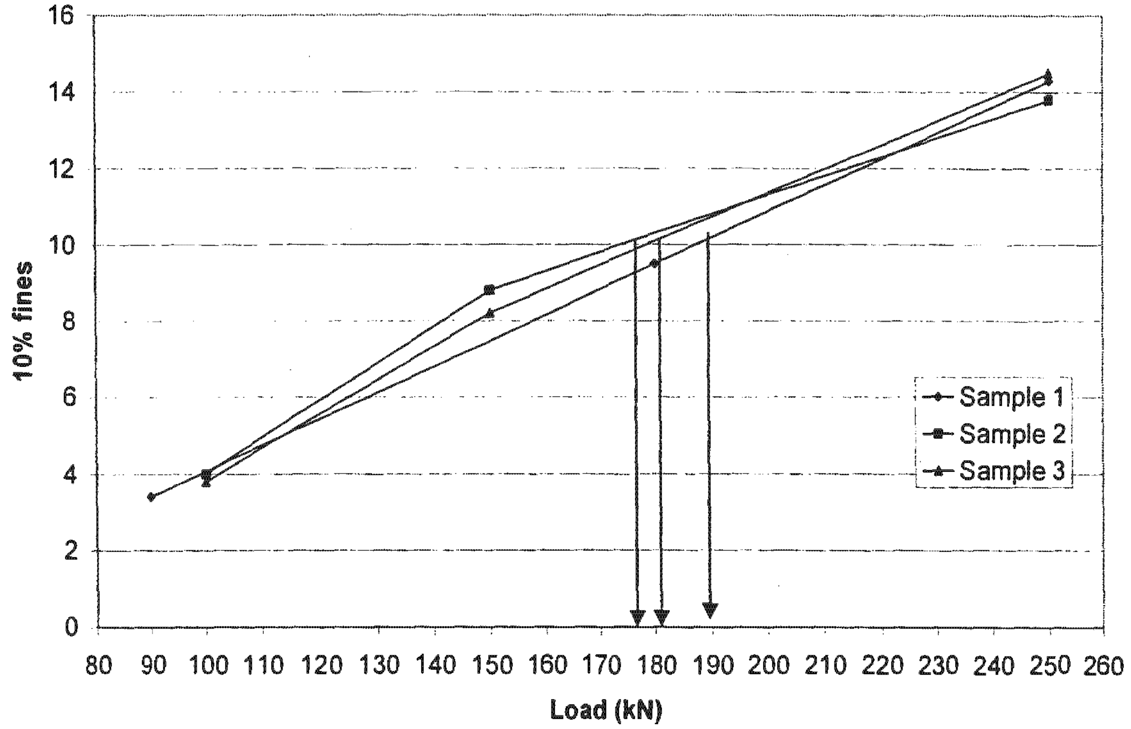


Figure 4.7: 10% FACT of dry RCA

Since there is no SANS test method to determine the friability of a concrete aggregate, 10 % FACT results were used as an indirect indicator of aggregate friability. The friability of an aggregate is usually determined by visual inspection. Friable aggregates are disadvantageous since they are liable to disintegrate in mixing, transporting and placing of concrete leading to increases in water requirement or workability loss. Also these friable materials if situated at the surface of hardened concrete will be susceptible to undue weathering in severe exposure conditions and so cause surface blemishes. Friability of an aggregate is also important in determining the abrasion resistance of a concrete.

4.8 Summary of aggregate properties and discussions

Properties of RA have been covered in this section and summarized in Tables 4.4 and 4.7. Table 4.4 is the summary of aggregates properties of the batch taken for the purpose of the dissertation work, and Tables 4.7 and 4.8 contain summary of aggregate properties taken from Bradis crushing plant at 2 month intervals to analyse any possibilities of variation in composition and physical properties of these materials. These results are compared with properties of NA obtained in South Africa given in Tables 4.9 and 4.10.

It was generally observed that RCA was composed of stone, concrete, mortar and brick in large quantity and others materials such as tiles, timber and chipboard in smaller amount, table 4.8 and figure 4.9. This can be categorised as class II according to RILEM classification or group 2 according to South African classification. Other researchers have reported similar composition. However, composition of RA differs considerably depending on the source of recycled C&DW. This was revealed by the results obtained from this work. Despite all materials analysed being from the same source, there were different composition and physical properties. This was attributed to the type of C&DW recycled by Bradis crushing plant. The crushing plant is set up on an old dump/tipping site, whereby C&DW rubble which has been disposed there over the years is recycled to produce RA.

Bulk density and relative density of RA were found to be lower than NA while water absorption of RCA and RFA were 4 and 10 times higher than NCA and NFA respectively. Other researchers have reported similar results. Lower bulk density and relative density values are contributed by the porous nature of RA and lower RD of mortar, brick and concrete particles. High porosity also influences high water absorption of RA. The 10% FACT values show that they decrease as the amount of concrete, brick and mortar increased in the RA. This is attributed to breaking up of the weaker layer of mortar attached to the natural aggregates. Also, since brick and mortar are weak, they produce fines at lower load. Comparing the physical properties of RA with the NA found in South Africa, Tables 4.9 and 4.10, it can be said that RA density and relative density are within the range of densities of most South African NA. 10% FACT values are within the range of dolomite and granite aggregate. As expected water absorption was found to be very high in comparison with other NA.

Table 4.7: Variation in composition of RCA taken from the same source at 2 month intervals

Components	February 2004	April 2004	June 2004
Stone	47.3	30.5	36.8
Concrete	18.6	33.2	28.3
Mortar	20.9	18.7	21.4
Brick	10.2	14.8	12.1
Others*	3.2	2.8	1.4

* These are contaminants such as wood, chipboard, plastics, paper and bitumen conglomerate

Table 4.8: Variation of RCA properties taken from the same source at 2 month intervals

Properties	February	April	June
Compacted bulk density (kg/m3)	1455	1389	1404
Loose bulk density (kg/m3)	1321	1293	1326
Relative density	2.46	2.41	2.43
Water absorption (%)	3.6	4.3	4.1
10% FACT (kN)	172	165	167

Table 4.9: Physical Properties of NCA found in SA (Davis and Alexander 1992)

Aggregate type	Relative density	Water absorption (%)	Loose bulk density (kg/m^3)	Compacted bulk density (kg/m^3)	10% FACT (kN)
Andesite	2.7 – 2.94	0.42	1505	1605	440 – 475
Dolerite	2.83 – 3.05	0.1 – 0.6	1575	1740	180 – 450
Dolomite	2.71 – 2.88	0.21	1375	1445	140 – 240
Felsite	2.63 – 2.67	0.24	1370	1455	230 – 380
Granite	2.60 – 2.72	-	1365	1460	120 – 280
Greywacke	2.64 – 2.78	0.41	1405	1525	299
Quartzite	2.58 – 2.80	-	1420	1515	155 – 310

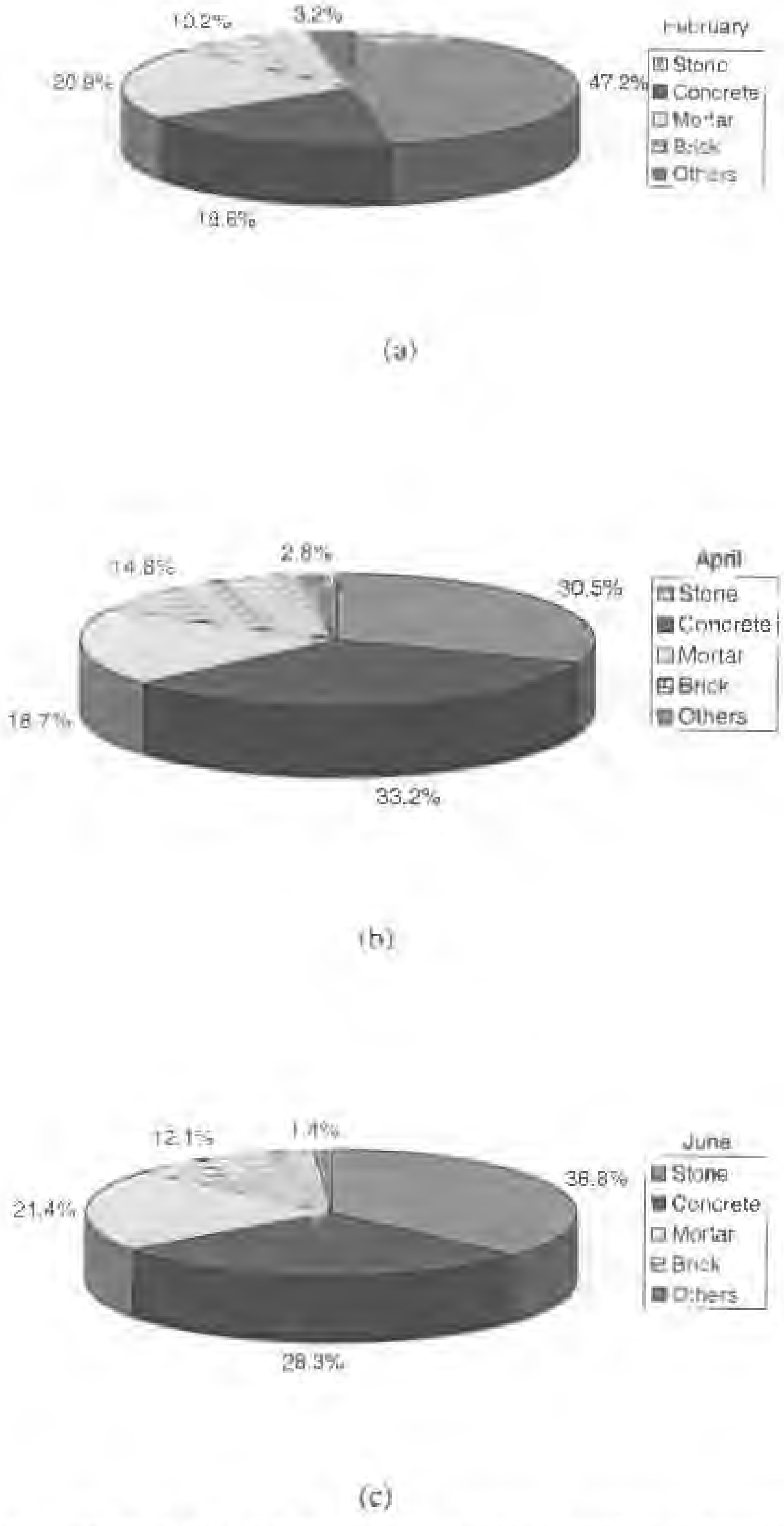


Figure 4.8: Composition of RCA taken from Bradis crushing plant at 2 month intervals (a) February, (b) April and (c) June

Table 4.10 Physical Properties of NFA found in SA (Davis and Alexander 1992)

Aggregate type	Relative density	Loose bulk density (kg/m^3)	Compacted bulk density (kg/m^3)	FM
Andesite crusher sand	2.91	1720	1885	3.23
Natural sand (decomposed Granite)	2.68	1555	1705	2.94
Dolerite crusher sand	2.97	1800	1930	3.24
River sand	2.75	1585	1685	3.02
Dolomite crusher sand	2.86	1735	1849	3.64
Harmse natural sand	2.66	1465	1620	2.69
Granite crusher sand	2.65	1530	1680	2.78
Klipheuwel pit sand	2.65	1855	2010	1.83
Phillippi dune sand	2.66	1745	1880	2.15
Umgeni river sand	2.65	1500	1615	2.56

Since the composition and properties of RA fluctuates considerably as shown in Tables 4.7 and 4.8, and Figure 4.8, it is therefore important that relevant densities and water absorption of RA are determined carefully prior to their use in concrete production. This should be done in order to achieve concrete of adequate workability, stability and cohesiveness, and also to avoid large variations in properties of hardened concrete.

4.9 Conclusions

- Both RCA and RFA are continuously graded, that is all sizes are present. However, RFA contained other coarser particles of about 33 % by mass.
- The fineness modulus of the fine material only (i.e. material of size 4.75 mm or less) present in the RFA was found to be 3.0, which corresponds to a relatively high value indicating the relative coarseness of the fine material present in the RFA
- RCA fineness modulus was 6.9 and dust content in RFA was found to be 3.2 %, which is higher than 2.2 % found in NFA
- Stone content was the main component in the RA, with weight fraction of about 58%. Stone/mortar conglomerate (concrete) comprised about 21%, mortar comprised 12% and bricks comprised 8%. Other impurities such as wood, chipboards, and tiles totaled about 1 %. This can be categorized as class II with RILEM classification of group 2 according to South African classification.

- Contaminant such as bricks, plastic, timber, asbestos, tile, bitumen, fire damaged particles and chipboards were observed. Contaminants other than bricks were in a very small percentage of about 1% by mass.
- Inspection of the RA particles showed that they varied in shape, with a mixture of, cubical/chunky and angular particles. The surface texture was of a rough nature and highly porous.
- Compacted and loose BD of RA were found to be 1510 kg/m^3 and 1330 kg/m^3 respectively which were marginally lower than those of the NA which attained 1585 kg/m^3 and 1388 kg/m^3 for compacted and loose BD respectively.
- RFA attained 1533 kg/m^3 and 1430 kg/m^3 compacted and loose BD respectively, while NFA attained maximum compacted BD of 1778 kg/m^3 and loose BD of 1608 kg/m^3. Presence of higher content of stone (NA) in RCA might have contributed to the high value of RD and BD in RCA.
- Water absorption was found to be between 2.0% and 4.5% for RCA and between 7.5% and 10.4% for RFA. This is higher than that of NA which had water absorption of 0.4% for NCA and 1% for NFA.
- It was observed that the water absorption increased with decrease in particle sizes. Presence of high brick and mortar content in RA as the aggregate particle size decreased contributed to these results.
- The load required to produce 10% of fine materials (10%FACT) ranged between 175 and 188 kN which is greater than the value recommended by SABS 1083: 1994 for concrete exposed to abrasion and concrete of high-grade i.e. 110 kN and 170 kN respectively.
- Generally the results obtained from this study on properties of RA are within allowable limits suggested by various specifications in production of concrete.

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CHAPTER 5

PROPERTIES OF FRESH CONCRETE

5.1 Introduction

The properties of fresh concrete are important because they influence the handling of concrete, the degree to which the concrete can be compacted, and the uniformity of distribution of constituents within concrete. Handling of concrete has practical implications for construction while compaction and uniformity affects the properties of hardened concrete (Kellerman 2001).

The effect of RA on fresh concrete properties will be discussed in this chapter and will be compared with concrete made with NA. Fresh concrete properties considered include water requirement, workability, consistence, cohesiveness and bleeding.

5.2 Water requirement

Water requirement of fresh concrete is the water content of concrete, in litres per cubic meter, required to bring the mix to the specified consistence (Addis 1998). Because the strength of hardened concrete depends on water-binder ratio, water requirement has significant implications for the properties of hardened concrete which include strength, dimensional stability and durability. Water requirement is determined by the properties and contents of constituents in the mix and required consistence of the concrete. Mix constituent factors that affect water requirement of concrete are shown in table 5.1.

To overcome high absorption properties of RA, both coarse and fine RA were pre-saturated prior to mixing. Various trial mixes were performed to obtain concrete of good workability and consistence. After trial mixes were performed, free mixing water of 180 L/m^3 of concrete which gave a slump of approximately 80 mm was maintained in all mixes. To maintain the designed mix proportions, the amount of water and aggregate used in the mixing were adjusted according to the actual saturated moisture contents of the aggregates.

Table 5.1: Concrete constituent factors that influence the water requirement of concrete (Addis 1998)

Constituent	Factors that influence water requirement	Water requirement decreases with:
Stone	Average particle size	Increasing size
	Packing capacity • Shape • Grading	Improving packing capacity
	Surface texture	Increasing smoothness
Sand	Particle shape	Improving roundness
	Grading	Improving particle size distribution
	Surface texture	Increasing smoothness
	Ultra fines • Type, eg clay • Content	Decreasing content, especially clay
Cement	Type • Extender type • Content	Use of fly ash
	Source	-
Admixture	Type	Use of plasticizer and superplasticizer
	Dosage	Increasing dosage

Since RA had a high variability in absorption values (chapter 4, section 4.6) and since the average absorption values were used to determine the free water to be added in the mix (chapter 3), it was not possible to use a single absorption value for all batches. A portion of the designed free water content was reserved and used to adjust the workability to the desired level. It was assumed that the variations in the amount of water added were due to variations in the absorption properties of RA due to constituent variability and difficulties in justification of SSD condition of RA due to the sticky properties of very fine materials within RA. No other admixtures were used to adjust workability. The mix design, mix proportions and concrete production are covered in chapter 3.

5.3 Workability, consistence and cohesiveness

The workability of a mix is defined as the relative ease with which concrete can be transported, placed, compacted and finished without segregation or separation of the individual materials. It is not possible to measure workability, but the slump test together with an assessment of properties like cohesiveness and plasticity give a useful indication. The consistence of a mix is a measure of the stiffness or fluidity of the mix and cohesiveness is the tendency of concrete to remain a homogeneous mass without separation of the constituents.

Factors which can affect the workability and consistence of fresh concrete include time elapsed since mixing, the properties of aggregate, in particular particle shape and distribution, porosity and surface texture. Other factors are cement/binder type, admixtures and relative proportions of the mix constituents. Most results from various researchers (chapter 2) show that good workability and cohesiveness can be achieved when a mix is properly designed and RA is pre-saturated or extra water is added to counterbalance the absorption effect of RA.

5.3.1 Test procedure

To test for consistence, the slump test was carried out using the method in SANS 5862-1: 1994. The dampened mould was filled in three approximately equal layers. Each layer was subjected to 25 blows evenly distributed over the whole area of the layer. For the second and third layers, the rod was forced down to penetrate the previous layer. The surface was struck off by rolling the tamping rod across the top edge of the mould. After the mould was carefully removed, the slump was measured, being the distance between the top of the inverted mould and highest point of the concrete.

To determine possible loss of consistence in the mix (slump loss), theslump test was performed repeatedly up to a period of one hour at fifteen-minute intervals for all mixes with 0.45 and 0.60 water-binder ratios. Between the slump tests, the concrete was covered in the mixer with a plastic sheet to prevent evaporation. The concrete was briefly re-mixed in 10 seconds before conducting the slump tests. After the slump measurement, the slump base plate was tapped with the tamping rod to check the cohesiveness of the concrete. The mix was considered cohesive when the concrete settled in a solid mass and non-cohesive when the mix separated/segregated. All tests were performed under ambient temperature of 23 ± 1 ^{0}C.

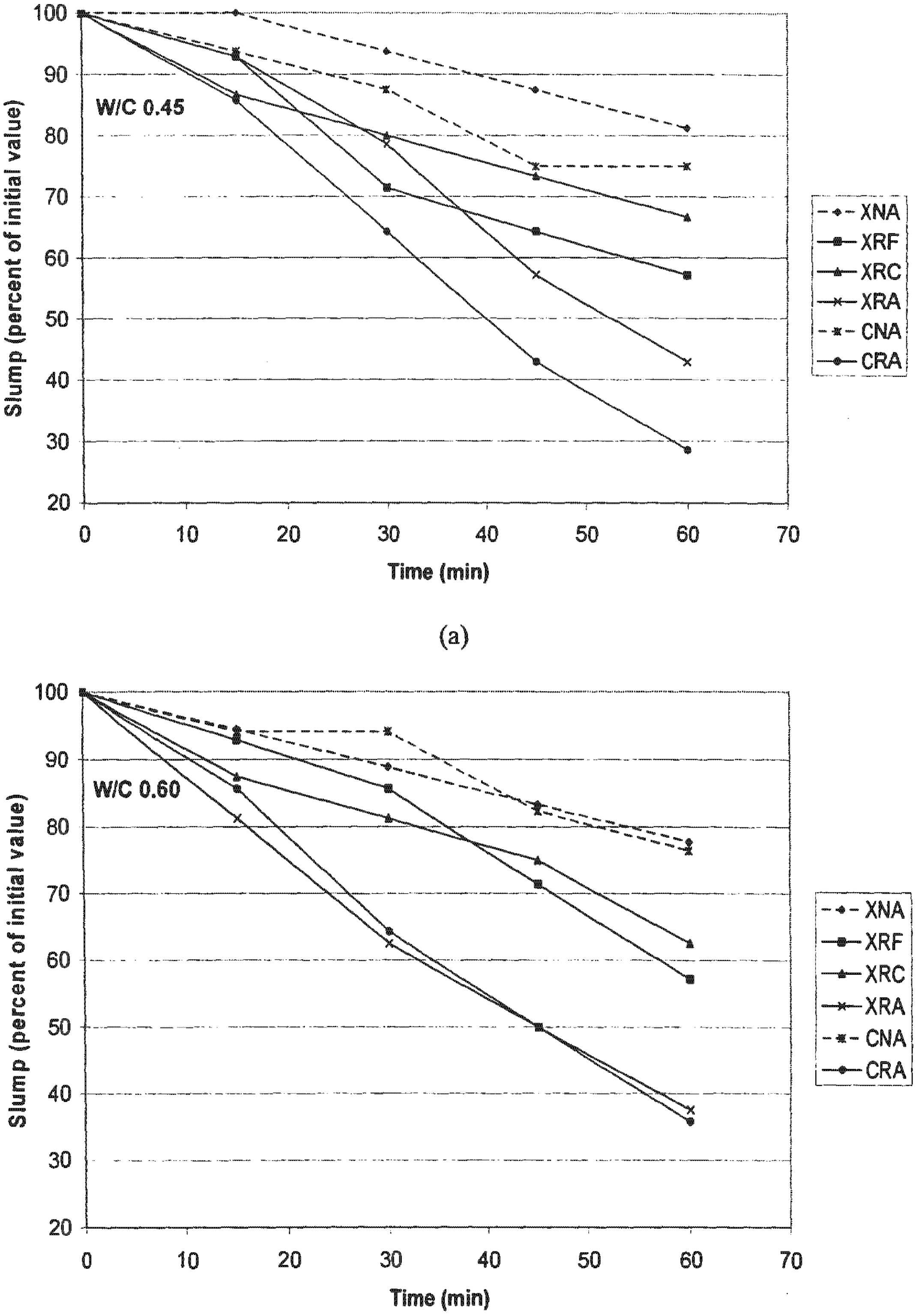
5.3.2 Results and discussion

There was little absorption effect on the fresh concrete as both coarse and fine RA were saturated before mixing. The slumps obtained in all mixes at different water-binder ratios ranged between 70 mm and 90 mm and were within the specified range of 75 ± 25 mm' as shown in table 5.2. Generally the workability and cohesiveness of all mixes were acceptable, although mixes XRF, XRA and CRA were found to be harsher and stiffer than concrete made with NA. Harshness might be attributed to the shape, size and texture of RA and stiffness due to the dust content in the RA and good packing of particles due to graded nature of RA. All mixes with RA were found to be hash and less cohesive at higher water-binder ratios. The mix broke apart when the base plate was tapped with the tamping rod after the slump test. Aggregate size and surface texture and lower binding properties of mortar due to low binder content may have contributed to the harshness and lack of cohesiveness of these mixes.

Table 5.2: Initial slump test results (values rounded to nearest 5 mm)

	Slump (mm) for water-binder ratio of:			
Mix type	0.45	0.60	0.75	0.90
X NA	80	90	80	90
X RF	70	70	80	80
X RC	75	80	80	90
X RA	70	80	75	80
C NA	80	85	85	80
C RA	70	70	75	75

Regardless of the use of pre-saturated RA in the mix, the consistence of concrete declined more rapidly in the RC than in the NC as shown in the figure 5.1. After an hour, concrete containing RA had lost between 50% and 65% of its initial slump while concrete made of NA lost about 25%. This might have been caused by breaking down of weaker RA particles such as mortar, brick and stone/mortar conglomerate during the remixing process which in turn increased the amount of fines in the mix. Other factors which would have influenced the slump loss are the loss of water by evaporation during slump testing and cement hydration. The effect of corex slag could be noticed as the concrete mix type XNA, XRF, XRC and XRA experienced lower loss of slump with time in comparison with mixes CNA and CRA.



(a)

(b)

Figure 5.1: Slump losses with time of fresh RC and NC at water-binder ratio (a) 0.45 and (b) 0.60

5.4 Bleeding

Bleeding is defined as the upward movement of mixing water, and the water that separates from the concrete is called bleed water. Cement and aggregates have densities about three times that of water. In fresh concrete they consequently tend to settle and displace mixing water, which migrates upward and may collect on the top surface of the concrete. Settlement and bleeding continue until the concrete sets (Kellerman 2001). The bleeding characteristics of concrete are influenced by many factors including physical properties of aggregate, binder type and water-binder ratio. Bleeding of concrete has advantages and disadvantages in relation to the properties of hardened concrete. One of the advantages is that it minimizes the potential of plastic shrinkage cracking. Plastic shrinkage cracking increases significantly when the rate of evaporation is faster than the rate of bleeding. Another advantage is the increase of the concrete strength (Neville, 1975). This is due to the fact that when water is removed from the fresh concrete, the water-binder ratio is lowered hence an increase in concrete strength.

Nevertheless, the disadvantages associated with bleeding often exceed the beneficial effects. A problem which may arise is the bleed water which may be trapped under coarse aggregates and horizontal reinforcing bars. This may create bleeding voids, thus increasing permeability of the hardened concrete (Addis 1998). The upward movement of the water provides bleed channels which may lead to durability problems as well (Mehta and Monteiro, 1993).

5.4.1 Test procedure

A modified version of the ASTM standard C 232-92 was used to determine the bleeding potential of the concrete. A rigid steel cylindrical container with inside diameter of 155 mm and inside height of 150 mm was used instead of the prescribed standard one which has inside dimension of 254 ± 6.4 mm diameter and 279 ± 6.4 mm height.. The concrete was placed in the container and compacted using a vibrating table. Bleeding measurements were taken at 30-minute intervals for a period of two hours, a syringe being used to draw out the bleeding water. The bleed cylinder was kept at a constant temperature of 23 ± 1 ^{0}C and covered to prevent evaporation. Cumulative bleeding in percentage was calculated as the ratio of bleed water to the free water added into the mix.

5.4.2 Results and discussion

Bleed water of fresh RC was between 40% and 60% lower than NC for all water binder ratios, as shown in Figures 5.2a to 5.2c and Table B3 in appendix B. The reduction of bleeding by the RA may be due to the presence of dust in both RCA and RFA, rough surface texture as well as the graded nature of RA which minimized the capillarity action within fresh concrete. Corex slag had an influence on the reduction of the bleeding as well. Mix XNA which had 50% corex slag had lower bleeding volume than mix CNA which had only CEM I 42.5. Corex slag has finer particles than Portland cement, which hold water in the mix and prevent excessive bleeding (Jaufeerally 2001).

At the end of bleeding period, the concrete containing corex had a greater rate of bleeding than concrete made with CEM I only, Figures 5.2a to 5.2c. This indicates that there is extended bleeding time in mixes containing corex slag. The reason for this extended bleeding time of concrete containing slag is due to the longer setting time of corex slag concrete (Jaufeerally 2001). This delays the formation of hydration products which retard the upward movement of water. As expected, bleeding in all mixes increased as the water-binder ratios increased, Figure 5.3.

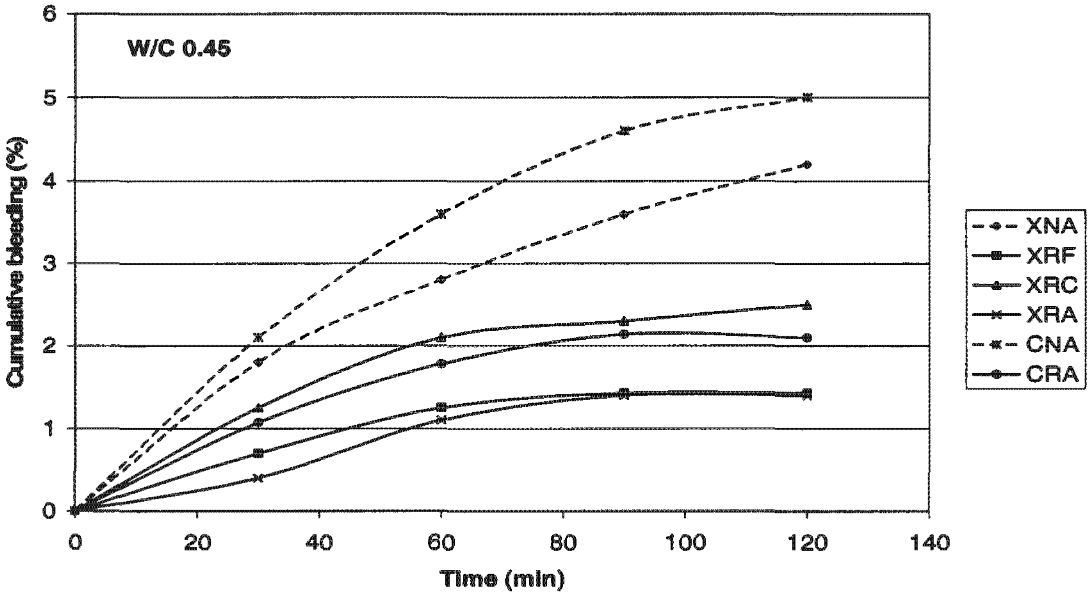
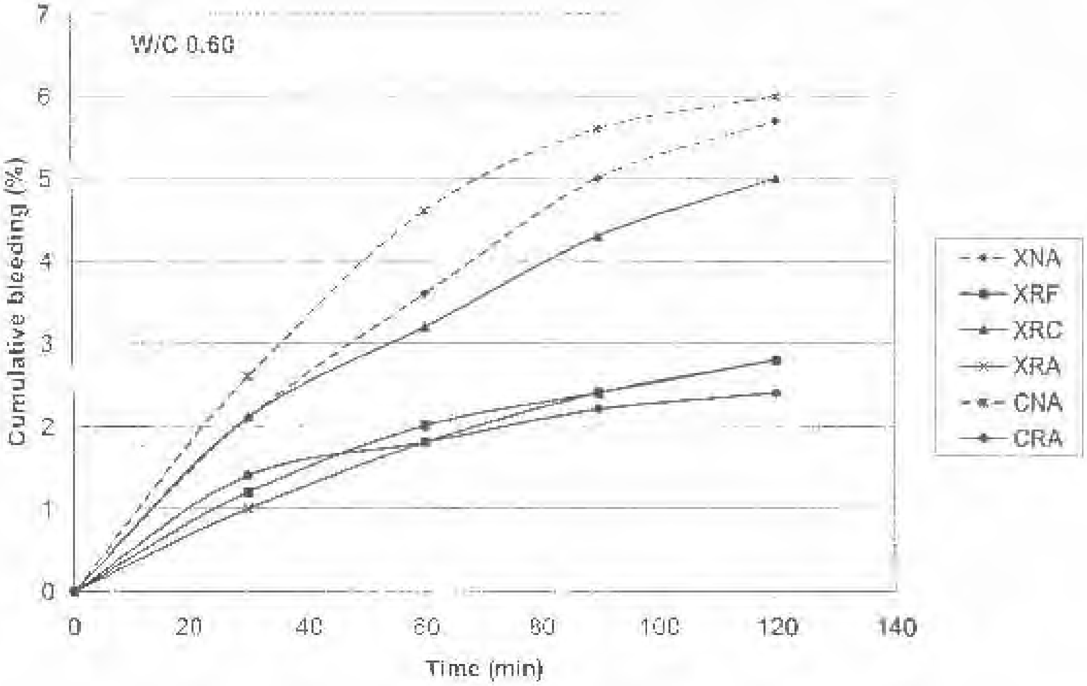


Figure 5.2a: Cumulative bleed water as percentage of the original mix water with time at 0.45 water-binder ratio.



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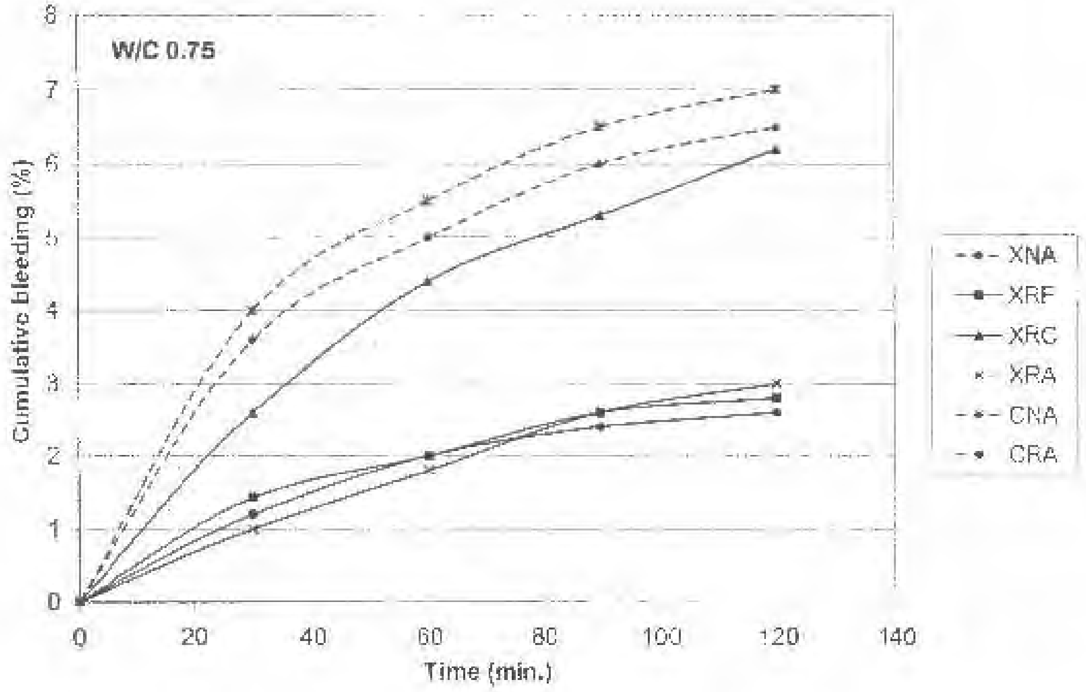

(ii)

Figure 5.2b: Cumulative bleed water as percentage of the original mix water with time at water-binder ratio (i) 0.60 and (ii) 0.75.

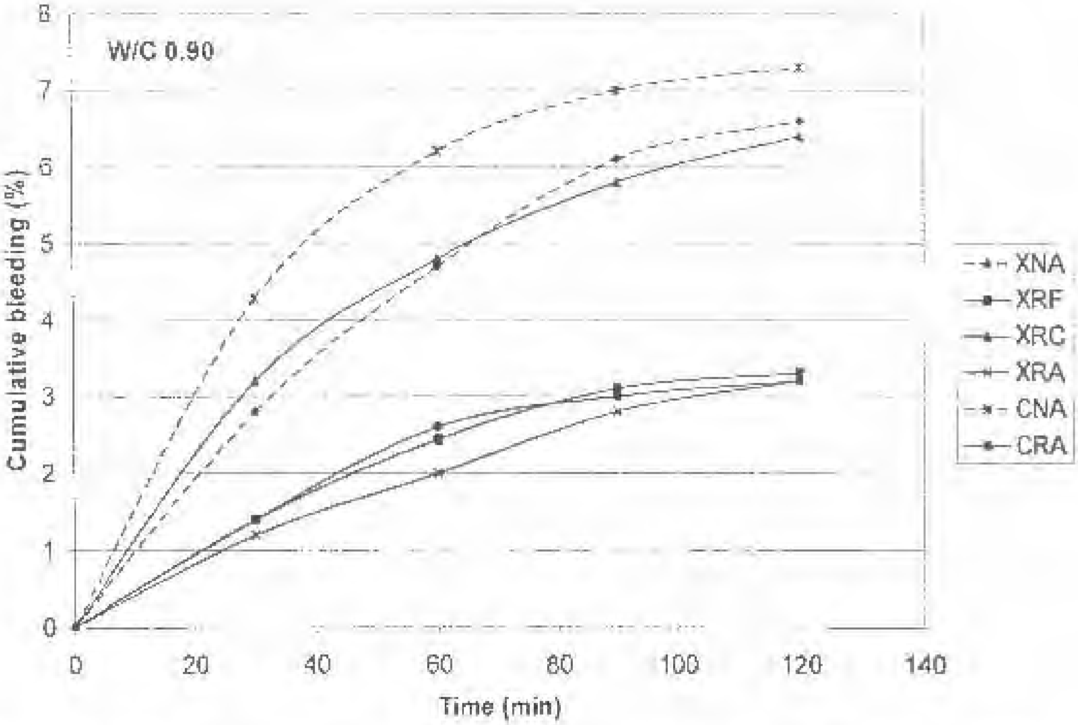

Figure 5.2c: Cumulative bleed water as percentage of the original mix water with time at 0.90 water-binder ratio.

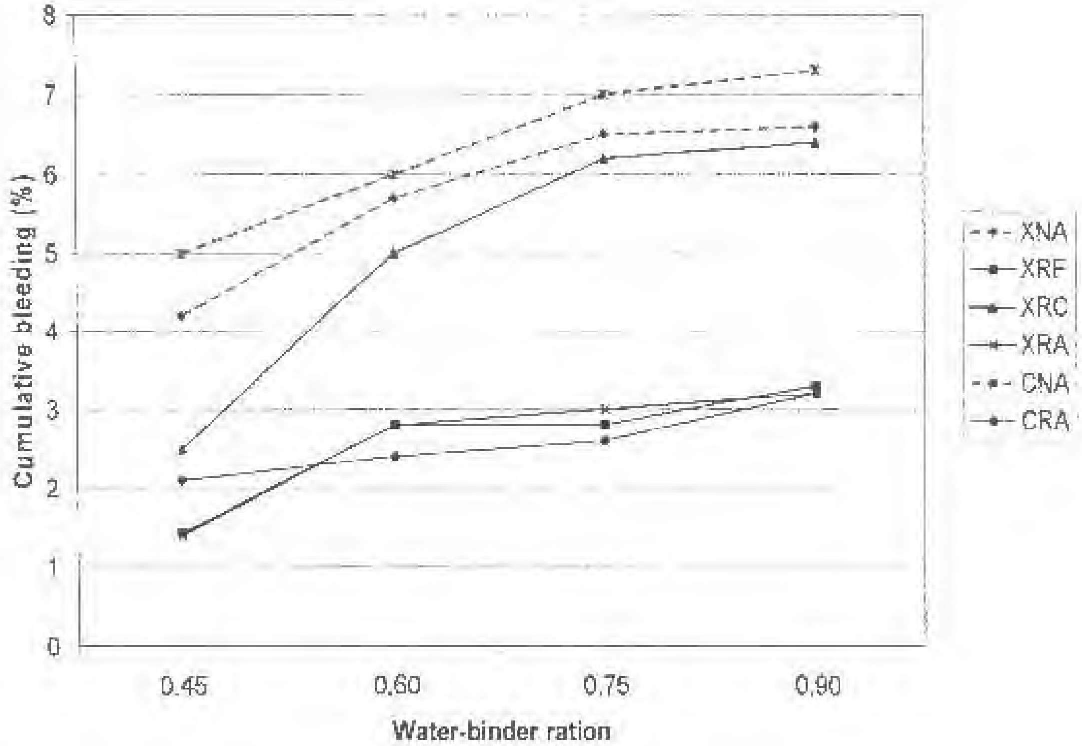

Figure 5.3: Bleed water at different water-binder ratios after 2 hours.

5.5 Density of fresh concrete

The density of concrete is affected by the density of the raw materials, water content, air content and degree of compaction. A change in water content of 10 L/m^3 may alter the density by about 15 kg/m^3 and an increase in air content of 1 % can reduce the density by about 25 kg/m^3 (Kellerman 2001). The density of fresh concrete can be used to confirm the mix propositions calculated using absolute volumes, and can also give an indication of the air content, and degree of compaction.

5.5.1 Test procedure

SANS 6250:1994 was used to determine the wet density of freshly compacted concrete. A cylindrical container with internal dimension of 155 mm diameter and 165 mm depth was used. The mass of the empty container was measured first and concrete was placed and fully compacted by using a vibrating table and the surface carefully struck off level with the rim. The mass of the container and concrete was determined and density was calculated.

5.5.2 Results and discussion

The results of density of fresh concrete made with RA and NA are shown in Table 5.3 and Figure 5.4. The density of fresh concrete made with RA was in a range of between 2129 Kg/m^3 and 2365 kg/m^3, and was less dense than that made with NA which ranged between 2414 kg/m^3 and 2465 kg/m^3. Lower density of RA is the result of the lower RD of RA discussed before. The porous nature of RA especially RFA contributed to the lower density of fresh RC. Binder type and water-binder ratio was found to have no appreciable effect on the density of fresh concrete.

Table 5.3 Densities of fresh concrete

	Density of fresh concrete (kg/m^3)		
Mix type W/C	0.60	0.75	0.90
X NA	2465	2414	2440
X RF	2296	2129	2195
X RC	2365	2353	2358
X RA	2169	2213	2258
C NA	2400	2410	2459
C RA	2144	2256	2256

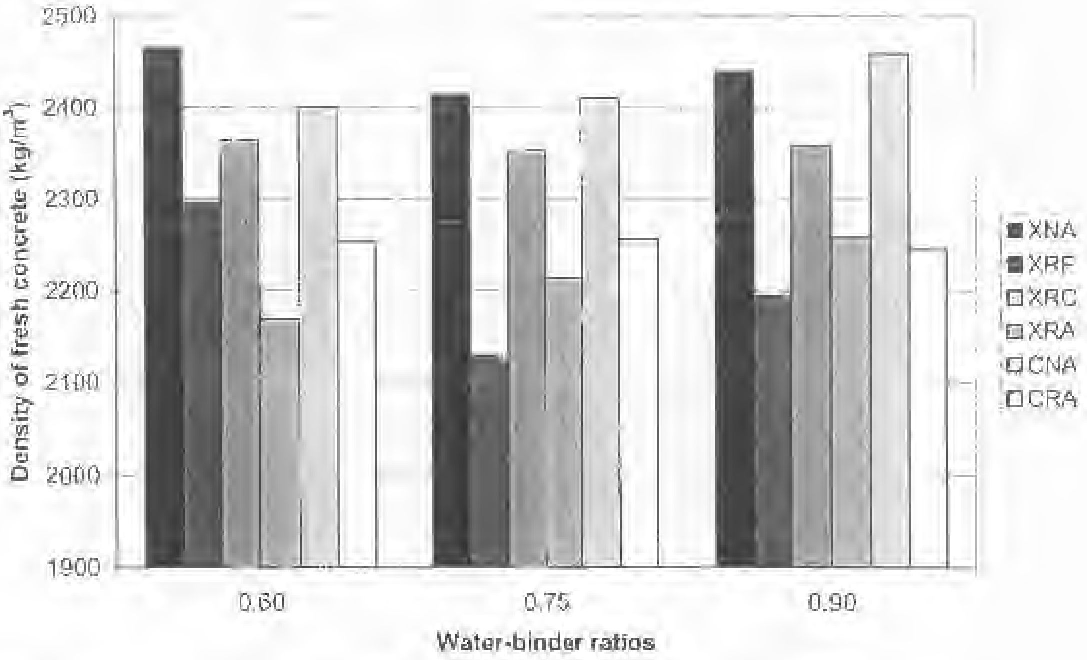

Figure 5.4: Density of fresh concrete at different water-binder ratios

5.6 Discussion and recommendations

In principle, mix design of RC is not different from mix design of NC, and therefore the normal mix design procedures used for NC can be used to design RC mixes. However, modifications are needed to overcome high water absorption properties of RA. Since bulk density, relative density and water absorption property of RA varies considerably, it is important that they should be carefully determined before it is attempted to design a mix of RA concrete and should be carefully monitored during concrete production. This should be done in order to achieve concrete of adequate workability, stability and cohesiveness; also to avoid large variations in properties of hardened concrete.

The absorption of RA due to porosity affects not only the workability of fresh concrete but also the density and the final properties of hardened concrete, including strength and durability. Use of aggregates which are in SSD condition or adding extra water in the mix to compensate for the water which will be absorbed by RA will overcome this problem. Use of superplasticizer may also assist to increase the workability of RC. Pre-wetted and SSD RA have been used in several studies (Sagoe-Crentsil et al, 2001 and Poon et al, 2004) in order to prevent a rapid decrease in concrete workability. These studies concluded that there was impact of pre-wetted RA on the mechanical properties of RC. It is difficult to determine the SSD condition of RFA precisely. This is due to high variability of water absorption and the cohesive nature of RA particles. Therefore, it is important to be careful when determining free water to be added in the mix.

Generally workability and cohesiveness of all mixes were acceptable in this investigation, although mixes XRF, XRA and CRA were found to be harsher and stiffer than concrete made with NA. Harshness is attributed to the shape, size and texture of RA and stiffness due to the dust content in the RA and good packing of particles due to the graded nature of RA. All mixes with RA were found to be hash and less cohesive at higher water-binder ratios. The mix broke apart when the base plate was tapped with the tamping rod after slump test. Aggregate size and surface texture and a less cohesive mortar due to low binder content contributed to the harshness and less cohesiveness of these mixes.

5.7 Conclusions

- After trial mixes were performed, free mixing water of 180 L/m^3 of concrete was considered and maintained in all mixes.
- To maintain the designed mix proportions, the amount of water and aggregate used in the mixing were adjusted according to the actual saturated moisture contents of the aggregates.
- Generally the workability and cohesiveness of all mixes were acceptable, although mixes XRF, XRA and CRA which were prepared by using NA and RFA for mix XRF and both RA for mix XRA and CRA, were found to be harsher and stiffer than concrete made with NA. Harshness might be attributed to the shape and texture of RA and stiffness due to the dust content in the RA and good packing of particles due to graded nature of RA.
- The slumps obtained in all mixes at different water-binder ratios ranged between 70 mm and 90 mm and were within the specified range of 75 ± 25 mm.
- Regardless of the use of pre-saturated RA in the mix, the consistence of concrete declined more rapidly in the RC than in the NC. After an hour, concrete containing RA had lost between 50% and 65% of its consistence while concrete made of NA lost about 20%. This might have been caused by

breaking down of weaker RA particles such as mortar, brick and stone/mortar conglomerate during remixing which in turn increased the amount of fines in the mix. Other factors which might have influenced the slump loss are the loss of water by evaporation during slump testing and cement hydration.

- Bleed water was between 40% and 60% lower for RC than NC for all water-binder ratios. The reduction of bleeding by the RA may be due to the presence of dust in both RCA and RFA as well as the graded nature of RA. As expected bleeding in all mixes was increasing as the water-binder ratios increased.
- Density of fresh concrete made with RA was found to be lower than that of NA. Mix XRC which was made with RCA and NFA had higher density than other mixes with both RCA and RFA. The porous nature of RA especially RFA contributed to lower the density of fresh RC.
- The density of fresh concrete made with RA, was in a range of between 2129 kg/m^3 and 2365 kg/m^3 less dense than NA which ranged between 2414 kg/m^3 and 2465 kg/m^3. Lower density of RA is the result of the lower bulk density of RA discussed before.

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CHAPTER 6

PROPERTIES OF HARDENED CONCRETE

6.1 Introduction

The properties of hardened concrete are of fundamental importance, since the serviceability, durability and life span of the structure depend largely on these properties. Properties of hardened concrete made with commercially produced RCA and RFA are not well reported in various local (South Africa) and international research reports, and therefore a wide range of experiments was performed. This included density of hardened concrete, compressive strength, modulus of elasticity, flexural strength, creep and shrinkage. Durability was monitored by durability index tests (oxygen permeability, water sorptivity and chloride conductivity). In this chapter the effects of RA on hardened concrete properties are presented, analyzed and discussed.

6.2 Compressive strength

Compressive strength is still regarded by many engineers as the most important property of hardened concrete and is of fundamental importance to structural engineers. The strength of a material can be determined in various modes such as compressive, tensile and shear. However for concrete, compressive strength is the property most frequently specified and used for structural design. The strength of concrete depends on the strength of aggregates, cement matrix and the interfacial bond between cement matrix and the aggregates.

"Concrete without adequate strength is useless, but on the other hand, concrete that is unnecessarily strong is too expensive" (Addis 1998). Therefore to be able to use concrete effectively, there is a need to measure the strength so that concrete can be specified according to its strength for a specific application. Compressive strength of concrete is also related to other properties such as elastic modulus.

6.2.1 Test procedure

The tests were performed in accordance with SANS 5863:1994. Compressive strength of hardened concrete was determined on 100 mm concrete cubes which were cast and water-cured at 23 ± 1 ^{0}C before being tested at ages of 3, 7, 28, 56, and 120 days. The cubes were weighed before they were tested for compressive strength to determine their density. Three cubes were tested at each curing age and the loading rate during testing was maintained at 3 ± 1 kN/s. After each test, the cubes were inspected to see if there was any unusual mode of failure. The compressive strength of concrete was calculated as the ratio of maximum applied load to the cross-sectional area of the specimen.

6.2.2 Results and discussion

Compressive strength results are presented diagrammatically in Figures 6.3a-c and in Table C2 of Appendix C. Generally the strength of RC was lower than that of NC except for mix XRC. All mixes which contained RFA were found to have a lower density as shown in Figure 6.1 and attained a very low compressive strength in comparison with other mixes. RC with both RCA and RFA attained a density of about 80% that of NC. However, density of RC made with only RCA and NFA was about 5% less than that of NC. This was attributed to porous nature of brick, mortar and old concrete particles contained in RA.

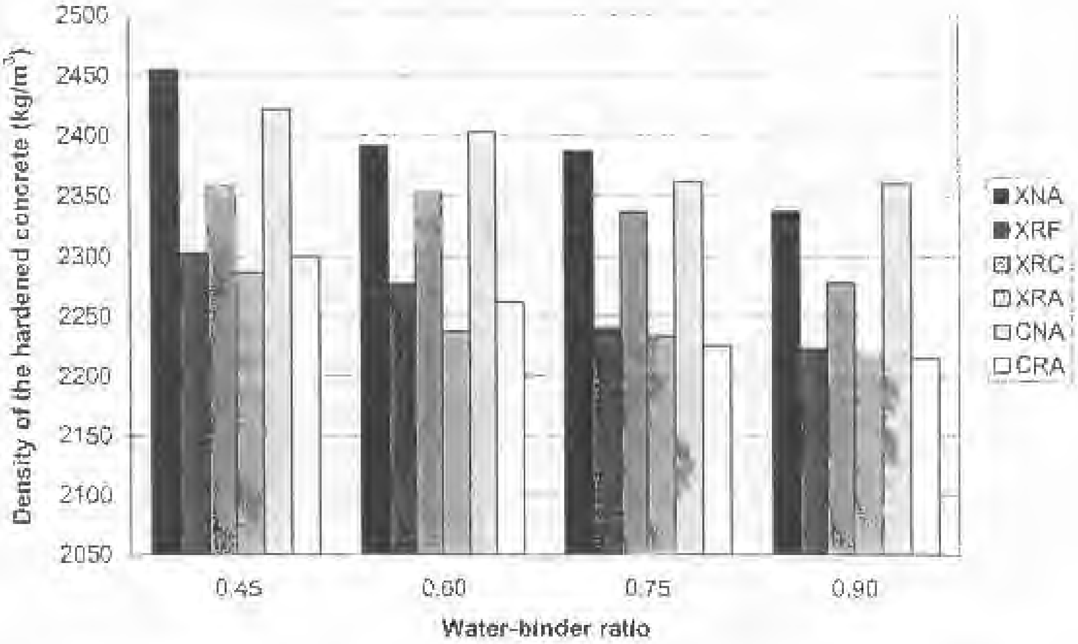
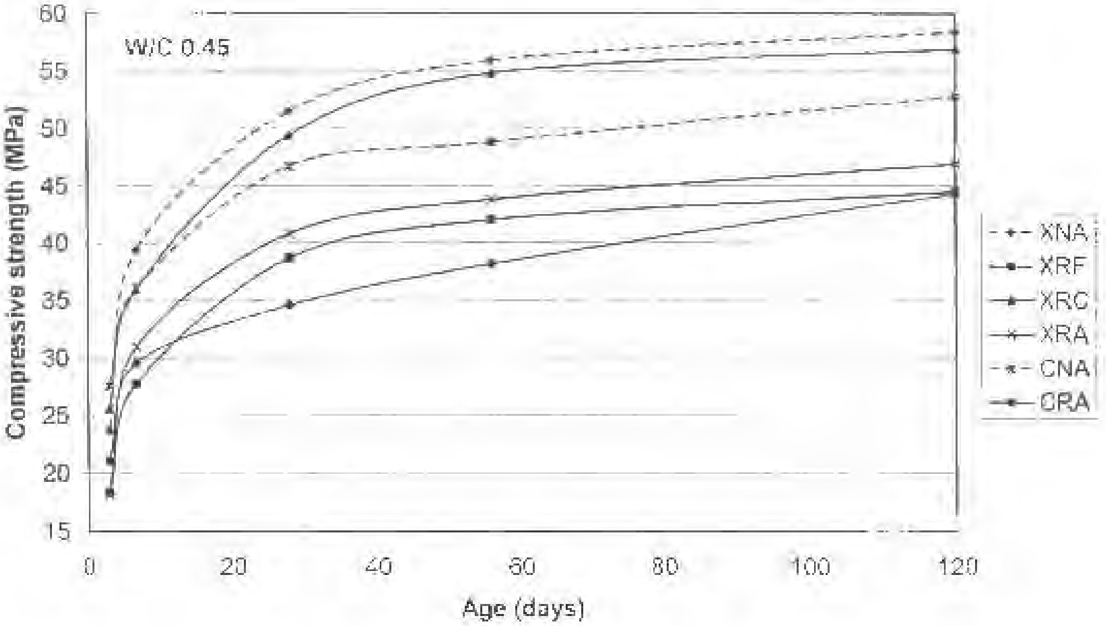


Figure 6.1: Effect of RA on the density of hardened concrete at different water-binder ratios

Lower compressive strength of RC was contributed by the lower density of RC and porous nature of both RCA and RFA and possibly contaminants within RFA. Not only weak aggregate particles in RA lowered the compressive strength, but also the presence of dust attached to RCA might have hindered the bonding between coarse aggregates and mortar. The failure mode during testing was observed to be through weaker RA particles and bond failure even at a later age, refer Figure 6.2.

Figure 6.2: Mode of failure of crushed cubes

At 120 days of age strength loss of 2% to 40% was observed in concrete containing RA over the full range of water-binder ratios as shown in Figures 6.3a-b. Maximum reduction of 40% compressive strength was observed in concrete mix XRF and XRA at water-binder ratios of 0.75 and 0.90. The different between RC and NC made with CEM I reduced with increased water-binder ratio while in the case of corex slag concrete, the difference of compressive strength increased with increased water-binder ratios (Figure 6.3c). Mix XRC was 2% and 10% lower in strength than control mixes XNA and CNA respectively. Compressive strength of mix XRC which contained only RCA was marginally lower than control mix XNA, but higher than control mix CNA. Binder type and water-binder ratios had an influence on the strength of hardened concrete. Compressive strength of mix XRC depended more on binder type than type of aggregate. Binder type had an effect on mix XRA and CRA also.



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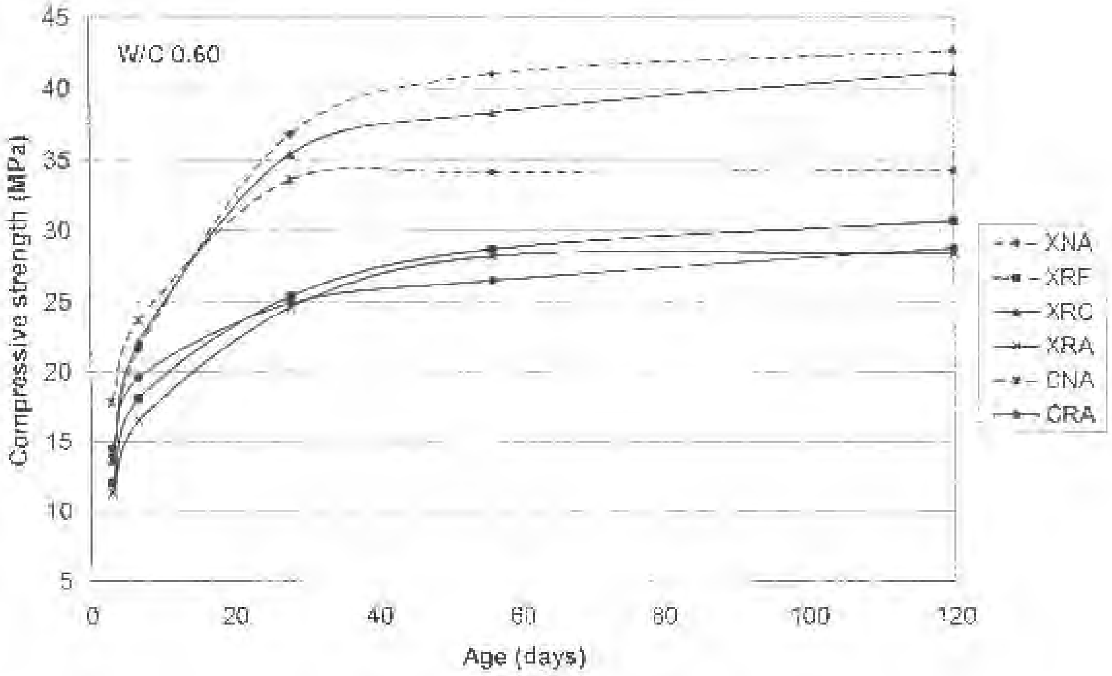


(ii)

Figure 6.3a: Effect of RA on compressive strength of hardened concrete with water-binder ratio of (i) 0.45 and (ii) 0.6

The effect of water-binder ratio on compressive strength can be explained by reduction in the cementitious content with an increase in the water-binder ratio. This has the consequence of decreasing the total products of hydration, thus reducing the bonding power of aggregates and mortar. This is illustrated by the good compressive strength results obtained by mix XNA at water-binder ratio of 0.45. The results obtained are similar to the findings of other researchers as seen in chapter 2.

6.2.3 The effect of RFA in the hardened mortar

A separate experiment was performed to investigate why RC mixes containing RFA attained lower compressive strength than other mixes. Two more tests on RFA were performed. The first test was performed using water drained from soaked RFA (recycled water-RW) to determine if there were deleterious substances in the mix water. Constitutes analysed were the pH of the water, potassium, sodium, magnesium, calcium and iron content. A second test was performed on mortar cubes made with RFA and recycled water (RW) and compared with mortar made with NFA and normal (tap) water.

Materials in three moisture states were considered. These were oven-dry (OD), air-dry (AD) and saturated surface-dry (SSD). Mixing water used to prepare the mortar was RW and normal tap water (TW). To overcome the absorption effect of RFA, extra water was added to mix containing AD and OD RFA. Mortar cube made with NFA was also prepared for comparison purposes. 50 mm mortar cubes with 0.6 w/c ratio were prepared and water cured. The specimens were tested at the age of 1, 3, 5, 7 and 14 days after casting. Table 6.1 shows the combination of the mixes prepared.

Table 6.1: Combinations of the mortar mixes

Mix type	Fine aggregate	Water	Moisture state
NFA	Natural aggregate	Tape water (TW)	OD, AD, SSD
RFA	Recycled fine aggregate	Recycled water (RW)	

Results showed that no deleterious substances were found and potassium, sodium, magnesium, calcium and iron contents in the recycled water were within allowable concentration. The water pH was found to be 7.7 which is normal for concrete mixing water. Figure 6.4 shows the results of the mortar compressive strength. Lower compressive strength was observed in mortar cubes made with RFA. Recycled water had no influence on reduction of strength. A substantially lower strength in RFA mortar was observed at the age of 5 to 9 days. However, the difference of compressive strength between RFA and NFA diminished at the age of 14 days.

The effect of moisture state of RFA was also monitored. It was revealed that RFA in SSD condition attained a lower compressive strength than when it was in AD or OD condition. Due to stickiness and cohesiveness of pre-saturated RFA it was difficult to judge the SSD condition of RFA which might have led to higher water content in the mix, thus reducing compressive strength. The factors which influenced the reduction of mortar strength arranged from most to least are: RFA, moisture state (SSD, AD) and recycled water (RW).

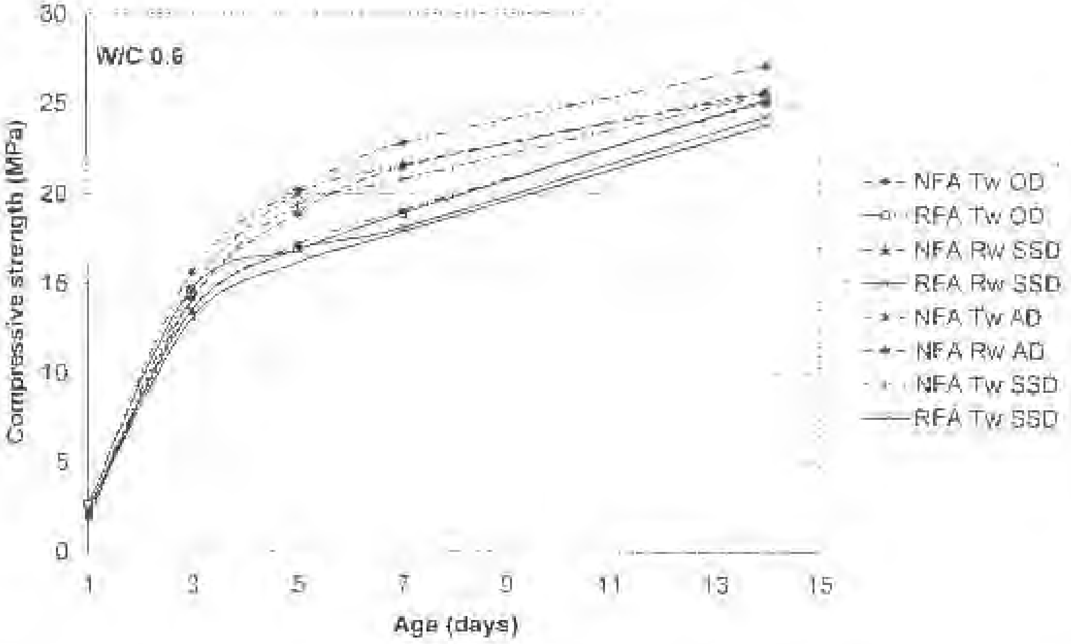


Figure 6.4: Compressive strength of mortar cubes of RFA and NFA at different moisture state.

From these results it can be deduced that the low compressive strength of RC can most likely be attributed to weaker RFA particles and the interfacial bond between coarse aggregate and RFA mortar. Difficulties in judging the SSD condition of RFA might have increased the water-binder ratio in the mix which in turn lowered compressive strength.

It can be concluded that concrete with high strength can be obtained using RCA and corex slag provided curing is properly done. Although RFA lowered the concrete strength at all ages and water-binder ratios, adequate concrete for simple applications such as in house foundations and floors can be produced.

Generally most research reports show that compressive strength of RC to be less or equal to that of NC when RC is made with lower or same water-binder ratio. The strength of RC is more reduced when both RCA and RFA are used. In such cases the compressive strengths of RC and NC made with the same water-binder ratios varies as much as 50% or more depending on the quality of the RA. However, differences between the two are smaller and less important when lower strength concrete is produced.

6.3 Modulus of elasticity E_c

This is a measure of material stiffness. When the ratio of the applied stress to the longitudinal strain produced is constant, the constant is called the modulus of elasticity or Young's modulus. Therefore elastic modulus is the ratio of the stress applied to the elastic strain produced. When a load is applied to a structural material it deforms. If on removal of the load the recovery is both complete and immediate the material is considered elastic. Concrete is not a perfectly elastic material. That is, all strain produced by the applied stress does not disappear on removal of the stress. This is due to non-linear stress-strain responses of the paste and interfacial transition zone ITZ, and to micro-cracking in the matrix (Alexander, 2001)

Factors affecting elastic modulus include mix proportions, in particular the volume and stiffness of aggregate, type of aggregates, age of concrete, moisture content and rate of loading. Many attempts have been made to correlate the modulus of elasticity and the strength of concrete. However, the factors which affect the modulus of elasticity of concrete do not always have a correspondingly similar effect on concrete strength. For example, the use of aggregate with higher modulus of elasticity does not necessarily produce a concrete of greater strength although it may increase the modulus of the concrete (Alexander, 2001).

Various structural design codes such as SANS 10100-1:1992, BS 8110: Part 2:1985, ACI 318M-95, and CEB-FIP 1990 recommend formulae for estimating E_c. All formulae base E_c on the strength of the concrete and some formulae incorporate a factor that accounts for the stiffness of the aggregate. Because of lower compressive strength of RC, modulus of elasticity of RC is also expected to be lower than that of NC.

6.3.1 Test procedure

Static elastic modulus was determined on 100 x 100 x 200 mm concrete prisms at the ages of 28 days and 120 days. Top and bottom surfaces of the prisms were ground to ensure plane bearing on the surface. Static elastic modulus was determined using the method proposed by BS 1881: Part 121: 1983. The samples were fitted into a mechanical compressometer rig which had an LVDT mounted in it. A stress equal to approximately one-third of the cube compressive strength was applied using an Amsler compression machine as shown in Figure 6.5 and the displacements recorded on graph paper as shown in Figure 6.6. The outputs were analyzed to determine the static elastic modulus of each sample and the average for each set of specimen was calculated.

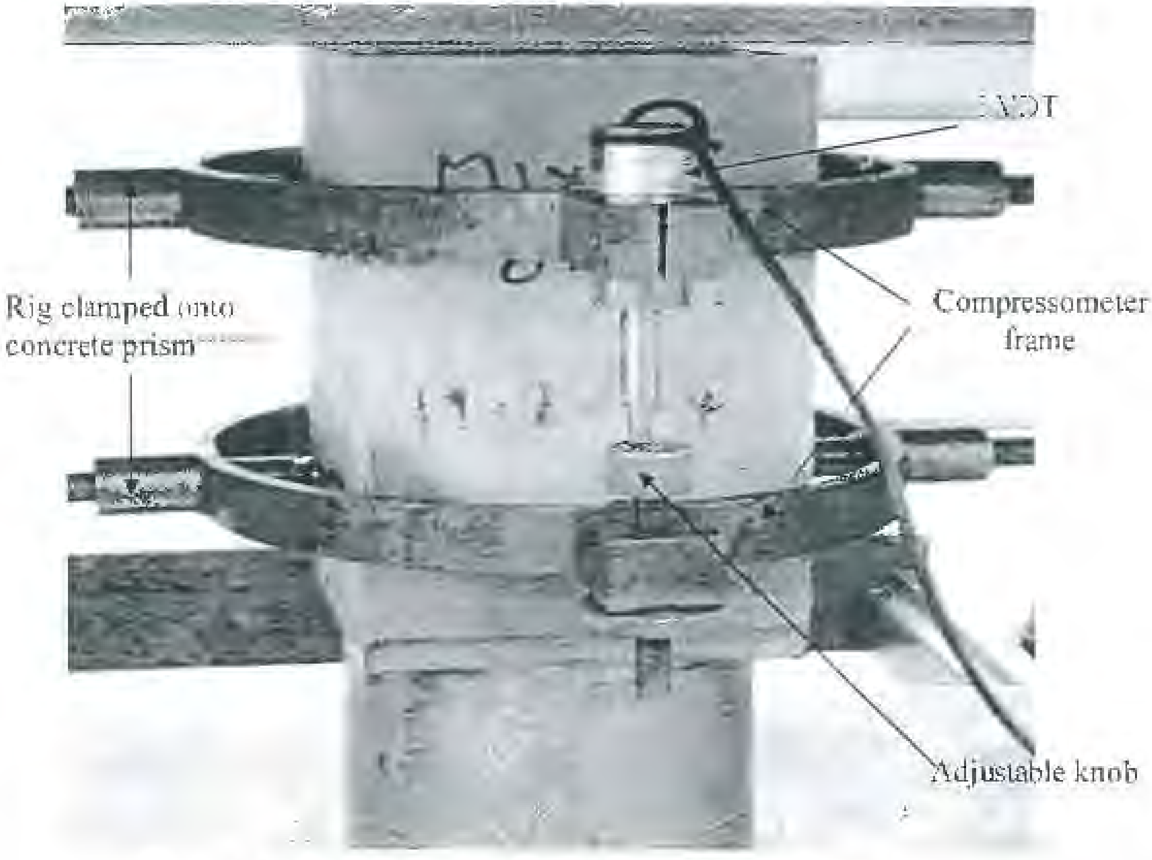


Figure 6.5: Young's modulus test set-up (100 mm gauge length)

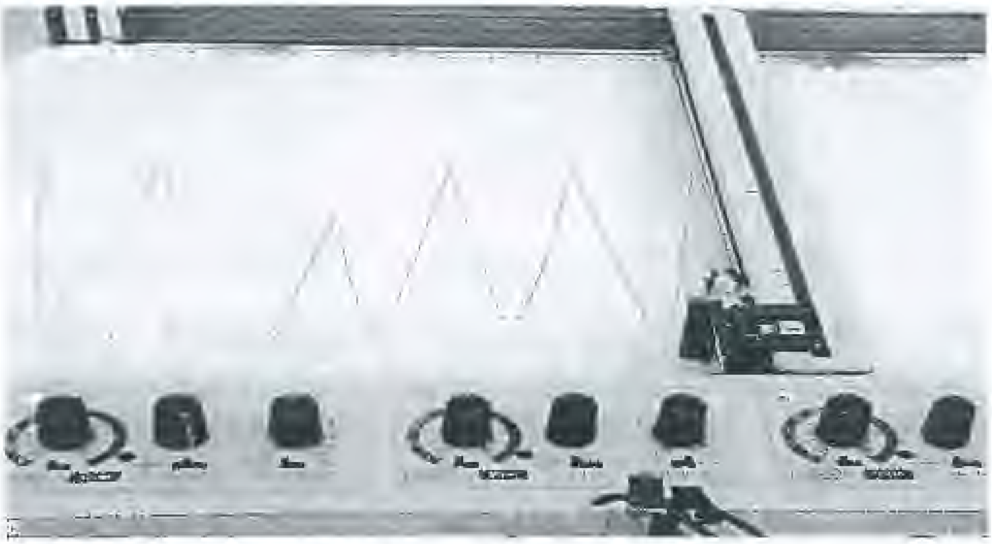


Figure 6.6: The plotter moving in x direction and plotting displacement in y direction

6.3.2 Results and discussion

Figure 6.7 shows the results of static elastic modulus for both RC and NC at the ages of 28 days and 120 days. It can be observed that the static elastic modulus values of RC were about 20% to 25% lower than those of NC for all water-binder ratios. There was a marginal increase of static elastic modulus with age and, as expected, decrease of elastic modulus with increasing water-binder ratio was observed.

The binder type had an effect on both RC and NC whereby concrete made with corex slag at water-binder ratio of 0.45 had higher elastic modulus than concrete with only CEM I at both ages. There was no noticeable difference in RC elastic modulus at higher water-binder ratios. Porosity of RA and contaminants such as timber, bricks and plastics which are very compressible contributed to the lower stiffness of hardened RC leading to lower elastic modulus values.

6.3.3 Estimation of E_c

The importance of elastic modulus depends much on the sensitivity of the structure to deformation (Alexander, 2001). Most concrete structures are not very sensitive to changes in elastic modulus; therefore sophistication in E_c prediction is not necessary. However, where deflections are critical, or where secondary cracking and distress is not acceptable, prediction of E_c is important and stiff concrete will be required. Otherwise, low E_c may be desirable in cases where cracking due to restrained movement should be avoided. Thus, RC can be used in such cases.

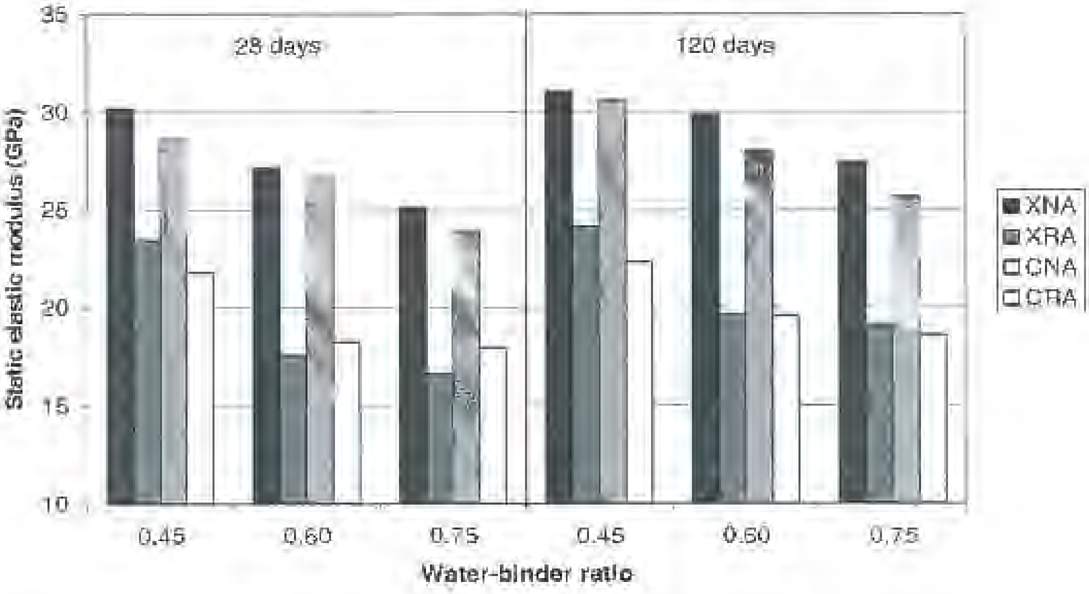


Figure 6.7: Effect of RA on modulus of elasticity of hardened concrete at different water-binder ratios.

Elastic modulus can be calculated using a South African expression given in equation 6.1 (Alexander, 2001), if the factors K_o and α are known.

$$E_c = K_o + \alpha \, f_{cu} \qquad 6.1$$

where,

E_c is the elastic modulus at a given time (GPa),

K_o is an aggregate stiffness factor (GPa),

α is a coefficient (GPa/MPa)

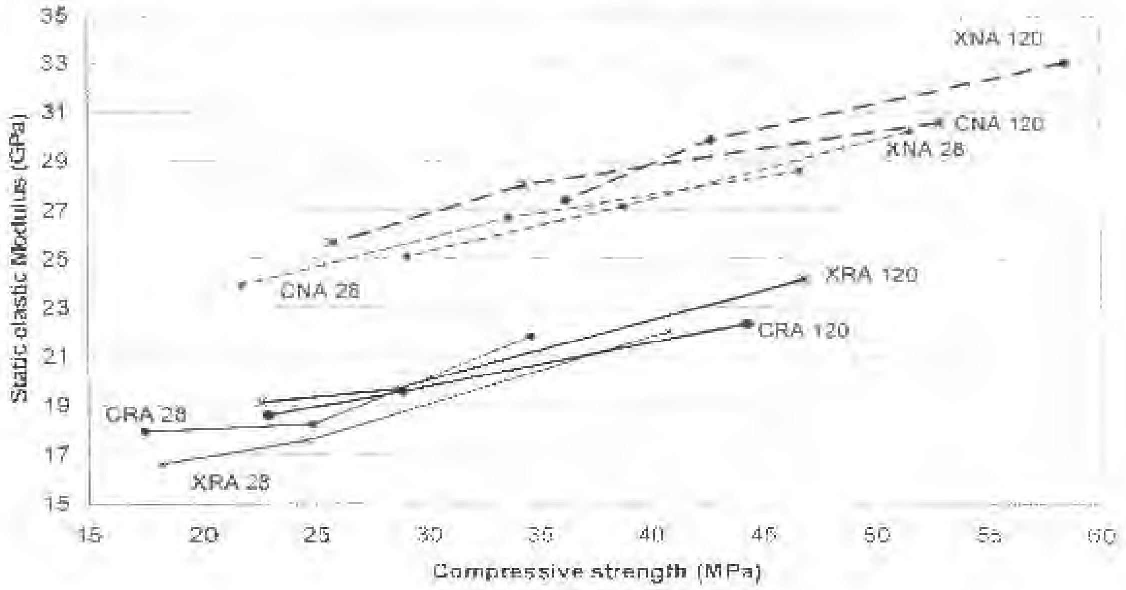
and f_{cu} is the characteristic concrete cube strength at a given time (MPa).

In this study, the K_o and α factors given in Table 6.2 were calculated from Figure 6.8 by using best-fit linear trend lines to the data points for any given concrete.

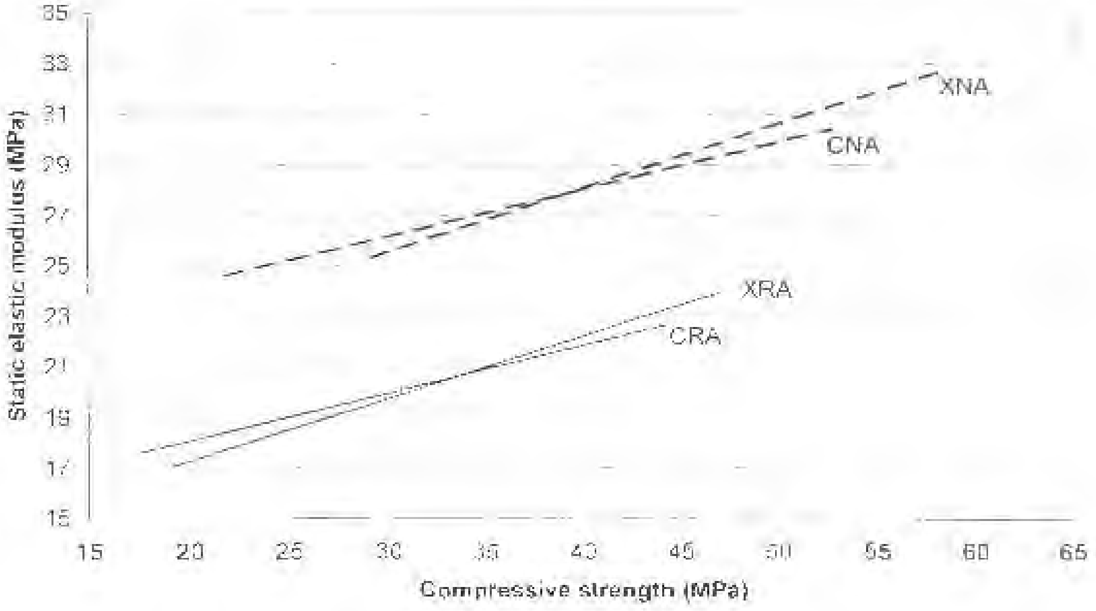
Table 6.2: Values of K_o and α for estimating elastic modulus of concrete containing RA and NA for ages of 28 and 120 days

Type of concrete	K_o and α value			
	28 days		120 days	
	K_o (GPa)	α (GPa/MPa)	K_o (GPa)	α (GPa/MPa)
XNA	18.4	0.23	19.0	0.24
XRA	11.8	0.24	13.9	0.21
CNA	20.0	0.19	21.0	0.18
CRA	13.3	0.23	14.5	0.17

The values of K_0 and α for NC made with CEM I obtained in this study are within the range reported by Alexander (2001). From Figure 6.8, it can be seen that concretes made with corex have a slightly steeper slope than concretes made with CEM I, which implies that concretes made with corex are stiffer than concretes made with CEM I, at higher strength. However, practically there is little to choose between the different binder types, although aggregate type has a larger influence as expected.



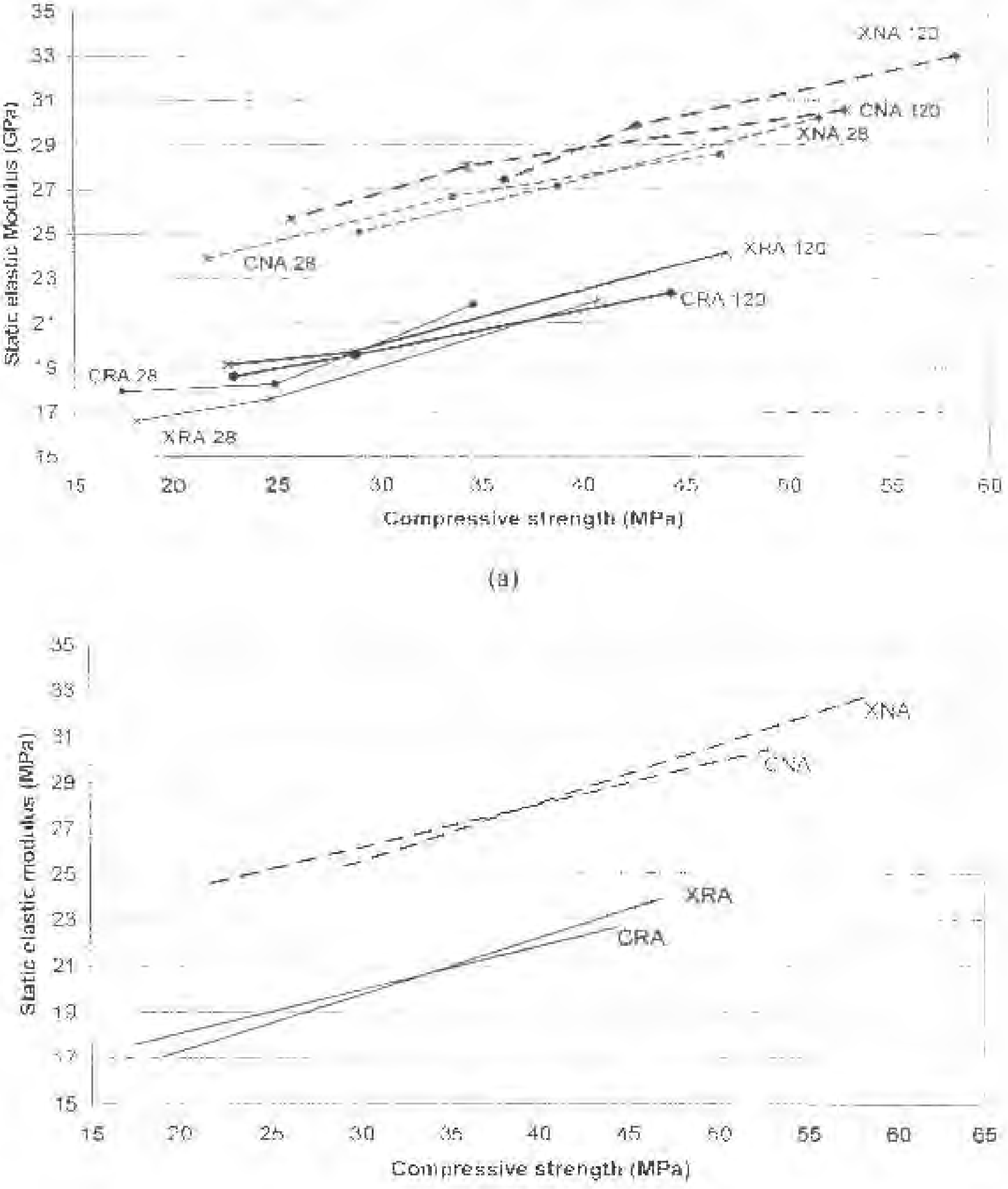
(a)



(b)

Figure 6.8: Relationship between static elastic modulus and cube compressive strength of RC and NC (a) at the age of 28 days and 120 days (b) best-fit trend lines for different concretes

The values of K_0 and α for NC made with CEM I obtained in this study are within the range reported by Alexander (2001). From Figure 6.8, it can be seen that concretes made with corex have a slightly steeper slope than concretes made with CEM I, which implies that concretes made with corex are stiffer than concretes made with CEM I, at higher strength. However, practically there is little to choose between the different binder types, although aggregate type has a larger influence as expected.



(a)

(b)

Figure 6.8: Relationship between static elastic modulus and cube compressive strength of RC and NC (a) at the age of 28 days and 120 days (b) best-fit trend lines for different concretes

Generally the elastic modulus values for RC obtained in this experiment ranged between 20% and 25% lower than those of NC for all water-binder ratios. These results are similar to the findings reported by other researchers (chapter 2). It has been reported that the elastic modulus of RC are lower than that of NC due to large amount of old mortar, concrete and brick contained in RA. Values of RC elastic modulus between 15% and 40% lower than NC have been reported in the literature.

6.4 Flexural strength

Knowledge of flexural strength is essential for the design of concrete roads, airport paving, water-retaining structures and floors on the ground, and is of considerable importance in estimating deflections of concrete structural members. Since RC is likely to be used in such areas, its flexural behaviour needs to be understood.

6.4.1 Test procedure

Concrete beams of 100 x 100 x 500 mm were tested for flexural strength in accordance with SANS method 5864:1994. The four-point loading method that produces a constant bending moment along the central part of the test specimen was used. From each mix three specimens were prepared and water cured for 28 days before being tested. The beam specimens were loaded at a constant rate of 0.03 ± 0.01 MPa/sec until the specimens failed. By using the formula suggested by SANS 5864:1994 as given below, the flexural strength of each beam was calculated and the average recorded.

$$f_r = F \times L/(b \times d^2) \qquad 6.2$$

Where,

f_r is the flexural strength (MPa)

F is the maximum load at failure (N)

L is the distance between the axes of the support rollers (mm)

b is the width of the specimen (mm)

d is the depth of the specimen (mm)

6.4.2 Results and discussion

The flexural strength results are shown in Figure 6.9. The flexural strength of RC was observed to be approximately 25% lower than that of NC. Binder type had an influence on both NC and RC for all water-binder ratios. Concrete with corex slag attained 10%, higher flexural strength than concrete with CEM I 42,5 only. There was however a marginal difference between corex and CEM I RC at 0.60 water-binder ratio. At 0.60 water-binder ratio, NC attained a flexural strength of 5 MPa and RC attained 3.6 MPa. As expected, flexural strength reduced with increasing water-binder ratio. This is due to reduction in cementitious content which reduces the binding power of aggregate and mortar.

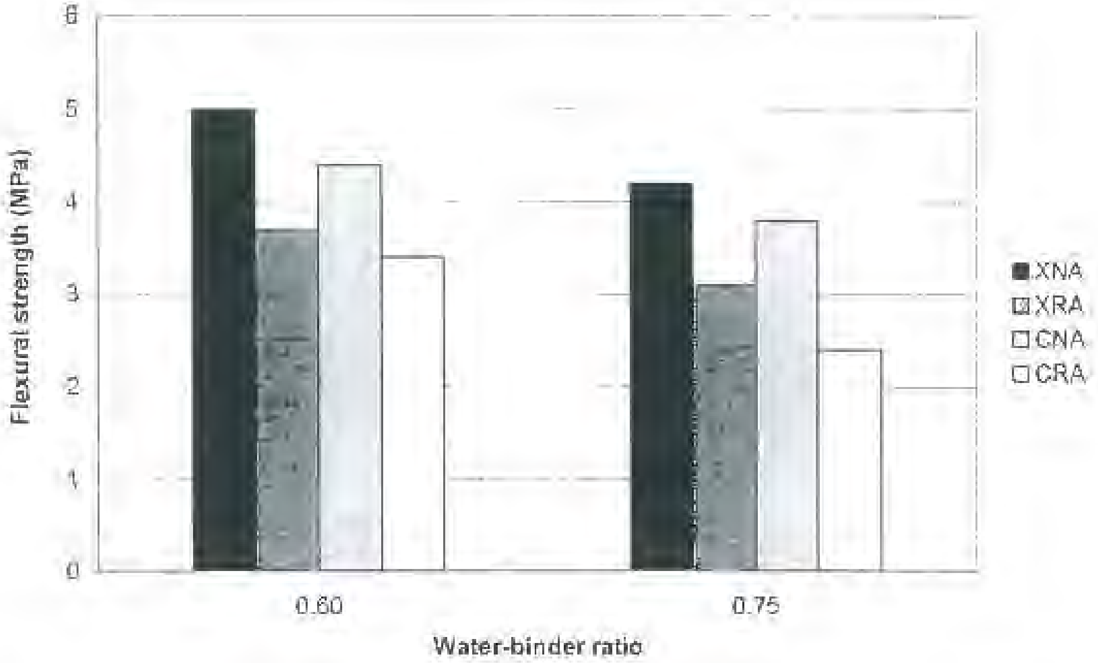


Figure 6.9: Flexural strength of RC and NC at 0.60 and 0.75 water-binder ratios

The flexural strength depends on a number of factors such as aggregate type, water-binder ratio, void content, curing conditions and age. It also depends on loading method, the rate of loading, and the size and the shape of the test specimen. Since all factors were kept constant except type of aggregate, the RA could be only the factor which led to lower flexural strength of RC. Weaker particles such as brick, old mortar and concrete which are porous facilitated the lower flexural strength.

6.5 Creep and shrinkage

6.5.1 Creep

Creep is the time-dependent increase in strain of a solid body under constant stress. Creep consists of basic creep, which is the creep experienced by concrete previously brought into hygrometric equilibrium with the environment (sealed sample), and drying creep which is the creep experienced when simultaneous drying of concrete is involved. Creep is a desirable material property from the point of view of structural behaviour, and without it concrete would be too brittle for use in the majority of structures. Other beneficial effects of creep include relief of concrete stresses due to differential structural movement and restrained shrinkage.

On the other hand, creep has detrimental effects on structures, such as increased deflections which can result in cracking, loss of prestress, and creep buckling of long columns. These effects can be minimized provided the designer is acquainted with the material and are taken into consideration during design. The source of creep in concrete is the cement paste, although aggregates have a substantial modifying effect on paste creep (Alexander, 2001).

There are a number of factors which affect the creep of concrete. These include water-cement ratio, moisture content of concrete, cement/binder type, admixtures, use of extender, aggregate properties and content. Other factors are specimen geometry and size, drying conditions (RH and temperature), stress-strength ratio, curing and age at loading, time under load and state of stress (tension or compression).

6.5.2 Shrinkage

Shrinkage is defined as the time-dependent reduction in volume of fresh or hardened concrete. Volume changes in concrete are related to movement of moisture into and out of the material (Alexander, 2001). Factors affecting shrinkage are similar to those of creep. Shrinkage influences the structural behaviour of concrete when the shrinkage is restrained and the structure is unable to accommodate movement without cracking. The amount of shrinkage that can be tolerated by a structure depends on the function of the structure and the finishes that it has to accommodate. For instance, a degree of shrinkage that has no effect on the structural efficiency of a bridge could result in deflections in a framed building that could cause cracking of walls , tiles and other finishing claddings or jamming of windows and doors. In an attempt to reduce the risk of cracking, loss of pre-stress and excessive deflections, values for maximum shrinkage have been specified. COLTO[1] (1998) specifies a maximum shrinkage value of 400 x 10^{-6} for concrete structures and roads, measured by SANS 1085 (2001).

There are different types of shrinkage which include volume changes due to cement solution, water absorption and adsorption, plastic shrinkage, autogenous volume change due to cement hydration, carbonation shrinkage and drying shrinkage. In this experiment only two types of shrinkage were considered. These were autogenous shrinkage and drying shrinkage.

Autogenous shrinkage: This is the volume reduction of hardened concrete caused by cement hydration. The hydration products are of smaller volume than the sum of the volumes of original separate components. Autogenous shrinkage typically ranges between 50 x 10^{-6} and 150 x 10^{-6} (Addis 1986) and are measured on sealed samples. Tazawa and Miyazawa (1993) reported that total amount of autogenous shrinkage can be more than 4000 x 10^{-6} for cement paste or 100 x 10^{-6} for concrete with low water-cement ratio.

Drying shrinkage: As the name implies this is caused by the withdrawal of water from hardened concrete stored in unsaturated air. The rate at which moisture is lost is fairly slow and the strain responses are therefore time-dependent. This is usually the volume change of most interest to the structural engineer.

6.5.3 Test procedure

Creep

Since there is no South African or British standard for creep testing, ASTM standard was used in this work. Numerous creep apparatus have been designed usually based on mechanical or hydraulic principles. The one used in this experiment was hydraulically loaded flat jacks with a gas-filled accumulator for load-maintenance (CEB hydraulic type). This loading frame is capable of applying and maintaining the required load on a specimen, despite any change in the dimension of the specimen. The loading frame structure is as shown in Figure 6.10.

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[1] Committee of Land Transport Officials

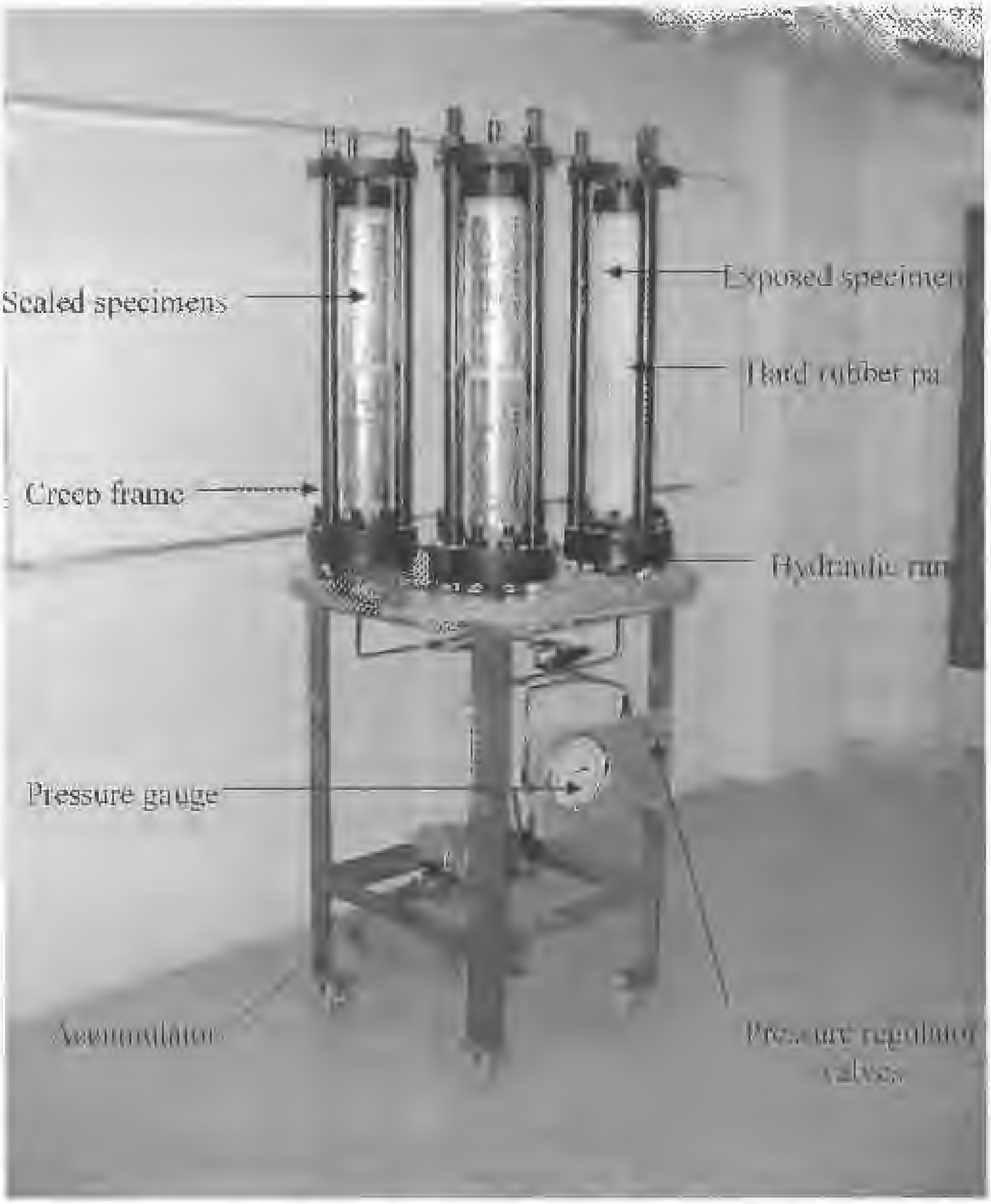


Figure 6.10: CEB hydraulic type creep loading frame and loading set up

Concrete cylinders of 105 mm diameter and 300 mm long were used in the creep and shrinkage experiments. Two pairs of sealed and exposed samples for creep measurement were prepared for each mix. All samples were cast and compacted in three layers and water-cured for 28 days at 23 ± 1 ^{0}C before being tested. Creep cylinders had their end face ground before loading to ensure plane bearing surfaces. The specimens were instrumented with small targets on their faces which were fixed using a quick setting epoxy. The targets were fixed on three different faces of the cylinder at 120^0 apart.

A sustained load less than 40% of the cylinder compressive strength was used. This load was determined by first converting the cube compressive strength into a cylinder compressive strength by multiplying the cube compressive strength by a factor of 0.85 (Neville 1981) at the loading age (28 days), then 35% of the compressive strength of the cylinder was used as the stress to load the specimen. Table 6.3 gives the stresses used to load the specimens together with the corresponding stress/strength ratio expressed as a percentage at loading. The creep samples were subjected to initial load of about 10% of their maximum load. This load was then removed and the samples were gradually reloaded at a loading rate 0.1 MPa/s to the final load. In order to minimize the effect of creep on the result, the initial elastic strains were measured as quickly as possible (within 10 minutes).

Table 6.3: Applied stresses on creep samples at time of loading (28 days)

Mix Type (w/c 0.60)	Applied stress (MPa)	Stress/strength ratio (%)
X NA	10.0	25.8
X RA	6.5	26.4
C NA	10.0	29.7
C RA	6.5	26.1

A mechanical strain gauge (Staeger – Type Pfender) with 100 mm gauge length was used to take strain measurements. Before taking any set of readings, the strain gauge was calibrated using an Invar steel reference bar. The strains were recorded at 2 hour interval for the first six hours of the first day, then daily for one week, weekly for one month and then monthly to the end of the experiment. Creep strain values from sealed and exposed specimens were taken as the average of the six strain measurements taken from two specimens. Throughout the experiment, the specimens were kept in a room where temperature and relative humidity were maintained at 23 ± 1 ^{0}C and 55 ± 5 % respectively.

Shrinkage

The method in ASTM C 157-80 was used to test the shrinkage properties of hardened concrete. Companion shrinkage specimens were prepared and cured in the same way as for the creep test. Sealed and exposed sample had their end faced sealed by wax in order to prevent end drying. The specimens were kept in the same room with identical temperature and relative humidity as the creep test samples. Strain measurements were taken daily for one week, weekly for one month and on a monthly basis until the end of the experiment. Shrinkage and creep tests started on the same day and were run parallel. The same instrument used to take creep strain was used to measure shrinkage strain.

6.5.4 Results and discussion

Creep strain

(i) Exposed specimens

Since the stresses acting upon the specimens were not the same, in order to be able to compare the creep characteristics of the different specimens, the results were expressed in terms of specific creep which is the creep strain per unit stress.

It can be observed in Figure 6. 11 that RC exhibited about 50% to 100% higher creep strain in the exposed condition compared with NC. Highest creep strain was observed in mix type CRA. High creep strain of RC was attributed to the presence of higher moisture content in RA. Since creep is associated with the presence of mobile water in the paste, the greater the moisture content, the greater the creep under drying condition. As the concrete was allowed to dry under compressive load, water in the RA moved out of the RA creating voids which in turn contracted, thus increasing the creep strain under sustained loading. Normal-density aggregates of hard gravel or crushed rock do not creep and aggregate reduces the creep of the concrete by diluting the paste and by restraining its movement. However, in the case of RA compressible materials which are also porous in nature such as brick old concrete and mortar also increased the creep strain.

Comparing binder type, it was found that the RC with corex slag experienced lower creep strain than that with CEM I 42.5. Creep of NC made with corex slag was marginally lower than NC made with CEM I. Greater strength development and lower porosity of concrete with corex slag after 28 days would have contributed to lower creep strain. From Table 6.3, it can be see that the stress/strength ratio for corex slag concrete was lower compared with CEM I concrete which resulted to lower creep strains. Another factor which contributed in lower creep strain in concrete is the high rate of increase in strength gained by corex slag concrete after 28 days.

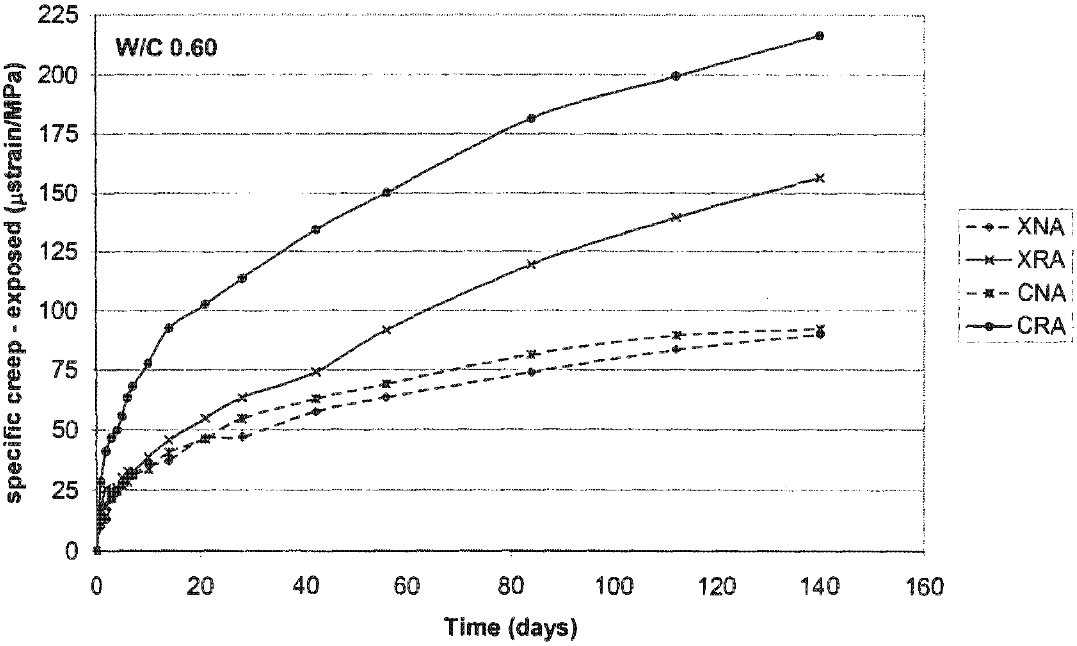


Figure 6.11: Creep behaviour of RC and NC under exposed condition

Jaufeerally (2001) reported similar results. For 0.60 water-binder ratio, he found that specific creep for NC made with corex slag and CEM I was virtually identical for the first two months of loading. After this period of time, the creep deformation of corex slag concrete increased at a greater rate.

According to Swamy (1997), slag has an effect on the pore size distribution. A decrease in large pore volume and an increase in fine pore volume were reported by him and these changes might have positive and decisive influences on the compressibility of RC.

(ii) Sealed specimens

In the case of sealed specimens, the difference between creep strain of RC and NC was lower as seen in Figure 6.12. RC exhibited a creep strain of about 5% to 15% higher than NC. Retained moisture within RA pores could have contributed to lowering the creep strain by providing an additional source of moisture to the matrix during hydration. Creep strain under sealed condition was also reduced due the presence of water in the voids which do not compress under load. The specific creep for corex slag concrete was lower than CEM I concrete for the first 28 days of loading. After this period, the creep deformation of corex slag concrete increased at a greater rate than

CEM I concrete in both RC and NC. A slight increase of specific creep for corex slag concrete at later age might have been due to continuation of hydration after 28 days of loading which resulted in withdraw of moisture from the matrix, which led to higher creep deformation due voids created. However, it was expected that increasing in hydration would also stiffen the matrix.

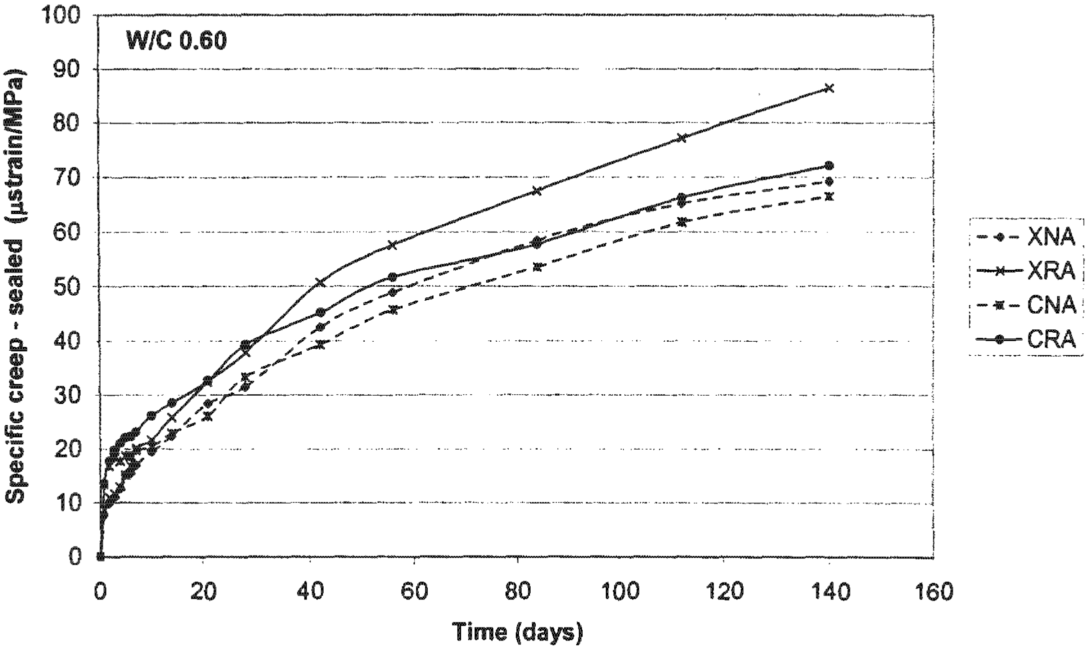


Figure 6.12: Creep behaviour of RC and NC under sealed condition

Shrinkage strain

(i) Drying shrinkage

The results of drying shrinkage strain for both RC and NC are shown in figures 6.13. Generally RC was found to have higher shrinkage value than NC. Lower restraining capacity of RA in comparison with NA contributed to higher shrinkage. The difference between RC and NC was small within the first 20 days of exposure for all concrete. After this period, shrinkage of RC made with both RCA and RFA and CEM I increased at a higher rate. The difference of drying shrinkage between RC and NC containing corex slag was marginal at all ages of exposure. Sagoe-Crentsil et al (2001) and Katz (2003) reported similar results (refer chapter 2).

The lower drying shrinkage of RC and NC made with corex slag might be attributed partially by low porosity content and small capillaries of slag concrete which have been reported by Swamy (1997), and reserved moisture in the RA. In the case of concrete made with CEM I 42.5 might be due to higher porosity and bigger pores which influenced high extraction rate of reserved moisture from the RA. This can be clarified by the results which were obtained in the water sorptivity test in section 6.6.

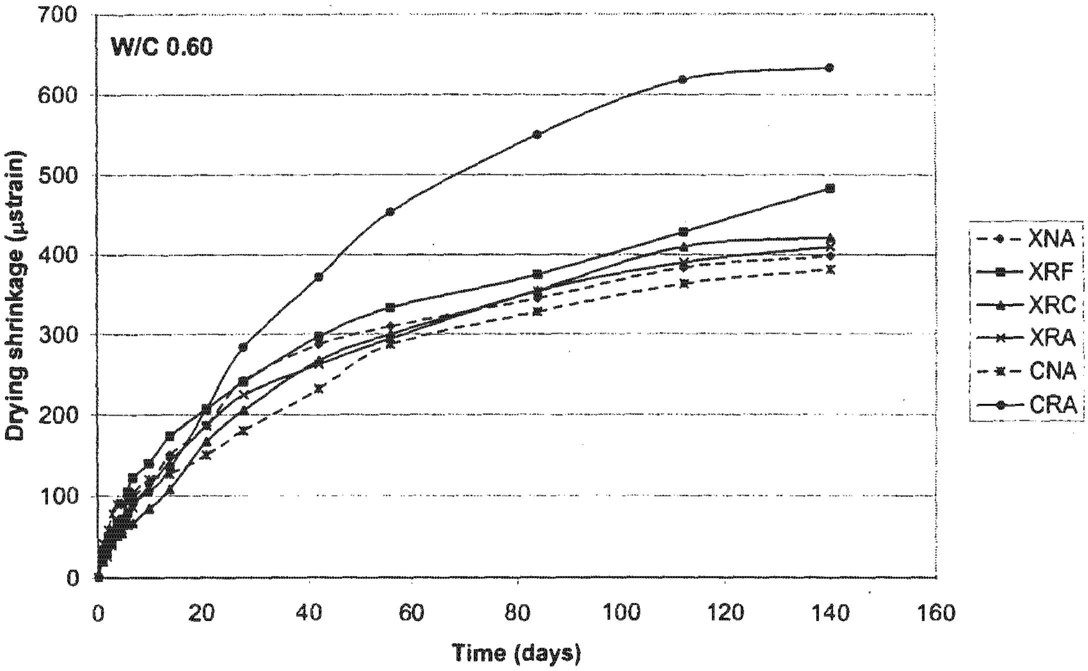


Figure 6.13: Drying shrinkage of RC and NC

Drying shrinkage of NC made with corex slag was slightly higher than NC made with CEM I. Jaufeerally (2001) reported also that corex slag concrete yielded higher drying shrinkage than CEM I concrete at later ages.

(ii) *Autogenous shrinkage*

A reversed trend was observed on sealed samples, whereby the autogenous shrinkage of RC was lower than that of NC, figure 6.14. RC made with RFA had the lowest autogenous shrinkage Retained moisture in RA would have contributed to lower values of autogenous shrinkage. As hydration takes place, cement/water system contracts, but in this case the extra moisture within the RA kept the system in balance as the extraction of water from the cement gel for hydration purposes proceeded. As expected, autogenous shrinkage for both RC and NC was lower than drying shrinkage. Autogenous shrinkage was about 25% and 50% for RC and NC drying shrinkage respectively.

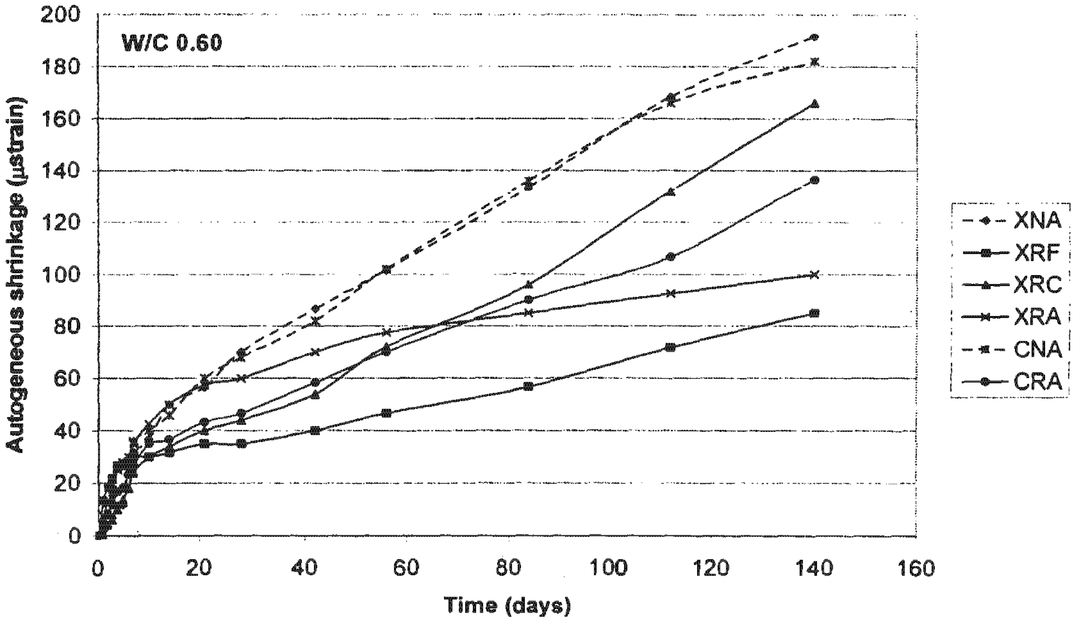


Figure 6.14: Autogenous shrinkage of RC and NC

Due to high content of old concrete, mortar and brick particle in the RA, drying shrinkage and creep of RC ranging from 40% to 80% higher than NC have been reported by Hansen (1992). RC containing both RCA and RFA has been reported to have the highest creep and shrinkage strain values, while RC made with only RCA and NFA have minimal shrinkage and creep effects. Autogenous shrinkage of RC have not been reported by researchers, therefore no data was available for comparison.

As the effects of high drying shrinkage and high creep tend to cancel out in restrained structural members, structures constructed using RC appear not to be widely susceptible to cracking due to drying shrinkage.

6.6 Durability of concrete monitored by durability indexes

Durability may be defined as the ability of material or structure to withstand the service conditions for which it is designed for over a prolonged period without significant deterioration. Neville (2001) defined durability of a structure as the ability of a structure to continue its intended function of maintaining its required strength and serviceability during the specified or expected service life. Deterioration of concrete begins almost immediately after casting as the hardened properties are influenced by phenomena which occur at an early age, such as plastic cracking, bleeding, segregation and thermal effects (Alexander et al 1999a). Deterioration is often associated with ingress of aggressive agents from the exterior such that the near-surface concrete quality controls the durability of the structure especially in reinforced concrete structures.

Although durability performance of construction materials has long been a concern for the engineer, the durability of reinforced concrete has received much importance lately due to the rapid deterioration of many modern structures. It is known that concrete cannot fulfill its role indefinitely and that concrete can be durable under one set of environmental condition of exposure and not necessarily under other conditions. For example a concrete structure can be durable in an inland environment, and deteriorate very quickly when in a marine environment.

The available controls on durability are guidelines and standards laid down in various codes of practice. Three durability index tests have been developed in S.A research recently to characterize concrete according to transport mechanisms (chapter 2). These are oxygen permeability for permeation, water sorptivity for absorption and chloride conductivity for diffusion.

RA being new materials in concrete production and with possibly greater fluid transport properties, it is vitally important to characterize the durability properties of concrete made with such materials so that designers and materials engineers can make an informed decision when choosing the material for a new structure. In this section, the durability properties of RC are investigated and compared with durability properties of NC produced and cured in the same manner.

6.6.1 Test procedures

For the durability index testing 100 mm cubes were cast. Three different wet curing periods of 3, 7 and 28 days were used. The samples which were cured for 3 and 7 days were thereafter air-cured at a temperature and relative humidity of 23 ± 1 °C and 60 ± 5% respectively in the environmental room until an age of 28 days. After 28 days, all cubes were removed from the respective curing regimes and were cored with a diamond tipped core barrel and cut into the standard size needed for durability testing. For each test, only three concrete discs of 68 ± 1 mm diameter and 25 ± 1 mm thick from each curing regime were used to determine durability indexes. The samples were pre-conditioned in the oven at 50 ^{0}C and relative humidity of less than 20% for 7 days.

Standard procedures given in the UCT Manual for Durability Index Testing (Alexander et al, 2004) were used to determine the potential durability of hardened concrete and compared with the suggested range of durability index values given in Table 6.4

Table 6.4: Suggested range of durability index values (Alexander et al 2004)

Durability class and application	OPI (Log scale)	Sorptivity (mm/h$^{1/2}$)	Chloride conductivity (mS/cm)
Higher durability requirement – where durability is of paramount importance	> 10	< 6.0	< 0.75
Durability requirement in most conditions – where durability requirement is of some concern	9.5 - 10.0	6.0 – 10.0	0.75 – 1.50
Durability in mild condition – where durability requirement is of less concern	9.0 – 9.5	10.0 – 15.0	1.50 – 2.50
Durability in non-aggressive condition – where durability is of no concern	<9.0	> 15.0	> 2.50

Oxygen Permeability test

The OPI test was conducted to measure the capacity of the concrete to transfer gas by permeation. Permeation describes the process of movement of fluids through the pore structure under an externally applied pressure whilst the pores are saturated with the particular fluid. Permeation is therefore a measure of the capacity for concrete to transfer fluids. It is dependent on the concrete microstructure, the moisture condition of the material and the characteristics of the permeating fluid (Alexander et al 1999a).

A falling head permeameter was used and the pressure decay with time was measured as oxygen permeated through concrete (Figure 6.15). A D'Arcy coefficient of permeability was determined and converted into OPI by taking the negative log of the D'Arcy coefficient.

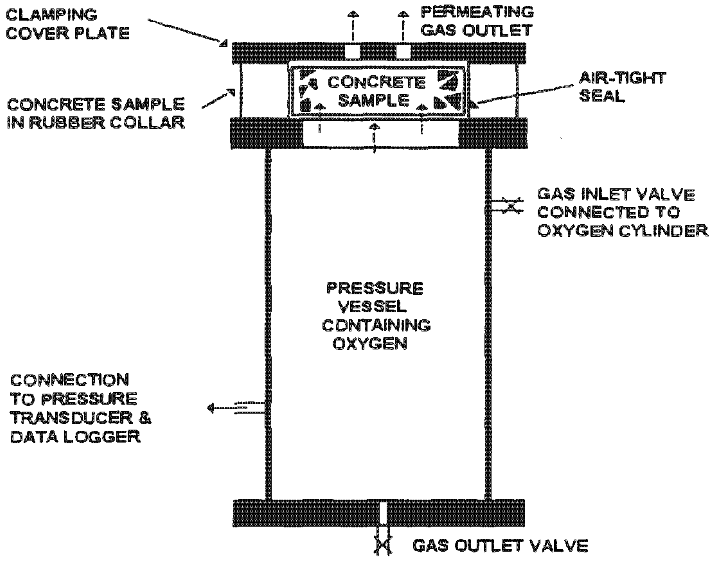


Figure 6.15 Oxygen permeability apparatus (Alexander et al 1999a)

Water sorptivity test

To measure the rate of movement of water through concrete and the porosity of the concrete, the water sorptivity index test was performed. Water sorptivity index measures the rate of movement of a wetting front through concrete under the action of capillary forces. This test uses the mass of water absorbed from the bottom face (i.e. originally exposed face) as a measure of the sorptivity of the concrete sample.

Absorption is the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces. The capillary suction is dependent on the pore geometry and the saturation level of concrete. Water absorption caused by wetting and drying at the concrete surface is an important transport mechanism near the surface but becomes less significant with depth. The rate of movement of a wetting front through a porous material under the action of capillary forces is defined as sorptivity.

The test is conducted by exposing one face of the concrete specimen to calcium hydroxide solution as shown in Figure 6.16 and measuring the mass of the samples at regular intervals using an electronic balance. A linear relationship should be obtained when the mass of water absorbed is plotted against the square root of time, and the sorptivity S of the concrete can be determined from the slope of the straight line.

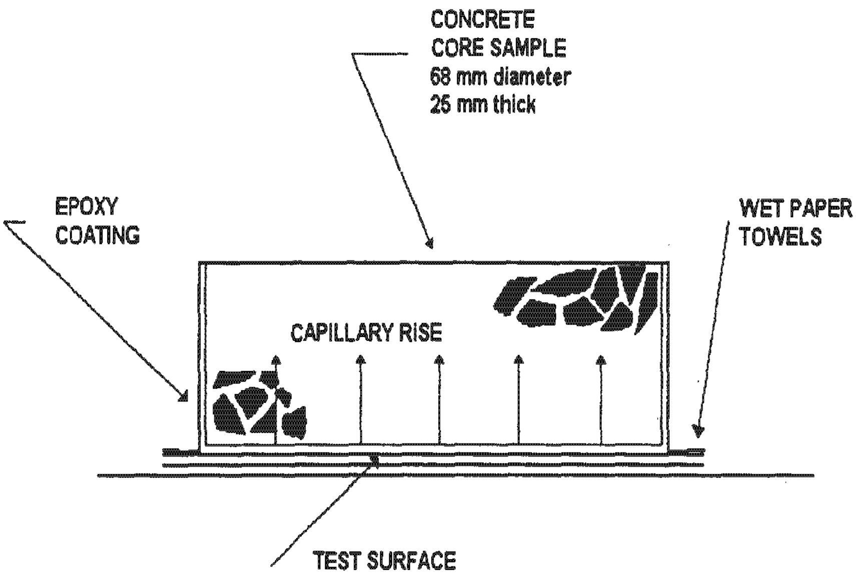


Figure 6.16 Water sorptivity test set up (Alexander et al 1999a)

Chloride conductivity test

Diffusion is the process by which liquid, gas or ions move through a porous material under the action of a concentration gradient. Diffusion occurs in partially or fully saturated concrete and is an important internal transportation mechanism for most concrete structures exposed to salts. Diffusion is related to the conductivity through the diffusibility relationship.

To measure chloride conductivity, the specimens were placed in a vacuum tank, which was evacuated to -80 kPa. The specimens were left under vacuum for 3 hours, and then vacuum-saturated for 5 hours in a 5 M NaCl solution. The vacuum was then released and specimens were soaked for another 18 hours in the solution. The Chloride conductivity test was carried out by applying 10V potential difference across a (pre-saturated) concrete disc placed in a conduction cell with 5 M NaCl solution, refer Figure 6.17. Conductivity was determined by measuring the current flowing through the concrete disc.

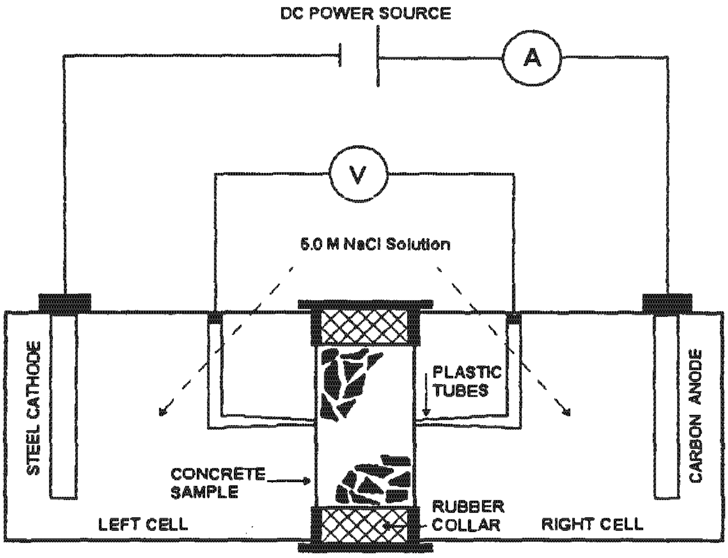


Figure 6.17: Chloride conductivity test set up (Alexander et al 1999a)

6.6.2 Results and discussion

Oxygen Permeability

The results for OPI are provided in Table 6.5 and diagrammatically illustrated in Figures 6.18 and 6.19. The results generally indicate improvements in OPI value with lower water-binder ratio and with increasing wet curing period (Figure 6.18). Results are compared in four categories. These are aggregate type, water binder ratio, curing regime and binder type.

Considering the aggregate type, the results show that concrete made with RA had lower OPI values than NC which implies that RC is more permeable. RC attained about 90% and 95% OPI values lower than NC made with corex and CEM I at all water-binder ratios and curing regime. The porous and more permeable nature of RA contributed to reduction of OPI value in hardened RC. Table 6.6 shows that RC had higher porosity than NC. However, when comparing OPI with suggested values in Table 6.4, it can be concluded that RC with acceptable permeability can be obtained.

OPI decreased with increasing of water-binder ratio as seen in Figure 6.19. The effect of water-binder ratio on OPI can be explained by reduction in the cementitious content with an increase in the water-binder ratio. This has the consequence of decreasing the total products of hydration, thus making the concrete more porous and more permeable to fluids. This is illustrated by the good OPI results obtained by mix CNA at water-binder ratio of 0.45.

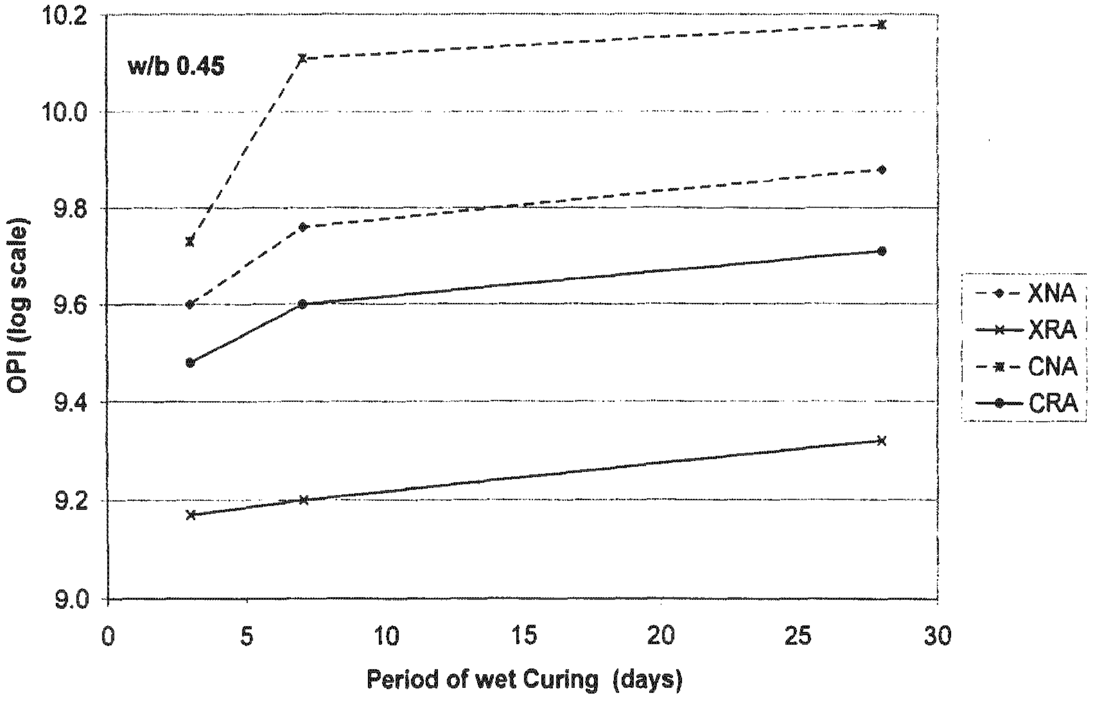
All mixes were sensitive to wet-curing for the first 7 days. OPI values generally improved with prolonged wet curing, which favours the contributed to the continued formation of hydration products. The gel products block the capillaries and pores, hence reducing the movement of gases, fluids and ions through the hardened concrete. This has also been reported by Jaufeerally (2001).

Use of corex slag in mixes XNA and XRA lowered the OPI value. Although mix XNA and XRA was found to be less porous than mix CNA and CRA respectively as shown in Table 6.6, they nevertheless gave lower OPI values. This can be explained as the effect of prolonged bleeding of fresh concrete which might have created small capillaries within hardened concrete which are interconnected. Slag concrete is supposed to reduce this effect but it is still not clear why corex slag concrete behaves this way. To clarify this more research in this area is needed to determine the microstructure of hardened concrete. From OPI results, it can be deduced that the use of corex slag results in more permeable concrete than CEM I 42.5, although the practical significance of this is not clear. Jaufeerally (2001) and Mackechinie (2001) reported similar results.

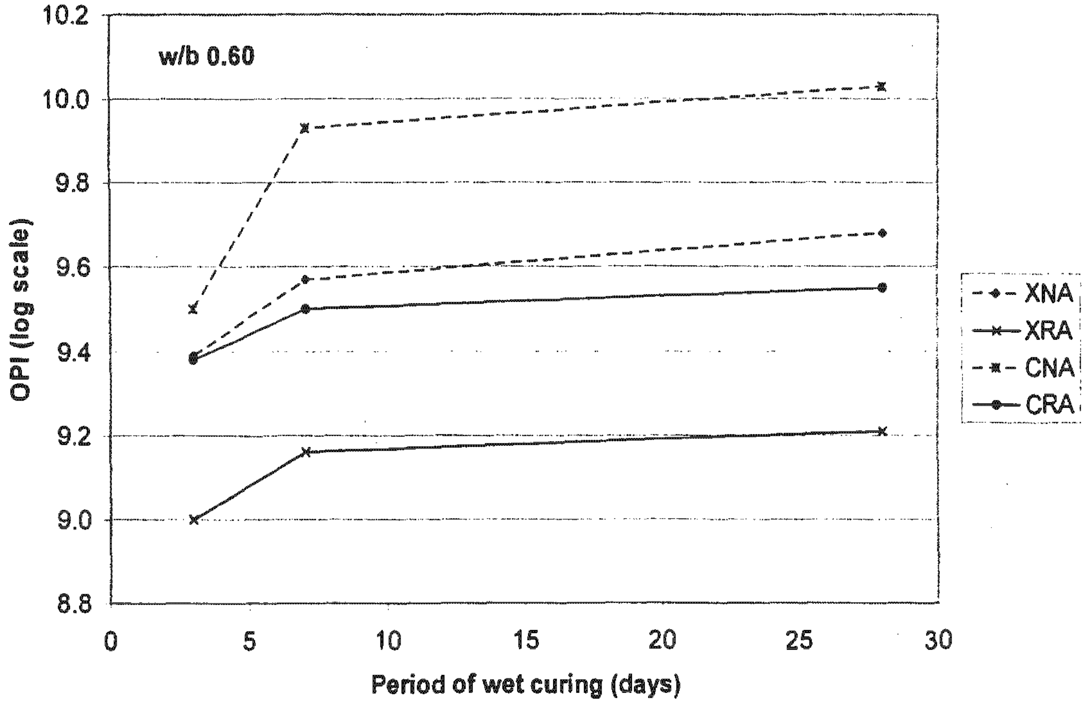
Table 6.5: Results of OPI test (log values)

Curing	Mix XNA		Mix XRA		Mix CNA		Mix CRA	
	OPI for water-binder ratio of							
	0.45	**0.60**	**0.45**	**0.60**	**0.45**	**0.60**	**0.45**	**0.60**
3 days	9.60	9.39	9.17	9.00	9.73	9.50	9.48	9.38
7 days	9.76	9.57	9.20	9.16	10.11	9.93	9.60	9.50
28 days	9.88	9.68	9.32	9.21	10.18	10.03	9.71	9.55

According to Swamy (1997), slag reduces the pore size distribution. A decrease in large pore volume and an increase in fine pore volume are observed and these changes have positive and decisive influences on the permeability of concretes. On the other hand, Ballim (1999), Van Dijk (1998) and Kasai et al (1983) found that the permeability of concrete increases with the use of slag and attributed it to longer time required for the densification of the cement matrix.



(a)



(b)

Figure 6.18: Effect of water curing on the OPI of concrete at water-binder ratio (a) 0.45 and (b) 0.60

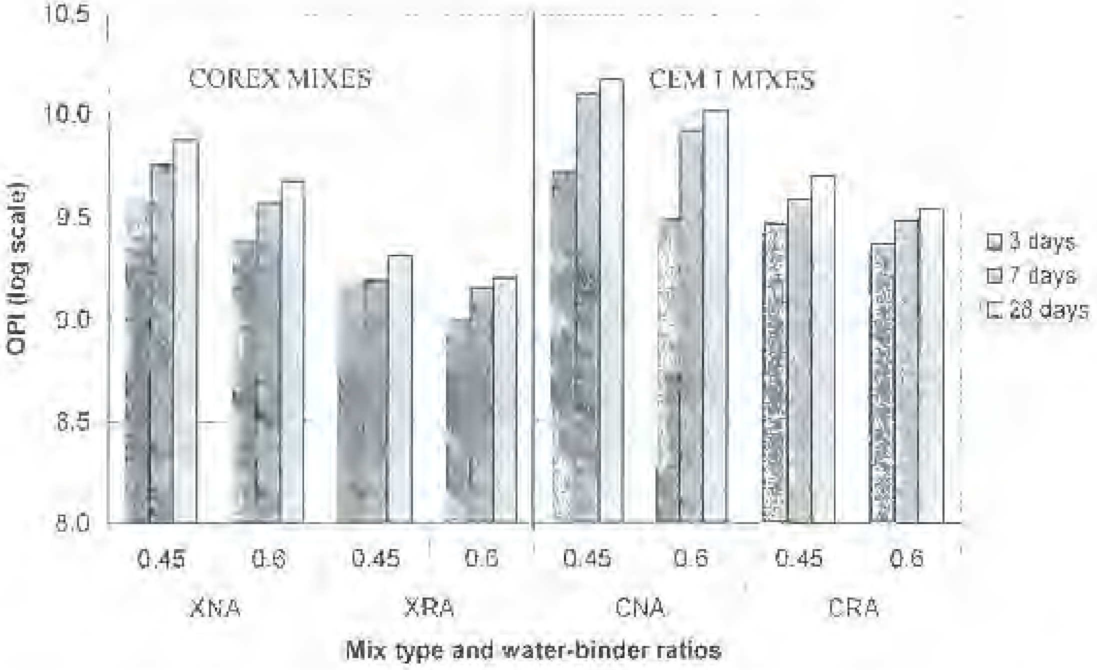


Figure 6.19: Effect of curing and water-binder ratio on the OPI of hardened concrete

Water sorptivity

Table 6.6, and Figures 6.20 and 6.21 show the results for water sorptivity and water-penetrable porosity for both RC and NC. From the water sorptivity results, it can be deduced that RA has a detrimental effect on the potential durability of concrete. The RC had higher water sorptivity values and porosity than NC. RC attained about 20% and 35% water sorptivity value higher than NC for 0.45 and 0.60 water-binder ratios respectively. Porosity of RC was more than twice than those of NC. The porous nature of RA would have contributed to these results. RA contained brick, old mortar and concrete particles which are more porous than NA (refer Figure 6.22).

Better sorptivity values were obtained on prolonged curing, which favours the contributed to the continued formation of hydration products. The gel products block the capillaries and pores, hence reducing the movement of fluids through the hardened concrete.

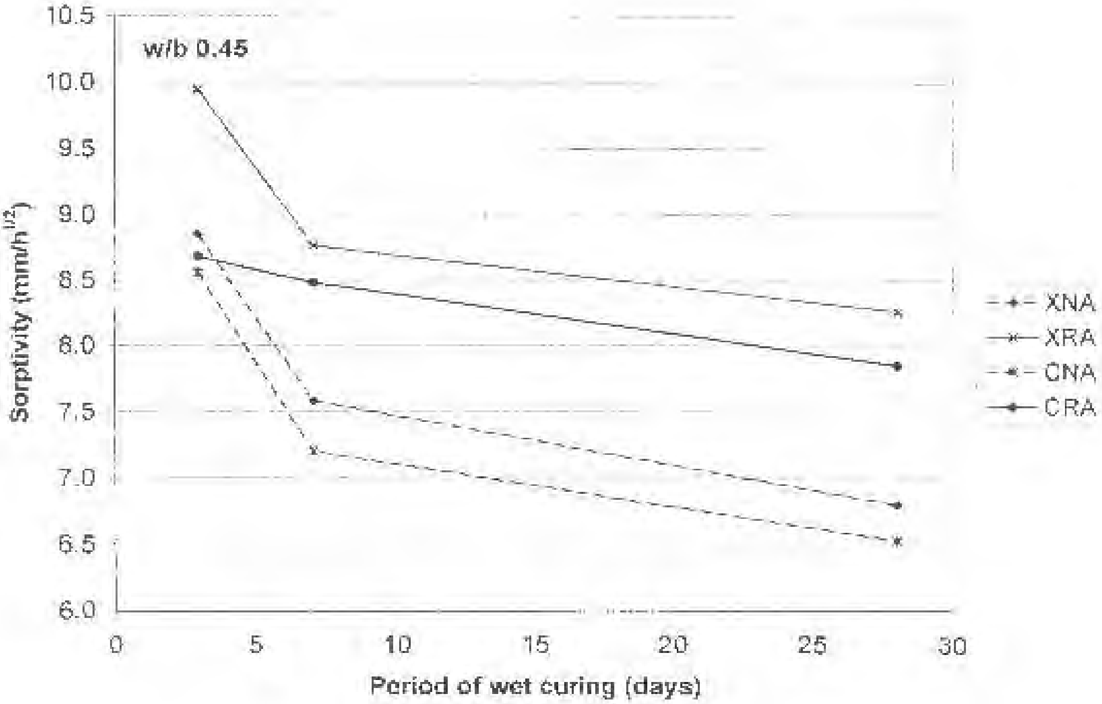
Water sorptivity value was better at lower water-binder ratios. The effect of water-binder ratio on water sorptivity can be explained by increasing in the cementitious content with decreasing in the water-binder ratio. This has the consequence of increasing the total products of hydration, thus making the concrete less porous and less permeable to fluids.

Use of corex slag in mixes increased the sorptivity of concrete than when CEM I 42.5 was used as a binder as shown in Figure 6.20 and 6.21. Despite the high porosity of the concrete with CEM I, the water sorptivity of concrete made with corex was about 10% and 20% higher than NC and RC respectively made with CEM I. The same explanation as that for CPI can be applied.

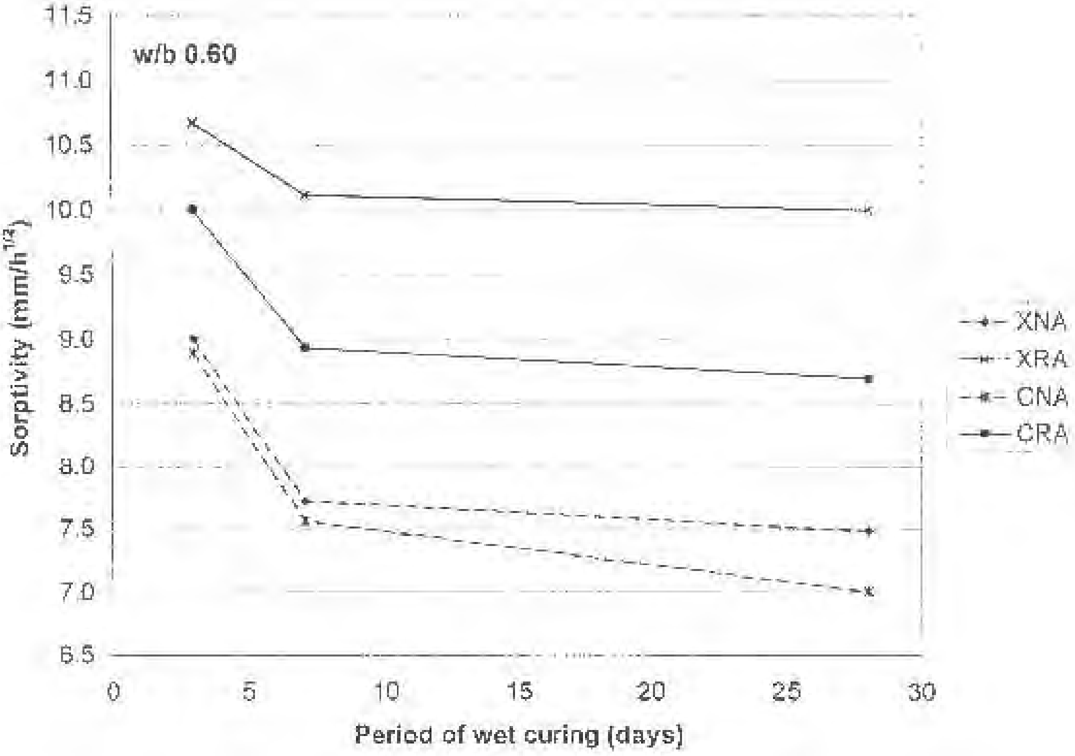
However, at longer curing age the sorptivity obtained was within reasonable limits of good concrete when compared with values in Table 6.4. It can be deduced therefore that good curing is very important for the durability performance of concrete. Longer curing improved durability potential of RC, but it should be borne in mind that concrete on site seldom ever receives more than three days of moist curing.

Table 6.6: Water sorptivity S (mm/$\sqrt{h}$) and porosity p (%) of hardened concrete

Curing regime	**Mix XNA**				**Mix XRA**			
	Sorptivity S and porosity p for water binder ratio of							
	0.45		**0.60**		**0.45**		**0.60**	
	S	p	S	p	S	p	S	p
3 days	8.85	6.9	9.00	8.6	9.95	16.8	10.67	16.9
7 days	7.58	6.6	7.72	8.3	8.76	14.8	10.11	16.9
28 days	6.80	6.5	7.48	8.3	8.26	13.8	10.00	17.0
	Mix CNA				**Mix CRA**			
3 days	8.56	10.0	8.89	13.0	8.68	21.4	10.00	21.4
7 days	7.20	10.0	7.56	12.6	8.48	16.4	8.93	21.0
28 days	6.53	9.5	6.53	12.4	7.85	16.1	8.70	19.8



(a)



(b)

Figure 6.20: Effect of curing on the sorptivity of concrete at water-binder ratio (a) 0.45 and (b) 0.60

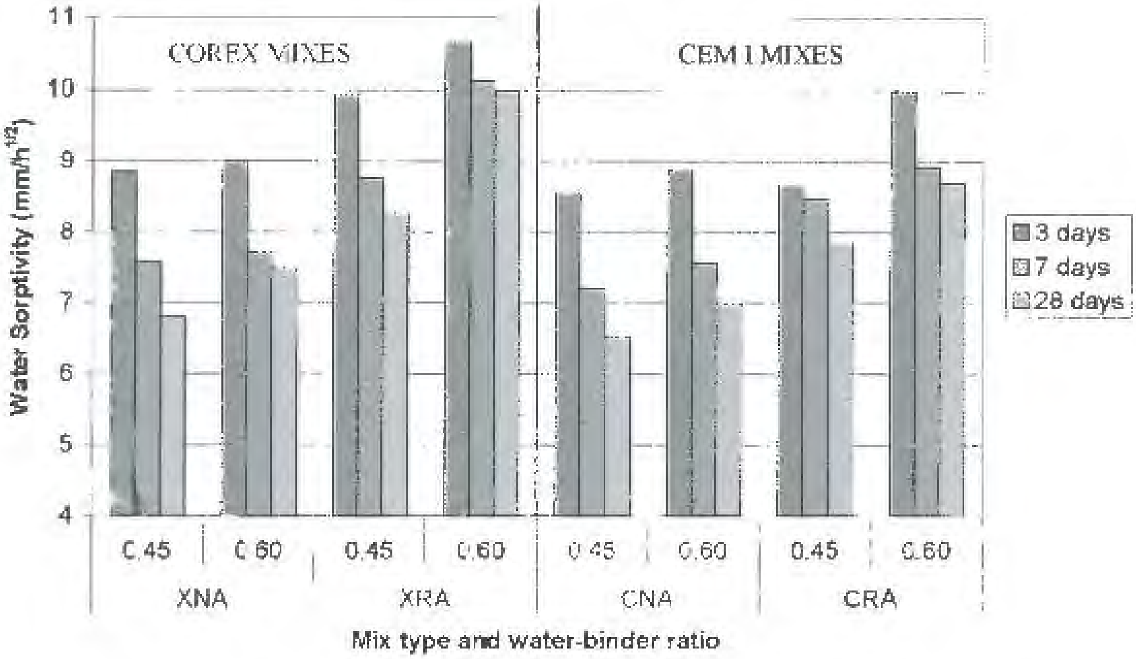


Figure 6.21: Effect of curing and water-binder ratio on the sorptivity of hardened concrete.

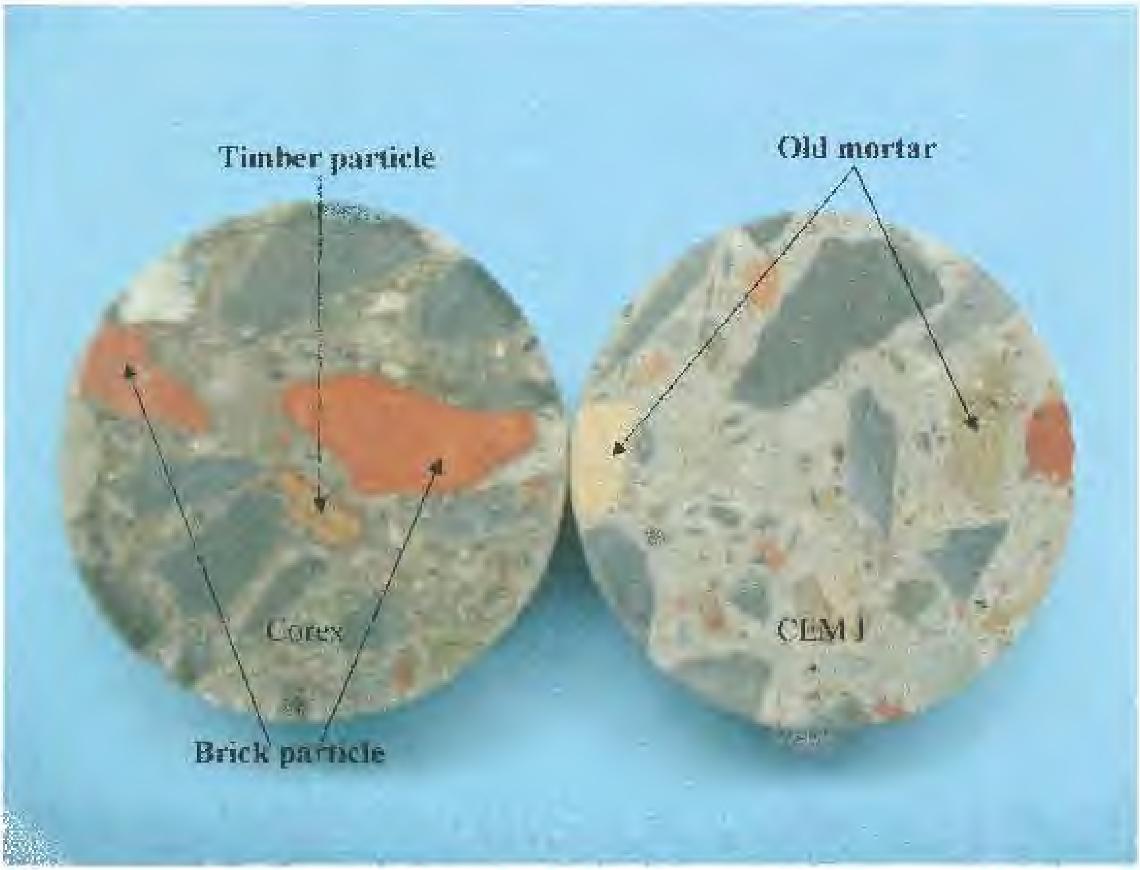


Figure 6.22: Concrete disc showing constituents which may influence water absorption

Chloride conductivity

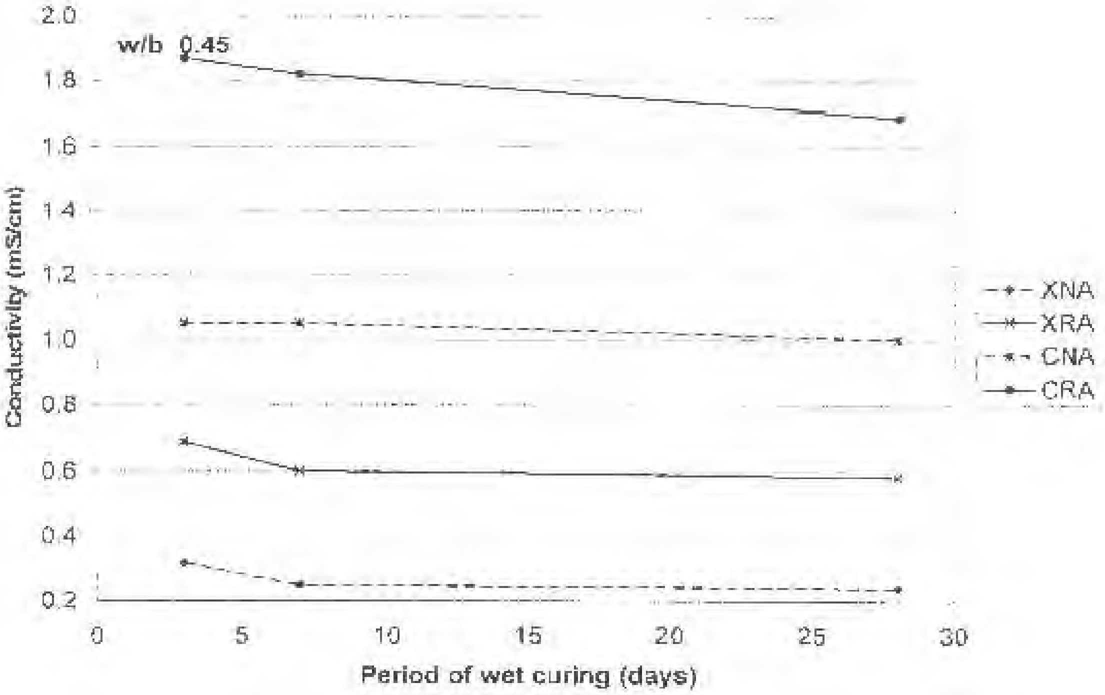
Chloride conductivity results are presented in Table 6.7 and diagrammatically in Figures 6.23 and 6.24. It was found that RC had higher chloride conductivity value than NC. Chloride conductivity of RC was about 50% and 100% higher than that NC made with CEM I and corex respectively.

Comparing binder type it was found that NC with corex slag had better chloride conductivity value than concrete made with only CEM I 42.5 and NA even at higher water-binder ratios. RC with corex slag and 0.60 water-binder ratios had better chloride conductivity value than NC made with CEM I and 0.45 water-binder ratio. In general, chloride conductivity values of RC improved by about 65% when corex was used. The reduction in chloride conductivity values can be attributed to higher chloride binding properties associated with slag concretes. Jaufeerally (2001) and Mackechnie (2001) reported similar results. They found that in all cases corex slag concrete specimens performed better. The reduction in chloride conductivity values have been reported to be attributed to a combination of a greater degree of impermeability and high chloride binding properties associated with slag concrete.

Better conductivity values were obtained on prolonged curing and lower water-binding ratios. Prolonged curing favours the continued formation of hydration products. The gel products block the capillaries and pores, hence reducing the movement of ions through the hardened concrete. The effect of water-binder ratio on conductivity can be explained by increasing in the cementitious content with decrease in the water-binder ratio. This has the consequence of increasing the total products of hydration, thus making the concrete less porous and less diffusible to ions

Table 6.7 Results of chloride conductivity test (mS/cm)

Curing regime	**Mix XNA**		**Mix XRA**		**Mix CNA**		**Mix CRA**	
	Conductivity values at water-binder ratio of							
	0.45	**0.60**	**0.45**	**0.60**	**0.45**	**0.60**	**0.45**	**0.60**
3 days	0.32	0.49	0.69	1.38	1.05	1.90	1.87	2.53
7 days	0.25	0.47	0.60	1.32	1.05	1.58	1.82	2.46
28 days	0.24	0.47	0.58	1.09	1.00	1.50	1.69	2.22



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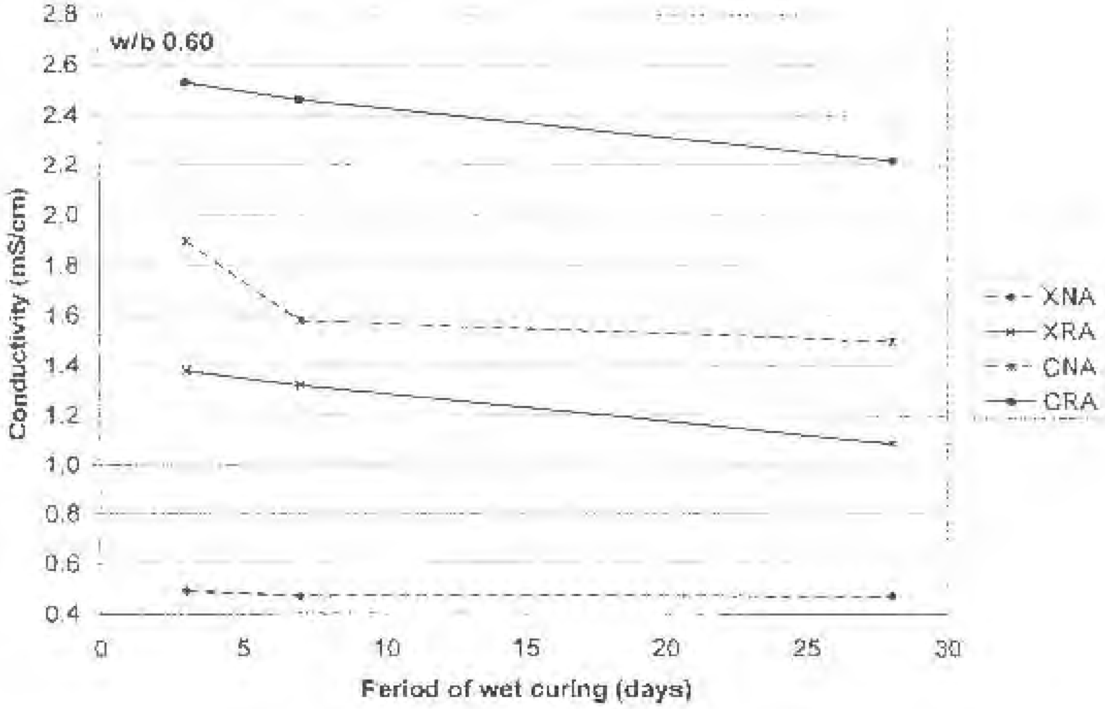

(b)

Figure 6.23: Effect of water curing on the conductivity of concrete at water-binder ratio (a) 0.45 and (b) 0.60

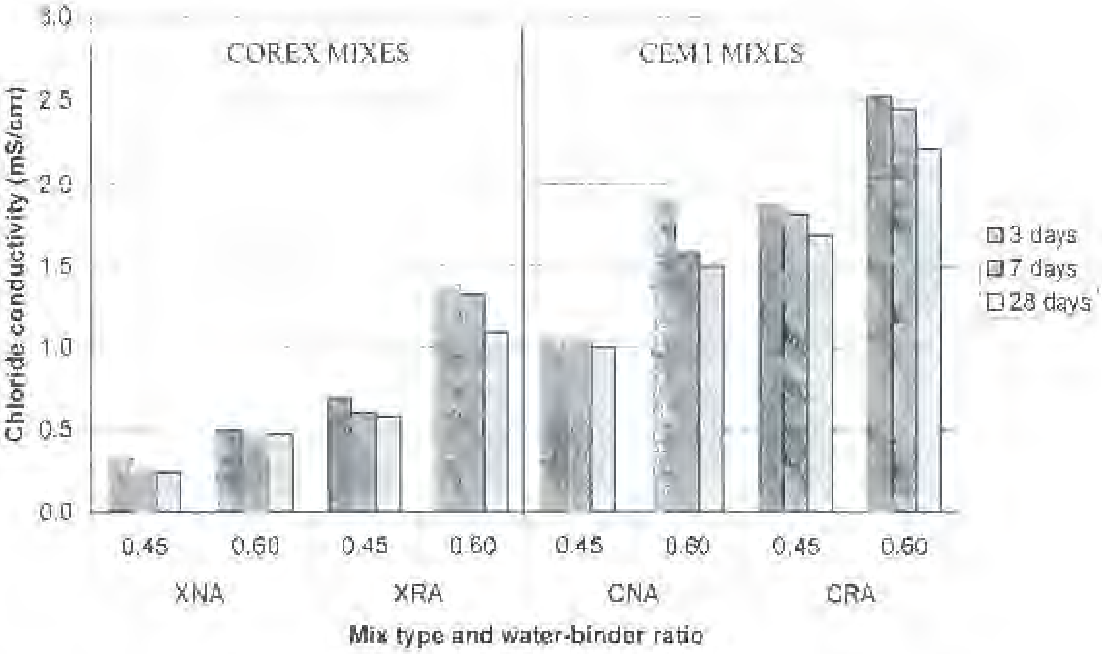

Figure 6.24: Effect of water curing and water-binder ratio on the conductivity of hardened concrete.

Comparing with the recommended value in Table 6.4, RC made with corex slag and with water-binder ratio of 0.45 and 0.60 attained good durability values which implies that RC can be used in a range of environmental conditions. Lower water-binder ratio increases the strength and bonding power of the aggregates and matrix thus reducing penetrability. RC obtained can therefore be used in a range of application.

Generally RA reduces durability quality of concrete. This phenomenon can be explained by the fact that porosity of old concrete, mortar and brick particles in RA render the RC susceptible to ease of permeation, diffusion and absorption of fluid and ions. However the quality of RC improves with prolonged curing. RC can be used where durability is less or is of no concern such as in the indoor structural members which are not exposed to drying and wetting conditions.

6.7 Conclusions

- Compressive strength loss of 2% to 40% was observed for concrete containing RA. Maximum reduction of compressive strength occurred in concrete containing both RCA and RFA.
- For all water-binder ratios, the compressive strength difference between concrete mixes with only RCA and NFA was marginal. This shows that RCA can produce a range of concrete with acceptable compressive strength.
- From these results it can be concluded that concrete with high strength can be obtained using RCA and corex slag provided curing is properly done. Although RFA lowered the concrete strength at all ages and water-binder ration, still concrete for simple applications such as in foundations (blundering) and floors can be obtained.
- Modulus of elasticity E_c of RC was about 20% to 25% lower than that of NC for all water-binder ratios. There was a marginal increase of E_c with age. Decrease of E_c with increase in water-binder ratio was observed.
- Porosity of RA and contaminants such as timber, bricks and plastic materials which are very compressible might have contributed to lower E_c values in RC
- The flexural strength of RC was observed to be 25% lower than that of NC. Binder type had an influence on both NC and RC for all water-binder ratios. Concrete with 50% corex slag had higher flexural strength than concrete with CEM I 42.5 only
- RC exhibited about 50% to 100% higher creep strain in exposed conditions compared with NC. This might be due to high compressibility of RA
- In the case of sealed specimens, there was a marginal difference between creep strain of RC and NC. Retained moisture within RA pores contributed to lower the creep effect by lowering the compressibility of RC.
- There was a marginal difference of drying shrinkage between RC and NC containing corex slag. However, drying shrinkage of RC was higher than that of NC for concrete made with CEM I 42.5 at later age
- A reversed trend was observed on sealed samples, whereby, the autogenous shrinkage of RC was lower than that of NC. Retained moisture in RA contributed to lower values of autogenous shrinkage in RC. As hydration takes place cement/water system contracts, but in this case the extra moisture within

the RA might have kept the system in a balance as the extraction of water from the cement gel for hydration purposes preceded.

- The overall results show that the RA reduced durability performing of concrete. This phenomenon can be explained by the fact that cracks and porous nature of RA render the concrete susceptible to ease of permeation, diffusion and absorption.
- OPI and water sorptivity of RC were improved when CEM I 42.5 was used while chloride conductivity improved when corex slag was used
- Acceptable durability index values were however attained by RC made with both RCA and RFA.
- Generally good and durable RC can be obtained provided proper curing and selection of binder is taken into consideration.

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CHAPTER 7

GENERAL DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

Recycled aggregates (RA) are aggregates resulting from the reprocessing of mineral materials from construction waste (new materials wasted during construction through over-ordering, breakage and rejection) and demolition waste (composed predominantly of crushed old concrete and brick masonry). Such aggregates can be in the form of recycled fine aggregates (RFA) or recycled coarse aggregates (RCA). RFA contains particles less than or equal to 4.5 mm and RCA contains particles greater than 4.5 mm. RA can contain in some circumstances significant quantities of natural aggregates, but excessive quantities of other materials such as wood, metal and other contaminants need to be removed before the aggregate is fit for use in concrete production. The composition and properties of RA vary depending on the source of construction and demolition waste. Commercially produced RA are expected to have variable properties.

Waste arising from construction and demolition constitutes one of the largest waste streams in South Africa and many other countries. The South African construction industry generates between 5 and 8 million tons of C&DW per annum. Over 1 million tons, mostly concrete rubble reaches landfill sites every year. More than 200 000 tons reach landfills in the Cape Peninsula, and the remainder is recycled or dumped illegally. A large percentage of C&DW is composed of 'core' C&DW that has the quality to be recycled, and consequently could reduce the amount of primary (natural) aggregates extracted.

Measures aimed at reducing the use of primary aggregates and increasing the use of recycled C&DW have been introduced in various countries, where it is technically, economically or environmentally acceptable. In South Africa, a large percentage of C&DW finds low-level applications in backfilling, landscaping, site levelling, landfill etc. Aggregate from recycled C&DW rubble finds application in road works as base and sub-base course, foundations in building construction and brick/block manufacturing.

Recycling of C&DW as aggregate offers a solution to the problems encountered with the quarrying of natural aggregates and the disposal of old concrete. With the growing production rate of C&DW in the Cape Peninsula, and the increasing difficulties in obtaining NA, recycling of C&DW and use of RA should be an obvious way forward. Ongoing research to analyse properties of RA and performance of concrete made with RA should be encouraged.

It is now recognized that one of the most environmentally responsible and economically viable ways of meeting challenges of sustainability within the construction industry is the use of recycled C&DW as aggregate in new concrete production. However, there still a number of practical problems that have to be addressed before the construction industry will have confidence to accept the recycling and re-use of C&DW on a larger scale.

There are three types of companies involved in recycling and use of aggregates from C&DW in the Cape Peninsula. These include commercial crushing companies, brick manufacturers and civil engineering contractors. The majority of construction companies apply RA materials in backfilling, landscaping, site levelling, landfill, road works as base and sub-base course, foundations as hard core and fill in building construction, construction of parking lots and brick/block manufacturing. Malans Quarries supplies more than 200 000 tons of RA annually and most of these aggregates are used in road works. Key barriers to wider acceptance of RA include lack of experience, lack of guidance and detailed case studies, as well as user resistance to 'second best' products. Very little is known in South Africa about the use of RA in concrete production, possibly because natural aggregates are still readily available in urban areas, or engineers are not confident with the use of RA materials due to lack of information on availability and suitability of these materials. Bradis Recycling Company produces RA which has been used in road works as well as in concrete production for light structures. Little work has been done to analyse the properties and performance of commercially produced aggregate in concrete production.

The use of C&DW as a source of aggregates for the production of new concrete has become more common in recent decades around the world. Test results by various researchers show that building rubble can be transformed into useful RA through proper processing. Performance tests also show that the properties of fresh and hardened concrete made with RA and natural aggregate are within manageable limits. The present challenge is how to improve RA both quantitatively and qualitatively. While the properties and performance of concrete made with laboratory-crushed recycled concrete aggregate have been extensively investigated and reported by various researchers, only limited data are available on commercially produced recycled coarse and fine aggregates, covering properties of RA, concrete mix proportions, fresh concrete properties and durability performance. Therefore the need to investigate and understand the behaviour of concrete made with aggregates from recycled C&DW rubble is obvious as such materials are likely to provide both environmental and economic advantages.

In this study, the availability of RA in the Cape Peninsula, as well as properties of both coarse and fine RA, and performance of RC were investigated. Aggregate properties included composition, grading, fineness modulus, particle shape and texture, bulk and relative density, absorption and 10% FACT. Fresh concrete properties investigated include water requirement, workability, consistence and segregation (bleeding). The aspects which were investigated for hardened concrete included density of hardened concrete, compressive strength, flexural strength, creep and shrinkage, and durability monitored by durability index tests (oxygen permeability, water sorptivity and chloride conductivity). The results of RA and RC obtained were compared with those of NA and NC and results of other researchers.

In the investigation of fresh and hardened concrete, water-binder ratios of 0.45, 0.60, 0.75 and 0.90 were used. Greywacke stone and Klipheuwel sand which are natural aggregates widely used in the Cape Peninsula for concrete production, were used in the control mixes. Ordinary Portland cement (CEM I 42,5) and Corex slag were used as binders. The production processes and chemical analysis of RA were not covered in this investigation.

7.1 Materials

Physical properties of recycled and natural aggregates were characterized. These included composition, grading, fineness modulus, particle shape and texture, bulk and relative density, absorption and 10% FACT.

The particle size analysis for RCA and RFA show that both RCA and RFA are continuously graded, that is, all particle sizes are present. The fineness modulus of the fine material only (i.e. material of size 4.75 mm or less) present in the RFA was calculated to be 3.0, which corresponds to a relatively high value indicating the relative coarseness of the fine material present in the RFA. RCA fineness modulus was 6.9 and dust content in RFA was found to be 3.2 %, which is higher than 2.2 % which was found in NFA.

It was observed that RCA was composed primarily of stone, concrete, mortar and brick, with materials such as tiles, timber and chipboard in smaller amounts. The main composition of RCA was stone with the mass fraction ranging from 30% to 58%. Old concrete comprised about 18% to 33%, mortar comprised 12% to 20 % and bricks comprised 8% to 15%. Other impurities such as wood, chipboard and tiles totaled about 1%. The stone fraction consisted mainly of greywacke natural coarse aggregate. The brick fractions were remnants of clay brick, and mortar fractions were made up of cement and fine aggregate and were of a porous nature. The RA used in this study can be classified as class II in accordance with RILEM classification or group 2 according to South African classification.

Visual inspection of the RA particles showed that they varied in shape, with a mixture of spherical, cubical/chunky and angular particles. The surface texture was rough and highly porous. Compacted and loose bulk density of RA was found to be 1389 kg/m^3 to 1510 kg/m^3 and 1293 kg/m^3 to 1330 kg/m^3 respectively which were marginally lower than those of the NA which attained 1585 kg/m^3 and 1388 kg/m^3 for compacted and loose bulk density respectively. Compacted and loose bulk density of RFA was much lower than compacted and loose bulk density of NFA. RFA had 1533 kg/m^3 and 1430 kg/m^3 compacted and loose bulk density respectively, while NFA attained compacted bulk density of 1778 kg/m^3 and loose bulk density of 1608 kg/m^3.

Water absorption was found to be between 2.0% and 4.5% for RCA and between 7.5% and 10.4% for RFA. This is higher than that of NA which had water absorption of 0.4% for NCA and 1% for NFA. It was also observed that the water absorption increased with decrease in particle size.

The 10% FACT results ranged between 175 kN and 188 kN for RCA. These were greater than the value recommended by SABS 1083: 1994 for concrete exposed to abrasion of 110 kN and above, while for high-grade concrete the required value is at least 170 kN.

It can generally be concluded that physical properties of both RCA and RFA met requirements needed for concrete production. Although absorption of RA was high, this can be minimized by pre-saturating the aggregates before being used in concrete production.

Since the quality of RA fluctuates considerably, quick test methods are required. It is important that bulk density, relative density and water absorption of RA are determined carefully prior to their use in concrete production. This should be done in order to achieve concrete of adequate workability, stability and cohesiveness; also to avoid large variations in properties of hardened concrete.

7.2 Influence of RA on fresh concrete properties

The fresh concrete properties investigated included water requirement, workability, consistence, cohesiveness and segregation (bleeding). It was observed that pre-saturated aggregates had not much effect on fresh concrete. Generally the workability and cohesiveness of all mixes were acceptable, although mixes which contained RA were found to be harsher and stiffer than concrete made with NA. There was little absorption effect on the fresh concrete as both coarse and fine RA were saturated before mixing. The slumps obtained in all mixes at different water-binder ratios ranged between 70 mm and 90 mm and were within the specified range of 75 ± 25 mm.

Bleeding was minimal in RC and was found to be between 40% and 60% lower than NC for all water-binder ratios. The reduction of bleeding by the RA was mainly due to the presence of dust in both RCA and RFA, as well as roughness and the graded nature of RA.

The results of slump loss with time for mixes with 0.45 and 0.60 water-binder ratios show that the workability of RC declined quickly regardless of the use of pre-saturated RA. After an hour, concrete containing RA had lost between 50% and 65% of its consistence while concrete made with NA lost about 25%. This might have been caused by breaking down of weaker RA particles such as mortar, brick and stone/mortar conglomerate during remixing which in turn increased the amount of fines in the mix. Other factors which might have influenced the slump loss are the loss of water by evaporation during slump testing, or cement hydration.

7.3 Influence of RA on hardened concrete properties

Six series of tests were performed to determine the performance of hardened concrete made with RA. These included compressive strength, modulus of elasticity, flexural strength, creep and shrinkage, and durability assessed by durability index tests (oxygen permeability, water sorptivity and chloride conductivity).

7.3.1 Compressive strength, modulus of elasticity and flexural strength

Generally the compressive strength of RC was lower than that of NC except for mix XRC. All mixes which contained RFA were found to have a lower density and attained a very low compressive strength in comparison with other mixes. After 120 days, compressive strength loss of 2% to 40% was observed in concrete containing RA for all water-binder ratios. Maximum reduction of 40% in compressive strength was observed in concrete with RFA at water-binder ratios of 0.75 and 0.90. Compressive strength of RC containing only RCA was found to be 2% and 10% lower than the control mix with corex slag but higher than the control mix which contained CEM I 42.5. Binder type had an effect on hardened concrete properties, as mixes containing corex slag achieved higher compressive strength than mixes containing only CEM I 42.5 at later ages owing to the excellent hydraulic properties of the slag.

The elastic modulus of elasticity of RC was about 20% to 25% lower than that of NC for all water binder ratios. There was a marginal increase of elastic modulus with age and as expected, elastic modulus increased with decreasing of water-binder ratios.

The flexural strength of RC ranged between 3 MPa and 4 MPa, about 25% lower than that of NC. Binder type had an influence on both NC and RC for all water-binder ratios. Concrete with 50% corex slag had higher flexural strength than concrete with CEM I 42.5 only.

From these results it can be concluded that adequate concrete of different strengths can be obtained using RA. Although RFA lowered the concrete strength at all age and water-binder ratios, concrete for a range of applications such as in foundation, floors and non bearing walls can be produced.

7.3.2 Creep and shrinkage

RC exhibited 50% to 100% higher creep strain in exposed conditions than NC. Highest creep strain was observed in RC with CEM I 42.5. RC with corex slag experienced lower creep strain than that with CEM I 42.5. Strength development of concrete with corex slag after 28 days might have contributed to lower creep strain.

In the case of sealed specimens, there was a marginal difference between creep strain of RC and NC. Creep strain of 80 x 10^{-6} under sealed conditions was observed in RC while NC attained creep strain of about 70 x 10^{-6}. Retained moisture within RA pores contributed to lowering the creep strain by providing an additional source of moisture to the matrix.

There was a marginal difference observed in drying shrinkage between RC and NC containing corex slag. However, drying shrinkage of RC was about twice as higher as that of NC for concrete made with CEM I 42.5. Strength development of concrete with corex slag after 28 days might have contributed to increased restraint strength, thus reducing drying shrinkage.

The autogenous (sealed) shrinkage of NC was about twice as high as that of RC. Retained moisture in RA contributed to lower the values of autogenous shrinkage. As hydration takes place the cement/water system contracts, but in this case the extra moisture within the RA kept the system in balance as the extraction of water from the cement gel for hydration purposes proceeded.

7.3.3 Potential durability of hardened concrete

Three durability index tests were performed to determine gas, liquid, or ion transport properties, and hence the potential durability of RC. These included oxygen permeability index (OPI), water sorptivity and chloride conductivity tests. For all tests, specimens of 25 mm thickness concrete discs and 68 mm diameter, cored from 100 mm cubes, were used.

The results indicated that RA reduced the OPI values (i.e. increased permeability) for all water-binder ratios and curing periods. RC was about 5 and 10 times more permeable to gas than NC made with corex slag and CEM I respectively at all water-binder ratios and curing regimes. The water sorptivity results show that RA has detrimental effects on the durability of concrete. The RC had higher water sorptivity values and porosity than NC. RC attained about 20% and 35% higher water sorptivity values than NC for 0.45 and 0.60 water-binder ratios respectively. This phenomenon can be explained by the fact that cracks and the porous nature of particles such as bricks, mortar, timber and old concrete present in RA render the concrete susceptible to ease of permeation and absorption.

It was found that RC had about 50% to 100% higher chloride conductivity values than NC. Nevertheless, RC with corex slag had better chloride conductivity values than concretes made with only CEM I 42.5, even at higher water-binder ratios. RC with corex slag and 0.60 water-binder ratio had better chloride conductivity value than NC made with CEM I and 0.45 water-binder ratio. The chloride conductivity values of RC improved by about 65% when corex slag was used. The reduction in chloride conductivity values is attributed to the higher chloride binding properties associated with slag concretes.

Durability of both RC and NC was improved with lower water-binder ratios and with increasing wet curing period. The effect of water-binder ratio on durability can be explained by an increase in the total products of hydration, thus making the concrete less porous and less permeable to gas, fluids and ions. Improvement of durability with prolonged curing is attributed to the continued formation of hydration products. The gel products block the capillaries and pores, hence reducing the movement of gases and fluids through the hardened concrete. Generally durability index tests revealed that curing time and water-binder ratio have an effect on the durability of both RC and NC, with the impact being more on corex slag.

It can therefore be concluded that commercially produced RCA and RFA can be used to produce concrete for various applications provided properties of RA are determined before being used in concrete production. Practical experience has shown that RC is as easy to batch, mix, transport, place, compact and finish as NC. However, because of the relatively high water absorption of RA, it is generally recommended to batch RA in a pre-soaked condition or SSD condition. The alternative is to add extra water or use a superplasticizer in the mix to counterbalance the absorption effect of RA and maintain workability of fresh RC. Prolonged curing is as important for RC as it is for NC for strength development and improvement of hardened concrete durability.

7.4 Recommendations and the way forward

7.4.1 General recommendations

The construction industry is not yet convinced that C&DW management and secondary market have a good potential to provide alternative resource for construction materials and help to improve industry performance. The use of innovative construction and demolition techniques and waste management planning can yield large quantities of useful C&DW materials for use in various applications including production of new concrete.

Maximum utilization of RA obtained from C&DW can be achieved if all stakeholders involved in the life-cycle of C&DW play their part. Companies involved in producing RA should build a good reputation in regard to quality of materials supplied. This requires good source control, good quality production and sufficient availability of

RA in quantity. The primary requirement for provision of good quality product is input control for materials received at the recycling plants. Each load of unprocessed C&DW material received at the plant should be inspected and, if accepted, be placed on a stockpile designated for the quality of aggregate to be produced. The frequency of testing of the RA produced should depend on the quality of output required, but it should also depend on the quality of information on the input. Higher quality materials can be obtained by inspecting demolition sites and preparation of demolition plans to maximize the usefulness of recovered materials.

The quantity of RA used in the Cape Peninsula is small in comparison to natural aggregates. Inadequate knowledge and experience about RA have played a vital role in the small utilization of RA. Therefore more workshops and seminars on the use of RA need to be conducted in order to increase awareness among stakeholders such as demolishers, designers, contractors, and clients. Taxes on RA materials and recycling plants and companies which utilize RA should be reduced and increased on NA materials. Such incentives would encourage the production of RA as well as the use of these materials. Further research should be conducted on establishing effective secondary markets in South Africa construction industry, as well as ways of enforcing effective waste management practices in small, medium and large contractors.

7.4.2 Technical recommendations

Results obtained in this study are encouraging but more work needs to be done. In this study it was observed that RFA reduced the strength and durability of hardened concrete. Another study is suggested to critically analyze the physical and chemical properties of RFA. Use of water-treated RA, (although it is an expensive approach) may improve the properties of RA and concrete made with such materials.

Because of the variability of RA material, characterizations of physical properties of RA need to be done frequently in order to monitor the quality and consistence of RA materials. Regular testing of RA by laboratories and recycling companies and readily available results will improve the perception of RA as suitable materials for concrete production.

The usage of inferior materials for construction purposes is not acceptable, but changing the perception of what is an acceptable material for construction is important. Changing of Standards and Specifications from being primarily materials-based to being more performance-based needs to be considered. More research and development with respect to types and methods of testing RA materials is needed in order to ensure that all materials are tested on merit and accommodated by specifications where appropriate.

APPENDIX A: PHYSICAL PROPERTIES OF MATERIALS

Table A1: Properties of aggregates tested and standards used

Test/experiment	Equipment/apparatus	Aggregate tested	Test methods (Standards)
Composition	Mass balance	RCA	BS 8500-2: 2002
Grading	Sieves, vibrating table	RCA/RFA/NFA	SANS 202: 2002
Particle shape and texture	Visual inspection	RCA/NCA	BS 812:Part 102:1994
Relative density	Pycnometer, balance, basket, bucket and sieve	RCA/RFA NCA/NFA	SANS 5844:1994
Bulk density	Cylindrical container tamping rod, balance	RCA/RFA and NCA/NFA	SANS 5845:1994
Absorption	Bowl, oven and balance	RCA/RFA and NCA/NFA	SANS 5843:2002
10% FACT	Mould, tamping rod, sieve and compression machine	RCA	SABS 5842:1994

Table A2: Composition of RCA taken from Bradis at 2 month intervals

Month Composition	February	April	June
Stone	47.3	30.5	36.8
Concrete	18.6	33.2	28.3
Mortar	20.9	18.7	21.4
Brick	10.2	14.8	12.1
Others	3.2	2.8	1.4

APPENDIX B: MIX DESIGN AND FRESH CONCRETE PROPERTIES

Table B1: Mix design of concrete with 0.45 water-binder ratio

Mix XNA

Materials	water absorption	water content
Greywacke	0.40%	0.10%
Klipheuwel sand	0.70%	2.00%
CEM I 42.5		
Corex slag		

Materials	Per m³			0.01m³	Batch qty	adjustment
Units	kg	RD	L	kg	kg	kg
W/C ratio = 0.45						
water requirement	180	1.00	180.0	1.8	6.3	6
50% CEM I 42.5	200	3.14	63.7	2	7	
50% Corex	200	2.90	69.0	2	7	
Coarse aggregates	1100	2.65	415.1	11	38.5	
			727.8			
			1000.0			
Fine aggregates	721.45	2.65	272.2			
Taken	725.00			7.25	25.38	25.8

Observations:

Slump:	90 mm
Cohesiveness:	good
bleeding:	4.20%

Mix XRF

Materials	water absorption	water content
Greywacke	0.40%	0.10%
Recycled fine aggregate	7.40%	8.90%
CEM I 42.5		
Corex slag		

Materials	Per m³			0.01m³	Batch qty	adjustment
Units	kg	RD	L	kg	kg	kg
W/C ratio = 0.45						
water requirement	180	1.00	180.0	1.8	3.6	3.3
50% CEM I 42.5	200	3.14	63.7	2	4	
50% Corex	200	2.90	69.0	2	4	
Coarse aggregates	610	2.65	230.2	6.1	12.2	
			542.8			
			1000.0			
Blended RFA	1142.88	2.50	457.2			
Take as	1145.00			11.45	22.9	23.2

Observations:

Slump:	80 mm
Cohesiveness:	good
bleeding:	1.40%

Mix XRC

Materials	water absorption	water content
Recycled coarse aggregate	3.00%	5.00%
Klipheuwel sand (NFA)	0.70%	2.40%
CEM I 42.5		
Corex slag		

Materials	Per m³			0.01m³	Batch qty	adjustment
Units	kg	RD	L	kg	kg	kg
W/C ratio = 0.45						
water requirement	180	1.00	180.0	1.8	4.5	3.80
50% CEM I 42.5	200	3.14	63.7	2	5	
50% Corex	200	2.90	69.0	2	5	
Coarse aggregates (RCA)	1060	2.50	424.0	10.6	26.5	27.00
			736.7			
			1000.0			
Fine aggregates	697.85	2.65	263.3			
Take	700.00			7.00	17.5	17.80

Observations:

Slump:	70 mm
Cohesiveness:	good
bleeding:	2.30%

Mix XRA

Materials	water absorption	water content
Recycled coarse aggregate	3.00%	5.00%
Recycled fine aggregate	7.40%	9.30%
CEM I 42.5		
Corex slag		

Materials	Per m³			0.01m³	Batch qty	adjustment
Units	kg	RD	L	kg	kg	kg
W/C ratio = 0.45						
water requirement	180	1.00	180.0	1.8	7.2	5.9
50% CEM I 42.5	200	3.14	63.7	2	8	
50% Corex	200	2.90	69.0	2	8	
Coarse aggregates (RCA)	770	2.50	308.0	7.7	30.8	31.4
			620.7			
			1000.0			
Blended RFA	948.35	2.50	379.3			
Taken as	950.00			9.5	38	38.7

Observations:

Slump:	70 mm
Cohesiveness:	good
bleeding:	1.40%

Mix CNA

Materials	water absorption	water content
Greywacke	0.40%	0.10%
Klipheuwel sand	0.70%	2.10%
CEM I 42.5		

Materials	Per m^3			0.01m^3	Batch qty	adjustment
Units	kg	RD	l	kg	kg	kg
W/C ratio = 0.45						
water requirement	180	1.00	180.0	1.8	7.56	7.3
CEM I 42.5	400	3.14	127.4	4	16.8	
Coarse aggregates	1100	2.65	415.1	11	46.2	
			722.5			
			1000.0			
Fine aggregates	735.42	2.65	277.5			
Taken as	736.00			7.36	30.91	31.3

Observations:

Slump:	80 mm
Cohesiveness:	good
bleeding:	6.0%

Mix CRA

Materials	water absorption	water content
Recycled coarse aggregate	3.00%	3.30%
Recycled fine aggregate	7.40%	10.50%
CEM I 42.5		

Materials	Per	1	m3	per 0.01m3	Batch qty	adjustment
Units	kg	RD	L	kg	kg	kg
W/C ratio = 0,45						
water requirement	180	1	180.0	1.8	7.56	3.3
CEM I 42.5	400	3.14	127.4	4	16.8	
Coarse aggregates (RCA)	770	2.5	308.0	7.7	32.34	
			615.4			
			1000.0			
Blended RFA	961.53	2.5	384.6			
Taken as	962.00			9.62	40.404	41.7

Observations:

Slump:	70 mm
Cohesiveness:	good
bleeding:	2.10%

Table B2: Properties of fresh concrete tested and standards used

Test/experiment	Equipments/apparatus	Test methods (Standards)
Water requirement	Mixer	C & CI/ trial mixes
Workability	Slump cone	SANS 862-1:1994
Consistence	Slump cone	SANS 5862-1:1994
Bleeding	Steel cylindrical container	ASTM C 232-92
Density	Steel cylindrical container/balance	SANS 6250:1994

Table B3: Bleeding volume of compacted fresh concrete

W/C	Bleeding volume in % (fraction of original mix water)					
	XNA	XRF	XRC	XRA	CNA	CRA
0.45	4.2	1.4	2.5	1.4	5.0	2.1
0.60	5.7	2.8	5.0	2.8	6.0	2.4
0.75	6.5	2.8	6.2	3.0	7.0	2.6
0.90	6.6	3.3	6.4	3.2	7.3	3.2

APPENDIX C: TEST ON HARDENED CONCRETE

Table C1: Properties of hardened concrete tested

Test/experiment	Mixes	W/C ratio	Equipments	Test methods
Density (28 days)	XNA,XRF XRC,XRA CNA, CRA	0.45,0.60, 0.75,0.90	Mass balance	SANS 6251:1994
Compressive strength (3,7,28,56 and 120 days)	XNA,XRF XRC,XRA CNA, CRA	0.45,0.60 0.75,0.90	Amsler comp. Machine	SANS 5863:1994
Flexural strength (28 days)	XNA,XRA CNA, CRA	0.60,0.75	Universal test machine	SANS 5864:1994
Elastic Modulus (28 and 120 days)	XNA,XRA CNA, CRA	0.45,0.60 0.75	Amsler comp. Machine/LVDT	BS 1881: Part 121:1983
Shrinkage • Exposed • Sealed	XNA,XRF XRC,XRA CNA, CRA	0.60	Strain gauge	BS 8110: Part 2:1985
Creep • Exposed • Sealed	XNA,XRA CNA, CRA	0.60	Molds, loading frames and strain gauges	BS 8110: Part 2:1985 ASTM: C 512:1994
Durability index test after 28 days cured for (3,7,28 days)	XNA,XRA CNA, CRA	0.45, 0.60	Vanier calliper, stop watch	UCT – manuals

Table C2: Density of hardened concrete at different water-binder ratios

Mix type	Density of hardened concrete (kg/m^3) at water-binder ratio of :			
	0.45	0.60	0.75	0.90
X NA	2455	2392	2387	2338
X RF	2303	2277	2240	2223
X RC	2360	2353	2337	2278
X RA	2287	2237	2233	2217
C NA	2422	2403	2362	2360
C RA	2300	2262	2225	2215

Table C3: Compressive strength results of hardened concrete (MPa)

	Compressive strength (MPa)					
Age (days)	X NA	X RF	X RC	X RA	C NA	C RA
	Water-binder ratio 0.45					
3	23.7	18.4	25.6	18.2	27.6	21.1
7	39.4	27.8	36.0	31.0	36.1	28.6
28	51.5	38.7	49.4	40.8	46.7	34.6
56	55.9	42.0	54.8	43.8	48.8	38.2
120	58.4	44.5	56.9	46.9	52.8	44.3
	Water-binder ratio 0.60					
3	13.9	12.0	13.6	11.3	17.8	14.5
7	21.6	18.1	22.1	16.5	25.7	19.6
28	38.8	25.4	35.4	24.6	33.6	24.9
56	41.0	28.7	38.3	28.2	34.1	26.5
120	42.7	30.7	41.2	28.4	34.3	28.8
	Water-binder ratio 0.75					
3	11.5	9.3	9.0	12.3	12.3	12.5
7	19.4	15.4	17.2	14.6	17.7	14.4
28	29.0	20.7	25.5	19.2	21.7	17.5
56	33.9	22.4	29.9	20.5	25.7	19.3
120	36.2	25.6	32.7	22.6	25.7	22.9
	Water-binder ratio 0.90					
3	6.0	4.2	6.8	5.3	7.8	7.5
7	10.8	7.3	11.2	9.4	10.1	9.7
28	19.1	11.2	16.8	13.5	13.7	12.6
56	20.2	12.9	19.6	14.9	16.2	13.9
120	22.6	13.1	21.2	15.2	17.1	15.4

Table C4: Static elastic modulus of hardened concrete

	Elastic modulus (GPa)					
	28 days			120 days		
Mix type	0.45	0.60	0.75	0.45	0.60	0.75
XNA	30.2	27.15	25.08	31.01	29.85	27.40
XRA	23.44	17.56	15.61	24.14	19.63	19.13
CNA	28.59	26.67	23.90	30.56	28.01	25.66
CRA	21.80	18.23	17.93	22.32	19.55	18.59

APPENDIX D: CREEP AND SHRINKAGE OF HARDENED CONCRETE

Table D1: Shrinkage results for sealed and exposed specimens of hardened concrete

Shrinkage in micro-strain												
Mix type	X NA		X RF		X RC		X RA		C AN		C RA	
Days	Sealed	Unsealed	Sealed	Unsealed	Sealed	Unsealed	Sealed	Unsealed	Sealed	Unsealed	Sealed	Unsealed
0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	22	13	32	0	20	8	20	4	42	5	22
2	3	38	18	50	4	30	13	25	8	58	8	38
3	7	56	22	57	6	42	18	40	14	78	12	43
4	12	58	27	68	10	52	25	57	26	90	17	63
5	12	62	27	72	14	55	28	60	28	92	18	68
6	27	80	28	105	18	85	30	64	30	95	23	77
7	32	98	30	122	24	67	35	86	36	103	27	92
10	37	115	30	140	30	85	43	112	40	120	35	105
14	50	150	32	173	34	108	50	142	46	127	37	133
21	57	187	35	207	40	167	58	186	60	150	43	207
28	70	242	36	240	44	205	60	224	68	180	47	283
42	87	287	40	297	54	267	70	262	82	232	58	372
56	102	310	47	333	72	300	78	294	102	287	70	453
84	133	345	57	375	96	355	85	354	136	328	90	550
112	168	383	72	428	132	410	93	390	166	363	107	618
140	192	398	85	483	166	422	100	410	182	382	137	633

Table D2: Specific creep strain of hardened concrete

Days	SPECIFIC CREEP (micro-strain/MPa)							
	X NA		X RA		C NA		C RA	
	Sealed	Exposed	Sealed	Exposed	Sealed	Exposed	Sealed	Exposed
0	0	0	0	0	0	0	0	0
1	8	10	9	17	13	14	14	28
2	10	13	11	26	17	19	18	41
3	11	22	12	25	18	22	20	47
4	13	24	13	26	18	24	21	50
5	15	27	15	30	19	27	22	56
6	16	31	17	33	19	28	22	63
7	17	31	20	33	20	31	23	68
10	20	36	22	39	21	34	26	78
14	22	37	26	45	23	41	29	92
21	29	47	32	55	26	46	33	102
28	32	47	38	63	33	55	39	114
42	43	58	51	74	39	63	45	134
56	40	63	58	92	46	69	52	150
84	58	74	68	119	54	81	58	182
112	65	83	77	139	62	89	66	199
140	69	90	86	157	67	92	72	216