



UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

HEAT TRANSFER THROUGH ANAEROBIC DIGESTER CONCRETE TANK WALLS

OWEN S. DAVIS

A DISSERTATION SUBMITTED AS PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
ENGINEERING

Supervisor: Emeritus Professor M. Alexander, Department of Civil Engineering

Department: Civil Engineering

Faculty: Engineering & The Built Environment

Research Field: Structural Engineering and Materials

Date of Submission: 23 December 2017

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

PLAGIARISM DECLARATION



UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

DEPARTMENT OF CIVIL ENGINEERING

CIV5017Z: MINOR DISSERTATION

Plagiarism Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and to pretend that it is one's own.
2. I have used the Harvard Convention for citation and referencing. Each significant contribution to and quotation in this report from the work or works of other people has been attributed and has been cited and referenced.
3. This report is my own work
4. I have not allowed and will not allow anyone to copy my work with the intension of passing it as his or her own work.

NAME: OWEN DAVIS

STUDENT NUMBER: DVSOWE003

DATE: 23 DECEMBER 2017

SIGNATURE:

Signed by candidate

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

CONTENTS

PLAGIARISM DECLARATION.....I

LIST OF TABLES V

LIST OF FIGURES V

LIST OF APPENDICES VI

ACKNOWLEDGEMENT 1

ABSTRACT 2

CHAPTER 1 - INTRODUCTION 4

 1.1 BACKGROUND 4

 1.2 ENGINEERING MOTIVATION..... 4

 1.3 RESEARCH OBJECTIVES, METHODOLOGY AND LIMITATIONS 5

 1.3.1 OBJECTIVES 5

 1.3.2 METHODOLOGY..... 6

 1.3.3 LIMITATIONS 7

 1.4 SYNOPSIS OF THE DISSERTATION 7

CHAPTER 2 - ANAEROBIC DIGESTION AND BIOGAS TECHNOLOGY..... 9

 2.1 AN INTRODUCTION TO ANAEROBIC DIGESTION 9

 2.2 BIOGAS TECHNOLOGY 10

 2.3 THE IMPORTANCE OF HEAT IN AEROBIC DIGESTER TECHNOLOGY
 10

 2.4 HEAT DEMAND OF DIGESTERS 11

 2.5 SUMMARY 13

CHAPTER 3 – AN INTRODUCTION TO HEAT TRANSFER THROUGH
 CONCRETE 14

Heat Transfer Through Anaerobic Digester Concrete Tank Walls
A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of
Engineering
Author: Owen Davis

3.1	THE MOVEMENT OF HEAT THROUGH PHYSICAL BODIES	14
3.2	EQUATIONS OF HEAT TRANSFER	14
3.3	THEORETICAL MODELLING OF HEAT TRANSFER THROUGH CONCRETE	17
3.4	SUMMARY	18
CHAPTER 4 - THERMAL CONDUCTIVITY OF THE CONSTITUENTS OF THE CONCRETE AND WALL		19
4.1	THE THEORY OF THERMAL CONDUCTIVITY IN CONCRETE	19
4.2	EFFECTIVE MEDIUM THEORY (EMT)	21
4.3	THE CONSTITUENTS OF CONCRETE USED IN THE STUDY	22
4.4	THE THERMAL CONDUCTIVITY OF THE BINDER PASTE	23
4.4.1	THE INFLUENCE OF CEMENT ON THE THERMAL CONDUCTIVITY OF THE BINDER PASTE	23
4.4.2	THE INFLUENCE OF COREX SLAG ON THE THERMAL CONDUCTIVITY OF THE BINDER PASTE	24
4.4.3	THE THERMAL CONDUCTIVITY OF THE HYDRATED PHASES	25
4.4.4	THE EFFECTS OF POROSITY ON THE BINDER PASTE	26
4.4.5	EFFECTIVE THERMAL CONDUCTIVITY OF THE BINDER PASTE	28
4.5	THE THERMAL CONDUCTIVITY OF COARSE AGGREGATE IN CONCRETE	29
4.6	THE THERMAL CONDUCTIVITY OF FINE AGGREGATE IN CONCRETE	32
4.7	THE EFFECTIVE THERMAL CONDUCTIVITY OF THE CONCRETE WALL.....	33

Heat Transfer Through Anaerobic Digester Concrete Tank Walls
A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of
Engineering
Author: Owen Davis

4.8	COMPARISONS OF THE THERMAL CONDUCTIVITY RESULTS WITH EARLIER RESEARCH.....	34
4.9	SUMMARY	35
CHAPTER 5 – ADDITIONAL FACTORS THAT MAY AFFECT THE THERMAL CONDUCTIVITY OR HEAT TRANSFER CHARACTERISTICS OF CONCRETE		36
5.1	THE EFFECTS OF THE INTERFACIAL TRANSITION ZONE BETWEEN THE AGGREGATE AND CEMENT PASTE	36
5.2	THE EFFECTS OF REINFORCEMENT ON HEAT TRANSFER IN CONCRETE	39
5.3	SUMMARY	40
CHAPTER 6 – SITE MEASUREMENTS, CALCULATIONS & COMPUTATIONAL MODELLING OF HEAT LOSS		41
6.1	HEAT LOSS THROUGH THE CONCRETE WALL	41
6.2	MEASUREMENTS AT NEW HORIZONS PROJECT.....	42
6.2.1	TEMPERATURE MEASUREMENTS AT NEW HORIZONS.....	42
6.2.2	DISCUSSION OF THE RESULTS	45
6.3	COMPUTATIONAL MODELLING OF HEAT TRANSFER.....	47
6.3.1	INPUT VALUES AND PARAMETERS	47
6.3.2	RESULTS OF THE COMPUTATIONAL MODELLING	49
CHAPTER 7 – CONCLUSION & RECOMMENDATIONS		50
7.1	SUMMARY	50
7.2	CONCLUSIONS	50
7.3	RECOMMENDATIONS.....	51
REFERENCES		53

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

APPENDICES – OUTPUT DIAGRAMS OF THE COMPUTATIONAL MODELLING & TANK LAYOUT57

LIST OF TABLES

Table 1. Concrete Constituents for New Horizons – per m³22

Table 2: Thermal Conductivities and Volume Fractions of the Binder Paste Constituents.....29

Table 3: Table of Temperature Measurements and Heat Losses43

Table 4: Average Temperature & Heat Loss46

LIST OF FIGURES

Figure 1: Photograph of a Typical Anaerobic Digester 5

Figure 2: Diagrammatical Representation of the binder paste structure (Tuson and Charman, 2012).....21

Figure 3: Reduction in the ETC of Cement Mortar Due to the effects of an ITZ.....38

Figure 4: Measurements at Area 144

Figure 5: Measurements at Area 2.....44

Figure 6: Measurements at Area 3.....45

Figure 7: Measurements at Area 4.....45

Figure 8: Applied Heat on the Internal Face of the Wall48

Figure 9: Heat on the External Face of the Wall.....49

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

LIST OF APPENDICES

Appendix 1: Computational Result of Temperature Gradient ($^{\circ}\text{C}$) Through the Cross Section of the Concrete Wall57

Appendix 2: Computational Results of Heat Loss ($\text{W}/\text{m}^2\cdot\text{hr}$) Through the Concrete Wall58

Appendix 3: Diagrammatic Representation of the Concrete Tank Layout59

Appendix 4: Diagram from Neville (2011) indication Capillary Water Content60

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

ACKNOWLEDGEMENT

I would like to acknowledge and thank my supervisor, Emeritus Professor Mark Alexander for his invaluable guidance and support in the research and writing of this dissertation. His expert knowledge of concrete materials and technology has allowed me to delve into an important aspect of sustainable energy production in South Africa.

I would further like to acknowledge and thank the developers and owners of the New Horizons Waste to Energy Facility in Cape Town for allowing me to use the facility as a source for obtaining the materials and structural information and to perform on-site measurements and tests.

Special thanks go to JG Afrika (PTY) Ltd for providing support and assistance during this period of study.

A very special thank you to my wife Melanie, children Keenan and Kirsten for allowing me the space and time for the completion of my studies and for the encouragement and support given to me during this period.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

ABSTRACT

This dissertation is a study of the heat transfer through concrete walls in anaerobic digester facilities. In the biogas industry, the term “heat loss” is synonymous with heat transfer.

The dissertation identifies the reasons why heat is critical in the operations of these facilities. Concrete has traditionally been a material used for the retention of liquid-based products and additionally provides good thermal insulating properties. It combines the benefits of being relatively cost effective for the construction of large tanks and requiring low maintenance during the operational life span.

The research focuses on the thermal properties of the various constituents of concrete and the influence these have on the overall thermal properties of the concrete tank. The constituents forming part of the study are cement, corex slag, water, fine and coarse aggregate. The study showed that the aggregates have a greater influence on the thermal conductivity than the other constituents. It also showed that the mineral composition of the aggregates has a greater effect on the thermal conductivity than the porosity of the aggregates. The study also looked at the influence of the interfacial transition zone around the aggregate and this was found to be not significant and generally can be ignored as a contributor to the thermal conductivity of normal / structural concrete.

The effects of the porosity of the binder paste does affect the thermal conductivity specifically when aqueous solutions are being retained. The capillary pores of the paste can be filled with liquid (mainly water) and less with air. Due to water having a higher thermal conductivity than air, the thermal conductivity of the binder paste is significantly increased.

The effects of reinforcement on the thermal conductivity of concrete was also investigated. Different types and arrangements of reinforcement could have a big influence. Steel fibres and reinforcement if aligned in the direction of the thermal gradient will greatly increase the thermal conductivity. However, it was found that the reinforcement used in the sample wall did not increase the thermal conductivity significantly as it was mainly aligned perpendicularly to the direction of the thermal gradient. Similarly, no steel fibres were used in the concrete.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Once the thermal conductivities of the constituent materials were determined, the effective thermal conductivity of the concrete could be calculated using the effective medium theory. The subsequent heat losses, which are a function of the thermal conductivity, the temperature gradient between the internal and external faces of the concrete wall, the contact surface area and the heat transfer coefficient, could be calculated as a function of time.

The New Horizons Waste to Energy Project in Cape Town was used as a reference project and the research was based on the materials used in the construction of the concrete anaerobic tanks. The project was also used for the measurement of the temperature gradients and subsequent calculation of actual heat losses at various points along the concrete walls.

Furthermore, a computational model was developed using Abaqus to compare the results with those derived from the theoretical model. The heat loss from the computational model compares very well with that of the theoretical model.

CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND

South Africa is embarking on a process of substituting coal-fired power stations (non-renewable) with more sustainable power generation methods such as wind, solar, biomass and biogas through the Department of Energy's (DOE) REIPPPP i.e. Renewable Energy Independent Power Project Procurement Program. The program aims to reduce South Africa's reliance on coal as a main source of power generation and use the natural resources of wind and solar and to a lesser extent, waste generated from municipal and industrial sources, as increasing alternatives for energy production.

Biogas has become an increasingly viable alternative method of producing energy from sources such as agricultural, municipal, and industrial waste. This technology is already a popular energy source in North America, Asia and especially in Europe. The first large-scale biogas plant was recently opened in Cape Town and is expected to produce good quality methane, carbon dioxide and compressed natural gas for commercial use. Due to the amount of waste being produced by humans and animals and the limited space available for new landfill sites, this relatively new technology will become a preferred method to reduce waste-to-landfill and provide alternative sources of energy.

A biogas facility generally comprises of a range of processes such as waste separation and cleaning, anaerobic digestion, gas collection and purification. Anaerobic digestion is the process of retaining the organic matter over a period of time to allow the bacteria to flourish and produce the various gases. The digestion process works best at constant optimum heat which is dependent on the quality of the waste feedstock.

1.2 ENGINEERING MOTIVATION

Traditionally, reinforced concrete has been the construction material of choice due to its long-term durability and low-maintenance requirements. Concrete used in anaerobic digestion facilities and tanks requires good resistance to weak acids and medium to high temperatures (35-80°C) to ensure the continued chemical reactions and production of biogas for a minimum operational period of 25 years.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Structural engineers have generally focussed mainly on the “structural” requirements of the concrete and less on its insulation properties. Additional materials can generally be used to increase the insulation and heat retention properties by applying an external cladding. Fig. 1 shows an image of a typical anaerobic digester.



Figure 1: Photograph of a Typical Anaerobic Digester

Numerous research has been conducted on the effects of short-term, high temperatures specifically related to the exposure of concrete to fires. This dissertation will focus mainly on the heat losses expected in the concrete at moderate temperatures (40°C) used for anaerobic digestion.

1.3 RESEARCH OBJECTIVES, METHODOLOGY AND LIMITATIONS

1.3.1 OBJECTIVES

The dissertation aims to provide an understanding of the importance of heat in anaerobic digesters and how it is transferred through concrete structures. It identifies the important constituents that influence the heat transfer properties of concrete. It also measures, models and evaluates the heat losses through digester

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

walls which provides a guide to owners and designers on ways to mitigate against these losses. Ultimately, the dissertation will provide guidance to structural engineers and concrete technologists on ways of improving the insulation properties of concrete and in so doing, minimise the need for additional heating measures and consequently decrease operating costs.

The dissertation will provide specific information on the following: -

- How the concrete properties and constituents affect heat transfer.
- Factors affecting the thermal conductivity of each constituent of concrete.
- Calculating the thermal conductivities of concrete constituents.
- Effects of reinforcement on heat transfer and thermal conductivity of concrete.
- Measuring surface temperatures and calculating the heat losses through concrete digester walls.
- Comparing the theoretical results with a computational model using Abaqus CAE.

1.3.2 METHODOLOGY

The following methodology was used to ensure that the dissertation provided a technical understanding of heat loss in anaerobic digesters: -

- Undertaking detailed literature reviews of published papers, journals and books.
- Undertaking critical reviews of technical reports on various laboratory experiments of concrete and masonry exposed to heat.
- Performing on-site temperature measurements of the concrete at the New Horizons facility.
- Compiling an Abaqus CAE computational model to simulate the heat transfer in concrete.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

1.3.3 LIMITATIONS

- The dissertation focuses exclusively on the materials used at the New Horizons Facility and does not incorporate other types of cements, extenders and aggregates.
- The dissertation does not delve into what effect concrete admixtures such as water reducing agents (plasticisers or superplasticisers) have on the thermal conductivity of the concrete.

1.4 SYNOPSIS OF THE DISSERTATION

This section provides a brief synopsis of the structure of the dissertation which corresponds with the stated objectives.

Chapter 1 – Introduction

This introductory chapter provides the background and motivation for the research focus into heat transfer in anaerobic digester tank walls. It also states the objectives of the dissertation and describes the methodologies used in the research and testing phases. It further suggests that the outcome was limited in certain aspect of the research.

Chapter 2 - Anaerobic Digestion and Biogas Technology

This chapter introduces anaerobic digestion and biogas technology and describes why heat is important in this type of technology. It further describes the processes involved in the production of biogas.

Chapter 3 – An Introduction to Heat Transfer through Concrete

This chapter expands on the heat transfer characteristics of concrete and identifies how heat transfer can be modelled. It introduces the concept of thermal conductivity and why this is important when calculating heat transfer.

Chapter 4 - Thermal Conductivity of the Constituents of The Concrete

This chapter focuses on the materials aspects of the research and identifies which constituents of concrete has the greater influence on the thermal transfer characteristics by calculating the conductivities of each constituent.

Chapter 5 – Other Properties of Concrete That May Affect the Thermal Conductivity of Concrete

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The chapter discusses the properties and materials that have a lesser influence on the thermal properties of the concrete such as the interfacial transition zone (ITZ) around the aggregates and steel reinforcement.

Chapter 6 – Site Measurements, Heat Loss Calculations and Computational Modelling

The temperature measurements performed at the New Horizons facility are described and reported in this chapter. Included are the methodology and results of on-site testing which lead to the calculation of heat losses in the concrete walls. A basic computational heat transfer model was constructed in Abaqus CAE to analyse the heat loss through a concrete wall using the same concrete parameters as the theoretical model.

Chapter 7 – Conclusion

This chapter forms conclusions from the research and provides recommendations on how the insulation properties of concrete can be improved.

CHAPTER 2 - ANAEROBIC DIGESTION AND BIOGAS TECHNOLOGY

2.1 AN INTRODUCTION TO ANAEROBIC DIGESTION

Anaerobic digestion (AD) is a bio-chemical process in which various types of bacterial microbes decompose organic substances or biomass into smaller composites, in the absence of oxygen. This process occurs in many natural environments such as stomachs of plant-eating mammals (cows, cattle, goats, etc.), sewage sludge treatment and so on.

AD facilities generally comprise of concrete or steel tanks where the digestate matter operates at elevated temperatures. Biogas comes from the breakdown of the organic matter in anaerobic environments in engineered anaerobic digesters. The solids and liquids from which the biogas derives is referred to as digestate.

In AD facilities, the organic source material, which is called feedstock, is anaerobically digested by the bacterial microbes in order to decompose it into the two main products, biogas and digestate. Different feedstock mixtures are experimented with to achieve an optimal and stable biogas production process. This process is called co-digestion.

Suitable feedstock includes fats, oils, sugars, cellulose and other biomass, consisting of easily decomposable material. Typical feedstock can be: -

- Animal manure, slurry and dung
- Agricultural residues and by-products
- Organic wastes from food industries
- Organic fraction of municipal solid waste
- Sewage sludge from wastewater treatment plants

AD is becoming a popular way of recycling waste and producing energy, fuels and compost. It also helps to reduce the release of methane and carbon dioxide gases into the atmosphere thereby reducing greenhouse gas emissions. Biogas can be used as a fuel in gas pipelines, combusted to produce electricity or compressed into a vehicle fuel. The remaining solids and liquids can be used as agricultural fertilizers.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

“Wet digestion” is the most common method of digestion. The term “wet” is used as all the substrates are in liquid form and are easily mixed and pumped. 3 – 15% of the slurries are in the form of solids. Ideally, the digestate is retained in the tanks for 20-40 days for optimal gas production.

For “dry” digestion, substrates are kept in a stackable or heaped form and remain so during the digestion process. Various wastes, such as food, domestic and green wastes are mixed to obtain the best structure and porosity and placed in a sealed container. Warm water is sprayed over the waste, which percolates and is collected and stored in a separate digester tank where the biogas is generated.

2.2 BIOGAS TECHNOLOGY

Biogas is produced by methanogens which are methane-producing bacteria which require specific temperatures to remain effective. Biogas is generally a mix of both methane (CH_4) and carbon dioxide (CO_2) but the proportions might differ due to the chemical composition of the source waste and the chemical pathway of the digestion process. Methane make up 40-80% by volume, carbon dioxide 15-45% with smaller amounts of hydrogen sulphide (H_2S), ammonia (NH_3), nitrogen gas (N_2) and other compounds and is normally saturated with water vapour (H_2O).

Factors, other than the type of feedstock can also affect the composition of the biogas. These include the design of the digestion systems and retention time of the digestate.

2.3 THE IMPORTANCE OF HEAT IN AEROBIC DIGESTER TECHNOLOGY

In order for the anaerobic digestion and the subsequent gas production process to work optimally, the digestate must be kept warm for proper bacteriological function. Heating coils are fitted to the internal face of the tank wall or placed inside concrete tank walls. For biogas production, the heating requirements are a major cost factor and ideally, excess heat from the facility's combined heat and power (CHP) unit should be used as a supplementary source of energy.

Digester tanks are mainly constructed using reinforced concrete as this material provides the long-term durability required for the storage of mildly aggressive liquids and gases. The tanks are generally circular in shape, but square or rectangular tanks have also been used. The concrete can be cast in-situ or precast panels tied

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

together. Most concrete tanks have an acid-resistant coating applied to the inside face of the wall above the water line as the gases can be corrosive.

In order to minimise the heat losses through the concrete wall, digester tanks are commonly insulated with either spray-on foam or rigid foam attached to the exterior tank surface and protected with metal cladding, brick veneer or other materials to ensure durability and improve the aesthetics. (Greene, 2015).

Furthermore, temperature levels of the digesters, which are usually heated by external sources such as municipal electrical supply or CHP (combined heat and power) units built as part of a biogas plant, are raised to allow for fast decomposition of the material.

Digesters are typically categorised into the following temperature levels:

Psychrophilic: below 25°C

Mesophilic: 25°C – 45°C

Thermophilic: 45°C – 70°C

Some biogas plants with several digesters in series often use different temperature levels in the digesters. The optimum temperature can only be determined once the feedstock, plant design, desired retention time, decomposition rate, and the type of heating mechanisms are known.

2.4 HEAT DEMAND OF DIGESTERS

Heat is a critical component of digester technology to ensure a stable and efficient process. For mesophilic biogas plants, temperatures generally range from 38°C to 44°C but this is dependent on the feedstock and on the overall process.

The heat demand of the digester will have a big influence on the economic viability of the gas production process. As the heat is generated using electricity from municipal sources or excess fuels from the plant, it can be expected that the cost associated with heat generation accounts for a relatively large proportion of the operational costs of a biogas plant. It will also affect the availability of surplus heat for further processing purposes. The heat demand of the digester is influenced by the ambient temperature and thus by climatic conditions. As can be expected, digesters located in colder climates have a higher heat demand than those located in warmer climates in order to maintain a constant digestate temperature.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

A biogas plant generally has two heat demand phases i.e. at start-up and during continuous operational phases. The initial heat demand is influenced by the specific characteristics of the feedstock, the feedstock mass flow and temperature.

The total heat that is lost during operational periods is the sum of all losses from the different digester surfaces and the digestate output. To calculate the heat losses the heat transfer coefficient must be determined (Equation 1.2). The heat transfer coefficient is a constant ratio between the heat flux (heat loss) through a concrete wall and the temperature gradient between the internal and external surfaces of the wall.

To increase the heat output, heat recovery systems, which also use the heat from the digestate leaving the digester, can be installed. The two most efficient measures to decrease heat losses is through insulation of all digester surfaces (including the floor, the walls and the roof cover) and heat recovery from the digestate.

Rustz et al (2015), developed Equations 1.1 & 1.2 to calculate the heat losses through the various surfaces of an anaerobic digester. With regards to the wall surfaces, these could comprise a combination of concrete and insulation. The equations are derived from the basic one dimensional steady-state equations for conduction and convection. Refer to Chapter 3 for further descriptions of the basic heat transfer equations.

$$Q_{\text{lost}} = A \times U \times \Delta T \times t \quad [1.1]$$

$$U = \frac{1}{\frac{1}{h_i} + \frac{d_1}{k_1} + \frac{d_2}{k_2} + \frac{1}{h_a}} \quad [1.2]$$

Where:-

Q_{lost} = Heat loss through walls, floor and roof [kWh]

A = Heat transfer surface area [m²]

U = Heat transfer coefficient [W/m²K]

ΔT = Difference in temperature between the inside & outside surfaces [K]

t = time [hours]

h_i = Convection heat transfer coefficient inside the digester [W/m²K]

h_a = Convection heat transfer coefficient outside the digester [W/m²K]

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

d_1 = Thickness of 1st layer [m] – generally concrete or steel

d_2 = Thickness of 2nd layer [m] – generally a form of insulation

k_1 = thermal conductivity of 1st layer [W/mK] – generally concrete or steel

k_2 = thermal conductivity of 2nd layer [W/mK] – generally a form of insulation

As the digester heating is influenced by many factors, including climatic conditions, it is difficult to calculate exact figures for the heat demand. (Rustz et al, 2015).

2.5 SUMMARY

To produce biogas of sufficient quantities, the anaerobic digestion process requires the heating of the digestate material for optimum bacteriological function. The costs of producing the heat, which is generated from electricity mainly sourced from external supply, accounts for a large proportion of the operating costs of a biogas facility. In order to minimise these costs, it is crucial that the heat losses are reduced through the various surfaces of the anaerobic digester. For operational reasons, it is important to accurately calculate the heat losses through the various surfaces of a digester. These calculations can be done using equations based on heat conduction theory.

CHAPTER 3 – AN INTRODUCTION TO HEAT TRANSFER THROUGH CONCRETE

3.1 THE MOVEMENT OF HEAT THROUGH PHYSICAL BODIES

All physical substances are made up of molecules and atoms which are always in motion. This motion can be in the form of translation, rotation or vibration. The motion creates heat or thermal energy. The more motion the atoms or molecules have the more heat or thermal energy is produced. Some atoms or molecules move faster than others due to their atomic or molecular composition.

Temperature is an average value of energy for all the atoms and molecules in a system. Temperature is not dependant on how much matter is in a system.

Thermal energy, in the form of heat, generally moves from a region of high temperature to one of low temperature, that is, due to the temperature gradient.

There are three basic mechanisms of thermal movement i.e. conduction, convection and radiation.

Thermal conduction (also called diffusion), is defined as heat transfer by movement or vibrations of free electrons and atoms from one part of the body to another.

Thermal convection is the movement of thermal energy via a gas or liquid under the forces or influences of external processes. Thermal radiation is the emission of thermal energy from matter in the form of electromagnetic waves.

Fourier's law is applicable to heat transfer i.e. the Law of Heat Conduction is stated as - heat transferred through a material is proportional to the negative temperature gradient and to the cross-sectional area through which the heat flows.

The wall of the digester is generally heated equally along its length or circumference. Therefore, heat will mainly flow one-dimensionally from the inside face to the outside face of the wall.

3.2 EQUATIONS OF HEAT TRANSFER

Various equations can be applied to best describe the heat transfer in AD facilities.

Equation 3.1 is a one-dimensional steady state governing equation for conduction and would be applied when a simplistic heat transfer in one direction is required at a single point in time: -

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

$$q''_k = k \frac{dT}{dx} \quad [3.1]$$

where,

q''_k - is the heat flux due to conduction. Heat flux is the rate of heat energy transfer through a given surface (SI = watt) for a unit time.

k - is the thermal conductivity of the material. Thermal conductivity is the rate at which heat passes through a specified material, expressed as the amount of heat that flows per unit time through a unit area with a temperature gradient of one degree per unit distance.

T – is the temperature gradient

dx – is an incremental distance through the specified material in the direction of the thickness.

Equation 3.2 is a three-dimensional transient governing heat transfer equation derived from the Law of Conservation of Energy where the total inflow of heat in a unit time across a certain element must be equal to the total outflow per unit time across a certain element. This equation would apply when the heat transfer in three dimensions is required.

$$\rho c \frac{\partial^2 T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} + k \frac{\partial^2 T}{\partial z^2} + s \quad [3.2]$$

where

ρ - is the density,

c - is the specific heat

k – is the thermal conductivity

T - is the temperature gradient

S – is the internally generated heat per unit volume per unit time

t – is time

x, y, z – are directional parameters of the element.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The initial conditions define the temperature distribution in the element at the initiation of the heat transfer i.e. at $t = 0$. The initial boundary conditions can be shown as: -

$$T(x,y,z,0) = T_0(x,y,z,0) \quad [3.3]$$

Where,

T – is the temperature gradient,

T_0 – is the temperature at initiation.

x, y, z – are directional boundary conditions of the element

0 – is the time boundary condition of the element

Equation 3.4 is a calculation to determine the temperature distribution (∂T) in the element as a result of heat transfer and can be defined at a certain boundary condition (∂u) as:-

$$-k \frac{\partial T}{\partial u} = h_c(T_s - T_f) \quad [3.4]$$

Where,

T_s – is the temperature of the solid surface

T_f – is the temperature of fluid (in the case of liquid retaining structures)

h_c – is the heat transfer coefficient of the element

k – is the conductivity of the element material.

u – is the direction of heat.

(Ahsan, 2011)

The Equations 3.1 to 3.4 form a basis for calculating the heat transfer through an element for given variables such as temperature gradients, directions of heat flow, instances in time, thermal conductivities, etc. The equations can also be manipulated to calculate the variables for known values of elemental and material heat transfer values.

3.3 THEORETICAL MODELLING OF HEAT TRANSFER THROUGH CONCRETE

Using Equation 3.1, the heat transfer through concrete can be calculated if the thermal conductivity, elemental thickness or depth and the temperature gradient through the wall is known.

Furthermore, the study by Lixia et al (2011), derived that the heat transfer through concrete is the sum of the product of the thermal conductivity and volume fraction of the various constituents of concrete. As concrete mainly consists of cement paste, fine aggregate, coarse aggregate and voids filled with either water or air, an equation can be written as follows: -

$$\lambda = k_c\omega_c + k_w\omega_w + k_{fa}\omega_{fa} + k_{ca}\omega_{ca} \quad [3.6]$$

where:

λ = heat flux

k = thermal conductivity of each constituent

ω = volume fraction of each constituent

c denotes cement

w denotes water

fa denotes fine aggregate

ca denotes coarse aggregate.

Lixia et al (2011) referencing Kook-Han et al (2003) noted that the thermal conductivity is mainly affected by the following characteristics of concrete:

- The amount of coarse aggregate,
- The fine aggregate fraction,
- Moisture condition and temperature of elements,
- The density of the concrete i.e. a higher density results in a lower thermal conductivity.

Furthermore, it can be seen that the thermal conductivities of the constituents play a very significant part in the overall heat losses through the concrete and therefore detailed analysis of the individual constituents are required.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

3.4 SUMMARY

The main mechanism of thermal movement through concrete is through conduction which is defined as the transfer of heat through the movement and vibrations of free electrons in a body. Fourier's Law of Heat Conduction is applicable and is stated as "heat transferred through a material is proportional to the negative gradient in temperature and to the cross-sectional area at right angles to the gradient through which the heat flows".

Equations are proposed for the calculation of heat transfer through an element for given variables such as temperature gradient, direction of heat flow, instance in time, thermal conductivity.

Heat transfer through concrete is identified as the sum of the product of the thermal conductivity and volume fraction of the various constituents of concrete. The constituents consist mainly of cement paste, fine aggregate, coarse aggregate and voids filled with either water or air.

CHAPTER 4 - THERMAL CONDUCTIVITY OF THE CONSTITUENTS OF THE CONCRETE AND WALL

4.1 THE THEORY OF THERMAL CONDUCTIVITY IN CONCRETE

The thermal conductivity of concrete is strongly dependent on the moisture content; the porosity of the cement paste and on the type and quantity of aggregate. Thus, it is dependent on the conductivities, types and volumes of the individual constituents of the concrete mixture as indicated in Chapter 3.

In order to obtain an effective conductivity of the concrete mixture, the principle of effective-medium approximation (EMA) in the theory of inhomogeneous materials can be adopted. An example of such a model is a simple mixing rule such as that described by Bruggeman (1935):

$$K^n = \sum_i v_i k_i^n \quad [4.1]$$

where

K = effective thermal conductivity the overall material.

v = volume fraction of component i .

k = thermal conductivity of component i .

n = dimensionless constant with a value between -1 and +1. Reasons for the variation of this exponent is if the multi-component laminate materials are in parallel or series form. A parallel model is obtained by applying the temperature gradient along the plane of contact of the materials whereas in a series model, the temperature gradient is perpendicular to the plane of contact. The parallel model (+1) represents the upper bound and the series model (-1) the lower bound of the thermal conductivity of the multi-component material.

A more general equation for a multi-component material developed by Wang et al (2007) is:

$$K = \frac{\sum_{i=1}^m k_i v_i \frac{d_i \tilde{k}}{(d_i - 1)\tilde{k} + k_i}}{\sum_{i=1}^m v_i \frac{d_i \tilde{k}}{(d_i - 1)\tilde{k} + k_i}} \quad [4.2]$$

Where:

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

\tilde{k} is the effective conductivity of the overall medium and therefore = K

k_{i-m} is the conductivity of the individual component.

V_{i-m} is the volume fraction of the individual component

m is the number of components in the material,

d = 3 for spherical particles.

Another model that is widely used in literature is the Maxwell-Eucken model and is a special case of the Effective Medium Theory (EMT) (see section 4.2). In the Maxwell-Eucken model, small particles are dispersed in a continuous matrix of a different component. The particles form a discontinuous phase and are far enough apart not to interfere with their “neighbour’s” temperature distribution. There are two forms of the equations depending on which component is the continuous phase (i.e., if the thermal conductivities of the two components are not similar then quite different results will be obtained depending which is taken as the continuous phase.

Cement, as a solid material, has a thermal conductivity based on the individual volume fractions of its constituents i.e. limestone, shale / clay and gypsum.

However, due to the reactions between cement and water and the subsequent hydration process, the thermal properties should be based on the hydrated binder phase as opposed to the individual constituents.

Research by Qomi et al (2015), indicates that the homogenized thermal conductivity of cement paste can be indirectly expressed in terms of hydration degree and the thermal-conductivity values of individual constituents. The thermal conductivity of cement paste decreases with increasing hydration degree. This is because thermal conductivity values of clinker constituents are higher than those of hydration products (CSH and CH). The macroscopic thermal-conductivity values should decrease with increasing w/c ratio in later stages of hydration. While the volume fraction of portlandite decreases with increasing w/c ratio, the volume fraction of unreacted water increases. If we consider that the thermal conductivity of bulk water is less than that of portlandite, then it would make sense that the thermal conductivity of cement paste at macroscale decreases with increasing w/c ratio.

By applying the principle of effective-medium theory (EMT), the effective thermal conductivity of the cementitious paste can be determined more accurately.

4.2 EFFECTIVE MEDIUM THEORY (EMT)

The EMT, which was first developed by Landauer (1952) and further described by Hochstein (2013), is an ideal method of determining the effective thermal conductivity (ETC) of cement paste. The theory assumes that the distribution of different materials in the composite is random and evenly dispersed.

Diagrammatically, the distribution of the material can be shown as:



Figure 2: Diagrammatical Representation of the binder paste structure (Tuson and Charman, 2012)

For a composite of n materials, the equation for the ETC can be shown as:

$$\sum_{i=1}^n \phi_i \frac{k_{EMT} - k_i}{k_i + 2k_{EMT}} = 0 \quad [4.3]$$

Where:

k_{EMT} is the effective conductivity of the overall medium and therefore,

k_{i-n} is the conductivity of the individual component,

ϕ_{i-m} is the volume fraction of the individual component,

n is the number of components in the material.

With the main hydrating paste ingredients making up the paste being cement, water, corex slag and a lignosulphonate water reducing admixture, the ETC can be derived from the properties of these materials using Eq. 4.3.

Research by Fu and Chung (1999) showed that various admixtures decrease the thermal conductivity of cement paste. However, the study did not specifically include the use of lignosulphonates as a water-reducing admixture. The water-

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

reducer dissolves completely in the water and owing to the limited research on the effects of lignosulphonate admixtures on the cement paste, this dissertation will disregard any reduction in the ETC that the water-reducer might effect.

4.3 THE CONSTITUENTS OF CONCRETE USED IN THE STUDY

As part of this study, the New Horizons Waste to Energy Facility, situated in Athlone, Cape Town, was used as a physical source for obtaining experimental data and as a basis for the theoretical and computational modelling of the various reinforced concrete structures of an anaerobic digester facility.

The facility consists of two large anaerobic digesters tanks and smaller pre-digester and centrate storage tanks. Refer to Appendix 3 for a basic layout of the tanks. The tanks have reinforced concrete walls of varying thickness and volumes of steel reinforcement. This study focuses on the heat transfer properties of the reinforced concrete walls of the digester tanks.

The concrete mix constituents used for the tanks are indicated in Table 1: -

Table 1. Concrete Constituents for New Horizons – per m³

Concrete Mix Code	19mm Grey-wacke Stone (kg)	Crusher Sand form crushing process of Grey-wacke (kg)	Philippi Dune Sand (kg)	CEM II /A-L (kg)	Corex Slag (kg)	Mid-range water reducing admixture (ml)	Water (L)	Total binder Content (kg)	w/b ratio
40/19	1170	308	443	241	103	722	181	344	0.53
Volume Fraction	0.517	0.136	0.196	N/A	N/A	N/A	0.181	0.152	

The reinforcement has mainly been designed for the flexural requirements of the walls and therefore varies dependent on its location on the wall. The location for the

physical testing for heat loss on the wall was dependent on suitable access and this therefore determined the exact reinforcement type, size and spacing for the theoretical modelling.

4.4 THE THERMAL CONDUCTIVITY OF THE BINDER PASTE

The binder used for the concrete walls consisted of a blend of cement and ground granulated corex slag. The blend was a 70/30 mix of cement / corex slag.

4.4.1 THE INFLUENCE OF CEMENT ON THE THERMAL CONDUCTIVITY OF THE BINDER PASTE

The cement is a plain Portland Cement blended with approximately 9% of ground limestone. Based on the report by Naik et al (2003), in their research on the effects of limestone fillers in cement and concrete, it was found that the limestone adds finer particles to the cement paste, thereby filling the pores between the cement particles. Limestone filler has been effective in reducing the porosity and subsequent diffusion coefficient of chloride ions in concrete. Although very little research has been conducted on the effects of limestone fillers on the thermal conductivity of concrete, it can be deduced that due to the reduction in porosity, thermal conductivity would also be reduced.

Although the thermal conductivity of dry Portland cement is generally reported to be 0.29 W/mK, the ability of cement to hydrate in contact with water results in a changing microstructure of the resultant cement paste, altering the original properties of the constituent cement and water.

Hydrated cement paste can have a microstructure which depends on the local changes which occur around individual cement grains during hydration. The resulting microstructure for a given paste will depend on:

1. The phases present and their distribution within the grains. The phases are crystalline and amorphous, viz. alite (C_3S), belite (C_2S), portlandite (CH) and calcium silicate hydrates (CSH), where S, C, and H, respectively, stand for SiO_2 , CaO, and H_2O in cement chemistry notation.
2. The grain-size distribution.
3. The degree of hydration (related to age, moisture state, and temperature).
4. The water / cement ratio.

The phases and grain size are determined by the character of the cement powder and, together with the degree of hydration, are particularly important in determining the distribution of the C-S-H product in the microstructure. The water / cement ratio determines the amount of initial water-filled space in the fresh cement pastes. For a w/c of 0.5, this is about 60% initially. CSH gel is regarded as an isotropic and homogeneous material at an engineering scale, comprising gel porosity and paste holding anhydrous cement clinker and other hydration products together. This is consistent with a composite view of cement paste.

Based on the research of Qomi et al (2015), the thermal conductivity of CSH paste at microscale is affected by the packing density and the saturation level of the CSH mesopores (pores with diameters between 2 and 50 nm). They indicate that the macroscopic thermal-conductivity values should decrease with increasing w/c ratio in later stages of hydration. Their numerical models indicate thermal conductivities of CSH between 1.05 – 1.45 W/mK for w/c ratios between 0.5 – 0.3. Typically, the CSH phase makes up approximately 90% of the cement phases and therefore it can be postulated that the thermal conductivity of the hydrated cement paste is equivalent to that of the CSH.

4.4.2 THE INFLUENCE OF COREX SLAG ON THE THERMAL CONDUCTIVITY OF THE BINDER PASTE

Corex slag is a ground granulated slag produced by the direct reduction iron process at the Saldanha Steel Plant in the Western Cape. The molten slag is quenched with water and forms sand-like glassy particles. Slag consists mainly of silica and alumina derived from iron ore, with lime added as a fluxing agent. The Corex slag is ground much finer than Portland cement. Corex slag undergoes hydration similar to ordinary cement but at a slower rate. It significantly improves the durability of the concrete, particularly reducing permeability and providing greater chloride resistance for structures in aggressive environments (Alexander et al 2003).

Based on the work done by Mills et al (2011), the thermal conductivity of unhydrated glassy slags can be calculated from models derived from their ongoing research. They have found that the thermal conductivity of glassy slags reduces as the temperature increases. Based on the specific chemical composition of the corex slag sourced from the Saldanha Steel Plant, the thermal conductivity of the glassy slags range between 0.66 to 0.96 W/mK for a temperature range between 10 to

35°C. The glassy slag is ground into powdered form and blended with the CEM II A-L cement.

However, the slag reacts in the presence of alkalis released by the cement hydration, in the presence of water. The alkalis are mainly calcium hydroxide $[\text{Ca}(\text{OH})_2]$ or CH in cement notation] which is the by-product of the hydration of cement, but also NaOH, and KOH, both high alkalinity metal hydroxides. Both slag and cement hydrate but at different rates and therefore the effective thermal conductivity of the hydrated product should be considered.

4.4.3 THE THERMAL CONDUCTIVITY OF THE HYDRATED PHASES

Zhang et al (2016), in their study of slag / cement blended concrete, derived a numerical model to evaluate compressive strength development at various curing temperatures. In this study, they calculated the gel-space ratios of hardening concrete using the reaction degrees of cement and slag. The gel-space ratio is defined as the ratio of the volumes of cement reaction products to the sum of the volumes of the hydrated cement and of the capillary pores. For cement / slag blends, the reaction products of binders consist of cement hydration products and slag reaction products.

The degree of reaction of slag is dependent on the following factors: -

- slag replacement ratios
- water to binder ratios
- curing temperatures
- Blaine surface fineness
- age of reaction

Iyoda et al (2011), measured the various degrees of slag reaction taking the above factors into consideration. From the results of a slag / cement blend having the following characteristics (with the corresponding values for the binder used at New Horizons shown in ()): -

- Slag replacement of 30% (30%)
- $w/b = 0.5$ (0.53)
- curing temperature at 20°C (21°C average)
- Blaine surface fineness of 400m²/kg, (467m²/kg for Corex slag)

the reaction degree of slag was 60% at 45 days, therefore 40% of slag remains unreacted. The characteristics of the slag / cement blend used in the study is very similar to those of the binder used at New Horizons and the reaction degree will therefore be adopted.

For the degree of hydration of cement, Neville (2011), produced a graph estimating the percentage of hydrated cement from the water / cement ratio of paste. For a w/c of 0.75, the degree of cement hydration is 100%. Applying a weighted average to the degrees of reaction / hydration based on the blend proportions of 70/30 cement to slag, results in an overall degree of hydration equivalent to 88% at 45 days.

Yang et al (2012), in their study of the effects of alkaline solutions on the engineering properties of alkali-activated ground granulated blast furnace slag paste, found that the thermal conductivity of the slag reactant is affected by the dosage of the alkaline solution. Using a combination of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solution in varying quantities, the thermal conductivity of the slag paste varied between 0.585 and 0.773 W/mK.

These values are generally lower than the predominant CSH phase of the binder paste and will reduce the effective thermal conductivity of the binder paste.

4.4.4 THE EFFECTS OF POROSITY ON THE BINDER PASTE

Based on the work by Hochstein (2013), the total porosity of the cement paste is the sum of the capillary pores and the gel pores. The four relevant components of binder paste are the unhydrated binder grains, the solid portion of the binder gel, the gel pores, and the capillary pores.

Hochstein uses Hansen's Model (1986) to calculate the following:

Volume fraction of unhydrated binder (Φ_{uc}):

$$\Phi_{uc} = \frac{0.32(1-\alpha_h)}{\frac{w}{b}+0.32} \quad [4.4]$$

Volume fraction of solid portion of binder gel (Φ_{cgs}):

$$\Phi_{cgs} = \frac{0.49\alpha_h}{\frac{w}{b}+0.32} \quad [4.5]$$

Volume fraction of gel pores (Φ_{pg}):

$$\Phi_{pg} = \frac{0.19\alpha_h}{\frac{w}{b}+0.32} \quad [4.6]$$

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Volume fraction of capillary pores (Φ_{pc}):

$$\Phi_{pc} = \frac{\frac{w}{b} - 0.36\alpha_h}{\frac{w}{b} + 0.32} \quad [4.7]$$

Volume fraction of total pores (Φ_p):

$$\Phi_p = \Phi_{pc} + \Phi_{pg} = \frac{\frac{w}{b} - 0.17\alpha_h}{\frac{w}{b} + 0.32} \quad [4.8]$$

Volume fraction of binder gel (Φ_{cg}):

$$\Phi_{cg} = \Phi_{cgs} + \Phi_{pg} = \frac{0.68\alpha_h}{\frac{w}{b} + 0.32} \quad [4.9]$$

where $\frac{w}{b}$ is the water binder ratio,

α_h is the degree of hydration of the binder ($0 \leq \alpha_h \leq 1$)

Due to the sample concrete having a water / binder ratio of 0.53 and from 4.4.3, the binder is 88% hydrated i.e. $\alpha_h = 0.88$, the following volume fractions apply: -

- $\Phi_{uc} = 0.045$
- $\Phi_{cgs} = 0.507$
- $\Phi_{pg} = 0.197$
- $\Phi_{pc} = 0.251$
- $\Phi_p = 0.448$
- $\Phi_{cg} = 0.704$

Transport of water is generally through the pore system of the cement paste, particularly near the aggregate-paste interface. However, despite the higher porosity at the interfacial zone, it is generally found that water movement in concrete is predominantly controlled by the bulk of the hardened cement paste, which is the only continuous phase in concrete.

The percentage of capillary pores that is filled with water, can be calculated using the diagram compiled by Neville (2011) and further shown in Appendix 4. Based on a w/b ratio of 0.53 and hydration degree of 88%, the following volume fractions apply: -

- $\Phi_{uc} = 0.060$ (unhydrated binder) close to the 0.045 by Hansen

- $\Phi_{cgs} = 0.542$ (hydrated solid products) close to the 0.507 by Hansen
- $\Phi_{gw} = 0.211$ (Gel Water)
- $\Phi_{cw} = 0.134$ (Capillary Water)
- $\Phi_{ecp} = 0.062$ (Empty Capillary Pores)

4.4.5 EFFECTIVE THERMAL CONDUCTIVITY OF THE BINDER PASTE

The thermal conductivities of the various constituents of the binder paste are as follows: -

- From 4.4.1, the thermal conductivity of the hydrated cement paste is derived from the that of the CSH. Therefore k_{hcp} (hydrated cement paste) = 1.01 W/mK. From 4.4.2, the thermal conductivity of the slag reaction product is equivalent to an average value for k_{sr} (slag reactant) = 0.679 W/mK. Using a weighted average for the thermal conductivity of the hydrated binder products, therefore $k_{hbp} = \underline{0.911}$ W/mK.
- k_w (water) = 0.615 W/mK (for water temperature at an average 30°C).
- k_a (air) = 0.026 W/mK (for air temperature at average 30°C)
- From 4.4.1, k_{uc} (unhydrated cement grains) = 0.29 W/mK. From 4.4.2, k_{us} (unhydrated slag) = 0.81 W/mK. Using a weighted average for the thermal conductivity of the unhydrated binder products, therefore $k_{ubp} = \underline{0.446}$ W/mK.
- k_{wr} (water reducer) will be ignored as not enough information is available to satisfactorily determine the conductivity, although it is known that water reducing admixtures reduce the overall concrete conductivity.

The volume fractions for each constituent are taken from Neville in 4.4.: -

- From 4.4.4, the volume fraction of hydrated binder paste $\Phi_{hbp} = \Phi_{cgs} + \Phi_{pg} = 0.542 + 0.211 = \underline{0.753}$.
- From 4.4.4, the volume fraction of unhydrated binder paste $\Phi_{ubp} = \Phi_{uc} = \underline{0.060}$.
- From 4.4.4, volume fraction of capillary pores (Φ_{pc}) filled with water is = 0.134.
- The volume fraction of air = 0.062.
- Φ_{wr} will be ignored as described above.

Table 2: Thermal Conductivities and Volume Fractions of the Binder Paste Constituents

Binder Phases	Thermal conductivity (W/mK)	Volume Fraction
Hydrated binder paste (k_{hbp}), (Φ_{hbp})	0.911	0.753
Unhydrated binder paste (k_{ubp}), (Φ_{ubp})	0.466	0.060
Water (k_w), (Φ_w)	0.615	0.134
Air (k_a), (Φ_a)	0.026	0.062

Applying the effective medium theory to the binder paste from Equation 4.3:

$$\sum_{i=1}^n \phi_i \frac{k_{EMT} - k_i}{k_i + 2k_{EMT}} = 0$$

$$\phi_{hbp} \left(\frac{k_{EMT} - k_{hbp}}{k_{hbp} + 2k_{EMT}} \right) + \phi_{ubp} \left(\frac{k_{EMT} - k_{ubp}}{k_{ubp} + 2k_{EMT}} \right) + \phi_w \left(\frac{k_{EMT} - k_w}{k_w + 2k_{EMT}} \right) + \phi_a \left(\frac{k_{EMT} - k_a}{k_a + 2k_{EMT}} \right) = 0$$

$$0.753 \left(\frac{k_{EMT} - 0.911}{0.911 + 2k_{EMT}} \right) + 0.060 \left(\frac{k_{EMT} - 0.466}{0.466 + 2k_{EMT}} \right) + 0.134 \left(\frac{k_{EMT} - 0.615}{0.615 + 2k_{EMT}} \right) + 0.062 \left(\frac{k_{EMT} - 0.026}{0.026 + 2k_{EMT}} \right) = 0$$

Therefore, k_{EMT} for the binder paste = 0.757 W/mK.

4.5 THE THERMAL CONDUCTIVITY OF COARSE AGGREGATE IN CONCRETE

Research has shown that the type, composition, texture, volume fraction, porosity and size of aggregate all affect the thermal conductivity and heat capacity of concrete. The research includes Kim et al (2003), in their experimental research into the effects of the composition, unit weight, texture and size, and Kodide (2010), in the effects of the type of aggregate.

The main factors that influence the thermal conductivity of both the parent rock and the aggregate are its mineralogical composition, porosity, and degree of saturation. During the crushing process, internal cracks may form within the aggregate which would increase its porosity.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Research by Hochstein (2013), shows that the mineral composition found in aggregates greatly influences the thermal conductivity of the aggregate. It can be imagined that aggregate with a high volume of ferrous elements would result in higher thermal conductivities.

The size, shape and texture of the aggregate influences how the heat flux lines behave when they encounter the aggregate and the packing density of the aggregate in the mortar. Aggregates are generally sparingly porous, but large or continuous pores can allow water movement by capillarity, and hence can contribute to sorptivity.

The use of a graded fine aggregate will result in a higher maximum packing fraction than if single-sized aggregate is used. The thermal conductivity of concrete is generally increased by the higher volume fraction of aggregate.

The interfacial transition zone (ITZ) refers to the region around aggregate particles which have different properties than the bulk cement paste. The ITZ forms due to the inability of the unhydrated cement grains to pack tightly around the surface of the aggregate. This could lead to micro-structural cracking, higher porosity and reduced bonding in the ITZ. The properties of the ITZ are dependent on the size of the largest unhydrated cement grain, the roughness of the aggregate, and the overall water-cement ratio of the cement mortar. The ITZ is further covered in Chapter 5.

The aggregate composition used for the construction of the concrete tanks at the New Horizons Facility consisted of the following: -

- 19mm Stone Meta-greywacke (Hornfels) with RD = 2.7 (1170 kg/m³)
- Crusher Sands Meta-greywacke (Hornfels) with RD = 2.7 (308 kg/m³)
- Dune Sand - quartzose with significant shell fragments (443 kg/m³)

Meta-greywacke, also known as Malmesbury shale in the Western Cape, is a fine-grained tough rock known for its hardness, dark colour, and generally crushes to an angular shape. It consists of quartz, feldspar, mica and iron oxides. It has a relative density between 2.64 - 2.8, a water absorption of 0.41% and a coefficient of thermal expansion (CTE) of approx. $3.3 \times 10^{-5} / ^\circ\text{C}$ (Robertson, 1998). It is also described as hornfelsic, quartzitic, argillaceous sandstone more commonly referred to as meta-greywacke.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The crusher sands generated by the crushing of greywacke are used to improve the quality of concrete made with Cape Flats dune sand which is commonly lacking in the finer fractions. The finer crusher sands blend well with the dune sand and reduces bleeding of the fresh concrete mix while improving the surface finish and durability of the hardened concrete.

It is important for the aggregate to have a similar thermal expansion to that of concrete paste to ensure that both materials react similarly when heated and cooled to ensure homogeneity. Meta-Greywacke has a CTE that is similar to that of concrete at 60% volume fraction of aggregate.

The porosity of the aggregate is important to reduce the intake of “free” water (absorption) and hence alter the particle density and thermal conductivity of the aggregate. Meta-greywacke has a relatively low absorption which should not materially affect the thermal conductivity of the aggregate. However, fissures and cracks mainly due to the crushing process could affect the behaviour of the aggregate.

The study by Clauser & Huenges (1995), has shown that the thermal conductivity of rock at room temperature (300K) is influenced by the porosity, presence of fissures, mineralogy, pore fluid, and anisotropy. Robertson (1998), uses an empirical approach which considers the combined effects of porosity, saturating fluid and dominant mineral phase. Plotting measured thermal conductivities of various rocks versus the square of solidity γ (where γ is the ratio of volume of solids to the bulk volume, therefore $\gamma=1$ – for no porosity), linear relationships are indicated whose slopes vary with the content of a specific mineral (e.g. quartz, olivine, etc.).

The thermal conductivity of Meta-greywacke is generally influenced by the mineralogy of the rock. Quartz has a higher thermal conductivity than feldspar and iron oxides and therefore the mineral composition is critical in determining the thermal conductivity. Additionally, the purity and temperature of the minerals also has a big influence.

Research by Perold (2006), in evaluating the quality of clays in the northern regions of Cape Town for the manufacture of brick-making material, found that the Malmesbury shale (meta-greywacke) has a quartz content of 78%. Similar studies by Heckroodt (1991) identified clay derived from Malmesbury shales with high quantities of quartz.

An empirical equation (Eq. 4.10) by Robertson (1998), is used to calculate the thermal conductivity of the aggregate.

$$k_a = k_f + \gamma^2[(k_s + \rho S) - k_f] \quad [4.10]$$

where:-

- k_a = thermal conductivity of the aggregate
- k_f = pore fluid intercept at $\gamma^2 = 0$, therefore 0.063×10^{-3} cal/cm.s.deg.C
- γ = the solidity factor, which is equal to 1 - porosity. Porosity is estimated at 1%, therefore $\gamma = 0.99$. Robertson (1998) correlates porosity with bulk density. The meta-greywacke has a bulk density of approximately 2.7 g/cm^3 , therefore the porosity is approximately 1%.
- k_s = solid rock intercept at $\gamma^2 = 1$, therefore 3.5×10^{-3} cal/cm.s.deg.C.
- ρ = % quartz, therefore 78%-0% clay = 78% as indicated by Robertson
- S = slope constant from intercept values of $\gamma^2 = 1$, therefore 0.09.

Using the above formula and research data for shale with pores filled with air as developed by Robertson (26): -

$$k_a = 0.063 + 0.99^2 [(3.5 + (78 \times 0.09)) - 0.063] = 10.31 \times 10^{-3} \text{ cal/cm.s.deg.C or } \underline{4.31} \text{ W/mK.}$$

4.6 THE THERMAL CONDUCTIVITY OF FINE AGGREGATE IN CONCRETE

Fine aggregate for concrete (sand) is generally rich in quartz and should contain negligible amounts of organic material and chlorides. 90 per cent of the sand by mass should be less than 4750 microns with a maximum dust (< 75 microns) content of 5% by mass (South African Bureau of Standards, 2006).

The contribution of fine aggregate to the effective thermal conductivity of the concrete is mainly dependant on the volume fraction and dispersion as the impact of the individual grains are minimal due to the size of each particle but in total, can contribute substantially to the overall thermal conductivity.

Research by Limbachiya et al (2009) found that an increase in the volume fraction of fine aggregate increases the thermal conductivity due to its higher quartz content and greater homogeneous distribution in the concrete matrix.

The sand used for the concrete in the New Horizons Project was sourced from the Philippi open cast mining process where dune sand is mined. This sand forms part of the Witzand Formation and is a coastal aeolian sand (Walker, 2013). The Witzand

aeolian dunes consist of well-sorted, fine to medium grained, cross-stratified, quartzose (high levels) sand, containing fractions (up to 30%) of comminuted marine shell fragments. The dunes are generally composed of grains having sizes smaller than 1,0 mm but larger than 0,1 mm (Fulton, 2009). The grains are sub-rounded to angular.

The sands of the Philippi area are generally formed from the sandstones which are rich in quartz, called arenite sandstones and are characteristic of the Peninsula Formation of the Table Mountain Group. Arenites are types of sandstone that have less than 15% clay between the framework grains. The sandstone grains are composed of quartz, feldspars or rock fragments (Walker, 2013). Quartz arenites are sandstones that contain more than 90% of siliceous (SiO₂) grains (Boggs, 1999). It can be argued that due to the high composition of SiO₂, the effective thermal conductivity of the sand particle will be similar to that of silica i.e. 1.4 W/mK (Lasance, 2004).

These sands, when used together with the hornfels crusher sands, provide a good blend for concrete, improving the grading of the fine aggregate fraction.

4.7 THE EFFECTIVE THERMAL CONDUCTIVITY OF THE CONCRETE WALL

The thermal conductivity of the aggregates can be combined with the TC of the cement paste to produce the effective thermal conductivity (ETC) of the concrete wall.

Using the Effective Medium Theory (EMT) as proposed by Landauer (1952) and Hochstein (2013), the ETC of the concrete can be determined. Adapting Equation 4.3: -

$$\Phi_{bp} \left(\frac{k_{EMT} - k_{bp}}{k_{bp} + 2k_{EMT}} \right) + \Phi_{ca} \left(\frac{k_{EMT} - k_{ca}}{k_{ca} + 2k_{EMT}} \right) + \Phi_{fa} \left(\frac{k_{EMT} - k_{fa}}{k_{fa} + 2k_{EMT}} \right) + \Phi_{cs} \left(\frac{k_{EMT} - k_{cs}}{k_{cs} + 2k_{EMT}} \right) = 0$$

Where: -

- Φ_{bp} = volume fraction of the binder paste,
- k_{bp} = thermal conductivity of the binder paste,
- Φ_{ca} = volume fraction of the coarse aggregate,
- k_{ca} = thermal conductivity of the coarse aggregate,
- Φ_{fa} = volume fraction of the dune sand,

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

- k_{fa} = thermal conductivity of the dune sand,
- Φ_{cs} = volume fraction of the crusher sand,
- K_{cs} = thermal conductivity of the crusher sand.

From Table 1:

- $\Phi_{bp} = 0.152$
- $\Phi_{ca} = 0.517$
- $\Phi_{fa} = 0.196$
- $\Phi_{cs} = 0.136$

From Section 4.4:

- $k_{bp} = 0.757 \text{ W/mK}$

From Section 4.5:

- $k_{ca} = k_{cs} = 4.31 \text{ W/mK}$

From Section 4.6:

- $k_{fa} = 1.4 \text{ W/mK}$

Equation 4.3 can be written as: -

$$0.152 \left(\frac{k_{EMT} - 0.757}{0.757 + 2k_{EMT}} \right) + 0.517 \left(\frac{k_{EMT} - 4.31}{4.31 + 2k_{EMT}} \right) + 0.196 \left(\frac{k_{EMT} - 1.4}{1.4 + 2k_{EMT}} \right) + 0.136 \left(\frac{k_{EMT} - 4.31}{4.31 + 2k_{EMT}} \right) = 0$$

Therefore, k_{EMT} for the concrete unit wall = 2.91 W/mK

4.8 COMPARISONS OF THE THERMAL CONDUCTIVITY RESULTS WITH EARLIER RESEARCH

Previous research into the thermal conductivity of concrete has produced varying results. These variations are mainly due to mineralogical characteristics of the aggregate, the degree of saturation of concrete, increased density and different proportions of the constituents.

Concrete produced with quartzite aggregate i.e. aggregate with over 90% quartz content as opposed to 78% used for the meta-greywacke (Malmesbury shale) in this research, is generally shown to have a thermal conductivity between 3.3 to 3.5 W/mK (Fulton 2009, Neville, 2011).

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

However, as indicated in the research of Hu et al (2009), the thermal conductivity is greatly influenced by the condition and exposure of the concrete to moisture due to water having a higher thermal conductivity to that of air. For quartzite concrete, the thermal conductivity ranges from 2.3 W/mK for dry conditions, 2.7 W/mK for 50% relative humidity to 3.3 W/mK for wet conditions.

In Section 4.4.4, the water content in capillary pores is calculated as 68.3%. Based on the comparisons with Hu et al (2009), it can be assumed that the thermal conductivity of the concrete should be 2.88 W/mK.

The thermal conductivity calculated for the sample concrete in Section 4.7 i.e. 2.91 W/mK, therefore compares well with the research of Hu et al (2009).

4.9 SUMMARY

Concrete comprises of a variety of different constituents which each contribute to the overall thermal conductivity. The constituents used for the concrete at the New Horizons project is cement, corex slag, fine and coarse aggregate.

To determine the thermal conductivity of the binder paste, the hydrating phases of the binder need to be evaluated instead of the individual constituents of the binder i.e. cement, corex slag and water. The Effective Medium Theory (EMT) was used to calculate the effective thermal conductivity of the binder paste i.e. $k_{bp} = 0.757$ W/mK.

The aggregate in concrete has a big influence on the thermal conductivity as the individual volume fractions and thermal conductivities are higher than the binder paste. The higher the mineral content in the aggregate, especially quartz, the higher the thermal conductivity.

The thermal conductivities of the dune sand and crushed aggregates are 1.4 and 4.31 W/mK respectively.

Using the Effective Medium Theory to calculate the overall thermal conductivity of the concrete by applying the various volume fractions and thermal conductivities of the binder paste, fine and coarse aggregates, the effective thermal conductivity is 2.91 W/mK.

CHAPTER 5 – ADDITIONAL FACTORS THAT MAY AFFECT THE THERMAL CONDUCTIVITY OR HEAT TRANSFER CHARACTERISTICS OF CONCRETE

This chapter focuses on the added factors and materials, other than the constituents of concrete, that could influence the thermal conductivity or heat transfer characteristics of concrete.

In section 4.5, the interfacial transition zone between the aggregate and binder paste was stated as potentially influencing the thermal conductivity and heat transfer of concrete. Section 5.1 in this chapter expands on the characteristics of the zone and provides an understanding of how this zone influences the heat properties of concrete.

Steel reinforcement is commonly used on reinforced concrete to improve the flexural and tensile characteristics of concrete. Reinforcement is overwhelmingly produced from ferrous metals which has a very high thermal conductivity. It can therefore be expected that the reinforcement in concrete will substantially increase the thermal conductivity and heat transfer characteristics of concrete. Section 5.2 provides further insight on the impact of reinforcement.

5.1 THE EFFECTS OF THE INTERFACIAL TRANSITION ZONE BETWEEN THE AGGREGATE AND CEMENT PASTE

The interfacial transition zone (ITZ) between the aggregates and cement paste is rich in the finer particles of cement and has a higher water / cement ratio than the bulk of the cement paste (Neville, 2011). This zone also has a higher porosity than the bulk paste.

Although the influence of the ITZ is greatest around the coarse aggregate particles, such a zone, although limited, is also formed around the fine aggregate particles. Even though the thickness of the zone is smaller than with coarse aggregate, the surface effects originating from the fine particles interfere with those of the coarse aggregate and thus affect the overall extent of the ITZ.

Neville (2011) suggests that the ITZ occupies as much as one-third to one-half of the total volume of hardened cement paste. It has a different microstructure from the bulk of the hardened cement paste which could lead to early microcracking with

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

increased permeability of concrete. However, Neville references Larbi (1993) who found that, even though the ITZ has a higher porosity, the permeability of concrete is controlled by the bulk of the hardened cement paste, which is the only continuous phase in concrete, as indicated in Section 4.4.3 on porosity.

Hochstein (2013), states that the TC of the ITZ should be considered when determining the effective thermal conductivity (ETC) of the concrete. Having tested cement mortars with varying volume fractions and particle sizes of fine aggregate, he found the following:

- the ETC of the mortars increases as the aggregate volume fraction increases. This points to the fact that the TC of aggregate is generally higher than the cement mortar.
- If the volume fractions are kept constant, the mortar with the smaller particle size results in a lower ETC. By keeping the volume fraction the same, the number of grains increase with more individual zones and possibly, more interconnected zones. The higher w:c ratio and lower quality of the ITZ's would result in a lower TC and have a significant effect on the ETC of the concrete matrix.

Hochstein references Nadeau (2002) in developing a model that predicts the reduction in thermal conductivity due to the ITZ with that of a bulk cement paste (with no ITZ). This model assumes the aggregate is spherical and considers the size and volume fraction (ϕ) of the aggregate as well as the overall water : binder ratio. However, it does not consider the roughness of the aggregate. r_a is the radius of the aggregate in mm.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

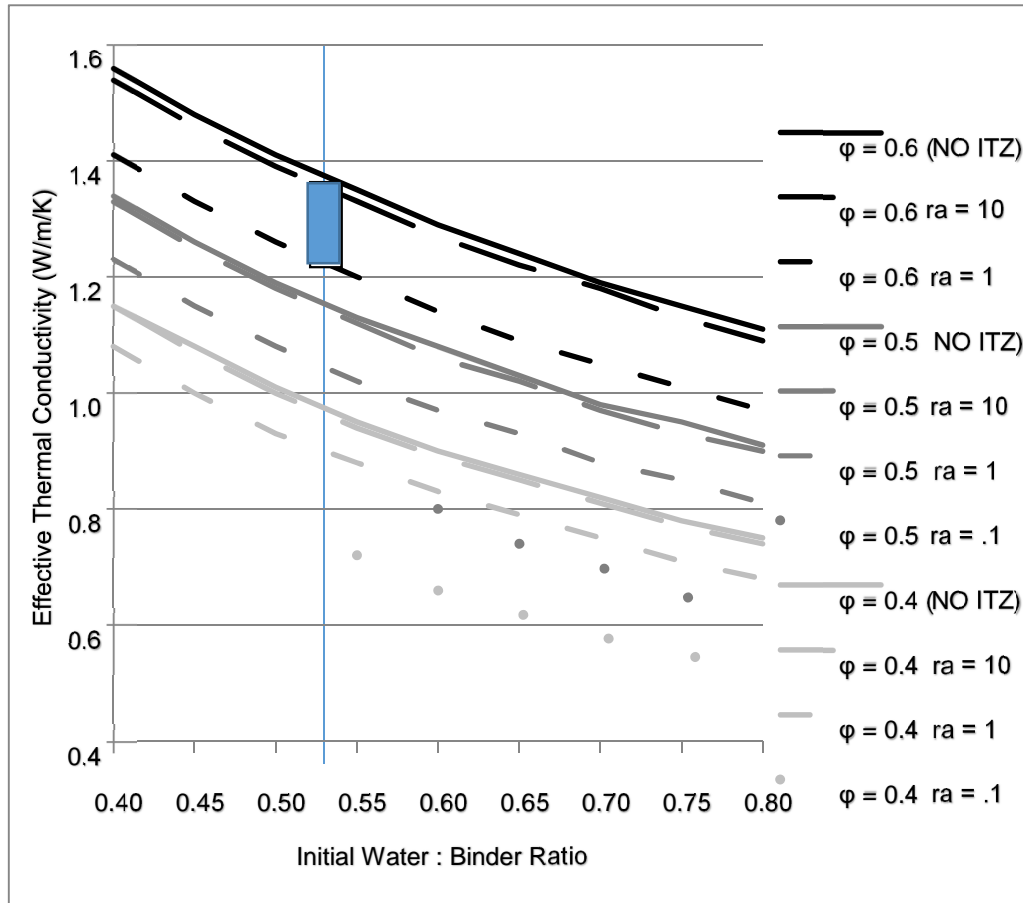


Figure 3: Reduction in the ETC of Cement Mortar Due to the effects of an ITZ

(Adapted from Hochstein (2013))

Hochstein (2013) notes that Fig. 3 should be used as a guide to determine the reduction of the thermal conductivity of the bulk cement paste due to the effects of the ITZ.

From Table 1 - the volume fraction of total aggregate = 0.676. The water : binder ratio is 0.53.

From Fig. 3 - For aggregate of 20mm (10mm radius) – the reduction of the ETC due to the ITZ is approximately 0.01 W/mK.

From Fig. 3 - For aggregate of 2mm (1mm radius), the reduction is approximately 0.15 W/mK.

Therefore, it can be deduced that the effects of the ITZ on this concrete sample would be less than 0.15 W/mK and therefore can be practically ignored.

It is therefore postulated, that the effects of the ITZ on the effective thermal conductivity of concrete is not significant and that porosity, in the form of the capillary pores in the hardened cement paste is the biggest contributor to the permeability and subsequent thermal conductivity of concrete.

5.2 THE EFFECTS OF REINFORCEMENT ON HEAT TRANSFER IN CONCRETE

Studies by Kanbur et al (2013) have shown that the inclusion of steel reinforcement in concrete has a significant influence on the thermal conductivity of concrete.

The study used three vertical concrete slabs, with a width x height x thickness of 500x500x100mm. The concrete of the three samples was a standard 30MPa grade. The samples differed in the following way: -

- Sample 1 had no reinforcement.
- Sample 2 had 12 No. of 10mm bars spaced at 100mm centre parallel to the heat direction. This equates to 3770mm²/m².
- Sample 3 had 12No. of 12mm bars spaced at 100mm centre parallel to the heat direction. This equates to 5428mm²/m².

The study showed that the thermal conductivity of Sample 2 increased by approximately 4.8% over Sample 1. Sample 3 increased by approximately 9.9% over Sample 1. If the results are viewed simplistically, it can be deduced that the increase in thermal conductivity of Sample 2 over Sample 1 is at a rate of 0.00127%/mm²/m² and Sample 3 over Sample 1 is at 0.00182%/mm²/m².

The study also showed that the size and volume of reinforcement further influences the heat transfer. It can further be deduced from the study that the position and direction of the reinforcement i.e. parallel to the direction of heat transfer will greatly increase the rate of heat transfer from the heated to the non-heated surface.

The study indicated that the inclusion of steel reinforcement increases the thermal conductivity between 3 – 10% over that of plain unreinforced concrete.

A study by Adeyanju and Monahar (2011) have shown that the inclusion of steel fibres greatly increases the thermal conductivity of concrete.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The extent of the increase of heat transfer is dependent on the size and length of the fibres and the ratio of fibres to concrete. The proper mixing and batching of the fibres into the concrete to ensure adequate dispersion will influence the quality of the concrete including its thermal conductivity.

The study indicated that the inclusion of steel fibres increases the thermal conductivity by 45 – 90% over that of plain unreinforced concrete for a fibre / concrete ratio of 0,66%.

The concrete wall at New Horizons does not have any fibres, only flexural reinforcement. The size and spacing of the reinforcement is dependent on the flexural requirements but is mainly placed perpendicular to the wall thickness i.e. perpendicular to the direction of heat transfer. A minimal amount of reinforcement in the form of links (to maintain the reinforcement spacing and position) are placed at 800mm centres and these are placed in the direction of heat transfer. This is equivalent to $122\text{mm}^2/\text{m}$ and if multiplied by the average rate of increase in thermal conductivity i.e. $0.0015\%/ \text{mm}^2/\text{m}$, then the increase in thermal conductivity due to the reinforcement in the wall is equal to 0.19% which is negligible and can be ignored.

5.3 SUMMARY

The effects of the interfacial transition zone (ITZ), situated around the coarse and fine aggregate, on the thermal conductivity of the concrete is found to reduce the effective thermal conductivity of the concrete by an insignificant amount and therefore can be disregarded.

Additionally, the effects of reinforcement on the thermal transfer properties of concrete, if positioned and aligned in the direction of the thermal gradient would have a significant effect on the thermal conductivity. It was found to increase heat transfer by 3-10%. Furthermore, steel fibres also increase the thermal conductivity as much as 45–90% and is dependent on the fibre dosage, length and dispersion in the concrete matrix. However, in the concrete tank walls used at New Horizons, the lack of fibres and general alignment of the reinforcement has resulted in the effects on the thermal properties being insignificant at 0.19%.

CHAPTER 6 – SITE MEASUREMENTS, CALCULATIONS & COMPUTATIONAL MODELLING OF HEAT LOSS

6.1 HEAT LOSS THROUGH THE CONCRETE WALL

The anaerobic digester (AD) tanks are generally of a circular form storing heated liquid digestate. At New Horizons, the digestate is heated to a constant 40°C. The walls are 350mm thick. Other than heat escaping directly through the wall, it can also escape via leaks between the PVC roof and the wall and pipes inserted through the wall.

As the focus of this research is only on the direct heat losses through the walls, Eq. 1.1 & 1.2 can be re-written as Eq. 6.1 & 6.2 for heat loss through concrete walls with the part associated with the losses through insulation omitted from this calculation.

$$Q_{\text{lost}} = A \times U \times \Delta T \times t \quad [6.1]$$

$$U = \frac{1}{\frac{1}{h_i} + \frac{d_1}{k_1}} \quad [6.2]$$

Where:-

Q_{lost} = Heat loss through the digester wall [Wh]

A = Heat transfer surface area [m²]

U = Heat transfer coefficient [W/m² °C]

ΔT = Difference in temperature at concrete faces i.e inside / outside [°C]

t = time [hours]

h_i = Convection heat transfer coefficient of air (as heat remains in the system while still in the wall but is lost when it escapes into the atmosphere) = 10 W/m²K for air that is relatively still.

d_1 = Thickness of concrete wall = 0.35m

k_1 = thermal conductivity of the digester concrete = 2.91 W/mK

Therefore,
$$U = \frac{1}{\frac{1}{10} + \frac{0.35}{2.91}} = 4.54 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

Sections 6.2, 6.3 and 6.4 cover heat flux measurements and calculations from the New Horizons Project.

6.2 MEASUREMENTS AT NEW HORIZONS PROJECT

Measurements were taken at the New Horizons Project to determine the actual temperature gradients leading to the calculation of the heat losses. This was done in mid-winter 2017 (June – August) to obtain the lowest external ambient temperatures thereby providing the clearest indication of heat losses. The internal digestate material is regulated by heating systems to ensure a constant temperature of 40°C.

Four areas were identified where the external concrete surface of the wall is exposed. Refer to Appendix 3 for a diagram of the tank layout and measurement positions. Two of the areas were in a pump room with internal ambient temperatures ranging between 19 – 25°C and two were external with ambient temperatures between 13 – 18°C. The equivalent wall temperatures range between 28 - 31°C in the pump room and 24 – 28°C for the external positions which clearly indicates the heat losses between the digestate and the external surface of the wall.

The temperature measurements were completed using an infrared thermometer which measures the temperature at the wall's surface. Infrared thermometers use lenses or mirrors and a filter which selects the wavelength range over which the thermometer is sensitive. The radiation is focused onto a detector whose output indicates the intensity of the radiation and hence the temperature. The detector is a 'thermal-detector' which senses the temperature rise produced by the energy absorbed. The instrument's degree of accuracy is +/- 1.5°C for the temperature range 0 - 500°C.

6.2.1 TEMPERATURE MEASUREMENTS AT NEW HORIZONS

From the measurements of the temperatures at the various surfaces and positions, the following calculations were done to determine the heat losses through the concrete wall (the measurements of 23 June 2017 are used as an example of the calculations): -

- Temperature difference between digestate and the external face of the wall. For Area 1 on 23 June 2017, this is equivalent to $40^{\circ}\text{C} - 28.1^{\circ}\text{C} = 11.9^{\circ}\text{C}$.
- Temperature difference between external face of the wall and the ambient temperature. For Area 1 on 23 June 2017, this is equivalent to $28.1^{\circ}\text{C} - 19.6^{\circ}\text{C} = 8.5^{\circ}\text{C}$.
- Heat Loss (q) using Equations 1 & 2. For Area 1 on 23 June 2017, using a U of 4.54 W/m² °C, $q = 1 \times 4.54 \times 11.9 \times 1 = 54.03 \text{ W/m}^2\text{h}$.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The following temperatures were measured at the New Horizons Facility and the subsequent heat losses calculated and reflected in Table 3.

Table 3: Table of Temperature Measurements and Heat Losses

TEMPERATURE MEASUREMENTS AT NEW HORIZONS										
Date	Time	Area	Internal External	Temp: Wall	Temp: Amb	Temp: Digest. 1	Temp: Digest. 2	Diff: Digest. Wall (°C)	Diff: Wall - Amb. (°C)	q _k (W/m ² .hr)
23-Jun	12:00	1	Internal	28.1	19.6	40.0		11.9	8.5	54.0
23-Jun		2	external	24.1	13.6	40.0		15.9	10.5	72.2
23-Jun		3	Internal	-	19.6		40.0	-	-	
23-Jun		4	external	-	13.6		40.0	-	-	
29-Jun	17:45	1	Internal	31.1	24.8	40.0		8.9	6.3	40.4
29-Jun		2	external	27.2	15.2	40.0		12.8	12.0	58.1
29-Jun		3	Internal	28.3	24.8		40.0	11.7	3.5	53.1
29-Jun		4	external	24.7	15.2		40.0	15.3	9.5	69.5
03-Jul	13:30	1	Internal	28.0	22.6	40.0		12.0	5.4	54.5
03-Jul		2	external	25.1	17.1	40.0		14.9	8.0	67.6
03-Jul		3	Internal	25.7	23.0		40.0	14.3	2.7	64.9
03-Jul		4	external	25.4	17.5		40.0	14.6	7.9	66.3
14-Jul	07:45	1	Internal	30.1	20.4	40.0		9.9	9.7	44.9
14-Jul		2	external	24.0	9.1	40.0		16.0	14.9	72.6
14-Jul		3	Internal	28.0	20.1		40.0	12.0	7.9	54.5
14-Jul		4	external	24.9	9.1		40.0	15.1	15.8	68.6
18-Jul	18:00	1	Internal	27.5	21.0	40.0		12.5	6.5	56.8
18-Jul		2	external	27.1	15.9	40.0		12.9	11.2	58.6
18-Jul		3	Internal	28.0	21.2		40.0	12.0	6.8	54.5
18-Jul		4	external	27.4	15.9		40.0	12.6	11.5	57.2
24-Jul	18:15	1	Internal	31.9	24.7	40.0		8.1	7.2	36.8
24-Jul		2	external	27.5	16.1	40.0		12.5	11.4	56.8
24-Jul		3	Internal	27.5	24.4		40.0	12.5	3.1	56.8
24-Jul		4	external	28.4	16.1		40.0	11.6	12.3	52.7
21-Aug	14:00	1	Internal	28.2	24.0	40.0		11.8	4.2	53.6
21-Aug		2	external	23.6	14.2	40.0		16.4	9.4	74.5
21-Aug		3	Internal	27.9	24.0		40.0	12.1	3.9	54.9
21-Aug		4	external	20.6	14.2		40.0	19.4	6.4	88.1
29-Aug	08:00	1	Internal	31.0	22.8	40.0		9.0	8.2	40.9
29-Aug		2	external	24.9	14.8	40.0		15.1	10.1	68.6
29-Aug		3	Internal	28.3	23.0		40.0	11.7	5.3	53.1
29-Aug		4	external	24.6	14.8		40.0	15.4	9.8	69.9

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The temperature differences and heat losses are reflected in the Figures 4-7 for the four areas. From the figures, it can be observed that the larger heat losses are equivalent to the periods with the larger temperature differences, as expected.

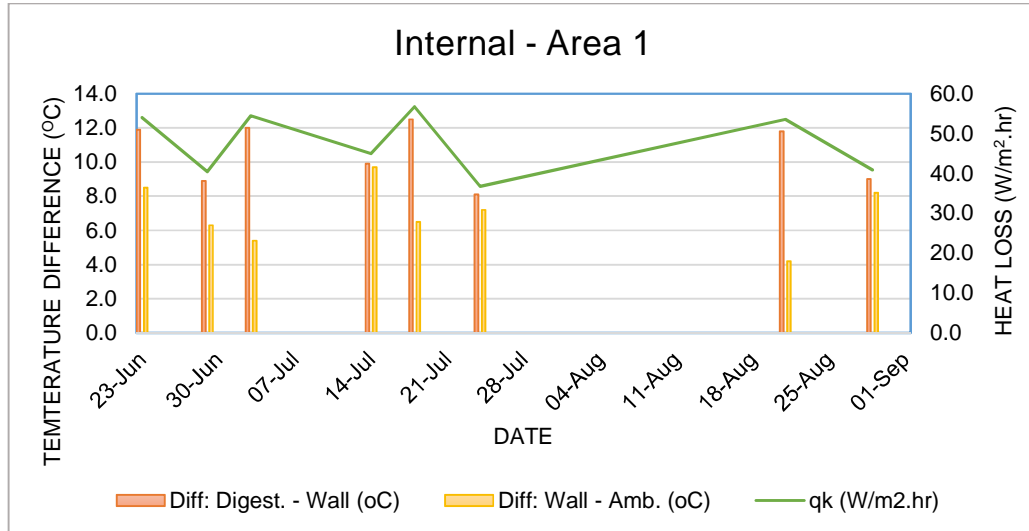


Figure 4: Measurements at Area 1

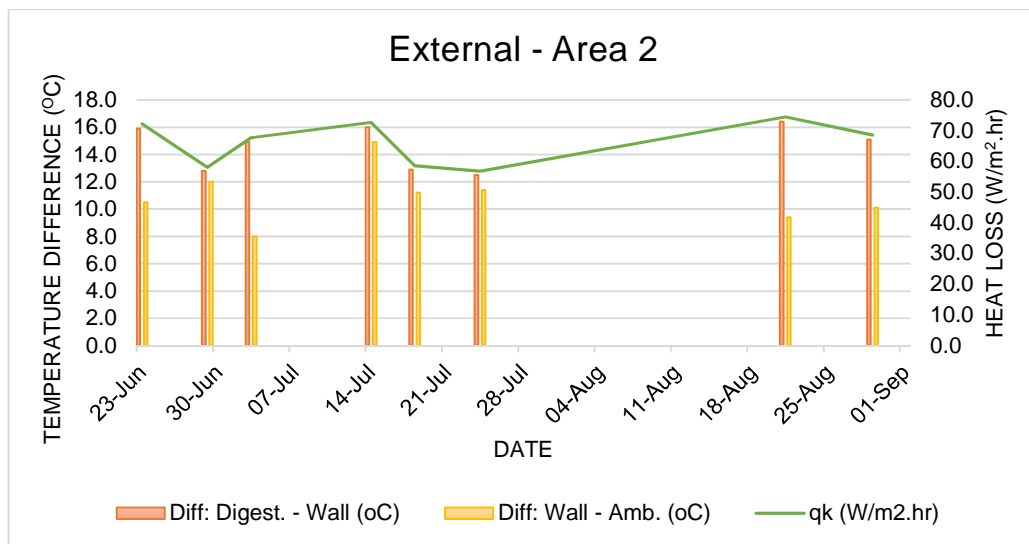


Figure 5: Measurements at Area 2

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

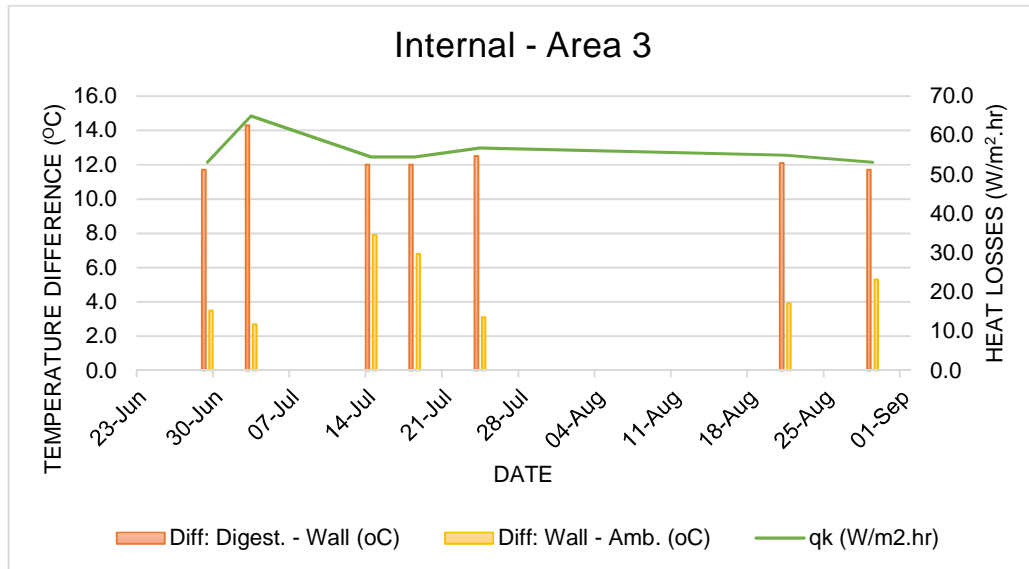


Figure 6: Measurements at Area 3

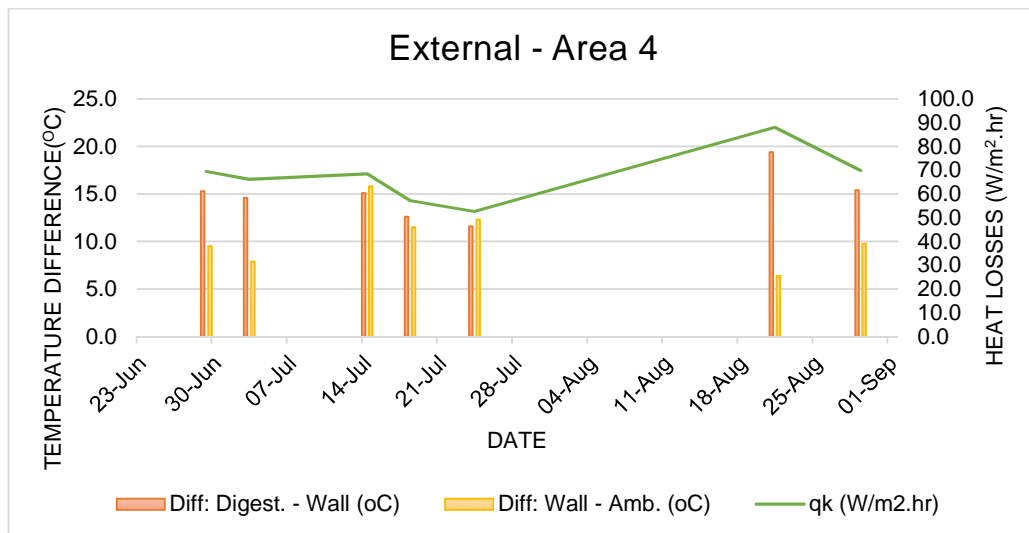


Figure 7: Measurements at Area 4

6.2.2 DISCUSSION OF THE RESULTS

From the results given in the section above, it is apparent that the degree of heat loss (q_k) is dependent on the ambient temperatures that the external surfaces of the tanks are exposed to, as shown in equations 6.1 & 6.2. Surfaces exposed to colder external ambient temperature display higher heat losses than surface exposed to

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

the warmer internal temperatures. The weighted average heat losses for the various areas are shown in Table 4 below.

Table 4: Average Temperature & Heat Loss

Weighted Average Temperature at the Surfaces of the Wall		
Area	Internal / External	Temp (°C)
1	Internal	29.5
2	External	25.4
3	Internal	27.7
4	External	25.1
Average temperature proportionally determined between internal & external surface areas i.e. external surface area = 736.5m ² & internal surface area = 37.5m ²		25.4
Average Heat Loss per Area - q_k (ave)		
Area	Internal / External	q _k (ave) (W/m ² .hr)
1	Internal	45.3
2	External	66.1
3	Internal	56.0
4	External	67.5
Average Heat Loss based on equations 6.1 & 6.2 $Q_k = A \times U \times \Delta T \times t$ with $A=1m^2$, $U=4.54 W/m^2 \text{ } ^\circ C$, $\Delta T=40-25.4=14.6 \text{ } ^\circ C$, $t=1 \text{ hour}$ $U = 1/(1/h_i + d_1/k_1)$ with $h_i = 10 W/m^2K$, $d_1=0.35m$, $k_1=2.91W/mK$		66.28

Refer to Appendix 3 for a diagram of the tank layout and measurement positions.

Digester Tanks 1 & 2 had the following dimensions and temperatures: -

- An internal wall circumference of 102.1m. With a wall thickness of 0.35m. The circumference to the centre of the wall is 103.2m.
- Height of wall in contact with the digestate is 7.5m
- Only 5m of the wall is adjacent to the pump room having internal ambient temperatures, resulting in 98.2m exposed to external ambient temperatures.
- The average temperature on the external surface of the wall is 25.4°C.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

- The average heat loss through the concrete wall is 66.28 W/m².hr.

Therefore, the total heat loss through the full concrete wall is 66.28 x 103.2 x 7.5 = 51 300 W/hr or 51.3kW/hr.

With current electricity tariffs ranging between R1.50 – R2.50 per kW/hr, the cost of additional electricity due to the heat losses through the walls for the two anaerobic digesters could range between R77/hr – R128/hr. Therefore, annual heat loss costs could range between R674 520 and R1 121 280.

It should be noted that the temperature measurements were done in winter where external ambient temperatures are lowest providing bigger temperature gradients. Temperature data for a full year would be required in order to provide a more definitive estimate of heat loss costs for the digester tanks.

6.3 COMPUTATIONAL MODELLING OF HEAT TRANSFER

In order to validate the theoretical model and calculations, a computational heat transfer model was created. The modelling was done using Abaqus CAE finite element software package. The program is ideal for modelling the concrete wall, steady-state temperature profiles at the surfaces and thermal conductivity of the concrete.

6.3.1 INPUT VALUES AND PARAMETERS

A simple elemental computational heat transfer model was constructed in Abaqus CAE to analyse the heat loss through a concrete wall using the same concrete parameters as the theoretical model. The wall was modelled for steady-state conditions. It is expected that the computational model will provide confirmation of the results of the numerical calculations in Chapter 6.

Abaqus applies the Fourier Law for Heat Conduction i.e. $Q = k \frac{\Delta T}{d_1}$ where,

Q = Heat Flux (Loss)

k = thermal conductivity of concrete

ΔT = change in temperature

d_1 = wall thickness

Boundary conditions in the form of the film coefficient and sink temperature is included in the calculation to obtain the heat flux.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

The model consisted of the following inputs: -

- Unit wall size of 1m^2 .
- Wall thickness of 0.35m equivalent to the wall thickness of the tanks at the New Horizons Facility.
- A thermal conductivity value of 2.91 W/mK acting isotropically as calculated in Chapter 4.
- The applied heat on the inside face of the wall of 40°C (temperature of the digestate inside the tank).

A diagrammatical representation of the input data is provided in Fig 8 & 9 below.

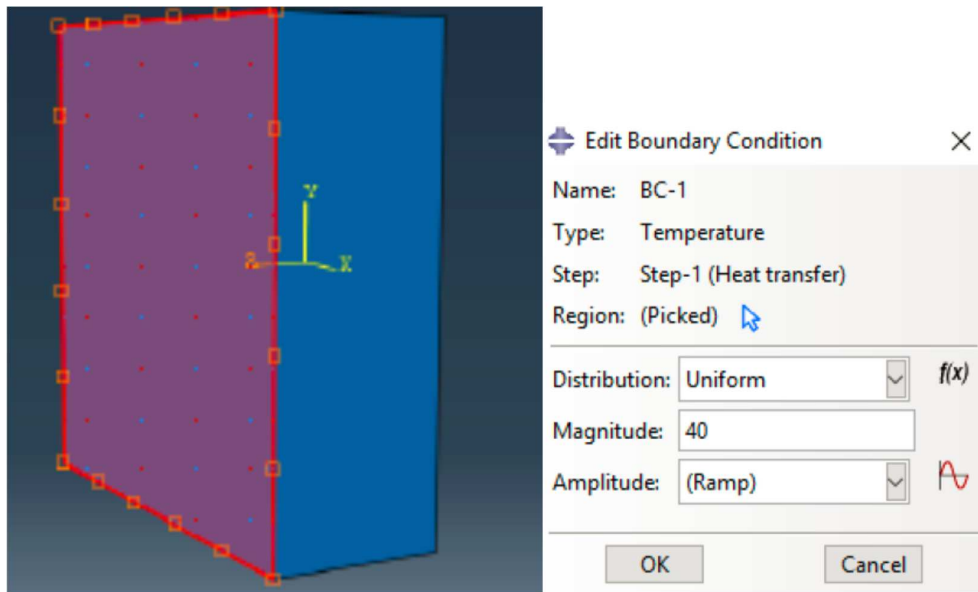


Figure 8: Applied Heat on the Internal Face of the Wall

- The temperature on the outer face using an average of 25.4°C as calculated in Table 5.
- The convective heat transfer coefficient (film coefficient as described in Abaqus) is $10\text{ W/m}^2\text{K}$.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

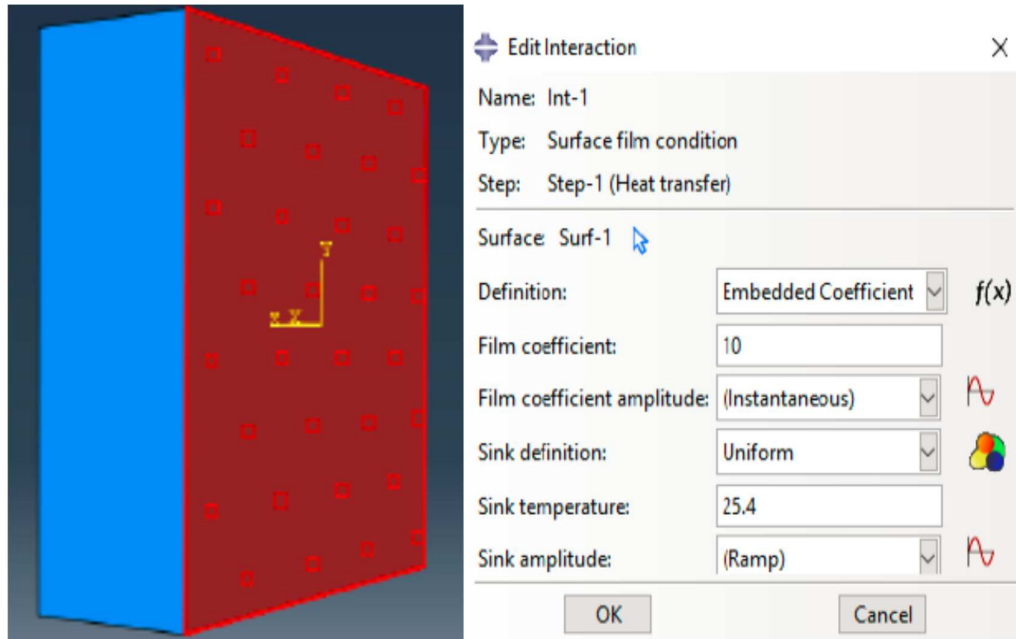


Figure 9: Heat on the External Face of the Wall

6.3.2 RESULTS OF THE COMPUTATIONAL MODELLING

The results of the computation model produced a heat flux (heat loss) of 66.28 /m².hr. The result correlates well with the heat loss calculated numerically in Chapter 6, Table 5 i.e. 66.28 W/m².hr.

The results are illustrated graphically in Appendix 1 and 2.

It can therefore be confirmed that a concrete wall of 0.35m wide and with a thermal conductivity of 2.91 W/mK and a temperature gradient of 14.6°C, will have a heat loss of 66.28 W/m²hr.

CHAPTER 7 – CONCLUSION & RECOMMENDATIONS

7.1 SUMMARY

The heat losses experienced in anaerobic digester tanks can be attributed mainly to losses through the roof structure, the floor and the walls of the tank. This dissertation focused on the heat losses through the reinforced concrete walls of a typical digester tank.

Concrete is one of the better construction materials for structures required to maintain constant temperatures. However, heat losses do occur through concrete which might result in additional insulation materials being used to reduce these losses. This research looked at the constituent materials and the effect each material has on the overall concrete insulation properties.

7.2 CONCLUSIONS

Based on concrete used for the anaerobic digester tanks at the New Horizons Facility, the various thermal conductivities for the constituent materials could be determined.

- ❖ The hydrating materials making up the binder paste had a relatively low thermal conductivity with the effective thermal conductivity of the binder paste being 0.757 W/mK.
- ❖ The aggregates, both coarse and fine, exhibited higher thermal conductivities than the paste and these materials greatly influence the overall thermal conductivity of the concrete. The thermal conductivity of the coarse aggregate is 4,31 W/mK and that of the fine aggregate is 1.4 W/mK.
- ❖ Using the Effective Medium Theory for composite material with random and evenly-dispersed materials, the effective thermal conductivity for the concrete wall was calculated as 2.91 W/mK.

The research also focused on the effects of other important properties of concrete and reinforcement used in reinforced concrete.

- ❖ The effects of the interfacial transition zone (ITZ), situated around the coarse and fine aggregate, on the thermal conductivity of the concrete was also investigated. It was found to reduce the effective thermal conductivity of the

concrete by less than 0.15 W/mK and therefore insignificant on the thermal conductivity of the concrete.

- ❖ Additionally, the effects of reinforcement on the thermal transfer properties of concrete was also investigated. Reinforcement, if positioned and aligned in the direction of the thermal gradient would have a significant effect on the thermal conductivity. It was found to increase heat transfer by 3-10%.
- ❖ Steel fibres also greatly increase the thermal conductivity of concrete. The increase could be as much as 45–90% and is dependent on the fibre dosage, length and dispersion in the concrete matrix. However, in the concrete tank walls used at New Horizons, the lack of fibres and general alignment of the reinforcement has resulted in the effects on the thermal properties being insignificant at 0.19%.

In order to determine the heat losses through the digester concrete wall, on-site investigations, numerical calculations and computational modelling were required.

- ❖ Temperature measurements taken at New Horizons has shown that the heat losses through the concrete walls of the digesters are significant and would require additional heat replacement and insulation to minimise the losses. The results have indicated that the total heat loss through both digester walls is 66.28 kW/m².hr and results in a substantial annual heat loss costs.
- ❖ The Abaqus computational model of a unit wall of 0.35m thick with a thermal conductivity of 2.91 W/mK showed a heat loss of 66.28 W/m².hr which compares well with the heat loss of the theoretical model of 66.28 W/m².hr.

Additional heat loss in the digester tank would include losses from the digestate, through the concrete floor into the supporting ground, and to the biogas and through the PVC roof cover to the external ambient air. Although these losses were not covered in this dissertation, it is assumed that these are significant and would further increase the heat loss costs of a digester tank.

7.3 RECOMMENDATIONS

Other than applying external insulation and cladding, which is a common method of reducing heat loss in digester tanks, the concrete thermal properties could be improved by the using alternative aggregates or additives.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

This research has showed that the biggest contributor to heat transfer / loss is the aggregate. The coarse aggregate used at New Horizons is a hornfels / metagreywacke which has a thermal conductivity of 4.31 W/mK.

Types of aggregate that could reduce the heat loss in concrete are: -

- The inclusion of clay lightweight aggregate. Research into the effects of lightweight clay aggregate by Yun et al (2014), has shown that these aggregates do reduce the thermal conductivity of concrete but still maintain a relatively high compressive strength required for these types of structures. Tests have shown that these aggregates have a thermal conductivity of 1.25 W/mK which is substantially less than that of most natural aggregates.
- Types of natural aggregates that should have a lower thermal conductivity compared to shales are carbonates, basalts or andesites (Clauser & Huenges 1995) due to having lower levels of quartzite and other minerals with high thermal properties.
- In South Africa specifically, the aggregate that could be used are basalts of the Karoo Supergroup, Drakensberg, Ventersdorp Supergroup and andesites from Southern Gauteng and Ventersdorp Supergroup.

Other than aggregate, materials that can be used to reduce the thermal conductivity of concrete include the following: -

- Polystyrene beads, as a lightweight additive, could assist in lowering the overall thermal conductivity but would have to be used in limited quantities so as not to comprise the compressive strength of the concrete.
- Polypropylene or synthetic fibres, in lieu of steel fibres, have a lower thermal conductivity yet still provide acceptable strength and performance.

REFERENCES

1. Adeyanju, A.A., Monahar, K. 2011. Effects of Steel and Iron Fillings on Thermal and Mechanical Properties of Concrete for Energy Storage Application. *Journal of Minerals and Materials Characterization & Engineering*. 10(15):1429-1448.
2. Alexander, M., Jaufeerally, H., Mackechnie, J. 2003. Structural and Durability Properties of Concrete Made from Corex Slag. Monograph NO.6. University of Cape Town University of Cape Town
3. Amimul Ahsan. Ed. 2011. Convection and Conduction Heat Transfer. InTech. 301
4. Ballim, Y., Graham, P.C. 2004. A Numerical Model for Predicting Time-Temperature Profiles in Concrete Structures Due to The Heat Of Hydration of Cementitious Materials. Research Monograph No. 8. School of Civil and Environmental Engineering, University of the Witwatersrand.
5. Boggs, J.R. 2000. Principles of Sedimentology and Stratigraphy, 3rd ed. Toronto, Merrill Publishing Company.
6. Bruggeman, D.A.G. 1935. *Ann. Physik. Leipzig*. 24, 636.
7. Cavanaugh, K. Chair. 2002. Guide to Thermal Properties of Concrete and Masonry Systems. Test Report 122R-02. ACI Committee 122. 122R-4.
8. Clauser, C., Huenges, E. 1995. Thermal Conductivity of Rocks and Minerals, Rock Physics and Phase Relations. A Handbook of Physical Constants. American Geophysical Union. 115.
9. Fu, X., Chung, DDL. 1999. Effects of admixtures on the thermal and thermomechanical behaviour of cement paste. *ACI Materials Journal*. 96(4):455-461.
10. Hansen, T. Physical Structure of Hardened Cement Paste. A Classical Approach. *Materials and Structures*, 19(6):423-436.
11. Heckroodt, R.O. 1991. Clay and Clay Materials in South Africa. *Journal of the South African Institute of Mining and Metallurgy*. 91(10):343-363.
12. Hochstein, D. 2013. Thermal Conductivity of Fibre-Reinforced Lightweight Cement Composites. Ph.D. Dissertation. Columbia University, 13-14.
13. Hu, H., Ge, Z., Wang, K. 2009. Study of Iowa PCC Thermal Properties for Mechanistic-Empirical Pavement Design. *Proceedings of the 2009 Mid-*

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Continent Transportation Research Symposium, August 2009, Ames, Iowa.

5

14. Iyoda, T., Inokuchi, K., Uomoto, T., 2011. Effect of Slag Hydration of Blast Furnace Slag Cement in Different Curing Conditions. Proceedings of 13th International Congress on the Chemistry of Cement, 3–8 July, Madrid.
15. Kanbur B.B., Atayilmaz, S.O., Demir, H., Koca, A., Gemici, Z. 2013. Investigating the Thermal Conductivity of Different Concrete and Reinforced Concrete Models with Numerical and Experimental Methods. Recent Advances in Mechanical Engineering Applications. 101.
16. Kim, K.H., Jeon, S., Kim, J., Yang, S. 2003. An Experimental Study on Thermal Conductivity of Concrete. Cement and Concrete Research. 33:363–371.
17. Kodide, U. 2010. Thermal Conductivity and Its Effects on The Performance of PCC Pavements In MEPDG, MSc. Thesis. Louisiana State University.
18. Kook-Han, K., Sang-Eun, J., Jin-Keun, K., et al. 2003. An Experimental Study on Thermal Conductivity of Concrete. Cement and Concrete Research. 33(3):363-371.
19. Landauer, R. 1952. The Electrical Resistance of Binary Metallic Mixtures. Journal of Applied Physics. 23, 7.
20. Larbi, L.A. 1993. Microstructure of The Interfacial Zone Around Aggregate Particles in Concrete. Heron. 69.
21. Lasance, C. 2004. The Thermal Conductivity of Silicon Dioxide. Design, Materials, Compounds, Adhesives, Substrates Journal, Volume 10.
22. Limbachiya, M., Kew, H. 2009. Excellence in Concrete Construction Through Innovation. Concrete & Masonry Research Group. London. 314.
23. Lixia, G., Lei, G., Ling, Z., Yueming Z. 2011. Thermal Conductivity and Heat Transfer Coefficient of Concrete, Journal of Wuhan University of Technology – Material Science Edition. 26(4):792.
24. Mills, KC., Yuan L., Jones, RT. 2011. Estimating the Physical Properties of Slags. The Southern African Institute of Mining and Metallurgy, 111(38):649-658.
25. Nadeau, J.C. 2002. Water-Cement Ratio Gradients in Mortars and Corresponding Effective Elastic Properties. Cement and Concrete Research 32. 481-490.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

26. Naik, T., Canpolat, F., Chun, Y. 2003. Limestone powder use in cement and concrete. Test Report No. CBU-2003-31, REP-525. Department of Civil Engineering and Mechanics, College of Engineering and Applied Science, The University of Wisconsin – Milwaukee.
27. Neville, A.M. 2011. Properties of Concrete. 5th Edition, Pearson.
28. Owens, G. Ed. 2009. Fulton's Concrete Technology, ch. 3.
29. Paul Greene. 2015. Anaerobic Digestion & Biogas. Albany, New York. Natural Systems Utilities.
30. Perold, J. 2006. Ceramic Parameters in The Financial Evaluation of Brick Clay Deposits, With Reference to Two South African Examples. Faculty of Natural and Agricultural Sciences, University of Pretoria, Ch 3-5.
31. Qomi, A., Javad, M., Ulm, F.J., Pellenq, R. 2015. Physical Origins of Thermal Properties of Cement Paste. Physical Review Applied 3. Massachusetts. American Physical Society.
32. Robertson, E. 1998. Thermal Properties of Rocks, Report 88-441. United States Department of the Interior Geological Survey. 25.
33. Rustz, D., Mergner, R., Janssen, R. 2015. Sustainable Heat Use of Biogas Plants – A Handbook, 2nd Ed. Munich. WIP Renewable Energies. 7-22.
34. Sabir, B.B., Wild, S., O'Farrell, M. 1998. A Water Sorptivity Test for Mortar and Concrete. Materials and Structures, 31:568-574.
35. Tuson, A., Charman, R., 2012. Thermal Material Properties for Modelling of the 2 Metre Box. Inutec Report (10) P019. 23.
36. Walker, B. 2013. Fine Aggregate Resources in the Greater Cape Town Area. MSc. Dissertation. University of Cape Town.
37. Wang, J., Carson, J.K., North, M.F., Cleland, D.J. 2007. A New Structural Model of Effective Thermal Conductivity for Heterogeneous Materials with Co-continuous Phases. International Journal of Heat and Mass Transfer 51 (2008). 2391.
38. Yang, TR., Chang, TP., Chen, BT., Shih, JY., Lin, WL., 2012. Effect of Alkaline Solutions on Engineering Properties of Alkali-activated GGBS Paste. Journal of Marine Science and Technology, Vol. 20, 311-318.
39. Yun, T.P., Jeong, Y.J., Youm, K. 2014. Effect of Surrogate Aggregates on the Thermal Conductivity of Concrete at Ambient and Elevated Temperatures. GS E&C Research Institute. 9 pgs.

Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

40. Zhang, L.I., Xiao-Yong, W., Koh, K.T., 2016. A Microstructure Based Strength Model for Slag Blended Concrete with Various Curing Temperatures. *Advances in Materials Science and Engineering*. 12 pgs.
41. Zhang, S.P., Zong, L. 2014. Evaluation of Relationship between Water Absorption and Durability of Concrete Materials, *Advances in Materials Science and Engineering*, Vol. 2014 (650373), 8 pages.

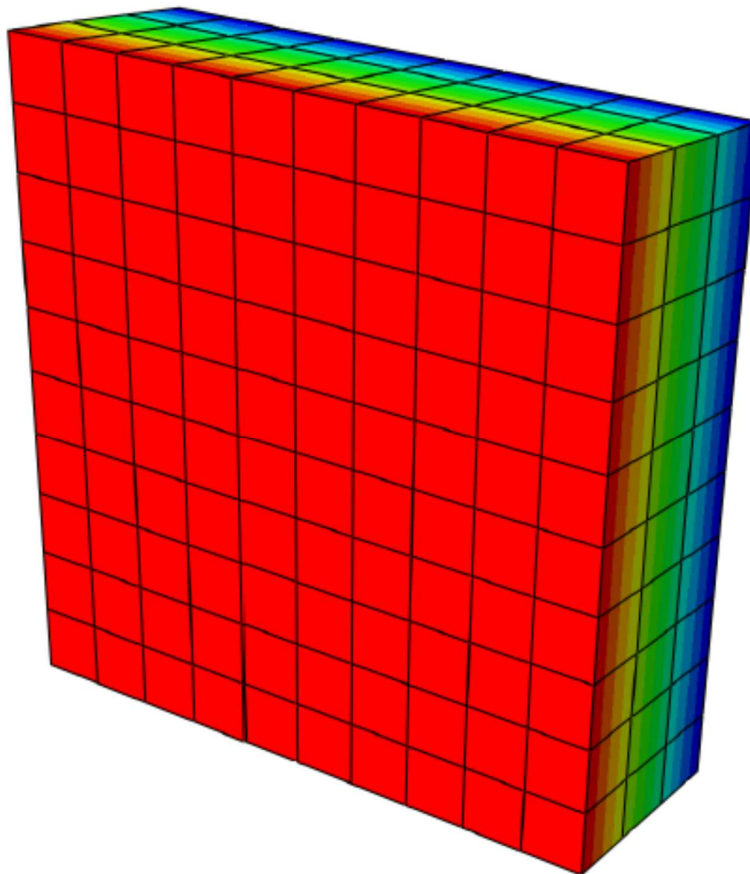
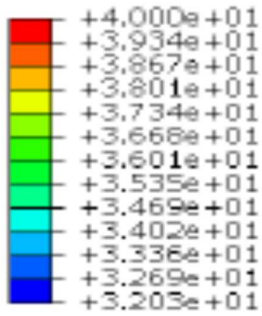
Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

APPENDICES – OUT PUT DIAGRAMS OF THE COMPUTATIONAL MODELLING & TANK LAYOUT

Appendix 1: Computational Result of Temperature Gradient (°C) Through the Cross Section of the Concrete Wall

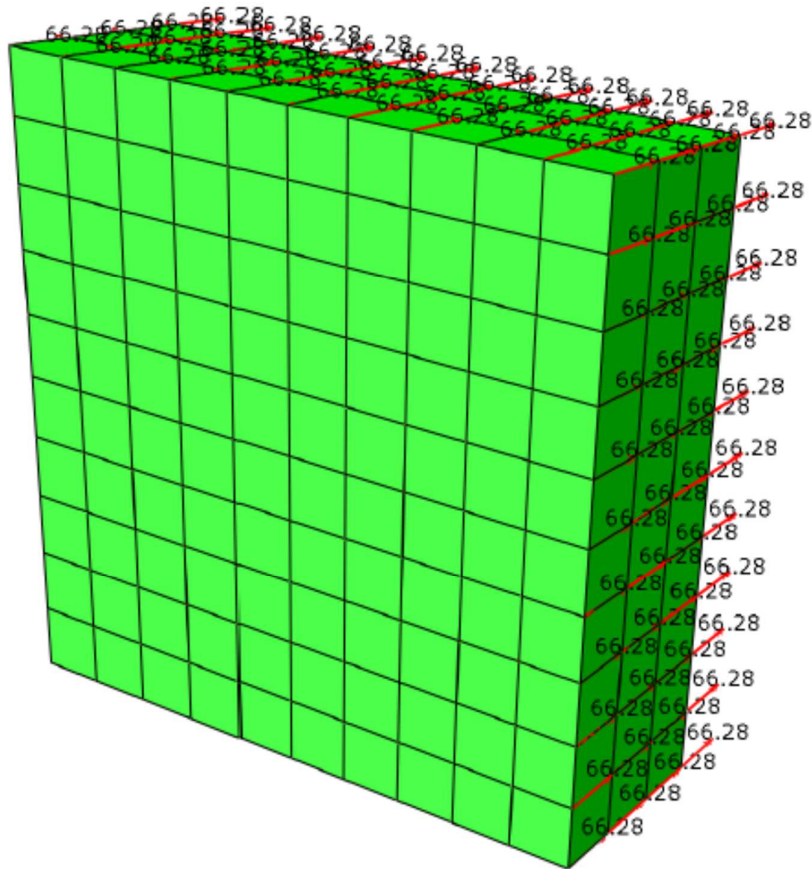
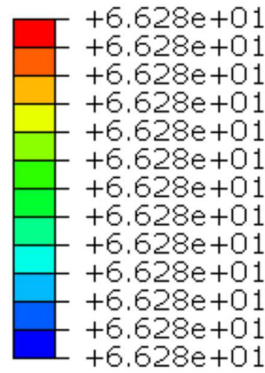


Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Appendix 2: Computational Results of Heat Loss (W/m².hr) Through the Concrete Wall

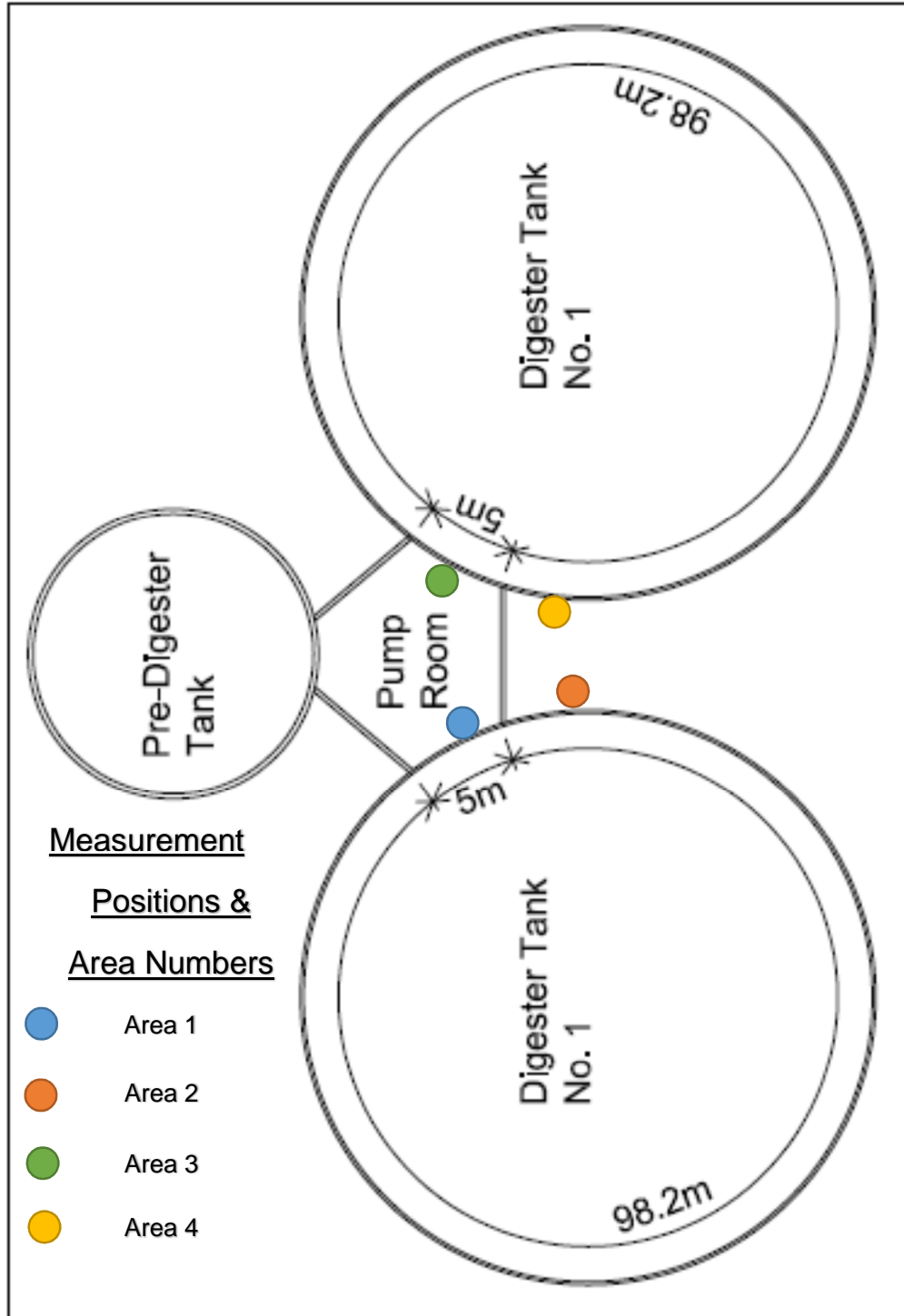


Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Appendix 3: Diagrammatic Representation of the Concrete Tank Layout



Heat Transfer Through Anaerobic Digester Concrete Tank Walls

A dissertation submitted as partial fulfilment of the requirements for the Degree of Master of Engineering

Author: Owen Davis

Appendix 4: Diagram from Neville (2011) indication Capillary Water Content

