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BUILDING THE AFRICAN CITY OF THE FUTURE USING MORE ECOLOGICALLY SUSTAINABLE MATERIALS WITH A FOCUS ON THE USE OF RECYCLED TYRE FIBRE TO 'TOUGHEN' CONCRETE

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Civil Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard Campus, South Africa. The research was financially supported by the DSI/NRF/CSIR SARCHI Chair Waste and Climate Change.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Supervisor: Prof. Cristina Trois

Date: 19 June 2023

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My role in each paper and presentation is indicated. The * indicates the corresponding author.

Chapter 2

Smith, F., Tramontin, V. and Trois, C. (2017). Assessment of alternative building systems available in ASOCSA South Africa based on sustainability indicators.
August 2017 Durban, South Africa
Conference: 11th Built Environment Conference

Chapter 2

Smith, F. and Trois C (2018). Preliminary results on the innovative use of paper-mill waste sludge and fibre from waste tyres as performance enhancers of green concrete Wastecon 2018, Johannesburg, South Africa.

Chapter 2

Smith, F., Trois, C. and Tramontin, V. (2017). The use of waste materials as substitutes in sustainable construction materials in a circular economy. Sardinia 2017 Sixteenth International Waste Management and Landfill Symposium, Cagliari, Sardinia, Italy.

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ABSTRACT

The title of this thesis is ‘Building the African city of the future using more ecologically sustainable materials with a focus on the use of recycled tyre fibre to ‘toughen’ concrete’. The goal of providing ‘adequate’ housing for all South Africans, as required in the 1996 Constitution, created a major challenge for the country and remains a goal and not a reality. Minimum housing standards have increased and there is now an emphasis on providing sustainable building systems which need to be considered an important part of this challenge. Low-cost housing systems available globally and specifically in South Africa are reviewed and a gap becomes evident in the ‘improved utilisation’ of concrete by the incorporation of industrial waste materials.

The key aim and focus of this research are, therefore, to research global trends in sustainable low-cost housing, with an emphasis on finding practical and meaningful improvements that can be implemented, assisting with the sustainability of building materials, whilst also, reducing the quantity of industrial waste going to landfill.

As a grounding to the research, a case study is conducted, of an existing ‘state of the art’ construction method, meeting the latest government standard brick housing project regulations, in a ‘deep-rural’ area of South Africa in the KwaZulu-Natal region. This is followed by a survey of South African-approved ‘Alternative Building Systems’, assessed in terms of selected sustainability indicators. Gaining a clearer picture of the current scenario raises the question ‘How Can We Help’ in terms of Academic Research/Materials Engineering, waste-to-landfill reduction and the innovative utilisation of specific waste material properties. In the winding research path of this thesis, the experimental section focuses on the utilisation of polymer fibre from end-of-life vehicle tyres as a ‘performance enhancer’ in concrete. Improving the toughness of concrete for applications where improved crack resistance is required at a low cost. The measurement of the fracture toughness of concrete also brings a dimension not normally covered in traditional concrete development. The output of this thesis, in addition to providing meaningful test data, is intended to leave signposts and open doors for new Engineering graduates to continue to build confidence from meaningful data, supporting Civil and Environmental Engineers in the quest for good housing for all South Africans.

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LIST OF ABBREVIATIONS

ABS	Alternative Building Systems
ASR	Alkali-silica reaction
ASCOSA	Association of Schools of Construction of Southern Africa
BNG	Breaking New Ground
CSSB	Cement Stabilised Soil Blocks
CBD	Compacted Bulk Density
CC	Cast Concrete
C & D	Construction and Demolition
CLC	Cellular Lightweight Concrete
CMOD	Crack Mouth Opening Displacement
CSIR	Centre for Scientific and Industrial Research
CTOD	Crack Tip Opening Displacement
E	Modulus of Elasticity
ELVT	End-of-Life Vehicle Tyres
ELTF	End of Life Tyre fibre
FA	Fly Ash
FRC	Fibre Reinforced Concrete
GF	Fracture Energy
GGBS	Ground Granulated Blast Furnace Slag
GPC	Geopolymer Cement
GPCC	Geopolymer Cement Concrete
HPC	High-Performance Concrete
LBD	Loose Bulk Density
NWMS	National Waste Management Strategy
NBR	National Building Regulations
OPC	Ordinary Portland Cement
PMS	Paper Mill Sludge
PPF	Polypropylene Fibre
RA	Recycled Aggregate
RFC	Reinforced Concrete Panels
RTF	Recycled Tyre Fibre
REDISA	Recycling and Economic Development Initiative of South Africa

RD	Relative density
RDP	Reconstruction and Development Programme
RDP	Round Determinant Panel
RTPF	Recycled Tyre Polymer Fibre
SF	Steel Frame
SANRAL	South African National Roads Ltd
SANS	South African National Standards
STF	Scrap Tyre Fibre
SG	Specific gravity
SCM	Supplementary Cementitious Materials
UKZN	University of KwaZulu-Natal
WMB	Waste Management Bureau
XPS	Expanded Polystyrene

CHAPTER 1

1 INTRODUCTION

1.1 Rationale

The research problem addressed revolves around the building of large numbers of low-cost houses; whilst addressing the social acceptance and economic viability in recent years, with satisfactory results, ecological sustainability has been largely overlooked. In terms of this research, all three of the universally accepted sustainability ‘pillars’ of economy, society, and the environment are considered equally, requiring more focus on the ecological aspects of the building systems considered, in combination with the raw material selection and processing of those raw materials to form the final structure most efficiently.

Considering low-cost housing for the “African city of the future”, a myriad of building materials, construction techniques and combinations thereof are available. Housing developers are often constrained by tried and tested materials and traditional construction methods, being cautious of new concepts. This research endeavours to take a ‘no-constraints’ approach to potential options. Considering novel and innovative opportunities, based particularly on recycled materials, making meaningful recommendations for practical implementation.

During this research, it becomes clear that before radically changing the largest volume of building material used (i.e., concrete) there is a gap, whereby industrial waste, which is a major environmental problem, can be used not only to divert material from landfill but also, to provide enhanced performance of the concrete. In the case of the final focus for the experimental work of this thesis, fibre from end-of -life vehicle tyres (ELVT) provided the most promising results on the improved crack resistance of concrete.

Furthermore, there is currently an elevated level of activity in:

(a) The application of fibre reinforcement for Additive manufacturing (AM), or 3D printing (a procedure which manufactures layered components from digital model data). Traditional Portland cement mortar and concrete are characteristically brittle, requiring steel reinforcement to achieve reasonable tensile properties. Fibre reinforcement improves the toughness of AM cement-based material.

(b) The emergence of room temperature manufactured Geopolymer cement which does not need the elevated temperature and high energy consumption needed for traditional Portland cement.

These two radical developments highlight the current shift from traditional high-energy consuming concrete.

This research can, therefore, be termed as a 'steppingstone' on the road to a paradigm shift, radically changing building systems, and providing momentum for ongoing improvements, particularly in developing countries needing a low cost.

1.2 Aim

The main aim of the research is to evaluate alternative, more ecologically sustainable options of building materials, for use in the construction of affordable housing, in African cities, without compromising social acceptance and economic viability. A key focus is the utilisation of waste material and the minimisation of the dependence on traditional high-energy consuming Portland cement concrete. To conduct in-depth experimental test work on potential candidate materials and on the most promising way to determine the feasibility of the application, while ultimately proposing a pathway for future research.

1.3 Objectives

Objective 1 - Determine the implications of former building systems

To determine the implications of the history of former low-cost/affordable housing developments on the current scenario and the potential for improvement.

Objective 2 - Determine the specific requirements for low-cost housing

To determine the specific requirements for low-cost housing, for the South African scenario.

Objective 3 - Analyse the suitability of currently available resources and technology

To analyse the suitability of currently available resources, including raw materials and technology for low-cost sustainable housing, relative to the specific requirements of South Africa. Using an 'Indicator based sustainability assessment tool' to provide a platform for further development.

Objective 4 - Propose innovative and novel approaches.

To propose innovative and novel approaches to the building of low-cost housing with an emphasis on the utilisation of waste material.

Objective 5 - Experimental investigation of one proposed building material

To select 'at least one' innovative and novel building system or material and run experimental work to assess its applicability.

1.4 Scope of the work

This thesis research encompasses the latest concepts and practical applications of sustainable building materials and construction methods on an international level before focusing on the South African scenario with an emphasis on the use effective utilisation of waste materials. Four topics are covered, which, for ease of reading and referencing, flow through the chapters in four streams.

Sustainable building materials for low-cost housing

Research is made into the latest low-cost housing systems, internationally and locally, within South Africa, including a survey of the South African Agrement certified alternative building systems. The study focuses on the sustainability of the building materials and the utilisation of waste materials in their construction.

Assessment of concrete with the inclusion of four industrial waste materials

A Practical assessment is made using a standard concrete mix with the introduction of four industrial waste materials, derived from four different industrial waste streams. The experimental work is conducted by four final-year BSc students as part of their practical assignment. Two of the waste materials are used as partial replacements for aggregate and two as potential performance enhancers of the concrete produced.

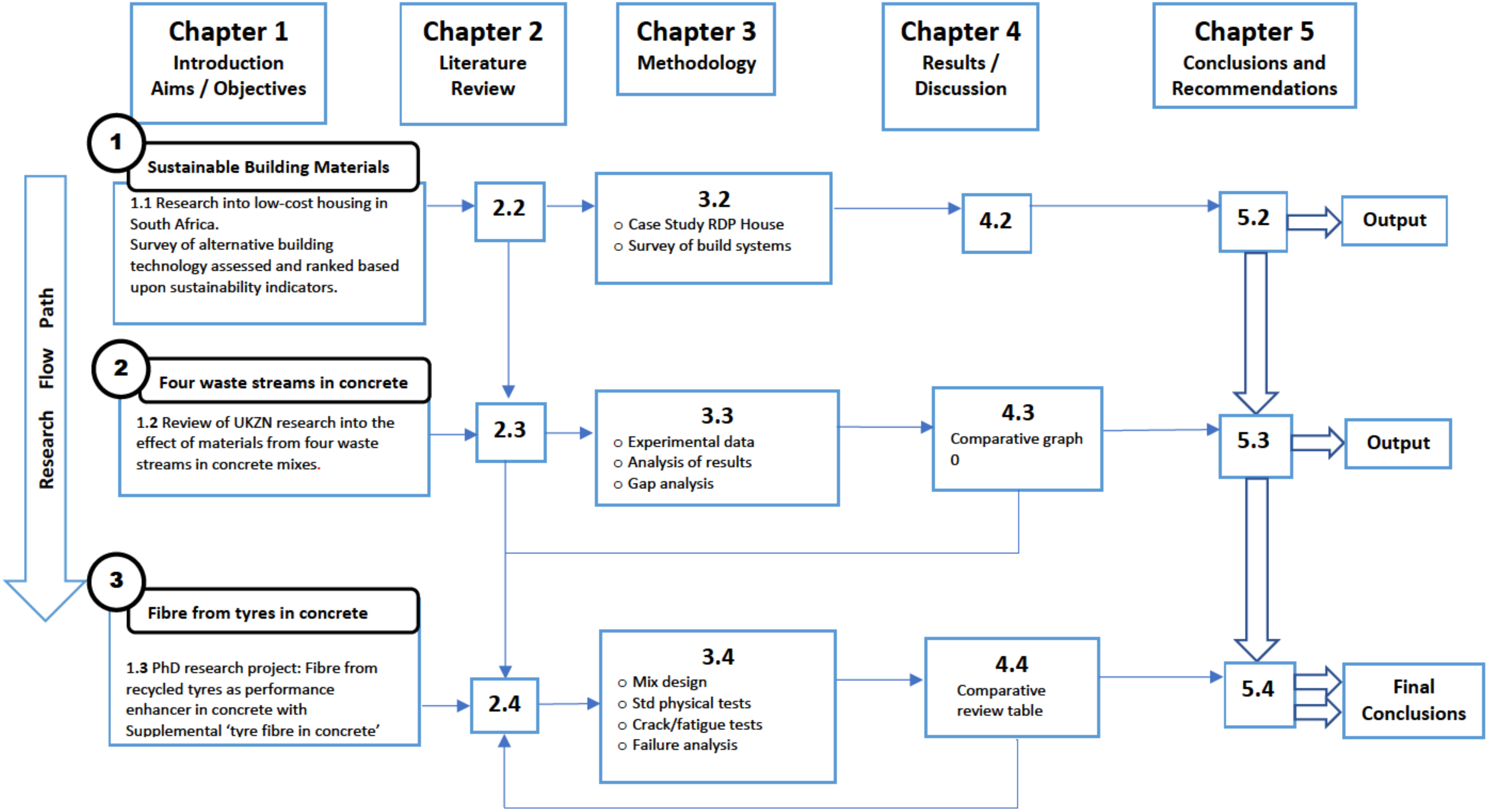
Assessment of concrete including fibre from 'end of life' tyres as a 'performance-enhancer'

From the four waste materials selected in 1.4.2, the most promising option was re-evaluated by a further 3 final-year Bachelor of Civil Engineering students at UKZN and by the Author. An in-depth analysis of the results was then conducted.

Waste as a building material resource and the sustainability of building system materials

Based upon the literature review, a survey of national and international building systems and the assessment of the test work completed, conclusions are drawn, and recommendations are made for further research with an emphasis on sustainability and the utilisation of waste.

1.5 Structure of the thesis



CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction to the literature review chapter

As discussed in the introduction, the focus of this thesis is to research the status, globally and in the South African context, of the use of sustainable materials in the building of low-cost housing with an emphasis on the utilisation of waste streams in a circular economy. Initially, a wide and global literature review was conducted and 'funnelled down' to a local level with a specific focus on local South African building systems and materials.

During the middle term of the literature review, it became apparent that before any radical changes in building methods for low-cost housing are adopted on a large scale, gaps in technology to significantly improve the efficiency and sustainability of the most widely used building material in the world, concrete, needed to be addressed. The results of the survey conducted to determine the sustainability of certified alternative building systems revealed excellent results for lightweight concrete building systems. The focus of the literature review was thus diverted to the utilisation of waste material in concrete with an emphasis on industrial waste, concurrently being reviewed for applications by the SARCHI Waste and Climate Change group, and the Civil Engineering Programme at UKZN.

Various industrial waste streams were reviewed, with a specific interest in fibre from end-of-life automotive tyres. The literature review was expanded to a global level as, at the time of review, only limited research and superficial test work had been published on the benefits and implications of incorporating tyre fibre in concrete at a local level. However, before the completion of this thesis in 2020, some research had been completed and published as conference proceedings; the key outcomes have been included as part of this literature review as a compounded contribution to knowledge. Towards the end of the experimental test phase, it was determined that traditional concrete test methods were not capable of determining the improvement in crack resistance or 'toughness' of the fibre-reinforced concrete and the literature review revealed a new and relatively simple method of performance testing that will be of great benefit for future research in this field.

Based upon this pathway and overview of the literature review, Chapter two, Literature Review, is broken down into three sections, corresponding with the same subsections in chapter three 'Methodology' and chapter four 'Results and discussion' as follows:

Trends in technology and materials in building sustainable low-cost housing (2.2)

This section is broken into two segments, as follows:

RDP housing in South Africa (2.2.1)

A literature review on RDP (Reconstruction and Development Programme) housing is followed by 3.2.1 Methodology, which is a case study in the Izingolweni region of KwaZulu-Natal and by Results from the case study in 4.2.1

Survey of building systems (2.2.2)

Following a review of the multitude of new and traditional low-cost building systems globally, the focus was put on research into low-cost housing in South Africa. The wide range of building methods and lack of common comparative data does not allow easy comparison, therefore a survey of building systems certified by the 'Agrement South Africa, innovative construction product assessments' was conducted. This section is drawn from a paper presented by the Author at the 2017 ASCOSA (Association of Schools of Construction of Southern Africa) conference in Durban (Smith, Tramontin et al. 2017).

The application of industrial waste stream materials in concrete mixes (2.3)

Waste from industry tends to be relatively consistent in quality and quantity as the process parameters are generally more controlled than municipal waste. They are also more readily available and easier to source in bulk. To ensure that this research is meaningful, the focus was placed on waste materials that are difficult to dispose of due to cost or environmental issues. A literature review and communication with waste specialists, together with access to concrete compounding and test facilities at UKZN led the research into the incorporation of four waste streams in concrete mixes. As a wide range of materials can be incorporated in concrete, the emphasis was on finding materials that are not only diverted from entering landfill sites but also have a positive effect on the performance of the concrete as 'performance-enhancers'. These waste materials, currently being sent to landfill were incorporated into standard concrete mixes, utilising standard concrete mixing equipment and physical testing was conducted utilising industry-standard destructive test methods (Compressive, Tensile, and flexural strength).

Focus on waste fibre from recycled tyres as a performance enhancer of concrete (2.4)

This is the experimental section of the PhD research, involving an in-depth review of the use of fibre in concrete mixes with a focus on previous research conducted utilising fibre from waste sources.

Summary of Literature review Chapter **(2.5)**

2.2 Affordable and sustainable alternative building systems

2.2.1 *RDP (Reconstruction and Development Programme) housing in South Africa.*

2.2.1.1 Introduction to RDP housing in South Africa

The South African National Housing Code, 2009 sets the underlying policy principles, guidelines and norms and standards which apply to Government's various housing assistance programmes introduced in 1994 and updated. The South African Constitution, of 1996 enshrines the right of everyone to have access to adequate housing and makes it incumbent upon the State to take reasonable legislative and other measures within its available resources to achieve the progressive realization of this right. In response to this Constitutional imperative, Government has in terms of the Housing Act, 1997 (Act No 107 of 1997) introduced a variety of programmes which provide poor households access to adequate housing (Department-of-Human-Settlements 2009).

2.2.1.2 RDP housing in South Africa

Ten years after the introduction of the housing programme in 1994, a comprehensive review was undertaken of the outcomes of the programme and the changes in the socio-economic context in the country. This lead to the approval of the Comprehensive Plan for Sustainable Human Settlement commonly referred to as "Breaking New Ground" or "BNG", by Cabinet in September 2004 (Department-of-Human-Settlements 2009).

There are several methods of persuading a municipality that a particular design complies with the requirements of the NBR (National Building Regulations), namely that the building will be constructed in accordance with a) A design that conforms in all respects with the Deemed-to-satisfy rules set out in SABS 0400; b) A certificate issued by the Board of Agrément SA, that is, an Agrément Certificate, or a MANTAG Certificate; and c) A rational design prepared by a competent person. Unconventional building methods, systems or components, are covered by an Agrément Certificate. This provides an assurance of fitness for purpose of non-standardised building and construction products and systems, by evaluating these against prescribed performance criteria. A MANTAG Certificate is a distinct type of Agrément Certificate dealing with:

Acceptable safety and health criteria for houses and related outbuildings, non-residential schools and primary health care centres in areas where the local authority is of the opinion that the type of construction is appropriate, given that in these areas it is of paramount importance that the buildings be erected at the lowest possible cost (Department-of-human-settlements 2009).

Recognising that sustainable, quality low-income housing is a national priority, the Department of Science and Technology (DST) commissioned the CSIR to investigate technology possibilities for improved low-income housing. The CSIR applied its collective science and technology expertise to contribute towards promoting sustainable human settlements. The desired outcome was to develop a demonstration house that is more comfortable, durable, faster to build, easily extendable and less dependent on municipal services (CSIR 2010).

2.2.2 *Affordable and sustainable alternative building systems*

2.2.2.1 Introduction: Affordable and sustainable alternative building systems

Extensive research was conducted into low-cost housing systems both globally and specifically in South Africa. The range of building systems globally is dependent on numerous factors such as climate, availability of materials, cultural preferences, and economic influences. Following a review of the multitude of new and traditional low-cost building systems globally, the focus was directed on research into low-cost housing in South Africa. However, finding criteria and data on which to base a comparative survey of alternative building technology was not practically achievable and to concentrate on the latest trends for low-cost housing with building systems that have been tested and approved to a common standard, a survey of building systems certified by the 'Agrément South Africa, innovative construction product assessments' was conducted (Agrément October 2010).

The building systems considered are assessed and ranked based on sustainability indicators.

As global research progressed, it became evident that this type of research can become almost endless as not only do people in various parts of the world have different ideas, but they also have diverse types of traditional buildings. The buildings also relate to local climate and customs. Therefore, particular focus was placed on interesting existing and new concept building systems.

The following section provides a review of the literature on the concept of sustainable construction and relevant building systems. The methodology of the study is then explained in detail, followed by a discussion of the preliminary results achieved.

2.2.3 *Survey of affordable and sustainable alternative building systems*

2.2.3.1 Introduction to Survey of affordable and sustainable alternative building systems

This survey was presented at the ASOCSA (Association of Schools of Construction of Southern Africa) Eleventh Built Environment Conference on 6 - 8 August 2017, Durban, South Africa (Smith, Tramontin et al. 2017). A myriad of building materials, construction techniques and combinations thereof have been proposed over recent years. Housing developers are often constrained by tried and tested materials ad traditional construction methods, being cautious of new concepts. De Villiers (de Villiers 2012) states that it is essential to find a balance between achieving reliability and consistency, but not hampering innovation and further development of alternative building systems. Furthermore, he states that identified drawbacks to performance-based regulation need to be addressed and a critical assessment conducted of the performance requirements and the system of accountability. The introduction of the Agrément certification of alternative building systems has created a guideline for the acceptability of the performance of each system based upon the benchmark of the 'standard brick house' (Agrément October 2010). However, it has not provided a meaningful reference for the merits of each system in terms of sustainability. The survey endeavours to initiate a path of research which may ultimately guide policy makers, designers and constructors in the direction of long-term sustainable construction solutions for low-cost homes in South Africa. The survey also aims to analyse the suitability of alternative building systems, active in terms of the Agrément Certification for low-cost housing as well as sustainability, in the context of South Africa and its sub regions. An 'Indicator-based sustainability assessment tool' was developed to analyse available systems through a questionnaire-based survey.

2.2.3.2 Output from the Survey of affordable and sustainable alternative building systems

Initial research concluded that the number of alternative building systems worldwide is vast and that the materials and processes used for construction vary greatly dependant on the global region (Wallbaum, Ostermeyer et al. 2012). For example, in many eastern countries, the use of bamboo has proven to be a very satisfactory building system as it is strong, light and durable and has gained widespread social acceptance, however in other parts of the world there may not be the local bamboo raw material or the required construction skills and the climate may not favour this type of structure.

The attention to the building sector arises from its energy consumption and greenhouse gas emissions which, in developed countries, represent 30% and 40% of the total quantities respectively (UNEP 2010). However, when addressing sustainability, the “green” aspect is often over-emphasised at the expense of the social and economic factors (Berardi 2013). Following an in-depth review of the definition of sustainability in the built environment, Berardi (2013) stated that “the social aspects of a sustainable building are still rarely investigated”.

An initial review of work carried out on the sustainability of low-cost housing revealed an extensive global study conducted by (Wallbaum, Ostermeyer et al. 2012), where 46 affordable building systems were evaluated in terms of sustainability. The paper concluded that “After the screening, assessing, and ranking 46 different construction technologies against 10 sustainability indicators, it is possible to conclude that the most promising technologies are closely connected to local production of materials”. Furthermore, the research concluded that there was a diverse range of top-ranking building systems and that there is no perfect solution to the sustainable affordable housing problem, but that combining multiple top-ranking technologies can provide an optimized solution.

The topic of sustainability, initially simple to understand in terms of functionality in the built environment, became more complex and ambiguous with ongoing research. The generally accepted concept of sustainable development means that “Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future” (WCED 1987)). Moving forward, the concept of sustainability now links the three aspects of ecological, economic and social wellbeing (Tessema, Taipale et al. 2009).

There are many published papers with more complex and differing concepts. A study from Berardi (2013) concludes that sustainability implies a consistent rate of uncertainty and suggests that it is more a transition path than the label given to a building. He also proposed that greater importance should be given to both the social and economic context of a building. Another challenge to sustainability that is particularly relevant to housing is the competitiveness of consumption markets. While this results in low prices for consumers, the high amount of competition reduces the incentive to develop sustainable products different to the societal norm. Indeed, a key component of sustainability is social acceptance, which means that for an activity or development to be successful in terms of purchases being made, it must ‘keep to specific social relations, customs, structure and value’(Arman, Zuo et al. 2009).

In South Africa, Agrément South Africa evaluates the fitness for purpose of non-standardised construction products, materials and systems against performance-based criteria. Performance criteria and test methods are established in consultation with the relevant experts, as required (Agrément October 2010). Agrément South Africa is mandated and funded by the Department of Public Works (Agrément October 2010) to promote innovative building products and protect consumers against unacceptable ones. This is done by testing non-standardised products against performance-based criteria to determine their fitness-for-purpose. The aspects that are taken into consideration as far as building materials and systems are concerned are structural strength and stability, behaviour in fire, water penetration, thermal performance, durability and the maintenance required, the likelihood of condensation forming on the inside of the building, acoustic performance and the applicant's quality system, as specified by (Agrément October 2010). The building system is assessed based on, as a minimum, being equivalent to a "standard brick house".

To have a building product certified by Agrément can cost up to R300k and it can take between 3 months and 3 years to complete the process, from application to issuing of the final certificate (de Villiers 2012). If the building system is found to be acceptable, a certificate is issued. The certificate is kept "Active" by payment of a subscription fee. The current scenario of expensive and strict performance regulation does not appear to be conducive to the innovation of holistic sustainable housing solutions.

2.3 The application of industrial waste stream materials in concrete mixes

2.3.1 *Introduction*

An extensive literature review is conducted on the use of waste material in building materials both globally and in South Africa. Initially, the scope of potential waste materials, building systems and building materials was unrestricted providing a platform to 'funnel in' on systems most suitable for the South African scenario and capable of being developed with the facilities available at UKZN and the local Durban vicinity. The research brings us to a choice of pathways; (a) radical change: developing new composite materials potentially utilising low-grade polymeric (plastic) waste in combination with more natural waste such as paper mill sludge, bagasse, fly ash or other, or (b) modification of the most common current building material, concrete, by the incorporation of waste materials. After much research and contemplation, the concrete route was chosen, mainly due to access to the concrete development facility within the Civil Engineering faculty at UKZN and the lack of a suitable development facility for the compounding and forming of polymeric materials.

Within the Civil Engineering faculty of UKZN, a new Environmental Engineering group was created and the option to use the concrete development facility was given to BSc students for final-year projects with the scope of incorporation of waste in concrete. Four of these projects are reviewed in this thesis. One material was selected for extended research.

2.3.2 *Concrete Technology*

2.3.2.1 Introduction

The increase of high-rise buildings in recent years, such as in Dubai, with the glass and metallic-looking facades, can give the impression that they are constructed largely from metals, glass and advanced composites, however, under the façade, one will largely find reinforced concrete. Concrete remains the construction material of choice for most buildings from small and affordable to exotic. In the early 1970s, experts predicted that the practical limit of ready-mixed concrete would be unlikely to exceed a compressive strength greater than 11,000 pounds per square inch (PSI) (76MPa). Over the past two decades, the development of high-strength concrete has enabled builders to easily meet and surpass this estimate. Two buildings in Seattle, Washington, contain concrete with a compressive strength of 19,000 psi (131MPa) (PCA 2021). Today, second only to water, concrete is the most consumed material, with three tonnes per year used for every person in the world. Twice as much concrete is used in construction as all other building materials combined. There is little doubt that concrete will remain in use as a construction material well into the future (Gagg 2014).

General concrete is a mixture of cementitious material (binding agent), aggregate (course and fine) and water. The addition of Supplementary Cementitious Materials (SCM), admixtures and cement extenders have been developed to modify the properties of Plain Cement Concrete (PCA 2021).

The oldest concrete discovered dates from around 7000 BC, found in 1985 when a concrete floor was uncovered during the construction of a road at Yiftah El in Galilee, Israel. It consisted of lime concrete, made from burning limestone to produce quicklime, which when mixed with water and stone, hardened to form concrete (Kosmatka 2011).

There are various types of concrete, based on different types of cement. However, Portland cement concrete is so prevalent that, unless otherwise identified, the term concrete is always assumed to mean Portland cement concrete. Portland cement was patented by Joseph Aspdin in 1824 and was named after the limestone cliffs on the Isle of Portland in England (Kosmatka 2011). Portland cement concrete is the most widely used manufactured construction material in the world (Zaniewski 2006).

Because of the advances made in concrete technology in the past few decades, concrete can be used in many more applications. Civil and construction engineers should be aware of the alternatives to conventional concrete, such as lightweight concrete, high-strength concrete, polymer concrete, fibre-reinforced concrete, and roller-compacted concrete. Before using these alternatives to conventional concrete, the engineer needs to study them, and their costs, in detail (Zaniewski 2006).

2.3.2.2 Cementitious and Supplementary Cementitious Materials (SCM)

2.3.2.2.1 *Cementitious Materials*

Portland Cement

Cementitious materials for concrete are fine mineral powders. When these materials are mixed with water, they react chemically to form a strong rigid mass that binds aggregate particles together to make concrete. Portland cement is the preferred cementitious material for construction because it is relatively cheap and concrete strength can be gained at ambient temperatures (PCA 2019).

In 1824, Joseph Aspdin, a British stone mason, obtained a patent for a cement he produced in his kitchen. The inventor heated a mixture of finely ground limestone and clay in his kitchen stove and ground the mixture into a powder to create a hydraulic cement-one that hardens with the addition of water. Aspdin named the product Portland cement because it resembled a stone quarried on the Isle of Portland off the British Coast. With this invention, Aspdin laid the foundation for today's Portland cement industry (PCA 2019).

ASTM C 125 and the Portland Cement Association (PCA) provide the following precise definitions:

Hydraulic cement: An inorganic material or a mixture of inorganic materials that sets and develops strength by chemical reaction with water by the formation of hydrates and can do so under water. Portland cement: A hydraulic cement composed primarily of hydraulic calcium silicates.

The main constituents of Portland Cement are oxides of calcium (lime), silicon (silica), aluminium (alumina) and iron. (Lime or calcium oxide (CaO) is not a naturally occurring material. It is formed by heating calcium carbonate ($CaCO_3$) to create calcium oxide (CaO) releasing CO_2.

$CaCO_3 \rightarrow CaO + CO_2$

Minerals of natural origin, as well as industrial products/by-products, can be used for cement production if the main components of cement (CaO, SiO_2, Al_2O_3, Fe_2O_3) are present in a required proportion on mixing and the impurities or undesirable components like alkalis, sulphur, chlorides, MgO etc. are below the allowable levels to ensure cement quality and operational stability. Cement mixes vary from 'natural cement rock', a single component which, as mined, contains appropriate proportions of all the required minerals, to 2 or 5 component mixes comprising one or two grades of limestone, hale or clay/silica stone, and one or more additives to augment SiO_2, Al_2O_3 or Fe_2O_3 levels, see Figure 1

FIGURE 1. RAW MATERIALS FOR CEMENT MANUFACTURE (CEMENTINDUSNEED 2021)

The selected raw materials are dependent upon the availability and cost at the location of manufacture; Table 1 provides a range of raw materials that are typically used in the production of Portland cement.

TABLE 1. SOURCES OF RAW MATERIALS IN PORTLAND CEMENT

Calcium	Iron	Silica	Alumina	Sulphate
Alkali Waste	Blast-furnace flue dust	Calcium Silicate	Alluminium-ore refuse*	Anhydrite
Aragonite*	Clay*	Cement rock	Bauxite	Calcium sulphate
Calcite	Iron Ore*	Clay*	Cement rock	Gypsum*
Cement-kiln dust	Mill scale*	Fly ash	Clay*	
Cement rock	Ore washings	Fullers earth	Copper slag	
Chalk	Pyrite cinders	Limestone	Fly ash*	
Clay	Shale	Loess	Fullers earth	
Fuller's earth		Marl*	Granodiorite	
Limestone*		Ore washings	Limestone	
Marble		Quartzsite	Loess	
Marl		Rice-hull ash	Ore washings	
Seashells		Sand*	Shale*	
Shale*		Sandstone	Slag	
Slag		Shale*	Staurolite	
		Slag		
		Traprock		
Note: Many Industrial by-products have potential as raw materials for the manufacture of Portland cement. *Most common sources.				

Small variations occur in the production of Portland cement, but the typical manufacturing process is displayed in Figure 2

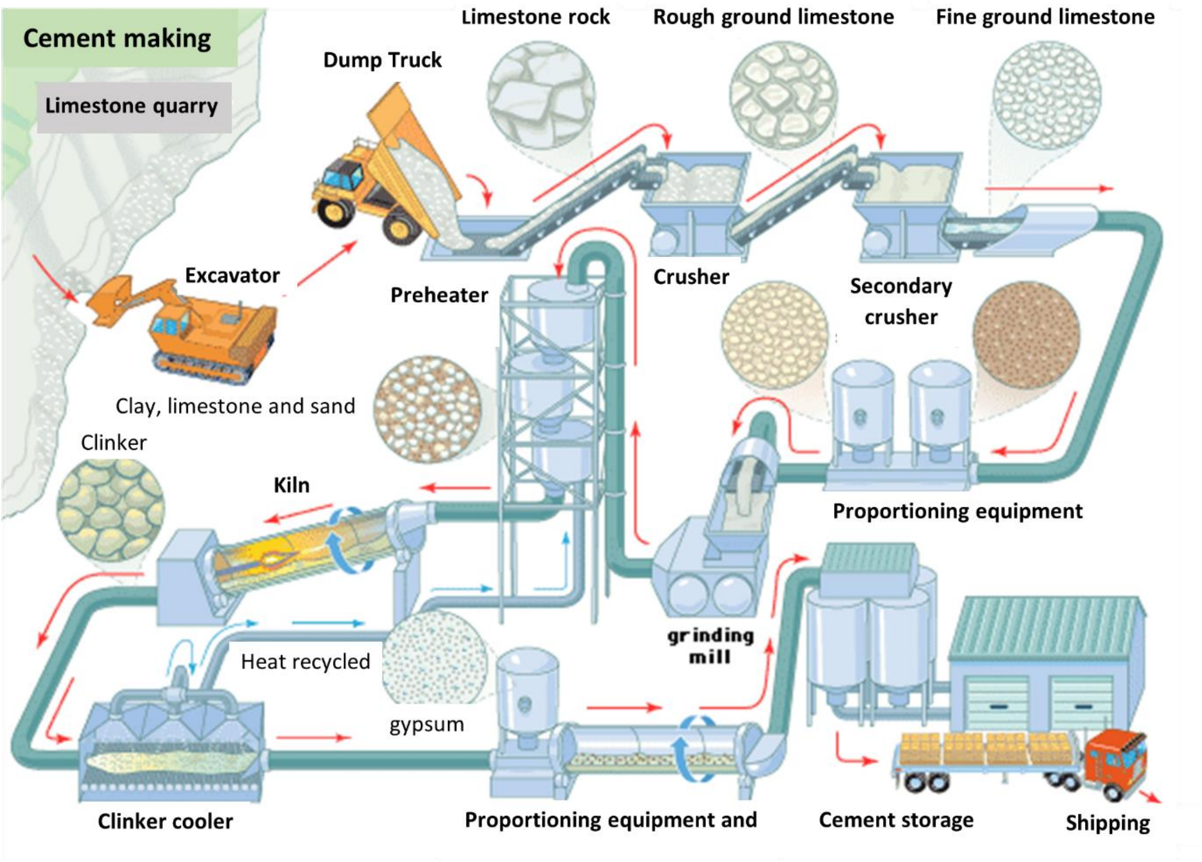


FIGURE 2. CEMENT MANUFACTURING PROCESS (CIVIL ENGINEERING FORUM, 2017)

The initial step in the process requires the quarrying of raw materials which includes excavation and crushing. Cement manufacturing facilities are normally situated near existing quarries to avoid logistical costs. In the next step, the materials are crushed into a fine powder, which produces a 'raw mix'. The raw mix is then heated in a rotating kiln to temperatures over 1500°C. Heating converts calcium carbonate to calcium oxide; this process produces cement clinker (CivilEngineeringForum2017). Gypsum (calcium sulphate) is then added to the cement clinker, and gypsum is used as a retarder to give the cement workability in the plastic state during the early stages of hydration (Kosmatka 2011). Other secondary additives and extenders are added to the cement clinker at this stage (SIKA 2018). Table 2 shows the main oxides in South African Portland cement clinker (Mamlouk and Zaniewski 2006).

TABLE 2. MAIN COMPOUNDS OF PORTLAND CEMENT (MAMLOUK AND ZANIEWSKI 2006)

Compound	Chemical Formula	Common Formula*	Usual Range by Weight (%)
Tricalcium Silicate	$3\ CaO \cdot SiO_2$	C_3S	45–60
Dicalcium Silicate	$2\ CaO \cdot SiO_2$	C_2S	15–30
Tricalcium Aluminate	$3\ CaO \cdot Al_2O_3$	C_3A	6–12
Tetracalcium Aluminoferrite	$4\ CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF	6–8

*The cement industry commonly uses shorthand notation for chemical formulas: C = Calcium oxide, S = silicon dioxide, A = Aluminum oxide, and F = Iron oxide.

Geopolymer Cement (GPS)

Based on the literature review of industrial wastes or by-products, the geopolymer process can have considerable potential to utilize industrial wastes and fulfil the sustainable construction material demands (Azad and Samarakoon 2021). Geopolymer cement concretes (GPCCs) are the most preferred among the new binder systems. Geopolymer is a generic and broad term. It comprises nine classes of materials representing a chain of inorganic molecules. However, Class F material consisting of aluminosilicate materials qualifies for civil engineering applications as it has the potential to replace partially at least OPC. However, its utility for structural and non-structural elements and its durability characteristics needs to be established from extensive R&D studies.

The program on waste to wealth undertaken internationally to use the large quantity of industrial wastes and by-products by cleverly attempting to replace partially or substitute the ingredients of concrete mix mainly, cement and aggregates have been the subject of research and applications. Some of these wastes include FA, ground granulated blast furnace (GGBS), alkaline sludges like red mud, and other materials. The wastes used are not necessarily pozzolanic. Considering these aspects, the deployment of GPC can provide significant environmental benefits. Over OPC, the setting process in GPC is much faster and does not affect the hydration process. The polymerization takes place under alkaline conditions on silicon–aluminium minerals. This creates a three-dimensional polymeric chain and ring structure. The ratio of Si to Al determines the final structure of the geopolymer. This mix gains strength over different timescales. However, one disadvantage is that one needs over 30°C temperature scales for curing.

Aside from their application as high-performance cement, GPCs find a range of niche applications such as in automobile car parts, waste immobilization, thermal boards, roof tiles, tooling materials, and decorated ceramics. GPCs result in a microstructure that is more heat resistant, fire resistant, and that has a superior thermal expansion, cracking, and swelling properties compared to PC. They exhibit a smooth surface and can be moulded easily (Iyer 2020) The global warming potential of the cement industries always alerts the environmentalist, due to the excessive contribution to CO_2 emission during the process of cement production; hence, the supplementary industrial rejects can be utilized as feed material, to decrease the energy requirement. The cost of alkali activators affects the energy consumption of geopolymer concrete; hence, it is necessary to find a possible low-cost alternative source. Overall, the geopolymer technique is helping in a scientific way to develop low-cost, sustainable, and desired mechanical strength construction materials to drop-down the environmental burden (Azad and Samarakoon 2021).

2.3.2.2.2 *Supplementary Cementitious Materials (SCM)*

Ground granulated blast furnace slag (GGBS)

GGBS or "slag cement" is a by-product of the iron production process. The main constituents of GGBS are silica and alumina. The rate of cooling plays a significant role in hydraulic reactiveness. Slow cooling will result in crystallization and is inefficient to use as a cement extender. Rapid cooling (quenching) results in glassification. This is then crushed into a fine powder which is used as a cement extender (ConcreteInstitute 2019). The material has a glassy structure and is ground to a particle size of less than 45µm. GGBS can be used in combination with Ordinary Portland Cement (OPC) and/or other cementitious materials, since on its own hardens very slowly (Mali 2017).

GGBS has been proven to add many advantageous properties to concrete such as lower water requirement, reduced chloride penetration and increased durability. Since the setting time is slow when compared to concrete made from OPC, this increases the time the concrete is in the plastic state hence increasing workability for a longer period. This can be beneficial for applications where large volumes of concrete are required. Since GGBS is a by-product of iron production there is no significant waste generated making it a very 'green' alternative to OPC (Suresh 2015).

Fly Ash (FA)

FA is extracted from the flue gasses of furnaces which are used to burn pulverised coal. FA can be divided into two groups based on particle size and chemical composition (class C and class F). The fine fraction (Class F) of which approximately 10% is retained on the size 45µm sieve is classified as a pozzolanic material, and the remaining course fraction (class C) is classified as an SCM (ConcreteInstitute 2019). The name pozzolan is derived from a volcanic ash mined at Pozzuoli in Italy. A pozzolan is a siliceous or siliceous and aluminous material which has little cementitious properties on its own, but when reacted in the presence of water and calcium hydroxide will form a compound which has cementitious properties (Sutter 2013). FA is normally consigned to landfills so using it as a cement extender will greatly increase the environmental benefit of the material. For every ton of FA substituted for OPC, CO2 emissions are reduced by approximately 0.85 tonnes. Concrete produced from FA has better workability and durability compared with concrete made from OPC. The use of FA is limited to many applications such as pavements due to many uncertainties and lack of information (Zulu 2015). As progressive environmental research and development continue, data is leading to higher confidence in the efficient application of fly ash. Yu, Mishra et al. (2018) reveal recent developments where green structural concrete where 80% cement is replaced by Chinese local fly ash to achieve a target characteristic compressive strength of 45 MPa in China. Such green concrete mixes are not only cheaper but also embody lower energy and carbon footprint, compared with conventional mixes. The study aims to adopt such materials using no less than 80% fly ash as a binder in routine concrete works in countries like India with the commonly used lower target characteristic compressive strength of 30 MPa, by the simple and practical method of adjusting the water/binder ratio and/or superplasticiser dosage.

2.3.2.3 Aggregates

Aggregate are materials derived from crushed rocks and are divided into two categories: coarse aggregate (stone) and fine aggregate (sand). Aggregate is of particular importance in this study since it focused on substituting aggregate with waste material. Aggregates make up the bulk of the concrete volume hence its properties greatly influence the mix design (Smith 2001).

2.3.2.3.1 *Influence of Aggregate Properties on Concrete*

Concrete has two states: plastic (fresh) and elastic (hardened) state. The aggregate used in a concrete mix will affect both states. In the fresh state the concrete needs to have workability. Workability is defined as the ability of the concrete to be transported, placed and compacted without separation of the particles. In the hardened state the concrete needs to be durable, rigid and have a good aggregate interlock to prevent cracking (Domone 2010).

2.3.2.3.2 *Aggregate Grade*

The aggregate grade refers to the particle size distribution of the fine aggregate used in a concrete mix. Grading limits are specified because it affects the volume of course aggregate, cement and water required for a particular mix (PCA 2021). The aggregate used in a mix design should be uniformly graded to reduce the amount of cement paste (cement and water) required to fill the voids. Poorly/gap-graded aggregate will result in a greater amount of cement paste required and reduce the workability of the concrete mixture (Kozul 1997).

2.3.2.3.3 *Aggregate particle shape and surface texture*

Particle shape and surface texture affect the workability of the concrete in the plastic state and the water requirements. The surface texture can either be smooth or rough. A smooth surface texture offers greater workability, but a rough surface texture offers greater adhesion between the aggregate particles and cement paste. A compromise has to be made between workability and bond strength (C.G. Rocco 2016). The particle shape is normally assessed by the eye although a Flakiness Index test described in SANS 5847 could be used to assess the degree of flakiness or elongation of course aggregate (Institute 2019). It is desirable to use rounded particles as this reduces the number of voids in the mix. Natural fine aggregates such as river sand are well-rounded and provide good workability (PCA 2021). Rough-textured, angular, and elongated particles require more water to produce workable concrete than the smooth, rounded compact aggregate. Consequently, the cement content must also be increased to maintain the water-cement ratio. Generally, flat and elongated particles are avoided or are limited to about 15 percent by weight of the total aggregate (PCA 2021).

2.3.2.3.4 *Aggregate Packing Density*

During extensive research by Kozul and Darwin for The Reinforced Concrete Research Council with the US National Science Foundation For The U.S. Department of Transportation Federal Highway Administration, using crack mouth opening displacement (CMOD) it was determined that the fracture energy of high-strength concrete decreases with an increase in aggregate size, while the fracture energy of normal-strength concrete increases with an increase in aggregate size (Kozul 1997).

Packing density is a fundamental principle for designing High-Performance Concrete (HPC) mixes. The concept is based on the belief that the performance of a concrete mix can be optimised by maximising the packing densities of the aggregate particles and the cementitious materials (Henry H.C. Wong 2005).

2.3.2.4 Mixing water

The volume of water required will be dependent on the moisture content of the aggregate particles and the 28-day target strength. Although the quality of mixing water may have little influence on the concrete, the water used for a concrete mix could affect setting time and the development of strength. SANS 51008 describes the maximum tolerable limits with regard to alkalis, chlorides, organic matter and other harmful substances. These substances will not only affect strength development but also cause corrosion of reinforcement (PCA 2021).

2.3.2.5 Physical Properties of Concrete

2.3.2.5.1 *Introduction*

In our built environment, concrete can be found everywhere. The infrastructure of our cities requires massive quantities of concrete. We live on concrete floors, surrounded by walls supported on concrete foundations. We drive on concrete roads, walk on concrete pavements and the water which we drink is probably stored in a concrete reservoir (PCA 2021). According to (PCA 2021), the following properties of concrete make it one of the most versatile and desired construction materials in the world, and the planet's most used resource after water. Concrete is an exceptionally durable material and can last for centuries if constructed correctly.

2.3.2.5.2 *Relative Density*

The relative density (RD) or specific gravity (SG) is the ratio of the density of a substance to the density of water. Relative density is useful for the calculation of volumes for a particular yield. RD of natural aggregates range between 2.60 and 2.95 (ConcreteInstitute 2019).

2.3.2.5.3 *Bulk Density*

The bulk density is the mass of aggregate that will fill a container of 1 m3 volume. Loose bulk density (LBD) is the density of the aggregate that has been placed into a container without compaction. Compacted bulk density (CBD) is the density of the aggregate particles after compaction. The CBD is used to determine the stone required for a mix. SANS 5845 describes the test procedure to obtain the CBD for stone. LBD is used for volumetric batching since it would be uneconomical to densify aggregate to determine the volumes required.

2.3.2.5.4 *Compressive Strength*

A fundamental property of concrete used in the design is compressive strength. The compressive strength of concrete is approximately 10 times more than the tensile strength (Nemati 1998). Concrete is a relatively strong building material in compression relative to other construction materials such as metal and wood. The typical use of concrete requires strengths between 30 and 50 MPa, however, strengths of up to 250 MPa have been achieved in laboratory studies. By selecting the right ingredients and careful proportioning, the concrete strength can be tailored to meet almost any strength requirement at the lowest cost (ConcreteInstitute 2019).

2.3.2.5.5 *Tensile and Flexural Strength*

Although Compressive strength is the most widely used method of determining and monitoring the strength of concrete, sometimes more important is the performance of the concrete in tension. The tensile strength of concrete is a very essential property, even though as a rule it is not explicitly used in design calculations. Without tensile strength, concrete would behave like a heap of sand without the ability to form beams, slabs, and columns. Indirectly the tensile strength is used in the shear strength design of slabs and beams for example. However, not only the tensile strength but also the behaviour at tensile fracture is of importance, particularly the toughness. If concrete were a perfectly brittle material, any small crack or flaw in a region with tensile stresses would cause a running crack, which might lead to a catastrophic failure (Hillerborg 1985).

The load capacity of concrete structures is affected by the cracking behaviour of concrete. Since the tensile strength of concrete is much lower than its compressive strength (approximately 10 times), concrete belongs to the group of brittle materials, but it is not perfectly brittle. Concrete is considered to be a quasi-brittle material, and therefore, when analysing the cracking behaviour of concrete, not only tensile strength but also tensile toughness is of paramount importance (Słowik 2019). Testing the tensile strength of concrete using a normal tensile test machine such as used with metals and polymers is very impractical as the test results are extremely dependent on the surface of the sample giving a wide scatter of results. The tensile strength of concrete is normally measured by compressing a solid cylinder perpendicular to its longitudinal axis creating tension forces midway between the compressive press platens. In this way, the results are more consistent, and the test is termed ‘indirect tensile strength’ or ‘splitting tensile strength’.

The deflection and cracking behaviour of concrete structures depend on the flexural tensile strength of the concrete. Many factors have been shown to influence the flexural tensile strength of concrete, particularly the level of stress, size, age and confinement to concrete flexure members, etc. The concrete members, in general, are of a large continuous size and have at least minimum reinforcement introducing a confining effect to the concrete. The confining reinforcement increases ductility and large deflections in structures provide a good warning of failure prior to complete failure of the flexure member and also for efficient use of constructional material (Ahmed, Mallick et al. 2016).

2.3.2.5.6 *Fracture Toughness*

Fracture and impact resistance are among the improved attributes of fibre-reinforced concrete (FRC). Toughness, which is a measure of the energy-absorption capacity, is used to characterize FRC's ability to resist fracture when subjected to static, dynamic, and impact loads (Gopalaratnam 1991).

The total amount of energy absorbed in a tensile test to failure is represented by the area below the load-deformation curve for the specimen (Hillerborg 1985). In practice, it is not easy to measure the deformation on the required small scale especially as the measurement needs to be measured in the specific crack deformation region.

The most direct way of determining GF is by means of a uniaxial tensile test, where the complete stress-deformation curve is measured. The test must be stable, which means that the deformation is increased slowly, without any sudden jumps.

Hillerborg (1985) justifies that the direct tensile test is the only test which gives all the relevant information for numerical analyses, i.e., the tensile strength f~ the modulus of elasticity E, the fracture energy GF and the shape of the descending branch.

Unfortunately, it is difficult to perform stable tensile tests and at present, only the best-equipped laboratories have testing facilities which allow for such tests. Uniaxial tensile tests are therefore not suitable as standard tests for the determination of GF. Maybe this situation will change within the next decades. It is much easier to perform stable bending tests on notched specimens. The simplest possible test of this type is the three-point bend test on a notched beam as shown in Figure 3

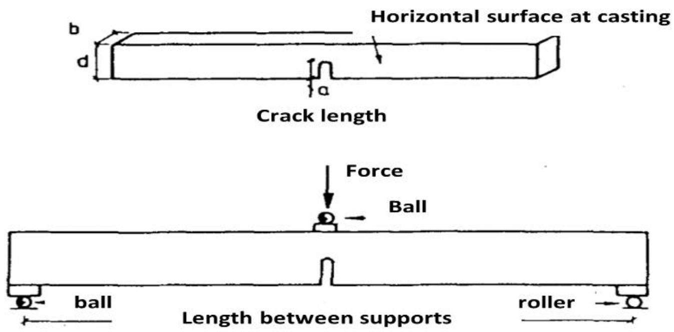


FIGURE 3. HILLEBORG (1985) MEASUREMENT OF GF (FRACTURE ENERGY) 3 POINT BEND METHOD

The general idea of this type of test is to measure the amount of energy which is absorbed when the specimen is broken into two halves.

This energy is divided by the fracture area (projected on a plane perpendicular to the tensile stress direction). The resulting value is assumed to be the fracture energy GF.
The three-point bending method provides a good prediction of fracture energy to determine the destruction energy.

Another recent development is the Round Determinant Panel (RDP) which has been proposed by ASTM and a version of this is detailed in the journal of testing and evaluation (Mitchell, Link et al. 2011). This test could be modified to suit specific needs, is very simple yet provides meaningful fracture toughness data Figure 4 gives an overview of the apparatus and output.

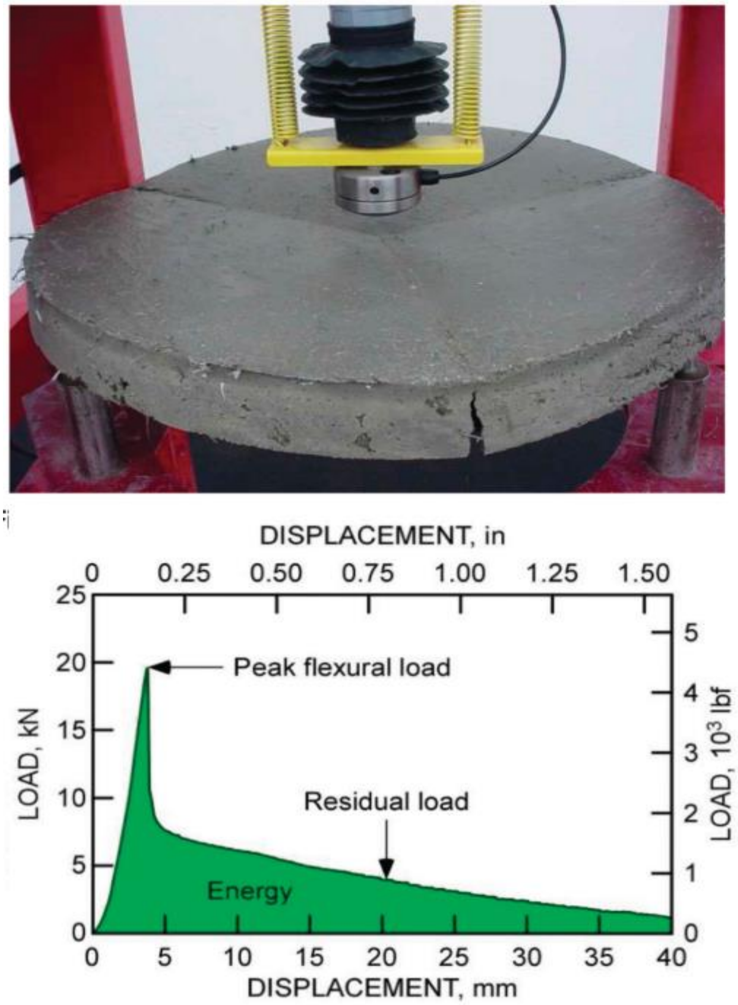


FIGURE 4. ROUND DETERMINATE PANEL - FRACTURE TOUGHNESS TEST (MITCHELL, LINK ET AL. 2011)

More recently, with the advent of more sophisticated test equipment and a better understanding of fracture mechanics, crack-tip-opening displacement and crack-mouth-opening displacement have become more recognised for determining material toughness. However, if a prediction of the fatigue performance is required, then cyclic fatigue testing is recommended, as utilised by (Yin, Tuladhar et al. 2015).

2.3.2.5.7 *Durability*

The durability of concrete is its ability to resist weathering action, chemical attack, abrasion or any other process of deterioration (ACI 2013). This property for concrete is generally directly related to porosity, hence porosity being the common standard for specifying durability performance.

2.3.2.5.8 *Reinforcing concrete with steel bar (rebar)*

The concept behind concrete reinforcement is to offset the low tensile strength of concrete by combining the superior tensile properties of the chosen reinforcing steel (rebar) with the compressive strength of concrete. This combination of properties will give rise to a durable and inexpensive structural material capable of withstanding bending and shear loads that will be generated in a loaded structure (Gagg 2014).

Accordingly, to make the most efficient use of the two materials, a beam should be designed so that the rebar starts to yield before the concrete fails in compression. This is also a safety measure, as the tensile yielding of rebar is progressive and the beam will remain load-bearing, whereas crushing of concrete is explosive and therefore catastrophic (Gagg 2014).

Figure 5 shows bending stresses induced in a beam cross-section are primarily tensile in the bottom section reaching a maximum along the bottom face and compressive in the top section reaching a maximum at the top face. Bending stresses are zero at the neutral axis.

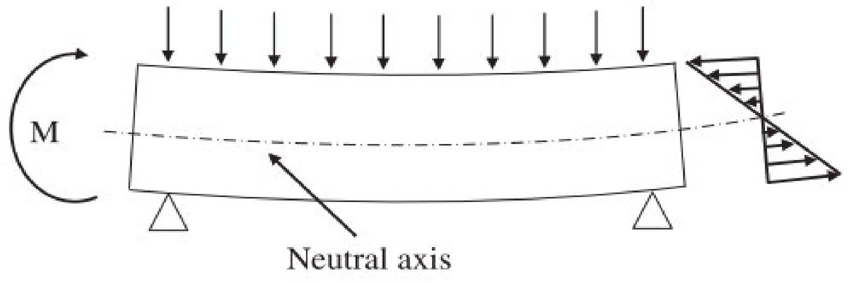


FIGURE 5. STRESS DISTRIBUTION IN A SIMPLE RECTANGULAR BEAM IN BENDING GAGG, C (2014)

Induced bending stresses can be calculated by the elastic bending relationship as shown in Figure 5, where y is the distance of the stress element from the neutral axis of the cross-section; M is the bending moment (Gagg 2014).

2.3.3 *The utilisation of waste material in concrete*

2.3.3.1 Introduction

According to (Stubbs 2022) the latest available statistics South Africans generate roughly 122 million tonnes of waste per year. Of this waste, a maximum of only 10% is recycled or recovered for other uses, while at least 90% is landfilled or dumped illegally. The South African waste management industry is evolving and is one of the most efficient on the continent. However, the country is still generating large amounts of waste annually and most of our landfill sites are fast approaching full capacity.

The requirement for a sustainable built environment demands the maximum reuse of resources through a circular economy approach. Many waste products are investigated by exploring the opportunity of recovering and reusing them or using them as part of a compound or composite material. Concrete is one of the most widely used materials in construction and offers a high degree of adaptability in terms of the possible addition or substitution of individual constituents to form composite materials.

The production of green concrete, targeting sectors of largely locally available waste products, can form part of a more holistic and integrated waste management approach, oriented to offer new opportunities to municipalities and the private sector in terms of circular economy and job opportunities. This is even more significant in developing countries, such as South Africa, where the implementation of effective waste management strategies has not reached full momentum. The concept of "Green Buildings" is gaining importance in a growing number of countries globally, including South Africa. These buildings are designed to ensure that waste is reduced at every stage during construction and the future operation of the building. "A green building is an integrative process that focuses on the relationship between the built and natural environment" (Kibert 2016).
Concrete is the most used construction material in the world. Consequently, the mass extraction of virgin materials required for concrete production causes major environmental impacts. With

a focus on promoting sustainability, numerous research studies on incorporating waste materials to replace virgin substances in concrete were undertaken. Despite this vast volume of published literature, systematic research studies on these sustainable concrete mixes that inform various stakeholders on current research trends, future research directions, and marketability options products are seldom conducted (Sandanayake 2020). An extensive research exercise was undertaken by Sandanayake (2020), involving a bibliometric assessment of 1465 research publications in which five key materials (plastic, glass, fly ash, slag) and construction and demolition waste were selected for the review. Ten industry experts were also interviewed providing invaluable data and guidelines for both research academics and industry stakeholders to systematically focus on sustainable concrete products that are market ready. Although many positive technical merits are evident from the extensive test work done, Sandanayake (2020) concludes that the major impediments include economic benefits for builders, compliance requirements, quality control issues, social acceptability, and government initiatives. If these can be effectively addressed, transitioning these sustainable products into market-ready products could become a reality.

It may be comforting for South African Environmentalists to note that at the Cement and Concrete SA Young Concrete Researchers, Engineers & Technologist Symposium (YCRETS) in July 2021, of the twenty-four papers presented, seven papers relate to research on concrete and waste (including one on Paper Mill Ash from UKZN Civil Engineering Faculty). Six of the papers focus on the incorporation of waste in concrete mixes and one on waste generated in the construction and demolition category (Cement&Concrete_SA 2021). We trust that with the global drive for sustainability, consistent research, development and assessment of progress will provide fruitful results.

To avoid confusion we should first examine the term ‘green concrete’ the American Concrete Institute's list of terminology ACI (2013) defines green concrete as concrete that has set but not appreciably hardened. This is in common with many materials whereby the term ‘green’ indicates that the material has yet to be converted into its final form. However ‘green concrete’ is now commonly used to refer to concrete that is more sustainable than traditional concrete due to its composition, manufacture, application or final properties (Al-Hamrani, Kucukvar et al. 2021) (Jin and Chen 2013). For this document, a ‘green’ material or process is one more sustainable or more environmentally friendly than their traditional or conventional equivalents.

2.3.3.2 Relevant South African Government Directives

The following mentioned government directives motivate the selection of the chosen waste streams as raw materials, avoiding disposal and landfill issues and minimising the source of new natural resources. Furthermore, the focus of this research study is not simply to 'politely' use the waste but to utilise its inherent property and provide a 'performance enhancer'.

Environmental Assurance (Pty) Ltd (ENVASS) verifies that on 28 January 2021, the South African Minister of Forestry, Fisheries and the Environment published the National Waste Management Strategy, 2020 ("National Waste Management Strategy"), 2020 version focusses on the introduced concept of a "circular economy" aiming to reduce environmental impacts by re-use & recycling of processed materials. The reason to have materials that would end up as waste disposed of, reprocessed rather than extracting raw materials again, is at the core of the concept towards sustainable development. The concept and strategy are further expanded on through the three strategic pillars: 1. Waste Minimisation, 2. Effective and sustainable waste services and 3. Compliance awareness and enforcement (ENVASS 2021).
The overall purpose of the NWMS 2020 is to provide the government's policy and strategic interventions for the waste sector and an enabling environment for the implementation of the 2017 Chemicals and Waste Phakisa projects (Environment_Forestry_and_Fisheries 2020).

Following on from the prementioned directives, emphasis has been placed upon the material producer by the Regulations Regarding Extended Producer Responsibility
(1) to provide the framework for the development, implementation, monitoring and evaluation of extended producer responsibility schemes by producers in terms of section 18 of the Act.
(2) to ensure the effective and efficient management of the identified end-of-life products and
(3) to encourage and enable the implementation of circular economy initiatives (Creecy 2020).

2.3.3.3 Construction and Demolition Waste (C&D Waste)

2.3.3.3.1 *Introduction*

The conventional methods of raising and demolishing buildings and concrete structures are implemented in such a way that most of the resulting waste is sent to landfills, instead of being recycled or reused in new constructions. The use of recycled aggregates from construction and demolition wastes as a replacement for natural aggregates has been considered one of the most salubrious approaches towards greater sustainability in construction (Silva and Brito 2015). Global development and expansion of the built environment have contributed to severe damage to the natural environment and may consequently endanger its sustainability. The exploitation of non-renewable resources, in particular for construction purposes has led to millions of tonnes of construction and demolition (C&D) waste every year (RV Silva 2015).

C&D Waste from the process of construction, demolition or repair of houses, commercial buildings, roads, bridges, etc. is generally divided into commercial construction waste from construction companies and do-it-yourself (DIY) waste from homeowners making their own repairs (UN-HABITAT 2010).

2.3.3.3.2 *C&D Waste reused in concrete mixes*

C&D waste is a key waste type that can be reused in concrete applications, as its composition comprises cement and aggregate scraps which can be easily adopted as a replacement for virgin materials in concrete. Over the last decade, recycled C&D waste has mainly been used as a coarse aggregate replacement material in concrete and is often called recycled concrete (Sandanayake 2020). The recycling of concrete improves sustainability in several diverse ways. The simple act of recycling the concrete reduces the amount of material that must be landfilled. The concrete itself becomes aggregate and any embedded metals can be removed and recycled as well. As space for landfills becomes a premium, this not only helps reduce the need for landfills but also reduces the economic impact of the project. Moreover, using recycled concrete aggregates reduces the need for virgin aggregates. This in turn reduces the environmental impact of the aggregate extraction process. By removing both the waste disposal and new material production needs, transportation requirements for the project are also significantly reduced (PCA 2021).

Construction materials are increasingly judged by their ecological characteristics. Concrete recycling gains importance because it protects natural resources and eliminates the need for disposal by using readily available concrete as an aggregate source for new concrete or other applications (PCA 2021).

Construction and demolition waste typically consists of numerous materials which can be re-used or recycled in diverse ways; in this study, the use of crushed concrete is assessed. The Portland Cement Association refers to the use of recycled concrete in new concrete, stating that the crushing characteristics of hardened concrete are similar to those of natural rock and are not significantly affected by the grade or quality of the original concrete. Recycled concrete aggregates produced from all but the poorest quality original concrete can be expected to pass the same tests required of conventional aggregates' (PCA 2021).

According to these studies reviewed by Sandanayake (2020), the tipping fees and additional transportation costs are some economic implications that need to be considered and the importance of government incentives to promote the use of these waste materials was also highlighted. Another study emphasized the requirement to source recycled materials locally to maximize the economic and environmental impacts.

Tam, Tam et al. (2007) highlighted a lack of standards, insufficient financial incentives, and customer perceptions as some of the major barriers that restrict the use of recycled aggregate from C&D waste in concrete. Furthermore (Tam, Tam et al. 2007) noted obstacles in using Recycled Aggregate, stating that although it is environmentally beneficial to use RA, the current legislation and experience, however, are not sufficient to support and encourage the recycling of demolished concrete waste. These technical problems include weak interfacial transition zones between cement paste and aggregate, porosity and traverse cracks within demolished concrete, high level of sulphate and chloride contents, impurity, cement remains, poor grading, high variations in quality, which render the use of RA for structural applications difficult.

2.3.3.4 Glass cullet from recycled bottles

2.3.3.4.1 *Introduction*

Post-consumer and other waste glass types are a major component of the solid waste stream in many countries, and most are currently destined to be used as landfill. Several European Directives have tackled this problem by setting recovery and recycling targets for specific waste glass streams. EU Landfill Directive and the UK Landfill Tax Regulations have emerged to divert such waste into recovery and recycling programs and, specifically for post-consumer glass, the Packaging Waste Regulations have provided legislative pressure to increase recovery and recycling. Whereas in 2010 in the USA, 11.53 m tons of waste glasses were generated and only 27.1% of them were recovered, mostly from containers and packaging (Gerges, Issa et al. 2018). Furthermore, the volume of glass entering the municipal solid waste stream has remained relatively stable since 1970. The total volume of glass waste that was generated in the U.S. in 1970 amounted to 12.7 million short tons, and by 2017 it had decreased slightly to 11.4 million short tons. Of the 2017 amount, 6.87 million short tons were landfilled, 3.03 million short tons were recycled, and 1.48 million short tons were combusted with energy recovery (Statista 2021).

In South Africa, the Glass Recycling Company (TGRC), established in 2006 as a glass industry association body with the overall objective of reducing the total volume of glass being sent to landfills, has played a vital role over the past 13 years, ensuring that millions of tons of used glass packaging did not enter South African landfills. More than 80% of all glass packaging is now diverted from landfills (TGRC 2019).

2.3.3.4.2 *Review of glass waste in concrete*

After reviewing the state of the glass recycling market in South Africa, opportunities exist to explore new avenues concerning waste glass. Once the glass is collected it can be crushed into different grades, without colour sorting, this glass cullet can then be used for various applications without the need to be recycled into new glass, saving sorting and logistical costs. Harrison, Berenjian et al. (2020) report that incorporating waste glass in cement-based materials has the potential for creating a more sustainable future. Trials of waste glass being used in cement-based materials on the commercial scale were found to be limited; however, a few cases were found, including the 2012 Queen Elizabeth Olympic Park. The Olympic Delivery Authority (ODA) set sustainability as a key focus, aiming to reduce the concrete carbon footprint by 25% Due to the potential loss of strength, glass sand substituted fine aggregate at replacements of 0 to15% depending on the required strength designation, on average 2% of all fine aggregate used was substituted for glass. Another example is the Lion Nathan brewery which finished construction in 2010. The Lion brewery incorporated 3500 tonnes of waste glass within the concrete mix, using over 1.3 million recycled beer bottles [13]. However, the high silica content of glass saw the potential for alkali-silica reaction (ASR), which can cause swelling of the concrete leading to the formation of cracks. Preventing this required 12 months of lab research and testing to get the correct mix proportions to complete the project.

Research work was conducted by Alhumoud, Al-Mutairi, and Terro in Kuwait, on Proportions of 0–100% of crushed glass in the concrete, where specimens' compressive strength at temperatures up to 700°C was measured. The results indicated that the use of crushed glass in concrete is a viable and effective recycling option, in particular when used in proportions of between 10% and 25% where the compressive strength exhibited higher values than those of normal concrete at ambient and elevated temperatures (Jasem M. Alhumoud 2008).

However, the percentage of utilisation of waste recycled glass in concrete has been minimal because of the potential Alkali-silica reaction (ASR) risk and lack of information and outcomes of using waste recycled glass in concrete, in particular, the long-term observations.

Alkali silica reaction (ASR), commonly referred to as "concrete cancer", is a major durability problem in concrete structures. ASR is a chemical reaction that occurs between the reactive amorphous silica from the natural aggregates and the alkalis in cement in the presence of moisture. This reaction causes undue expansion and cracks in hardened concrete which over time results in deterioration. Since the problem of the ASR expansion was voiced, numerous research works were conducted worldwide to eliminate the deterioration effect of ASR (Dhir 2009). Expansion can be controlled by the use of GGBS and metakaolin, and it is probable that other materials, such as fly ash and condensed silica fume would also be effective (Dhir 2009).

Supplementary cement materials SCMs can effectively reduce ASR risk when used in concrete as cement replacement e.g., ground granulated blast furnace slag GGBS and pulverized fuel ash Aquino et al. 2001; Shehata and Thomas 2000. Meyer and Xi 1999 and Shehata et al. 1999 concluded that the alkalis available in the cementitious supplementary materials will be consumed in the chemical reaction of the hydration process to form hydration products. Therefore, the alkalis will not be available in the pore solution for further chemical reaction such as the ASR at later stages, as the alkalis will be chemically bonded in the hydration products (Taha and Nounu 2009).

The extensive research and development work conducted over recent years to mitigate ASR continues with effective results. A recent study concludes that the binary or ternary blends of 20% replacement of glass powder, slag, or silica fume can be utilized for ASR mitigation without compromising other concrete properties (Fanijo, Kassem et al. 2021). The contribution of paper mill sludge ash has also been proposed by The University of Southbank, London where concrete mixes with partial or full natural sand replacement by waste glass aggregate (WGA) were then produced and showed appropriate strengths and overall similar or better water absorption characteristics than control mixes with natural aggregates without manifest alkali-silica reaction (ASR) problems. This shows potential for applications in precast dry mix concrete units based on the required strengths that were achieved (Mavroulidou and Awoliyi 2018).

2.3.3.5 Paper Mill Sludge (PMS)

2.3.3.5.1 *Introduction*

For every tonne of recycled paper produced, approximately 300kg is sludge (Balwaik and Raut 2011), the disposal of which is a familiar problem confronting the paper industry. It is essential that we attempt to find new alternatives to cater for the exponentially increasing population demands, as landfills are becoming more expensive and a less viable option in many countries. For these reasons, the use of paper sludge for energy production has encountered increased attraction as being cost-effective, and an environmentally acceptable disposal method (Fava, Ruello et al. 2011).

2.3.3.5.2 *Incorporation of Paper Mill Sludge in Concrete*

There are three fundamental stages in the paper-making process, namely: preparatory, pulp-making and papermaking. During the preparatory phase, logs from trees, or wood pieces are fed into the system and broken down into uniform sizes via a crusher. They are then "cooked" in a chamber with other additional chemicals which digests the fibres and lays them in a uniform pattern. After this process is complete, the pulp-making process begins, consisting of further refining the wood particles, as well as bleaching and cleaning. The moisture is then removed from the material to produce pulp, which is a near-solid type of material. Finally, it is flattened to a specific thickness by a press.

Paper mill sludge is generally understood as waste originating from waste-treatment rejects that are separated from the mill effluent during the treatment process of (recovered) virgin or recycled paper (Fava, Ruello et al. 2011). Pulp and paper-mill sludge consist of cellulose fibres (and occasional wood particles), kaolinitic clay, ash-bearing compounds, calcium carbonate and moisture (up to 40%). (Likon and Trebše 2012) (Table 3) displays the organic content (mainly cellulose) in paper mill sludge from different sources, indicating that the highest cellulose content is found in primary paper mill sludge which is sourced from mills producing pulp or paper from wood source and not from recycled pulp.

TABLE 3. PAPER MILL SLUDGE TYPES AND CONTENT LIKON AND TREBŠE (2012)

	PMS origin	Organic content wt %	Ash content wt %	Heat value MJ/kg	CEC cmol/kg
Low-ash sludges	Primary sludge from pulp mill producing pulp from virgin wood	94.31	5,69	20,1	30,20
	Primary sludge from paper mill producing paper from virgin wood	93,79	6,21	19,8	32,41
High-ash sludges	Secondary sludge from paper mill producing paper fom recycled cellulose without deinking process	67,23	32,77	16,5	17,30
	Primary sludge from paper mill producing paper from recycled cellulose without deinking process	64,72	35,28	14,2	33,58
	Deinking sludge from papermill that recycled paper not recycled previously	60,36	39,64	12	18,12
	Deinking sludge from papermill producing newspaper	59,30	40,70	12,2	19,06

In the U.S., approximately half of the quantity produced (4.4 million tons) is sent to landfills, one quarter is incinerated, and the rest is used in some other way. It can also be used as a bulking agent for composting (Balwaik and Raut 2011) (Likon and Trebše 2012).
Following on from the research of Glass Cullet of the previous section of this thesis, it is evident that pozzolanic materials in cement mixes e.g. Pulverised Fuel Ash (PFA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF) or metakaolin (MK) can effectively counteract ASR (e.g. Almesfer & Ingham, 2014; Shafaatian et al, 2013); some of these are industrial by-products and their use in concrete is an excellent valorisation route with the additional environmental advantage of the low or no energy demand for their production compared to Ordinary Portland Cement (Mavroulidou and Awoliyi 2018). In addition to these pozzolanic materials, Mavroulidou and Awoliyi (2018) proposed the use of paper mill sludge ash to further eliminate ACR concerns from the incorporation of glass cullet in concrete.

However, this document intends to utilise the tensile properties of the paper fibres themselves in concrete crack mitigation, rather than incinerating the pulp and utilising the remaining ash. This document incorporates work conducted at UKZN by incorporating both dry and wet paper mill sludge in a concrete mix at varying percentages (Smith and Trois 2018).

2.3.3.6 Fibre from vehicle tyres

A database of recycled materials used for building purposes was created and the incorporation of end-of-life vehicle tyre fibre in concrete was selected as the subject of extended research See 2.4 [The initial study of tyre fibre in the concrete led to more extensive research, therefore the literature review has been combined]

2.4 Focus waste fibre from recycled tyres as a performance enhancer of concrete

2.4.1 *Introduction*

Annually, approximately 3 billion tyres are commercially transacted worldwide each year and an equivalent amount is disposed of by the end of their life. Despite the increase in the life of tires and the global economic and pandemic crisis, the number of discarded tyres is going to rise further due to the increasing demand for vehicles worldwide (approximately 5 billion tires by the end of 2030) (Grammelis, Margaritis et al. 2021).

In 2011 it was estimated that 60 million used tyres could be found on South African soil – more tyres than people. With a further 11 million new tyres entering the market each year, and a recycling rate of only 4%, the situation was a growing societal problem.

A fee of R2.30 (€0.14) per kilogram was levied on all new tyre rubber. Proceeds were used to establish an infrastructure for tyre collecting and downcycling and pay for its administration.

Within 3 years, REDISA (Recycling and Economic Development Initiative of South Africa) increased the recycling rate of new tyres to over 60%, from a baseline of 4%. (inno4sd 2019).

Technologies and innovations for recovering end-of-life tyres are well established. Reuse, re-treading, energy and material recovery of end-of-life tyres are viable options. However, the recycling of waste tyres is not globally successful (Sebola, Mativenga et al. 2018). The products from the processing of ELTs can be fragments of different sizes and types, including Trimmed rubber (70% by weight), steel wire (5–30% by weight), and fluff or textile fibres (up to 15% by weight) (Grammelis, Margaritis et al. 2021).

Although the 3-year change in the recycling of end-of-life vehicle tyres ELVT from 4% to 60% in South Africa is very impressive, the massive stockpiles of existing end-of-life tyres remain and the road to successfully creating a circular economy for vehicle tyres in South Africa is a rough one. In a positive light, this leaves a big opportunity to use tyres as a valuable raw material by developing new applications and markets.

2.4.2 *Polymer fibre in concrete*

The concept of using fibres for concrete reinforcement is not new. Previous studies investigated the effects of incorporating fibres in concrete, for example using fibre derived from recycled PET drink bottles. Generally, the addition of fibres to concrete would act as crack inhibitors and substantially increase the tensile strength, cracking resistance, impact strength, wear and tear, fatigue resistance and ductility of concrete (Koo, Kim et al. 2014). Kandasamy and Murugesan (2011) determined that the flexural strength of specimens with replacement of the fine aggregate with PET bottle fibres increases gradually with an increase in the replacement percentage (Al-Hadithi 2015) concluded that although the workability of the concrete mix decreased, the compressive strength increased with an addition of up to 1.5% and flexural strength increased with addition up to 1.75%. Yin, Tuladhar et al. (2015) describes this a sewing effect, increasing the ductility, it is also at times defined as a 'bridging' effect. Furthermore, Yin, Tuladhar et al. (2015) noted when testing beams that plain concrete beams failed almost instantaneously with the occurrence of the first crack, but the fibre beams (polypropylene fibre) failed over a period of additional bending as the bending force was transmitted to the fibres once the first cracks occurred, this was a result of the matrix action that is attributed due to the concrete mixed with the fibres. The ductility of the beam was improved. Figure 6 provides a good indication of the effectiveness of fibre reinforcement, The peak load was reached at a corresponding CTOD of less than 0.6 mm for all the specimens.

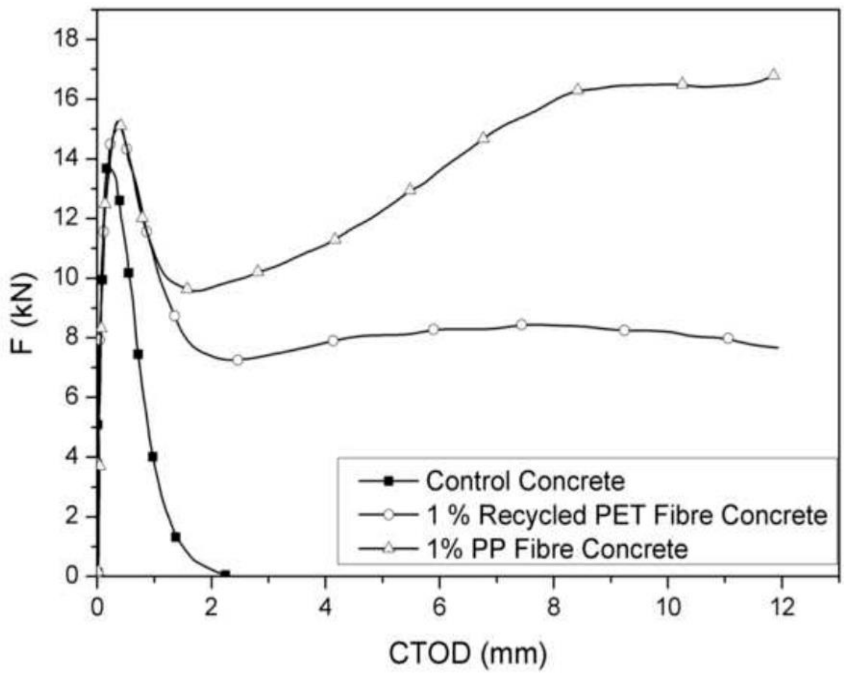


FIGURE 6. CRACK TIP OPENING DISPLACEMENT - POLYMER FIBRE REINFORCED CONCRETE, YIN, TULADHAR ET AL. (2015)

However, compared to the plain concrete, the ductility of the specimens after the peak load has significantly improved in the PP and PET fibre-reinforced specimens.

Pešić, Živanović et al. (2016) experimented with HDPE varying fibre length and concentrations concluding that the tensile strengths increased for all the substitution proportions.
This initial review of fibres in concrete was included in a paper presented in Sardinia at the Sixteenth International Waste Management and Landfill Symposium / 2 - 6 October 2017 (Smith, Trois et al. 2017).

2.4.3 *The South African Scenario for end-of-life tyres*

2.4.3.1 Government directive timeline

The following list provides an overview of the South African Government directives relating to end-of-life automotive tyres

2012 To kick-start the widespread recycling of used tyres, the government of South Africa approved the REDISA Integrated Industry Waste Tyre Management Plan (IIWTMP) (inno4sd 2019).
2015 Within 3 years, REDISA (Recycling and Economic Development Initiative of South Africa) increased the recycling rate of new tyres to over 60%, from a baseline of 4%
2017 van-Wyngaardt (2017) reports for Engineering news: 'REDISA placed under liquidation', The Recycling and Economic Development Initiative of South Africa (REDISA) has been placed under liquidation to safeguard the operations and assets associated with the programme.
Environmental Affairs Minister Dr Edna Molewa filed an urgent application for the liquidation at the Cape Town High Court.
2019 In January 2019, there was further news that South Africa's tyre recycling project, marred by allegations of widespread corruption, has been given a clean bill of health by the South African Supreme Court of Appeal (Broughton 2019).
2020 The CSIR (Centre for Scientific and Industrial Research) issued a draft document 'INDUSTRY WASTE MANAGEMENT PLAN – TYRES' Developed by the CSIR in terms of Section 29 of the National Environmental Management: Waste Act, 2008
DRAFT 1 FOR STAKEHOLDER CONSULTATION MARCH 2020.

This strategy follows the rejection of prior government strategies and in the interim, the waste tyre stream has been managed by the Waste Management Bureau (WMB) as provided in the transitional arrangements of the Waste Tyre Regulations, 2017.

The WMB have indicated that 170 266 tonnes of waste tyres are generated per year (2019 estimate) of which 77% is collected and 24% of the collected tyres are processed. A study undertaken in 2013, as part of the Waste RDI Roadmap (DST, 2014a) found that waste tyres can be recycled to produce rubber crumb, which can be sold for approximately R3,000 per tonne to road builders. However, collection and transport of waste tyres from tyre dealers cost between R700 and R1,900 per tonne, while processing to produce rubber crumb costs another R2,000 per tonne, excluding overhead costs. It is therefore clear that recycling tyres to produce rubber crumb in this scenario is not economically viable given the current technology. The tyre levy of R2.30/kg could partially address this, provided that the levy can be accessed. In the meantime, a core viable option may simply be to recover energy by using tyres in cement kilns or brick-making plants, where waste tyres can replace part of the coal currently being used to produce energy.

The intended purpose of this document is to serve as a "straw-dog" for the plan, i.e., the document present current thoughts and structure of the plan which will be used as the point of departure for stakeholder dialogue for the development of an Industry waste management plan for tyres. (Olofsa 2020).

2021 Parliament (2021) Department of Environment, Forestry and Fisheries Committee asked about the Waste Bureau's financial state and was informed that its operational costs for the current financial year would be about R384 million and would be funded by a levy imposed on the tyre industry. The Department terminated its relationship with REDISA in 2017, so the Waste Bureau was temporarily tasked with the mandate to improve the efficiency of tyre waste management. The CSIR was currently assisting the Department with a waste management plan. There were ongoing engagements to address the key challenges, and the plan would hopefully be finalised in March 2022.

Following the withdrawal of Redisa plan and promulgation of Waste Tyre Regulations 2017, Waste Bureau is mandated to manage waste tyres temporarily until a new Industry Waste Management Plan for waste tyres is approved. In May 2021, the Waste Bureau gave a presentation, with the following key areas relating to the destiny of end-of-life tyres:

Once the Section 29 Industry Waste Management Plan (IndWMP) is finalised and the implementer(s) of the plan have been appointed by the Department, then the Waste

Management Bureau will exit waste tyre management operations and then refocus on their broader mandate Section 34 NEMWA. 2020/ 2021 focus areas include:

- To target more brick-making facilities
- Skills training for secondary industry
- Promoting waste tyre exports

Promoting downstream demand for Tyre Derived products – SANRAL (South African National Roads Ltd), Provincial roads, municipalities, school playgrounds, etc.
(Department of Forestry 2021).

The status relating to the use of 'tyre-derived products can be confirmed that the utilisation of end-of-life tyre materials in a sustainable and environmentally friendly manner does remain on the Government agenda but in parallel with the use of tyres in industrial furnaces and the export of tyres.

The tyre recycling industry awaits the new Industry Waste Management Plan for waste tyres when the Waste Management Bureau exits from responsibility.

Despite a 'clean bill of health' being given to REDISA, in 2019 the tyre recycling momentum appears to have stagnated, despite the R384 million Rand that continues to collect from the tyre industry annually.

2.4.4 *Opportunities for recycling vehicle tyres*

2.4.4.1 Introduction

The most obvious method of utilising end-of-life automotive tyres is by incineration, using the heat energy for powering cement and brickworks, however, for environmental reasons, the efficient utilisation of the base raw materials is preferable.

It may be said that '*It is therefore clear that recycling of tyres to produce rubber crumb in this scenario is not economically viable given the current technology'* (Olofsa 2020). This may be valid for current technology in the current marketplace but as often seen, if the industry 'steps up' to meet environmental directives, in the process of research and innovation, new heights of efficiency and material utilisation are often achieved. If we don't set these directives, we are destined to fail.

2.4.4.2 Rubber crumb

A facility of note is the South African Mathe Hammarsdale plant, which runs 24 hours a day, seven days a week, and produces approximately 600 tonnes of rubber crumb monthly. Half of this crumb is used by the roads industry for resurfacing, while 15% goes to Van Dyck Floors and 35% of which is used as foundations for sports fields. The Mathe Group processed more than 150 000 used truck tyres in 2017 and the head of PFE International is confident that the plant will easily process over 200 000 tyres during 2018 (Averda 2021). The company currently only processes truck tyres due to the high return on steel recovery, however, the growing market for rubber crumb is providing a market for the recovery of rubber crumb from passenger car tyres.

2.4.4.3 Steel

Most steel is exported due to its high raw material value, herein may lie opportunities to reprocess this steel locally increasing its value.

2.4.4.4 Polymer fibre

The utilisation of polymer fibre from end-of-life tyres is the focus of this document by incorporating it into the concrete mix to improve the performance of the concrete instead of burning or more typically, sending the rubber-contaminated fibre to landfill sites.

Presently, only truck tyres are being processed for steel and crumb rubber but as the benefits of crumb rubber from end-of-life tyres are realised, market demand is increasing. With increased demand and limited supply, crumb rubber from passenger car tyres is being proposed which will result in a much higher quantity of polymeric fibre as the percentage of fibre is much higher in passenger car tyres than with truck tyres see 3.4.2 for tyre recycling company visit.

2.4.5 *Global innovations utilising end-of-life vehicle tyre fibre in concrete*

Fibre-reinforced concrete (FRC) is commonly employed in pavements (e.g., airports and highways), bridge decks, tunnel linings and offshore platforms, which may suffer from repetitive cyclic loading during its entire service life.

Onuaguluchi and Banthia (2017) concluded that while further studies are required to evaluate the performance of other types of polymeric scrap tyre fibres (STF), as well as the effects of higher STF content in mixtures and hybrid combinations of STF and other synthetic fibres, the present study indicates a huge potential for polyester based STF as a microfibre reinforcement for repair mortar applications. However, Onuaguluchi and Banthia (2017) also stated that
While the proposed reuse of STF in cement-based applications is an important step forward; however, to engender the interest and confidence of the construction industry in the quest to utilize STF in cement composites, its effects on durability properties need to be clarified.

Research by [Grammelis, Margaritis et al. (2021)](#) concluded that ELTs can be used for the production of concrete for special applications, as long as the proper processes are implemented. The produced concrete with ELTs components has a reduced specific weight, increased resistance to cracking, resistance to deformation, and higher ability to absorb vibrations. However, depending on the percentage, size, and type of ELTs used, the concrete may present reduced mechanical properties.

Figure 7 provides an interesting picture of how the incorporation of fibre into a concrete mix changes its microstructure. The two images on the left (A) are from 4% fine aggregate replacement with tyre fibre and on the right (B) 10% replacement of fine aggregate with tyre fibre. The upper images are at x50 magnification and the lower ones at x 3000, the latter giving an excellent view of how the cement matrix coats the fibre. The conclusion from experimental work concluded 'Concrete with waste tire cord yarn has much higher post-crack toughness than concrete without this waste' ([Malaiakieo , Nagrockieo et al. 2015](#)).

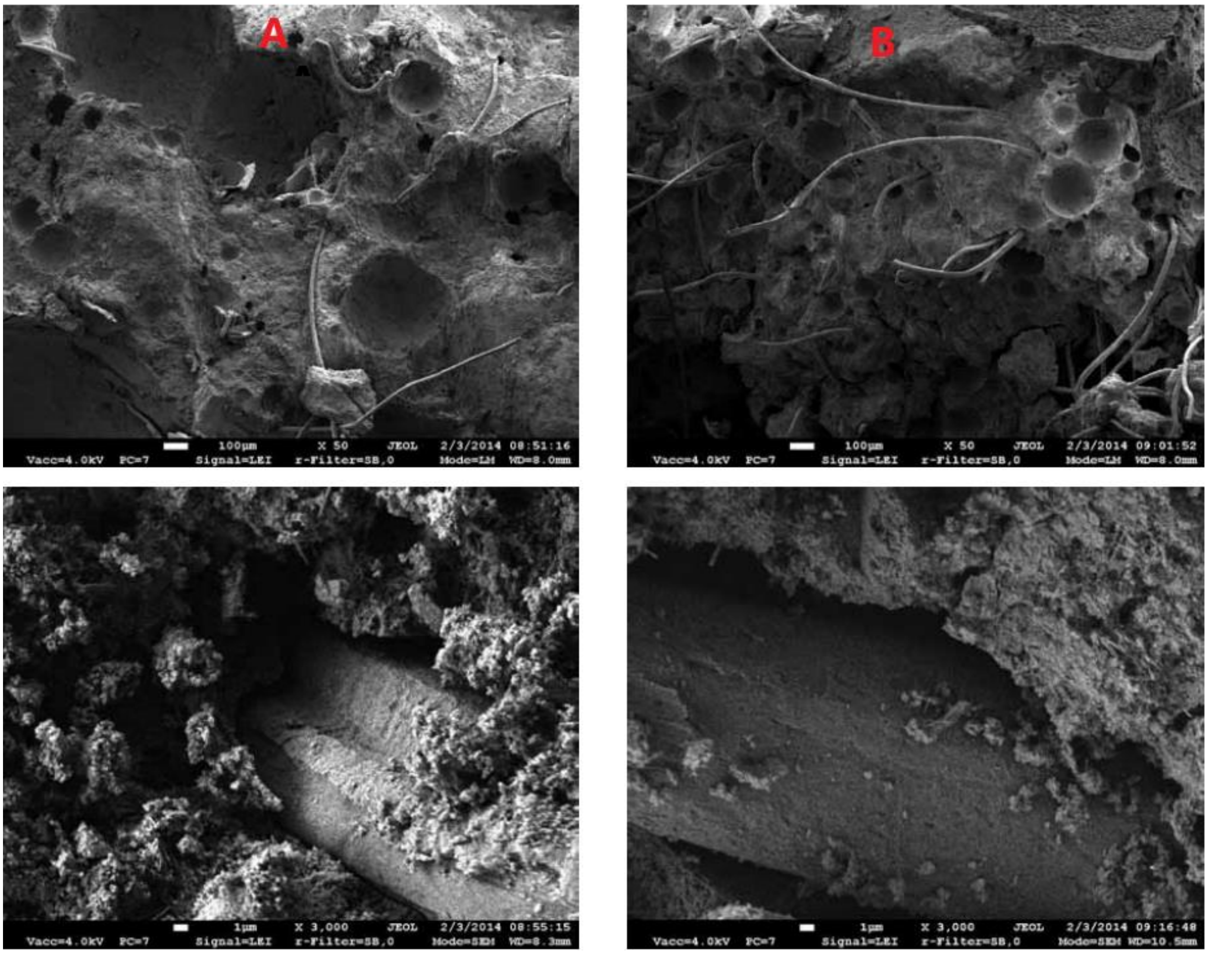


FIGURE 7. THE CONCRETE MICROSTRUCTURE (A) WITH 4% TEXTILE CORD WASTE, AND (B) WITH 10% TEXTILE CORD WASTE, (MALAIAKIEO , NAGROCKIEO ET AL. 2015)

Another study was conducted with end-of-life tyre polymer fibres related to concrete shrinkage, where ‘polypropylene fibres, used in concrete for controlling the formation of microcracks due to shrinkage, can be replaced with recycled polymer fibres obtained from end-of-life tyres. To evaluate the hypothesis, concrete mixtures containing polypropylene fibres and recycled tyre polymer fibres were prepared and tested. The experimental programme focused on autogenous, free, and restrained shrinkage. It was shown that PP fibres can be substituted with a higher amount of recycled tyre polymer fibres obtaining concrete with similar shrinkage behaviour. The results indicate promising possibilities for using recycled tyre polymer fibres in concrete products. At the same time, such applications would contribute to solving the problem of waste tyre disposal’ (Serdar, Baričević et al. 2015).

Based upon the work of (Onuaguluchi and Banthia 2017), (Serdar, Baričević et al. 2015), (Baričević, Jelčić Rukavina et al. 2018) and others; to provide more confidence for the practical inclusion of end of life tyre fibre in concrete mixes, the need for the assessment of durability and fatigue was evident. The fatigue behaviour of FRC is critically essential as it may fail due to the combination of its internally formed cracks induced by shrinkage or creep and increasingly developed cracks caused by the fatigue loading (Chen 2020).

Chen (2020) undertook to fill the above-mentioned gap in data by conducting fatigue tests and analysing the results utilising two-parameter Weibull distribution which can accurately predict the fatigue life using developed double-logarithm fatigue equations. To generate data samples, incorporating four different RTPF dosages ranging from 1.2 kg/m3 (0.1% Vf) to 9.6 kg/m3 (0.8% Vf) were adopted in this study to determine the optimal RTPF content in terms of flexural fatigue performance. Fatigue tests were performed under load control with a constant frequency of 5 Hz in sinusoidal waveform (Chen 2020).

Figure 8 displays the two fibres evaluated, on the left is polypropylene fibre that is commonly and successfully used in concrete mixes to prevent surface cracking during shrinkage that can occur during curing, often termed ‘plastic shrinkage cracking’. Figure 8 top image (a) shows the fibre as it is supplied which is seen to be clean, straight and close to 20mm long. The bottom left image (c) shows the same fibre using a scanning electron microscope (SEM). The end-of-life tyre fibre, contaminated with rubber particles ‘as received’ is shown in image (b) and the same fibre cleaned is viewed using SEM in image (d)

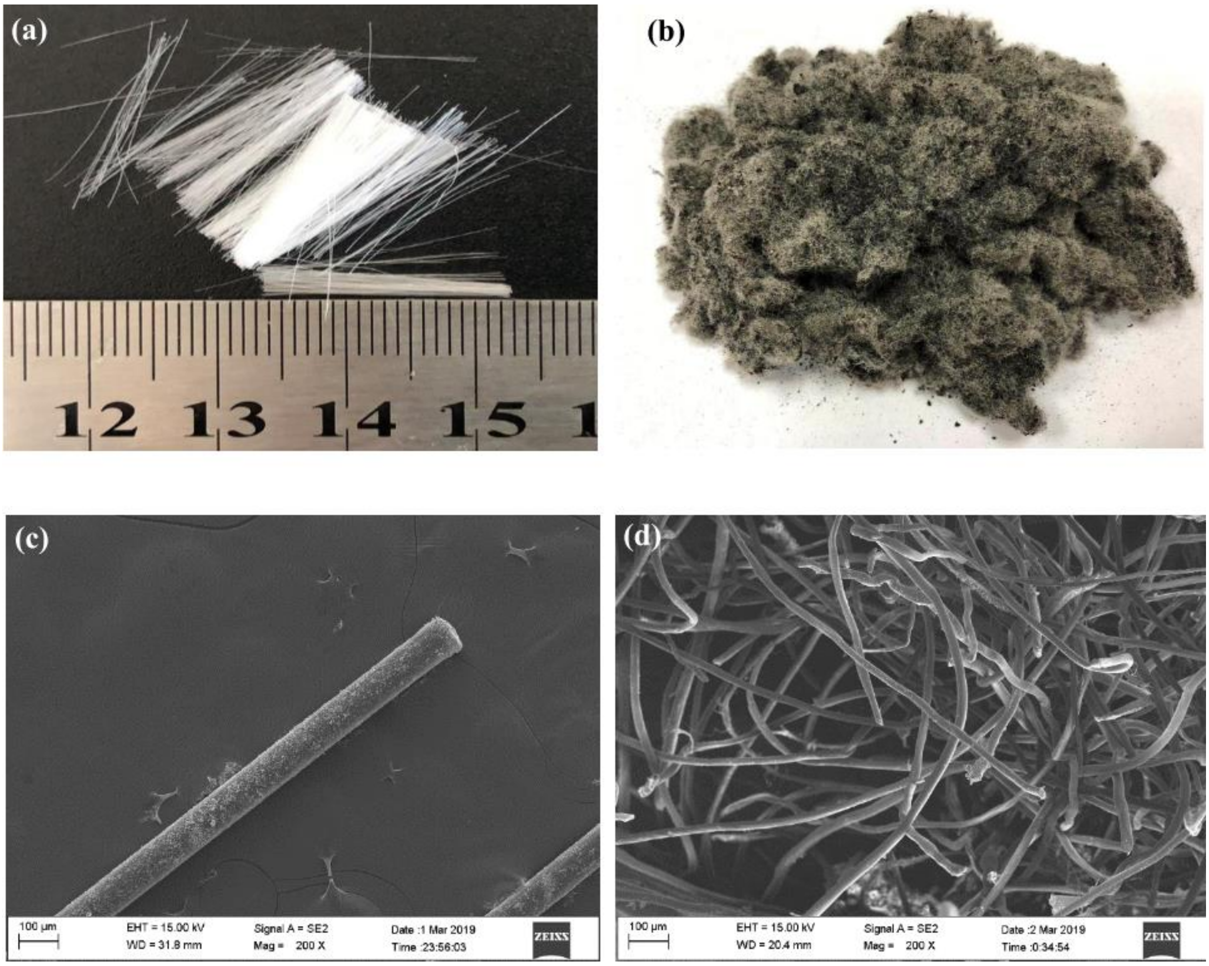


Figure 8. (a) PP fibre (b) Raw Tyre Fibre (as received with rubber particles) (c) PP fibre SEM (d) Tyre fibre SEM (Chen 2020)

The following key points were concluded:

- The overall fatigue performance of concrete was enhanced by incorporating a suitable amount of RTPF.
- Considering workability, compressive strength, flexural strength and fatigue behaviour, the appropriate RTPF content in FRC is in the range of 2.4-4.8 kg/m^3 (i.e., 0.2-0.4% V_f).
- The fatigue failure mechanisms of RTPF and PPF reinforced concrete were similar consisting of three main stages. Both RTPF and PPF may continuously experience pulling and crushing forces or friction with the matrix when they are pulled out or ruptured. By considering static, dynamic and fatigue performance, 0.1% V_f of PPF could be substituted by 0.2-0.4% V_f of RTPF in FRC.

Figure 9 displays End-of-life tyre fibre (RTPF) following the fatigue test. The images clearly show that the fibres have been stressed and deformed from crack mitigation forces.

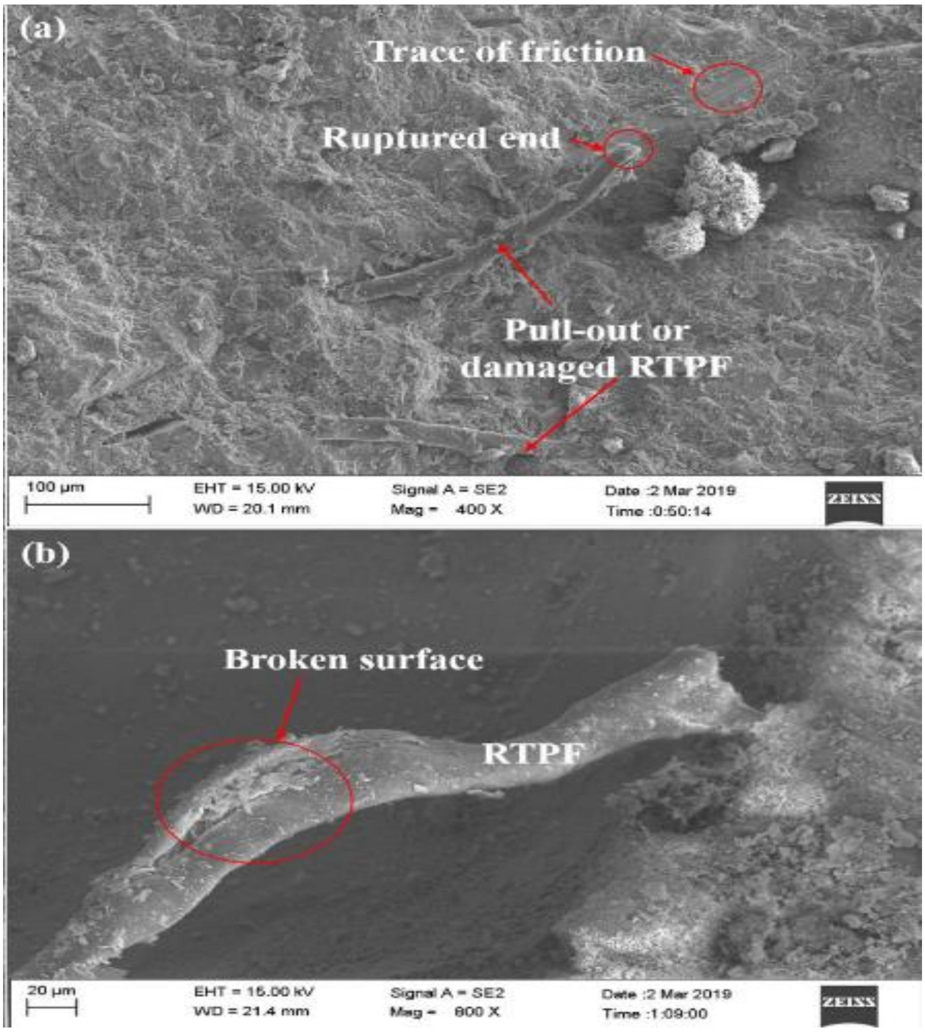


FIGURE 9. SEM MICROGRAPHS SHOWING THE MORPHOLOGY OF RTPF AFTER FATIGUE FAILURE (CHEN 2020)

Figure 10 shows damaged PP fibres following a fatigue test failure. Note the difference in fibre thickness, RTF fibre shown in Figure 10 is approximately 20µm and PPF approximately 25µm (Chen 2020).

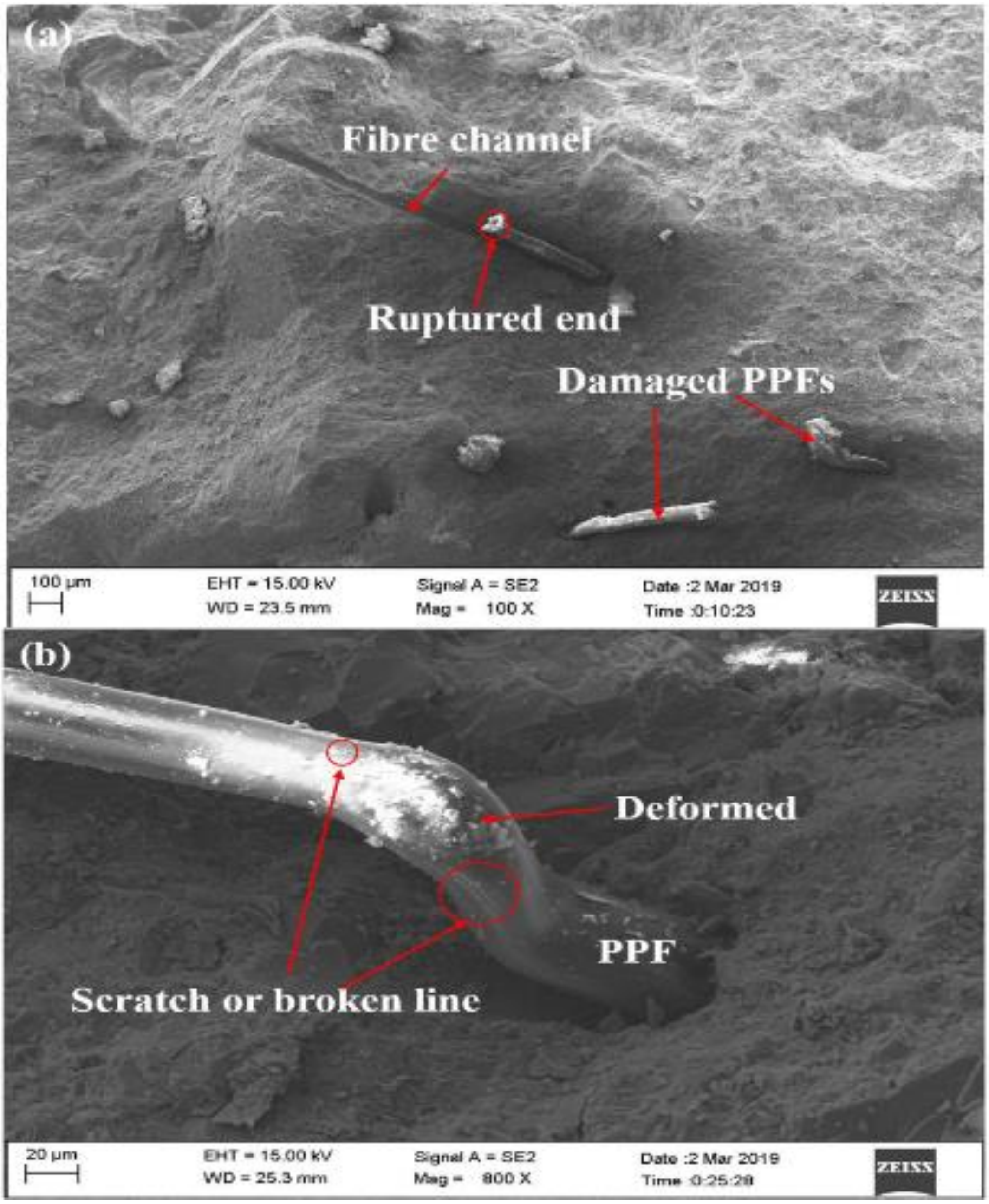


Figure 10. SEM micrographs showing the morphology of PPF after fatigue failure (Chen 2020**)**

Recent research by Balea, Fuente et al. (2021) concludes that the rubber attached to polymeric and steel fibres from waste tires is another issue that requires deep study. It is true that it contributes to increase notably the impact energy absorption at first crack and at ultimate stage, but rubber particles reduce the fibre-matrix interactions, decreasing the compressive and flexural strengths compared to those of industrial steel FRC.

2.5 Summary of the Literature Review chapter

The literature review starts with a broad global review of alternative building systems with an emphasis on sustainable materials and the utilisation of waste; it quickly becomes apparent that the multitude of building systems and materials used is so vast and specific to each region that the literature review moves specifically to the local South African scenario. Researching the existing South African building systems, the number of documented systems is vast and allows a comparative study of the Agrement certified building systems as a platform for comparative evaluation. The introduction of the Agrément certification of alternative building systems has created a guideline for the acceptability of the performance of each system based upon the benchmark of the 'standard brick house' thus providing a benchmark for comparative evaluation.

Following on from the literature review, (section 2.2), methodology section 3.2 begins with an on-site evaluation of the 'state of the art' construction of the RDP standard brick house. This is followed up by a survey of Agrement certified building systems, with performance ranked by sustainability indicators. The outcome of the survey, pointed to compressed soil bricks and lightweight concrete having the highest sustainability ranking, hence, opening a new phase of literature review focusing on concrete modification utilising industrial waste materials (Section 2.3), with experimental work covered in the Methodology section 3.3 Further funnelling down to the utilisation of fibre from end-of-life tyres in concrete (Section 2.4) with experimental work covered in section 3.4.

CHAPTER 3

3 METHODOLOGY

3.1 Introduction to the Methodology chapter

A major part of this section is devoted to the subject of waste and the environment. UKZN School of Environmental Engineering, in conjunction with the School of Civil Engineering, conducts research in green building technology and at the beginning of this research, there was a drive to work with industry to determine the most significant industrial waste streams that were impacting the environment and had the potential for re-use in construction applications. It was then logical as a first step in the utilisation of waste, to use the existing extensive concrete technology facility for the potential use and application of industrial waste materials as part of a concrete composite mix.
This chapter is broken into three sections 3.2, 3.3 and 3.4 which correspond with the same subsections in chapter two ‘Literature review’ and chapter four ‘Results and discussion’:

Affordable and sustainable alternative building materials in South Africa (3.2)
This section has two parts, the first part of the methodology involves the review of the low-cost housing in South Africa: historical, current and the latest local developments as well as reviewing the global scenario. As a grounding to this research, a case study of the baseline building system ‘standard brick house’ is performed; the house design, in its latest form, has been upgraded from the extremely basic RDP (reconstruction and development programme) house to the BNG (breaking new ground) house and the latest upgraded specifications are assessed during practical construction. The case study is performed on the site of a large rural building development in Izingolweni, Kwa-Zulu Natal and ‘state of the art’ efficient building methods are reviewed.

The second part follows the collection of data from a literature review and a survey of low-cost housing in South Africa. An endless array of building systems, using a wide range of building materials, each having many deviants, was revealed from the literature review. To 'funnel down’ the research and to provide quantifiable data, in this pre-experimental stage, a survey of alternative buildings certified by the Agrement guideline for acceptability is undertaken, whereby the performance of each system is based upon the benchmark of the ‘standard brick house’ thus providing a benchmark for comparative evaluation. To further funnel down the research, the focus was given specifically to the building walling systems and materials used. An assessment model, ‘Indicator based sustainability assessment tool for affordable housing construction technologies’ published in the Journal ‘Ecological indicators’ (Wallbaum, Ostermeyer et al. 2012) was used, concerning the three pillars of sustainability (economic, social and environmental impact). Additional indicators were also selected to improve the balance which was considered weak in environmental aspects and to localise to the South African-specific scenario.

Incorporation of Industrial waste stream materials in concrete (3.3)

Research into four waste stream materials in concrete mixes (part of ongoing research at the University of Kwa-Zulu Natal (UKZN)) Based upon the outcome of the survey of building systems, the University's existing resources were used in finalising the experimental focus. Final year undergraduates were co-supervised and in harmony with the University School of Environmental Engineering, the focus was made on currently available industrial waste sources and four were selected for evaluation by the incorporation into concrete mixes. The students, having experienced the development of concrete mixes and the utilisation of the University Civil Engineering concrete technology test equipment, were co-supervised in the modification of concrete utilising selected waste materials.

This section explores the potential for the incorporation of four waste streams, in concrete mixes. These waste materials that are currently being sent to landfill are incorporated into standard concrete mixes, using standard concrete mixing equipment and physical testing is conducted utilising industry-standard destructive test methods (Compressive, Tensile and flexural strength). Four materials assessed: Glass cullet from recycled bottles - Construction and demolition waste - Paper processing sludge - Fibre from recycled automotive tyres.

laboratory, each chose one material to research. Each student was co-supervised by the author for the duration of this research work.

Focus on tyre fibre as a performance enhancer in concrete (3.4)

Following the groundwork of formulating, mixing, testing and reviewing the four waste materials incorporated into concrete mixes, one waste material, fibre from end-of-life vehicle tyres, was selected to undergo more extensive research. Research is conducted into the use of polymer fibre in concrete and specifically fibre from end-of-life vehicle tyres. A site visit is made to a large tyre recycling company that currently disposes of tyre fibre into a landfill.

During the initial stage of this research, in the subsequent year, two more students opted to build on the work already done on tyre fibre, adding to the groundwork.

Utilising the data gained from, the base level of groundwork conducted, the author engaged in ‘in-depth' research into the utilisation of recycled vehicle tyre fibre in concrete. This included concrete mix design, raw material preparation, concrete mix processing, standard concrete testing, advanced and alternative material testing methods and both optical and SEM (scanning electron Microscope) microscopy.

3.2 Affordable and sustainable alternative building systems in South Africa

3.2.1 *Case Study - RDP Housing in Izingolweni, Kwa-Zulu Natal*

In the literature review of low-cost housing 2.2.1, information is provided on the developments that have taken place in South Africa to develop a standard RDP house, the concept, the implementation and improvement in the specification. To gain a better understanding of the construction, a site visit is made to Izingolweni, a rural location in the southern region of Kwa-Zulu Natal. The company contracted to build the houses, which were being made according to a recently upgraded standard, provided some interesting design/ assembly techniques, allowing the building of the houses, of the required specification, more efficient. The outcome of the case study is provided in 4.2.1

3.2.1.1 Case study: RDP Low-cost housing conducted in July 2016

Subject: Low-cost housing construction in the Izingolweni region of Kwa-Zulu Natal July 2016

3.2.1.1.1 *Location and terrain of the RDP housing contract*

Izingolweni or Ezinqoleni is a town in Ugu District Municipality in the KwaZulu-Natal province of South Africa. The town lies on the N2 national road in the far south of the province, as shown in Figure 11 (Smith 2015)

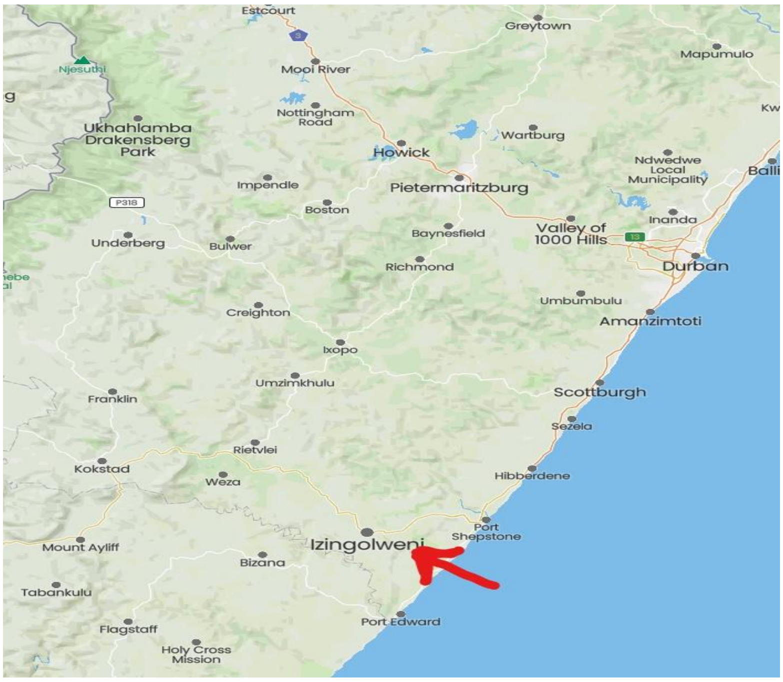


Figure 11. Izingolweni in the KwaZulu-Natal province of South Africa (Smith 2015)

The first impressions on seeing the area where houses were being built, were the rough terrain and difficulty to access each building site, see Figure 12. Not only accessed difficult but the individual houses are scattered over a very wide geographical area, resulting in each house being treated as an independent project with the understandable implication of the coordination of material and labour supply.

FIGURE 12. IZINGOLWENI LANDSCAPE (SMITH 2015)

Given the difficulties involved, the houses being constructed were very impressive, see Figure 13 showing a completed 2-bedroom house.

FIGURE 13. RDP HOUSE IZINGOLWENI 2016 (SMITH 2015)

An interview was held with the Site Manager to determine how the required specification was being achieved and with the aid of a pre-drafted questionnaire sheet, a series of questions were asked relating to different aspects of the build, such as Ground preparation method, method of foundation slab preparation, concrete preparation, material storage, labour force and training, speed of building and total quantity of houses, insulation materials, electrical and water supply systems. The outcome of the study is reported in Results and Discussion section 4.2.1

3.2.2 *Survey of building systems*

Introduction to the survey of building systems

A sample of active South African Agrément certified alternative residential building systems is assessed using sustainability indicators, considering Social, Economic and Environmental factors. Surveys, including documentary analysis and questionnaires, are used, providing an index of systems and assessing the sustainability of each through an assigned rating scale.

Practical implications: Although a larger number of alternative building systems are certified for use, the South African low-cost housing market remains dominated by concrete block and mortar construction.

3.2.2.1 Survey of building systems

The methodology is primarily based on a quantitative approach and focused on the following steps:

South African Agrément certified building and walling systems were investigated, providing a sample group specifically focused on alternative building systems and systems which have been certified as ‘fit for purpose’.

Suitable systems for low-cost housing were selected and further filtered considering only active Agrement-certified systems. Inactive certificates are not reviewed. Preliminary findings, therefore, refer to sufficient and useful data from the active certificated building systems. The analysis of the active certificates provides a representative sample of the original sample group. Therefore, the focus of the preliminary findings provides insight and data for the sustainability of alternative building systems for low-cost housing in the South African context. Through the sampling process mentioned above, the initial sample of 103 building systems was reduced to 41.

A sustainability assessment tool was developed based on performance indicators defined through the analysis of relevant literature on the topic, concerning the three pillars of sustainability (economic, social and environmental impact), and the South African-specific scenario, see Table 4

TABLE 4. SUSTAINABILITY INDICATORS REFERRED TO IN THE SURVEY QUESTIONNAIRE

Sustainability Indicator	Ref Doc	New Indicator	Economic	Social	Environ-mental
Cost / m² Infrastructure	Q	-	X	-	-
Cost / m² External walls	-	Q	X	-	-
Skill Level	Q	-	-	X	
Erection time	Q	-	X	-	-
Economy of scale	Q	-	X	-	-
Durability	Q	-	X	X	X
Maintenance Cost	Q	-	X	X	X
Demolition Recycling	Q	-	-		X
Local value	Q	-	-	X	-
Service interface	Q	-	X	X	-
Use of Recycled Materials	-	Q	-	-	X
Social Acceptance	-	Q	-	X	-
Geographic Locations	-	Q	X	X	X
Multi Story	-	Q	X	X	X
Number of buildings erected	-	Q	-	-	X

Q = Data based on survey questionnaire
Ref Doc = Indicator based upon core reference document (Wallbaum et al., 2012)

Ten sustainability indicators were considered in the article, 'Indicator-based sustainability assessment tool for affordable housing construction technologies' published in the Journal 'Ecological indicators' (Wallbaum, Ostermeyer et al. 2012). The survey utilises nine of these indicators and extends them by another 6, to 15 indicators, expanding the environmental and social aspects whilst considering the South African scenario.

A questionnaire was created with specific questions (mainly multiple choice) oriented to evaluate the above-mentioned indicators through performance-based values (quantitative) or qualitative ranking. A rating scale from 0 (N/A) to 5 (best performance) was applied to each of the indicators following the options given from worst performance to best performance. An example of qualitative ranking is provided in the following 'Degree of maintenance' example:

Maintenance seldom required = 5

Some maintenance required – low skill / low cost = 4

Moderate maintenance – medium skill / medium cost level = 3

Very frequent maintenance required = 2

Maintenance involving high cost and advanced skill level = 1

Information not available = 0

The sample of 41 building systems (as per the previously described sampling process) was targeted in this stage of the research. The questionnaire was sent to the 41 certificate holders, and this research presents the findings based on the response rate of 41% (17 completed questionnaires returned).

The data and info collected was analysed following the rating scale to provide an understanding of the performance of the system against the listed sustainability criteria.

Ethical aspects were strictly followed, and informed consent forms were provided to participants. The participation was clarified to be voluntary; confidentiality and anonymity were carefully maintained. All results are disclosed without mention of the companies or name of the product, but just the type of building system.

The questionnaire covers ethical clearance requirements and can be seen in Appendix 14

3.3 *Incorporation of Industrial waste stream materials in concrete*

Research into four waste stream materials in concrete mixes (part of ongoing research at the university of Kwa-Zulu Natal (UKZN))

3.3.1 *Introduction to **Research into waste stream materials in concrete mixes at UKZN***

This section of the methodology relates to work conducted at the University of KwaZulu-Natal on the incorporation of four waste stream materials in concrete mixes. The requirements for a sustainable built environment demand the maximum reuse of resources through a circular economy approach.

Many waste products are investigated by exploring the opportunity of recovering and reusing these as additions or substitutes for traditional construction materials or as new materials. Concrete is one of the most widely used materials in construction and offers a high degree of adaptability in terms of the possible addition or substitution of individual constituents to form composite materials. "Green concrete" is concrete that is more sustainable than traditional concrete due to its composition, manufacture, application or final properties (Al-Hamrani, Kucukvar et al. 2021), aimed at reducing the natural resource consumption and the environmental impact of construction. The production of green concrete, targeting sectors of largely locally available waste products, can form part of a more holistic and integrated waste management approach, oriented to offer new opportunities to municipalities and the private sector in terms of circular economy and job opportunities. This is even more significant in developing countries, such as South Africa, where the implementation of effective waste management strategies has not reached a high momentum.

3.3.2 *Research into four waste stream materials in concrete mixes at UKZN*

UKZN Civil Engineering and more recently the SARCHI Chair in Waste and Climate Change have been facilitating research into the use of waste material in concrete mixes. Materials have included: Fly ash, recycled rubber (rubber crumb), glass cullet, paper sludge from recycled paper, paper sludge from wood pulp, construction and demolition waste, fibre from recycled tyres and others. As part of this research, the author supervised students conducting the above-mentioned research and, as part of this research, focused on the use of waste streams that have the potential to improve or enhance the performance of concrete and four waste stream materials were selected. C&D waste; Glass Cullet; Paper mill sludge and vehicle tyre fibre.

The methodology followed a quantitative approach based primarily on experimental testing of green concrete materials incorporating various percentages of aggregate substitution using the two waste materials under investigation. Performance of the test concrete is assessed utilising four standard methods, compressive strength according to SANS 5863, flexural strength using the four-point bending method and tensile strength using the 'indirect' splitting cylinder method. Workability is assessed by performing a fresh state workability test according to SANS 5862-1 commonly known as a slump test. For each waste material, the option of evaluating the potential and feasibility as a possible replacement of 'virgin' materials in concrete derives from more overarching considerations extended to the barriers and challenges for the waste management process of these waste streams in South Africa.

3.3.3 *Incorporation of **Civil Engineering** students, final year dissertation research data as partial grounding for PhD research in this Thesis*

At the Civil Engineering Programme of the University of KwaZulu-Natal, Durban Bachelor of Science in Civil Engineering students are required to complete a research dissertation as partial fulfilment of the academic requirements for the degree of Bachelor of Science in Civil Engineering. This is typically completed at the end of their final year. The author co-supervises these students, providing guidance and support based upon his knowledge and experience in

the development of ‘advanced materials’ in the industrial environment. This section comprises a critical review of the co-supervised students work and final dissertations.
Whereas data from these dissertations is used or presented in this thesis, the contribution of the BScEng undergraduate students is duly acknowledged. The intention of this methodological approach was to enable the researcher to test more samples in many different conditions than he would have achieved on his own.

For consistency, the standard laboratory test methods and raw materials have been used, with testing based on the standard tests conducted by the BScEng students. The following section provides an overview of the experimental work that was conducted by each student for their undergraduate dissertations. The method of mix-design followed by the students and the relative percentage addition of waste material is shown in Table 5.

TABLE 5. FOUR WASTE STREAMS IN CONCRETE - MIX DESIGN OVERVIEW (SMITH 2019)

Waste-Stream	Design Comp (Mpa)	Design Slump (mm)	Control Slump (mm)	W/C ratio	Relative waste percentages (weight) based on mix design - shaded values = design mix (Calculated comparative values are displayed for reference)											
					Waste Addition			Waste Addition			Waste Addition			Waste Addition		
					A	B	C	A	B	C	A	B	C	A	B	C
Glass	32.5	50-100	95	0.60	10	25	50	11	28	56	24	61	122	3.9	10	20
Tyre Fibre (1st mix)	32.5	75 - 150	120	0.40	5			5.0			6.9			2.0		
C&D	14	50-100	65	0.86	14	28	56	10	20	40	45	90	180	4.7	9	19
Paper Sludge	31	76 - 150	80	0.62	2.0	4.0	6.0	1.5	3.0	4.6	5	10	15	0.8	1.6	2.3

As the waste materials have been utilised to substitute a certain ingredient in the mix design, for example, glass cullet and tyre fibre replace fine aggregate (sand), C&D waste replaces large aggregate (stone) and paper mill sludge replaces cement. Table 5. Four waste streams in concrete - mix design overview (Smith 2019)provides a common grounding for the addition level as a percentage of total weight. A gap analysis and assessment of the validity of the results was conducted as reported in APPENDIX 9:

3.3.4 *Construction and demolition (C&D) waste in concrete – Methodology review*

Methodology and test data is included from the following **2017** source:

Investigation into the feasibility of using construction and demolition waste as a partial aggregate replacement in concrete, by (Moodley 2017). Submitted in fulfilment of the *requirements for the degree of Bachelor of Science in Civil Engineering, University of Kwa-Zulu Natal*

3.3.4.1 Critique of the dissertation by Moodley (2017)

The study aims to assess the overall sustainability, waste reduction and feasibility of the introduction of recycled concrete waste in terms of aggregate into conventional concrete mixtures. In this study, waste material repurposed consisted of 35Mpa concrete cubes crushed to a size of 19mm. The recycled aggregate is hand crushed to ensure that the size of the natural aggregate is within comparable limits of 19mm. A comparative study of a controlled sample and a modified concrete sample is conducted to gain an understanding of feasibility and strength properties and thereafter adapt to a larger scale such as the use in low-income housing. All testing and mix designs are in accordance with the Concrete Institute using SANS test standards. Each of the individual mixes is balanced to obtain a 14Mpa compressive strength at 28 days as that produced by local suppliers of blocks for low-income houses. Of the four tests conducted, one includes a controlled sample containing only natural aggregate and the remaining three consisted of the substitution of 10%, 20% and 40% recycled concrete aggregate mixed with natural aggregate. To produce comparative results, the sand, water-cement ratio, and cement content are maintained in all mixtures. In addition to these tests, the sample obtained from local manufacturers of hollow blocks that are supplied for the construction of low-income houses is compared to those obtained from Cape Brick, in terms of a compression test and feasibility study. These hollow blocks are of the same size and consist of the same 7Mpa compressive strength at 28 days.

Standard slump test is conducted to determine the workability in its fresh state with tensile, flexure, and compression test are conducted for its hardened state. An economic analysis is conducted to assess the amount of material that may be saved and diverted away from landfills. The economic study also includes the amount saved per low-income household as obtained from the Department of Human Settlement.

3.3.4.2 Specific considerations with the incorporation of C&D waste in concrete:

The recycled aggregate is obtained from past concrete cubes cast at the University Civil Laboratory. All recycled concrete samples consist of a 35Mpa target mean strength. Each cube is hand crushed to a 19mm aggregate size; this is notable as the target strength of the experimental mix is 14MPa

3.3.5 *Glass cullet from recycled bottles in concrete – Methodology review*

Methodology and test data are included from the following **2016** source:

*"Investigation into the feasibility of using waste glass as a partial aggregate replacement in concrete", (*Naicker 2016*) Submitted in fulfilment of the requirements for the degree of Bachelor of Science in Civil Engineering, University of Kwa-Zulu Natal.*

3.3.5.1 Critique of the dissertation by Naicker (2016)

This study focuses on assessing conventional concrete modified with waste material modified with crushed glass (cullet) of sizes 2mm and 5mm. Equal proportions of each size of the cullet are used to simulate the natural fine aggregate. The strength characteristics and economic analysis of the modified concrete are assessed for the overall feasibility of adapting the method on a larger scale.

The concrete mix design and testing is in accordance with the Concrete Institute using SANS test standards. All mixes are proportioned to obtain a compressive strength of 32.5 MPa at 28 days. The tests conducted are done in accordance with the relevant clauses of the standards. Volumetric substitutions of 10%, 25% and 50% of cullet are used and a control sample containing only natural aggregates are cast to make relevant comparisons. The WC ratio and cement used were kept constants for all samples. No admixtures or extenders are used in the mix design.

As the glass used in this experiment exhibited different grading properties and densities when compared to the natural aggregates used, adjustments were made to compensate for this to ensure that the strength and workability parameters remain constant for all samples cast.

The glass cullet used is sourced from a processing plant with cullet graded to a specific size. The cullet selected has specific dimensions of approximately 2mm and 5mm as seen in Figure 14

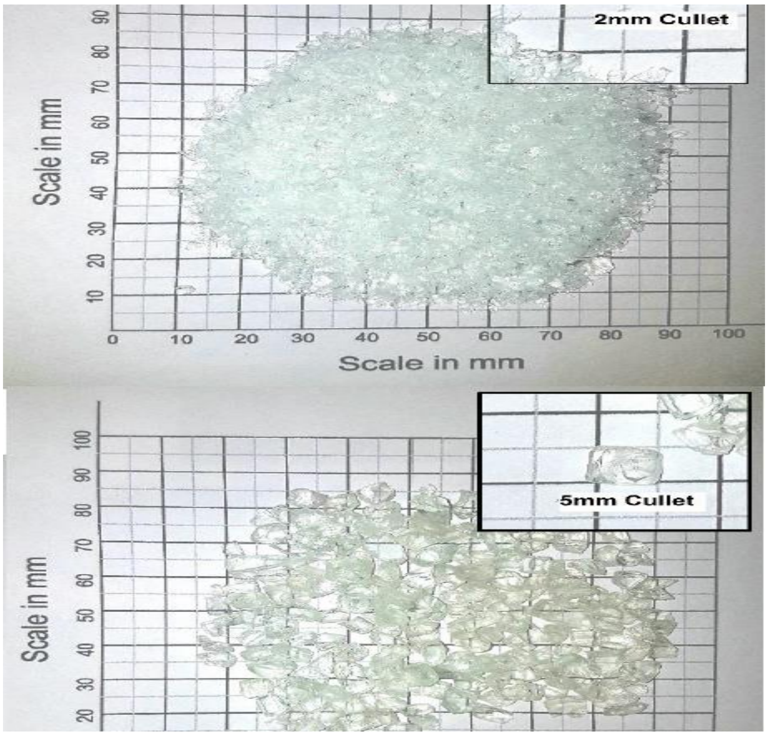


FIGURE 14. GLASS CULLET SIZE (J NAIKER 2017)

Paper mill sludge from recycled paper and from virgin wood pulp in concrete – Methodology review

Methodology and test data is included from the following **2017** source:

*"Investigation into the Feasibility of Using Paper-mill Sludge as a Partial Replacement for Cement" by (*Dheda 2017*) Submitted in fulfilment of the requirements for the degree of Bachelor of Science in Civil Engineering, University of Kwa-Zulu Natal.*

3.3.5.2 Critique of dissertation by Dheda (2017)

Paper-mill sludge is a by-product of papermaking, which is traditionally landfilled, incinerated or used for composting, however, there are environmental and economic impacts associated with these applications such as emissions of greenhouse gases into the environment and leaching of toxic substances into groundwater.

The investigation and analysis assess the functionality of partially replacing cement with paper-mill sludge. All testing and mix designs are in accordance with the Concrete Institute using SANS test standards and cement is substituted with paper-mill sludge at 5%, 10% and 15% (by weight)

Workability was assessed using a slump test.

The paper mill sludge was dried in a drying oven and shredded into fine flakes. For reference, the paper sludge addition level can be associated with 2, 4 and 6% of the fine aggregate by weight.

The paper mill sludge is dried and finely shredded as seen in Figure 15

FIGURE 15. PAPER MILL SLUDGE - DRIED (SHENAE DHEDA, 2017)

In-line with prior testing with paper mill sludge 'ash' as per (Mavroulidou and Awoliyi 2018) the student tried to simulate the methodology by substituting cement with dried and shredded paper mill sludge, whereby the dried material was shredded to an approximate particle size of 1mm negating the anticipated reinforcing effect of long paper fibres on crack suppression.

3.3.6 *Fibre from recycled tyres in concrete - Methodology review*

Methodology and test data are included from the following **2016** source:

*Green Concrete – Development of materials from waste for green building by (*Naidoo 2016*) Submitted in fulfilment of the requirements for the degree of Bachelor of Science in Civil Engineering, University of Kwa-Zulu Natal.*

3.3.6.1 Critique of the dissertation by Naidoo (2016)

Quantities of the materials were kept constant, except for the sand content and the percentage fibre content, this was to allow the effects of the fibre in the concrete to be evaluated alone without another variable. Tyre fibre replaced 5% fine aggregate; this was chosen as documented research had only been conducted on volumetric substitutions of up to 2%.

3.3.6.2 Specific considerations with the incorporation of tyre fibre

The condition of the fibres after cleaning to remove rubber particles and other contamination can be seen in (Figure 16).

FIGURE 16. TYRE FIBRE - CLEANED (NAIDOO 2016)

When incorporating fibre into the concrete drum mixer, it was suggested to the student that the fibre be added to the sand first, as a 'pre-mix' before adding other ingredients to provide better dispersion and distribution of the fibres in the concrete mix. This was done with the trial mix using a 5-minute pre-mix time. However, it was found that in practice, adding the fibre to the sand first, rather than improving the dispersion of fibres, caused agglomeration or 'clumping' of fibres. Breakdown of the agglomerates occurred with the addition of water, allowing the fibres to flow more easily.

3.3.7 *Physical test methods for the assessment of concrete performance*

The following tests are conducted on concrete containing the four waste stream materials: Workability or 'slump' test, which is used initially to develop the mix design consistency and used during the making of the actual test blocks to ensure that the workability remains within the required limits. Compressive strength is the most common concrete test and is conducted on a cube of concrete, with the result being the peak or maximum stress prior to failure. Flexural or flexure strength provides a measure of the materials resistance to bend and tensile strength which is measured 'indirectly' by compressing a cylinder which generates internal tensile forces.

3.3.7.1 Workability 'slump test' (SANS 5862-1)

The concrete slump test shown in (Figure 17) , accessed from (Cementconcrete.org 2020) is a laboratory or site test used to measure the consistency of concrete. The slump test shows an indication of the uniformity of concrete in different batches. The shape of the concrete slumps shows information on the workability and quality of concrete. The characteristics of concrete with respect to the tendency of segregation can be also judged by making a few tamping or blows by tapping-rod on the base plate. This test continues to be used since 1922 due to the simplicity of the apparatus and simple procedure. The shape of the Slump cone also shows the workability of concrete.

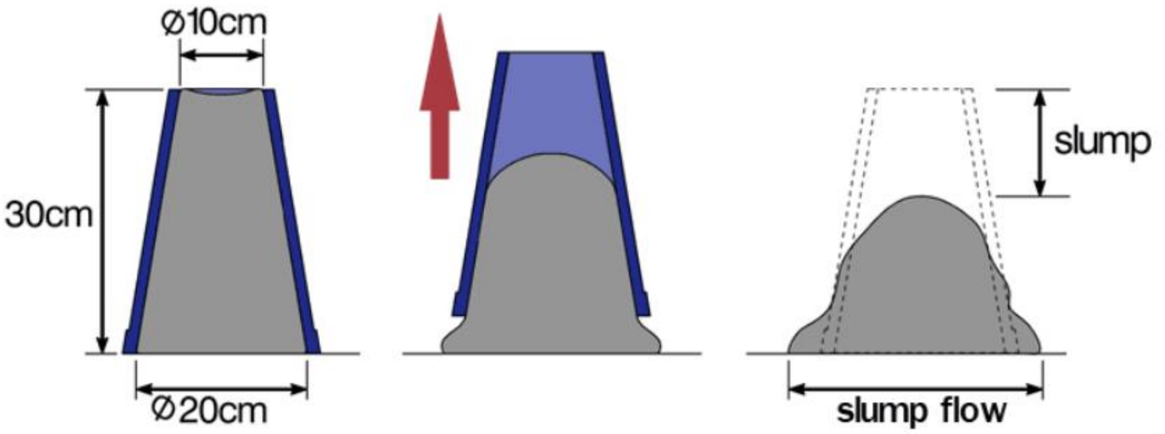


FIGURE 17. CONCRETE SLUMP TEST (CEMENTCONCRETE.ORG 2020)

3.3.7.2 Compressive Strength Test (SANS 5863)

Standard concrete compressive test as defined in SANS 5863 using a test cube of dimensions 150 x 150 x 150mm

3.3.7.3 Tensile Splitting Strength of Concrete (SANS 6253)

As concrete can be considered a 'brittle' material, tensile strength cannot be measured consistently due to the material's sensitivity to crack propagation, therefore 'indirect' tensile testing is typically adopted, such as the splitting tensile strength test whereby a compressive force on a cylinder induces tensile stress in the plane perpendicular to the applied force. Test sample dimensions 150mm diameter 300mm long, as shown in (Figure 18) accessed from (Constructor.org 2021)

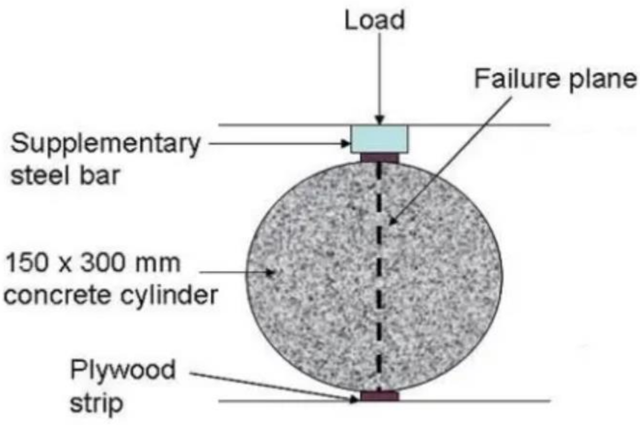


FIGURE 18. TENSILE SPLITTING STRENGTH OF CONCRETE (THE CONSTRUCTOR.COM 2021)

The American Concrete Institute ACI (2013) defines the test as the cylinder splitting tensile test a test for tensile strength in which a cylindrical specimen is loaded to failure in diametral compression applied along the entire length (also called indirect tension test).

3.3.7.4 Flexural Strength Test (SANS 5863)

The flexure or bending test creates a compressive force on the upper surface and a tensile force on the lower surface see Figure 19 accessed from (Substech.com 2021).

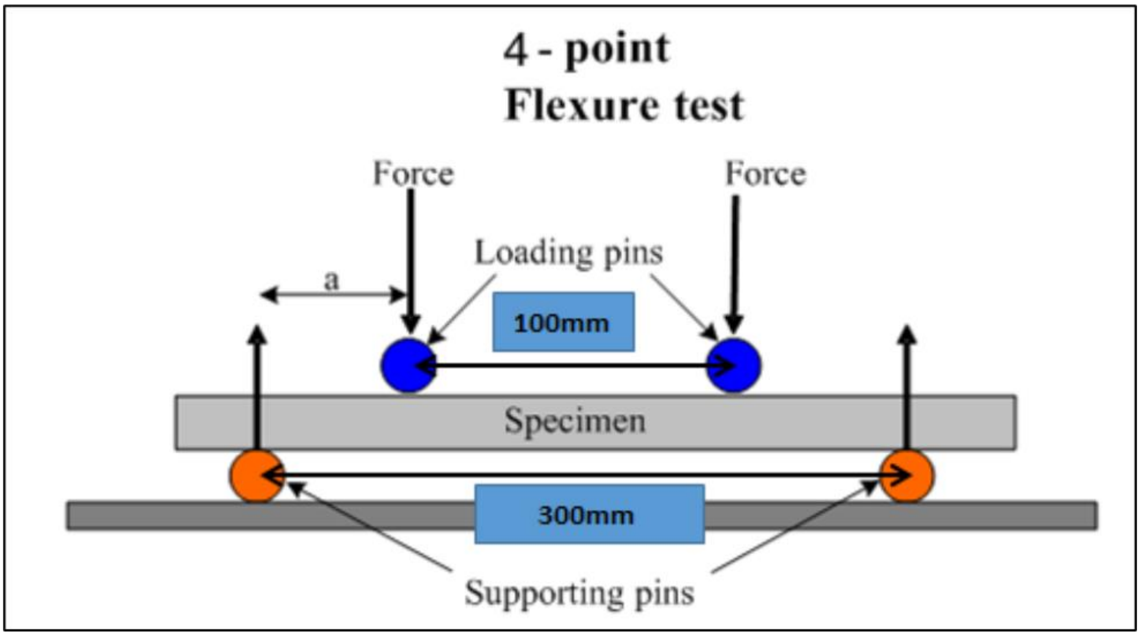


FIGURE 19. 4-POINT FLEXURE TEST (SUBSTECH 2021)

The four-point bending method provides more uniform stress across the length of the beam than the 3-point load option which has a peak stress in the centre of the beam, meaning that any defect (or lack of) in the central portion of the beam can lead to less consistent results.

3.4 Extended experimental research on waste fibre from recycled tyres as a performance enhancer of concrete

3.4.1 *Introduction*

Following the experimental testing of waste materials conducted by the four BSc students, it was decided to progress the research and experimental work on the incorporation of fibre from end-of-life-tyres as the most promising of the materials, in terms of its ability to behave as a performance enhancer in concrete and in-line with the ongoing focus of utilising end-of-life tyres. Test work completed in 3.3.6 (Fibre from recycled tyres in concrete - Methodology review) was used as a basis for the Author to extend this experimental work to a higher level, the initial test work is adopted as a base datum point, allowing the comparison of results and building up a consistent database of material performance. In parallel to the research work continued by the author, two final-year (2019) BSc students showed interest in the topic and requested to continue research into the application of end-of-life tyres in concrete, these students were co-supervised and guided, providing additional supporting data for the research of the author. The results of the experimental work have been included in this document.

To obtain tyre fibre from end-of-life-tyres for laboratory testing, a visit was made to the Mathe Group tyre recycling plant in Hammersdale, outer west Durban. The CEO Dr Mehran Zarrebini was kind enough to provide a guided tour of the plant and some tyre fibre for experimental work. The visit is detailed below in 3.4.2

3.4.2 *Key points from the visit to Mathe group, tyre recycling plant 31/Jan/2019*

- Location Hammersdale, outer west Durban
- Person seen: Dr Mehran Zarrebini
- Truck tyres are recycled only, passenger car tyres are believed to be of lower quality and have higher fibre content
- Truck tyres typically have 30% steel content
- The core business income from the tyres is the high-grade steel wire
- A secondary income has evolved from the processing and sale of crumb rubber from the tyre tread and wall
- Tyres are put through a shredder and then a rasper. A classifier returns large parts to the shredder before going to the rasper. The wire is taken out at this stage. Fine high-tensile wire is taken out from the rasper
- Note: During the visit, the shredder was not managing to manage the de-beading of the heavy gauge wire and a dedicated de-beader was being used, the de-beader physically

‘grabs’ and mechanically rips out the wire bead before the remaining tyre goes to the shredder

- Granulators are used to chop rubber to the required particle size and distribution based on the requirement order
- Applications: Asphalt to reduce cracking increase durability and road noise and as a process modifier; Sports flooring; carpets
- Sale price of rubber = R3.20 – R4.20/kg (Jan 2019)
- Production rate 1700kg to 2000kg/hr rubber

Fibre output was only 10 -15kg/day However, it is planned that new equipment would be purchased which will allow the use of passenger tyres with inherently much higher fibre content.

3.4.3 *Concrete Mix Design and test sample manufacture*

The experimental mix design was based upon the mix of Sachren Naidoo 3.3.6 to assure consistency and correlation of results shown in Table 7. Tyre fibre addition percentage. In addition to the 5% tyre fibre addition, a second mix with 2% tyre fibre was included.

The mix design is shown in APPENDIX 7: with additions and adjustments are shown on the second page of the same Appendix. A small addition of water was included to improve the workability of the test mix containing 5% tyre fibre.

3.4.4 *Test Methods*

3.4.4.1 Standard concrete tests

3.4.4.1.1 *Compressive strength*

Compressive strength tests were conducted according to the Standard concrete compressive test as defined in SANS 5863 using a test cube of dimensions 150 x 150 x 150mm the same method as used for other mixes in the experimental section of this document.

3.4.4.1.2 *Tensile Test*

An indirect splitting tensile test was performed as described in Figure 18

The difference in the failure mode between the control sample (without fibre) and the samples with fibre was very noticeable and images of the cracks were recorded.

3.4.4.1.3 *Flexural Test*

A flexural strength test was performed as described in Figure 19 to determine, not only the maximum flexural strength of the test beams but also the fracture toughness a request was made to measure the deflection of the beam relative to the applied force. Unfortunately, this measurement was not possible at the time of testing.

3.4.4.2 Additional testing to assess fracture toughness

3.4.4.2.1 *Ultrasonic crack detection*

Crack assessment at varying 4-point bending flexural loads using ultrasonic pulse speed measurement relative to load was performed was conducted, however, the test beam was not cast with steel reinforcing as required for this test and the failed before measurements could be recorded.

To repeat the test, flexural test beams were manufactured using the same control and 2% fibre mixes. Additional test beams were made to use the concrete mix material which had to be made up in a minimum mix quantity. This provided additional beams for other potential fracture toughness tests.

The second ultrasonic crack detection test was conducted with the transducers located in the transverse direction and not the longitudinal direction, leading to erroneous results.

A third test was conducted using the correct methodology and providing meaningful results.

3.4.4.2.2 *Plotting of Stress vs Time*

An attempt to simulate the flexural displacement relative to the applied force was made by recording the test duration relative to the elapsed time as shown in Figure 20

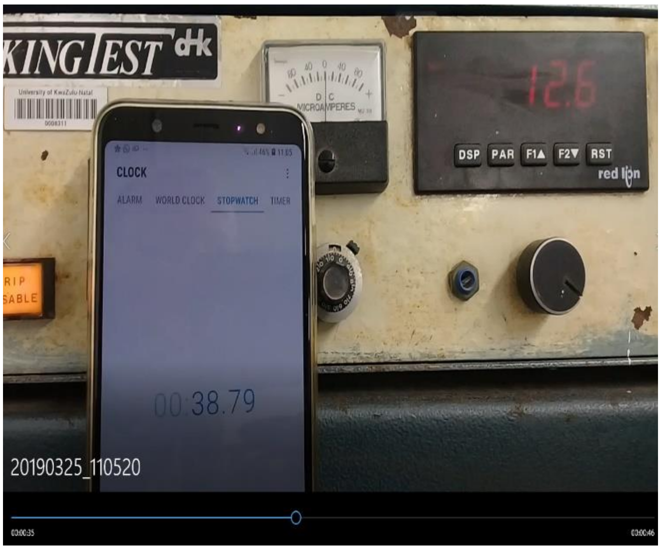


FIGURE 20. FLEXURAL STRESS VS ELAPSED TEST TIME - UKZN CIVIL ENG CONCRETE LABORATORY (SMITH 2019)

This is based on the assumption that flexural deformation relative to the elapsed time is the same for each sample. In practice this was not the case as the hydraulic press performing the deformation was not able to maintain steady deflection without manually increasing the hydraulic supply pressure. It was concluded that the press needed to be de-commissioned due to a leaking hydraulic seal. It was therefore not possible to determine the fracture toughness but only the maximum flexural strength required for failure.

3.4.4.2.3 *Plotting of stress vs deflection*

The assessment of fracture toughness, being key to the assessment of the incorporated tyre fibre, demanded a wider search for a testing facility. 'CONTEST' Concrete Technology Services company was recommended by UKZN Civil Engineering see Appendix A5. The facility was approached and agreed to assist.

In the absence of specific material toughness measuring apparatus i.e. crack tip opening displacement (CTOD), or Crack mouth opening displacement (CMOD) test facilities, the use of three-point bending of a notched specimen was proposed, based upon research and testing by Hillerborg (1985) 'The theoretical basis of a method to determine the fracture energy GF of concrete' and Zhang (2003) 'Determination of Fracture Parameters of Concrete by Three-Point Bending Test' see 2.3.2.5.6 'fracture toughness'.
One control mix beam and one 2% tyre fibre beam were taken to the test facility. The company was very supportive in trying to modify their three-point bending test machine but unfortunately, there was not enough space to mount the digital micrometer, however, it was possible on their four-point bending test machine which was utilised. Figure 21 shows the digital micrometer installed for measuring deflection relative to the force applied.

FIGURE 21. FOUR POINT BENDING - DISPLACEMENT MEASUREMENT (SMITH 2019)

The deflection was recorded manually at regular intervals of increased applied force.

3.4.4.3 Test results are displayed graphically in the results section,

3.4.4.3.1 *Optical Microscopy*

Stereo microscopy

Fractured concrete samples were viewed using a Nikon stereo AZ 100 microscope fitted with a Nikon DXM 1200C digital camera.

3.4.4.3.2 *SEM (Scanning Electron Microscope)*

Scanning electron microscopy (SEM)

Fractured concrete samples were adhered onto metal stubs using carbon tape and sputter coated with gold to a deposition of c. 30 nm using a Quorum Q150R ES sputter coater. Fractured surfaces of the concrete samples were assessed using a Zeiss LEO 1450 SEM and photomicrographs were captured.

Small samples were chipped from the failure surfaces of each flexural beam. To assess the distribution of fibres and evaluate any difference in failure mode, five samples were taken from each face of each of the three test beams, see Figure 22 (top, bottom, left, right and centre locations)

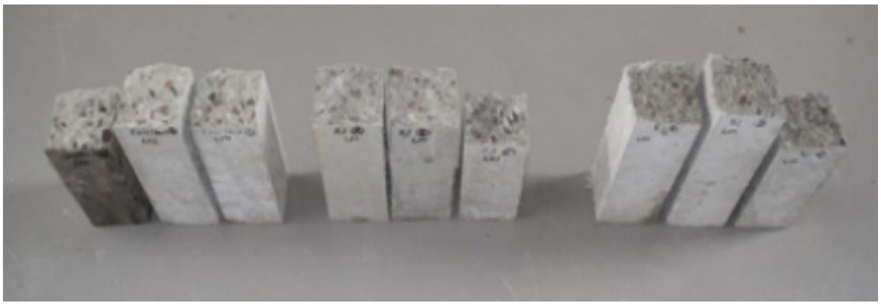


FIGURE 22. FAILURE ANALYSIS SAMPLE SOURCE - FLEXURAL STRENGTH BEAM FAILURE SURFACE (SMITH 2019)

The location of chip removal is displayed in Figure 23 Flexure beams were chosen for the sample due to (a) the ease of removal (b) the opportunity to take samples from areas that would have been in tension, compression or neutral stress areas immediately prior to failure.

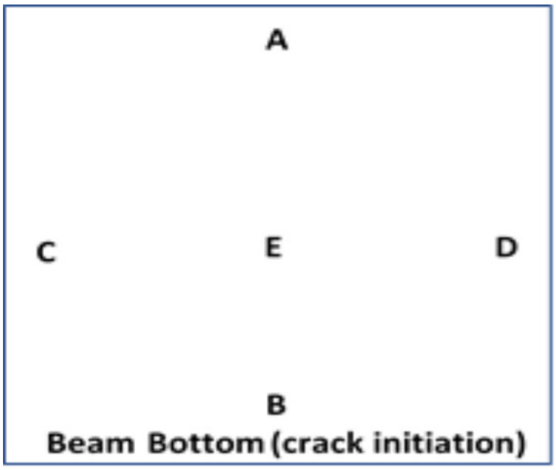


FIGURE 23. FAILURE ANALYSIS SAMPLE LOCATION (SMITH 2019)

Samples were carefully arranged in a box by sticking onto picture fastening putty as shown in Figure 24

FIGURE 24. MICROSCOPY TEST SAMPLES REMOVED FROM FLEXURAL TEST BEAMS (SMITH 2019)

The small chips from the fracture faces can be seen, ready for SEM analysis.

3.4.5 *Tyre fibre - Experimental data from two additional Final year BSc students*

3.4.5.1 Methodology and test data are included from the following 2019 sources:

In the same manner as the initial testing of four waste streams by final year students, two more students showed interest in the topic of the use of car tyre fibre addition to concrete and were co-supervised and guided by the author to supplement and fill gaps in work already completed.

"Sustainable Development: Green Infrastructure/Building", by Msizi Mkhize. Submitted in *fulfilment of the requirements for the degree of Bachelor of Science in Civil Engineering, University of Kwa-Zulu Natal (*Mkhize 2019*)*

*"An investigation into the influence of recycled tyre fibres in unreinforced concrete", by Yashay Basdaw. Submitted in fulfilment of the requirements for the degree of Bachelor of Science in Civil Engineering, University of Kwa-Zulu Natal (*Basdaw 2019*)*

The mixes by Msize Mkhize (Mkhize 2019) included the thorough separation and evaluation of the constituents of fibre contamination received and a comparison of the cleaned and uncleaned fibre, displayed in Figure 25

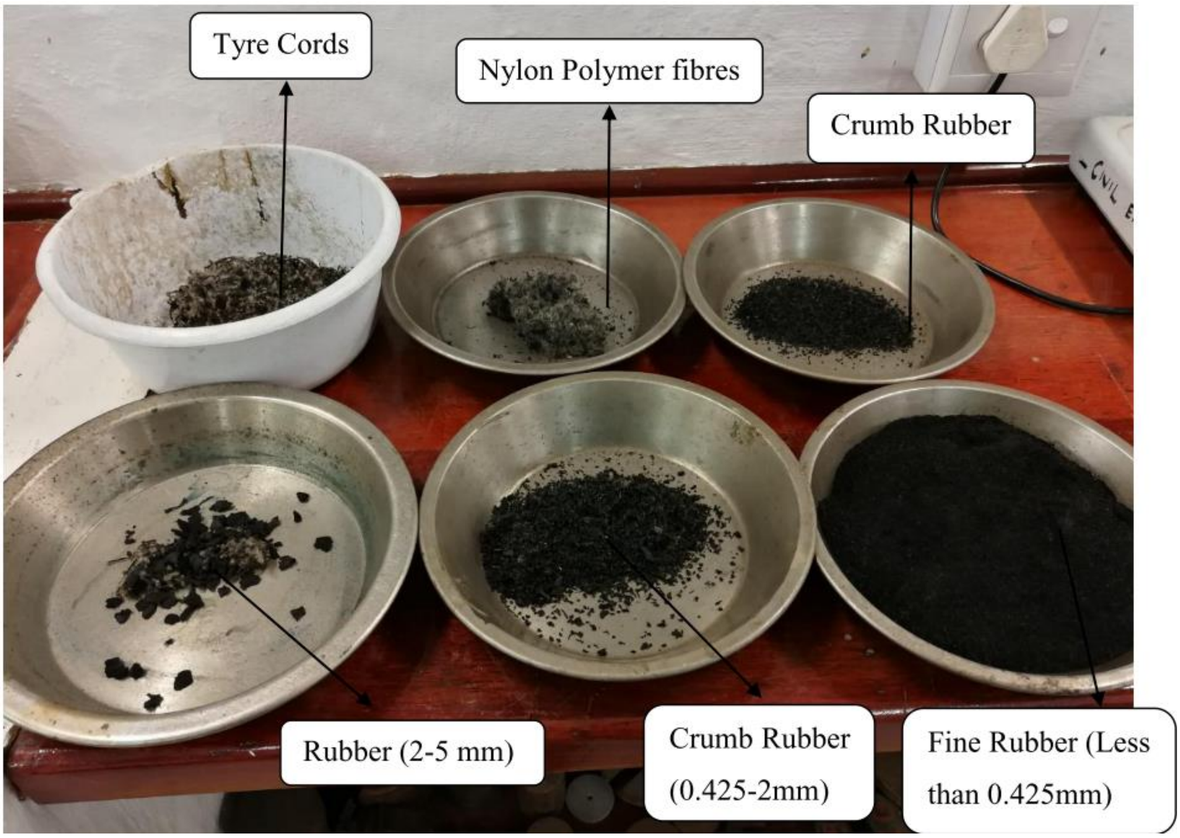


FIGURE 25. BREAKDOWN OF TYRE FIBRE RECEIVED FROM THE SUPPLIER (MKIZE 2019)

The figure provides a good overview of the composition of the typical breakdown of the raw material received.

Table 6 Provides an overview of the concrete mix composition of the five different test mixes evaluating the incorporation of tyre fibre.

Table 6. Tyre fibre in concrete - 4 study - mix overview (Smith 2019)

	Design Comp (Mpa)	Design Slump (mm)	Control Slump (mm)	Course aggregate Nom size	Cement type	W/C ratio
Tyre Fibre 1	32.5	75 - 150	120	13.2	NPC Plus CEM11B-5425N	0.40
Tyre Fibre 2	32.5	75 - 150	120	13.2	NPC Plus CEM11B-5425N	0.40
Tyre Fibre 3 Contam	25	60	60	19	NPC PRO CEM11B	0.80
Tyre Fibre 3 clean	25	60	60	19	NPC PRO CEM11B	0.80
Tyre Fibre PhD	32.5	75 - 125	129	19	NPC PRO CEM11B	0.44

It should be noted that the tyre fibre test programme 3 was performed specifically to evaluate the relationship between using cleaned and uncleaned tyre fibre. The water / cement ratio was increased to reduce the design strength, aiming to make the reinforcing effect of the tyre fibre more significant.

Table 7 displays the level of tyre fibre addition of the four concrete mixes evaluated in this research

TABLE 7. TYRE FIBRE ADDITION PERCENTAGE (SMITH 2019)

Waste Stream	Relative waste percentages (weight) based on mix design - shaded values = design mix (Calculated comparative values are displayed for interest)							
	Waste Addition % of sand				Waste Addition % of Total			
	A	B	C	D	A	B	C	D
Tyre Fibre Sachrin (contaminated)	5				2.0			
Tyre fibre 2019 Msize (a) cleaned (b) contaminated)	2				0.9	2	4	11
Tyre fibre 2019 Yashay (a,b)cleaned (c,d)contaminated	2	5	2	5	0.8	2	4	10
Tyre fibre FS (contaminated)	2	5			0.8	2		

The first four rows display the preliminary supervised test work conducted by final-year BSc students and the last row refers to the final extended testing conducted.

3.5 Summary of the methodology chapter

In the same manner, as the chapter 2 Literature review, the methodology chapter is split into three sections to allow for the ease of understanding the flow of this research.

Following on from the literature review, (section 2.2), methodology section 3.2 begins with an on-site evaluation of the 'state of the art' construction of the RDP standard brick house.

This provided the grounding, or benchmark on which to progress further research.

This is followed up by a survey of Agrement certified alternative building systems, with performance ranked by sustainability indicators. The outcome of the survey, pointed to compressed soil bricks and lightweight concrete having the highest sustainability ranking, hence, opening a new phase of a literature review focusing on concrete modification utilising industrial waste materials (Section 2.3), with experimental work covered in the methodology section 3.3, this being conducted in the UKZN Civil Engineering Laboratory by final year BSc students, supervised by the author.

Specific attention is then given to the most promising of the four industrial waste sources in concrete, utilisation of fibre from end-of-life tyres in concrete in section 3.4, supplementing the original tyre fibre test work from the methodology section 3.3 and to further reinforce the data, two more BSc final year students conducted specific supplemental testing.

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Introduction

Following the same structure of the Literature review and methodology, this chapter contains three sections:

Affordable and sustainable alternative building systems in South Africa (4.2)

As the output from section 3.2, which has two parts, the outcomes from the RDP house case study and the survey of alternative building technology are assessed. Alternative building technologies are ranked based on specific sustainability indicators. The results are displayed, reviewed and analysed, in conjunction with the findings from the literature review.

The application of industrial waste stream materials in concrete mixes (4.3)

Research into four waste stream materials in concrete mixes (part of ongoing research at the university of Kwa-Zulu Natal (UKZN))

Results from the UKZN experimental research into the incorporation of four waste streams, in concrete mixes, are reported and analysed.

- Glass cullet from recycled bottles
- Construction and demolition waste
- Paper processing sludge
- Fibre from recycled automotive tyres

A critical assessment is made to qualify the validity of the results, considering the different experimental methodologies evolving from each data source. The results are harmonised on a common platform for meaningful review and discussion of the key factors.

Tyre fibre as a performance enhancer in concrete (4.4)

- Description of tour sources of data are used

  (**1**): Tyre fibre data from section 4.3 (tyre fibre as one of the four waste streams utilised in concrete from co-supervised and guided students)

  (**2**): Experimental work 4.4 (named 'core study')

(3) & (4) Two supplementary studies of tyre fibre in concrete by co-supervised and guided BSc Final year students.

- Standard strength test data from all four sources is assessed in section 4.4.2 and an overview is presented in 4.4.5
- Evaluation of the effect of the incorporation of tyre fibre on the fracture toughness of concrete, evaluating data from the core study 4.4.3
- Failure analysis 4.4.6 to 4.4.10

4.2 Affordable and sustainable alternative building systems in South Africa

The following results and discussion relate to the case study survey into RDP housing constructed in the Izingolweni region of KwaZulu-Natal as described in the literature review 2.2.1 and methodology 3.2.1

Following on from the literature of low-cost housing in South Africa, the reconstruction and development programme with the 'RDP house' and subsequent 'BNG' (breaking new ground) house. A list of key building requirements was placed on a clipboard and a site visit was arranged to an area within easy reach of the authors home, Izingolweni.

4.2.1 *Case study Results: RDP (BNG) Low-cost housing*

The 2 bedrooms houses have a combined lounge/kitchen and a utility room. There is provision for an electrical supply but no water supply. Water harvesting from roof gutters is provided using a plastic storage tank.

The floor area is 40m². The recently upgraded BNG specification for, insulation, water harvesting, electricity etc is strictly complied with, by the contractor.

The contractor collaborated very closely with the local community to meet their specific needs including the location of the buildings and the training of local manpower to participate in the building.

Building specifications and notes:

- Floor area – $40m^2$
- (Plans were promised but not forthcoming)
- Ground prepared by JCB digger and Bobcat earth mover
- Slab and mortar are all provided as ready-mix to reduce the incidence of material theft
- Floor slab – $6.5m^3$
- Mortar – $3m^3$ provide in two deliveries 1.5 m^3 + 1.5 m^3 inhibited for 72 hours (previously 19 bags of cement were utilised)

- The labour force is based upon 70/30 imported /local labour ratio at the start of the project
- By training of local personnel imported labour is reduced to 30/70 imported / local ratio
- At the time of the visit the workforce constituted of 12 slab teams, 16 roofing teams, 8 completion teams and 1 surveyor
- The department of housing decides on the building specification
- Implementing Agent (IA) appoints the Contractor and Resident Engineer
- Housing inspection is done once per week
- Quantity of houses – Typically project consists of 1000 houses extended to 5000
- Production rate- Typically 70 to 120 houses per month
- Roof Insulation: Isotherm SANS 1381-1 2013 Type 1 (PET Fibre from recycled bottles) 145mm thick with an insulation R-value of 3.37 (m^2.K/W)
- Under-tile membrane: Type: Domestic 3 (Polypropylene / Aluminium laminate) 'Spunsulation' from Spunchem company.

Foundations

Foundations are made with removable steel frame shuttering. The shuttering is easily taken apart and moved from one site to the next. One team of builders is specifically responsible for foundations and the same is applied to walling and roofing see Figure 26

FIGURE 26. FOUNDATIONS MADE WITH SHUTTERING (SMITH 2019)

The shuttering frame is positioned and checked by a land surveyor prior to pouring concrete. The shutter frame is held in position with the aid of metal straps and rocks see Figure 27

FIGURE 27. FOUNDATION METAL SHUTTER FRAME HELD IN POSITION WITH METAL STRAPS, SUPPORTED BY ROCKS (SMITH 2019)

Once correctly positioned, the perimeter of the frame is surrounded with loose rocks to contain the cast concrete as seen in Figure 28 showing the area surrounding the shutter frame.

FIGURE 28. STONES ARE USED TO FILL GAPS AROUND THE SHUTTERING (SMITH 2019)

The frame is surrounded by rocks to stop concrete leakage. A concrete volume of $6.5m^3$ is used for the foundation. Slabs and mortar are all provided as ready-mix to reduce the incidence of material theft that previously occurred when using cement stored in small bags. Additionally, ready-mix provides confidence in a consistent concrete mix ratio.

Walling

$3m^3$ of ready-mix mortar is provided for the walls, provided in two deliveries $1.5\ m^3 + 1.5m^3$ inhibited for 72 hours (previously 19 bags of cement were provided but the theft was a concern). Figure 29 and Figure 30 shows bricklaying with strong 'brick-sized' door and window frames using full-size, uncut blocks.

FIGURE 29. BRICKLAYING (SMITH 2019)

FIGURE 30. WALLS BUILT WITH WHOLE BLOCKS (SMITH 2019)

Heavy-duty galvanised door and window frames are used see Figure 31

FIGURE 31. BLOCKS FIT INTO FRAMES AND GAPS FILLED WITH MORTAR (SMITH 2019)

The frames are designed to take one brick width and gaps are filled with mortar.
Lintels are eliminated by using two pieces of rebar on top of each frame to support the bricks see Figure 32

FIGURE 32. WINDOW FRAMES WITHOUT LINTELS (SMITH 2019)

The use of electrical conduit and trunking is avoided by protecting wires with steel mesh and encapsulating them with plaster, Figure 33 shows the wiring covered by metal mesh before plastering.

FIGURE 33. ELECTRICAL WIRES ARE PROTECTED WITH WIRE MESH AND OVER-PLASTERED (SMITH 2019)

Frames, as shown in Figure 34 are designed to be flush with the plaster for ease of plaster application and appearance.

FIGURE 34. THE PLASTER IS APPLIED FLUSH WITH WINDOW-FRAME (SMITH 2019)

There is a general appearance of good-quality buildings as seen in Figure 35

FIGURE 35. CEMENT TILE ROOF, PLASTIC GUTTERING ON FACIA BOARDS (SMITH 2019)

Smooth plastering of walls, concrete roof tiles and facia boards fitted on the sides and front of the house with neat gutters for rainwater harvesting all provide a sense of good quality construction.

Water harvesting

Figure 36 shows water harvesting from the total roof area is collected in a storage tank.

FIGURE 36. RAIN HARVESTING (SMITH 2015)

Roof insulation is installed using Isotherm SANS 1381-1 2013 Type 1 PET Fibre 145mm thick with and insulation R-value of 3.37 Figure 37

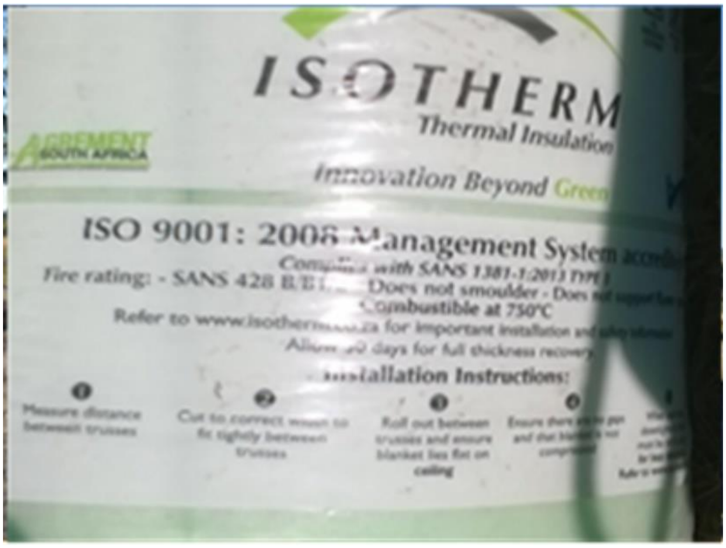


FIGURE 37. ROOF INSULATION -ISOTHERM SA NS 1381-1 2013 TYPE 1 PET FIBRE 145MM THICK R-VALUE 3-37 (SMITH 2015)

Figure 38 shows an included outside light and door frame flush with the wall plastering.

FIGURE 38. PLASTERING FLUSH WITH DOORFRAME (SMITH 2015)

Before visiting the site, a checklist was prepared to provide a basis for the assessment and evaluation of the project, Table 7 shows the completed checklist.

TABLE 8. RDP HOUSE - BUILDING CHECK SHEET (SMITH 2015)

Building Checklist Location: Izingolweni Date: 19 July 2016

Company: Multicrop Construction contact Louis Eisser 0832630169

National housing code 2009 (part 3)	Check	Comment
Floor area (40m²)	√	6.540m x 6.140m = 40. 155m²
Bedrooms (2)	√	
Separate bathroom with toilet, shower and hand basin	X	No water supply (Utility room provided)
Combined living area and kitchen with wash basin		Combined but no water
Ready board electrical instalation where available	√	Lights, switches and plug points included
Resistance to rainwater	√	Plastered walls, gutters and donpipes
Damp proofing	√	
Fire protection?	?	
Lighting and ventilation	√	No Ventilation provided (only windows)
Drainage	√	
North Facing orientatiom	X	Orientation variable upon request of owner
Main used rooms facing north	X	Orientation variable upon request of owner
North facing roof overhang to shade windows in midday summer	√	Moderate overhang ~ 150mm
East west windows minimal	√	
Ceiling instalation	√	
Roof insulation	√	
Plastered internal walls	√	

Walling system Std Concrete block:	Standard concrete block
Foundation type	Trenches with rebar and damp course 'U' Channel beam shuttering
Foundation size	
Foundation mix	Ready-mix
Sand	N/A
Cement	N/A
Stone	N/A
Building Regulations	National housing code 2009 (part 3)
Brick strength	
Brick source	
Morter Mix	Ready-mix (72 hour inhibited)
Sand	N/A
Cement	N/A

NOTES:

Building palns were promised but not provided
Buildings scattered around the community, often next to existing house or in remote area
Slab and mortar all provided as ready-mix to reduce the incidence of material theft
Floor slab – 6.5m³
Mortar – 3m³ provide in two deliveries 1.5 + 1.5 inhibited for 72 hours (previously 19 bags of cement)
Labour force 70/30 imported /local to start
Move towards 30/70 by training local people
At time of visit 12 slab teams, 16 roofing teams, 8 completion teams, 1 surveyor
Department of housing decide on the building specification
Implementing Agent (IA) appoints the Contractor and Resident Engineer
Housing inspection once per week
Quantity – Typically 1000 houses extended to 5000
Production rate- Typically 70 to 120 houses per month
Roof Insulation: Isotherm SANS 1381-1 2013 Type 1 (PET Fibre from recycled botles)
145mm thick R value 3.37
Under-tile membrane: Type: Domestic 3 (Polypropylene / Aluminium laminate) 'Spunsulation' from Spunchem

4.2.2 *Discussion of Results of RDP Housing*

Following the introduction of the upgraded RDP housing, making it more comfortable for human habitation, the challenge is to make as many houses as possible to supply the large demand, whilst staying within the allowed government contract price and meeting the improved level of the performance specification. This case study was conducted to review such a rural development and the following discussion highlights some key areas where innovative methods have been used to meet the improved standards in the most 'cost-effective' manner.

4.2.2.1 Meeting the South African National Housing Code BNG requirements

General discussion of Specific emphasis was placed on assessing compliance with the improved level of building standards of the latest BNG building requirements.

A check-box type table APPENDIX 13: was prepared before the site visit and it was found that all requirements checked had been exceeded with the pleasure of the local community. Some data was not available at the time of the visit but was not considered to be significant compared to the key requirements. The orientation recommended by the housing code was not followed as this was selected by the owner based on their specific needs. The bathroom was built according to specification but was designed as an easily converted storeroom, as a water supply was not available.

Considering the isolated rough terrain, the scattered location of each building site, the associated logistic concerns, the technical 'build', and the aesthetically pleasing finish were exceptional.

4.2.2.2 Innovative building methods

Having experience with the Japanese Automotive manufacturing systems and the drive for 'continuous improvement', the Author was most interested in the following methods which can be considered innovative methods of achieving a required standard given specific environmental constraints.

4.2.2.2.1 *Foundations*

A specific team was dedicated to building the foundations, allowing them to become fast and efficient. Following simple ground preparation by JCB digger and Bobcat, a simple removable steel shuttering frame is used, and the foundation slab is laid utilising concrete premix. The shutter frame is easily positioned in a perfectly level state using the rocks available to level the frame, in conjunction with steel straps to fill the frame taught and straight in all directions (like a giant trampoline frame). Concrete premix is used, providing consistent excellent quality concrete, at high speed and removing the tendency for theft of bags of concrete. On completion, each site is signed off by a dedicated building inspector.

4.2.2.2.2 *Walling*

In the same manner, as with the foundations, there are teams dedicated to building walls. Initially, 19 bags of cement were allocated for each house wall but due to theft and to improve efficiency, a change was made to the use of premixed walling mortar, which is inhibited to stay workable for 72 hours allowing enough time to build one house. Other innovations to improve the efficiency of building the walls are:

- Heavy duty galvanised door and window frames, designed to take one brick width with the remaining gaps being filled with mortar. Lintels are eliminated by using two pieces of rebar on top of each frame to support the bricks see Figure 32
- The window and door frames are designed to protrude from the bricks by the same amount as the required plaster thickness, see Figure 34
- The use of electrical conduit and trunking is avoided by protecting wires with steel mesh and encapsulating them with plaster, Figure 33 shows the wiring before plastering.

4.2.2.2.3 *Roofing*

Commercially available roof trusses, cement tiles, guttering and water harvesting systems are used, including the specified thermal insulation.

4.2.3 *Results of Survey of building systems*

The sample group of 41 Agrément certified building systems considered for this study, provided a data source of 17 systems. `Table 9. Building system categories (Smith 2019) provides a general description of the building systems analysed in this preliminary study, grouped into 12 general building system categories.

TABLE 9. BUILDING SYSTEM CATEGORIES (SMITH 2019)

No	Building System Category	Quantity
1	Cement soil stabilised blocks (CSSB)	2
2	Steel frame (SF) clad with fibre panels / boards	2
3	Cast concrete (CC)	3
4	Cellular lightweight concrete (CLC)	1
5	Expanded polystyrene (XPS) with cladding	1
6	Reinforced concrete panels (RFC)	1
7	Hollow expanded polystyrene (XPS) with concrete infill	1
8	Hollow Polyvinylchloride (PVC) filled with concrete	1
9	Factory produced timber panels	1
10	Hollow concrete blocks of concrete/expanded polystyrene (XPS) beads	1
11	Cellular lightweight concrete (CLC) with fibre cement (FC) board	1
12	Reinforced concrete (RFC) panel with expanded polystyrene/concrete core (or lightweight concrete core)	2

It became apparent in the early stage of this research that finding information on sustainability for the wide range of low-cost housing building systems in South Africa was going to be a major challenge. As the emphasis has been on producing housing at low cost and meeting the minimum specified building requirements with little emphasis on sustainability. In the case of material properties, little information on their properties in terms of sustainability was available. It should be emphasised that the results of this preliminary survey are based upon data received from a questionnaire and qualitative responses are at the discretion of the building certificate holder, who may or may not be over-optimistic about the performance of his own product.

In a few cases, questions were not answered, either because the information was not available or lack of knowledge, time/interest to find the required information, resulting in a zero score for that specific sustainability indicator.

4.2.3.1 Review of Results of the survey of building systems

After screening the assessed 17 building systems utilising 15 sustainability indicators, the building systems for walls were assessed in terms of Social, Economic and Environmental sustainability. The overall combination of all three categories is summarised in Figure 39

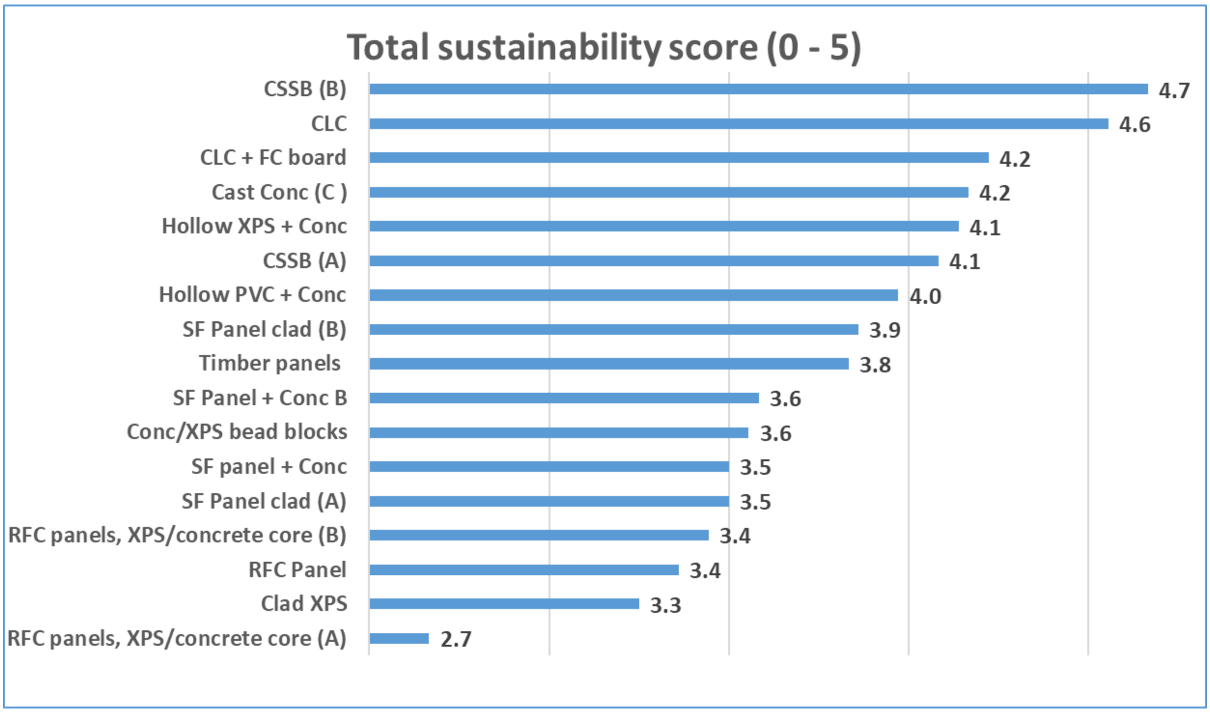


FIGURE 39. TOTAL BUILDING SYSTEM SUSTAINABILITY SCORE (SMITH 2019)

The overall results, including all assessed sustainability indicators show six items with a score of above 4 out of a maximum of 5. They include both cement stabilised soil block systems evaluated and a range of new generation cement-based systems such as cellular lightweight concrete (CLC) in the form of prefabricated panels or cast in situ and one of the three cast concrete methods with novel casting method.

4.2.4 *Discussion on the survey of building systems*

Focusing on the South African situation, the limited available data on sustainable building systems for low-cost housing is a clear indication of the lack of emphasis on the topic and suggests the validity and contribution to the knowledge of this topic and research. Furthermore, the current scenario of having a high level of performance-regulated priorities for alternative building systems should perhaps be modified. Whereby the health and thermal comfort of a material, its embodied energy, environmental impacts, acoustic properties, biodegradability and the overall system performance are considered with a view to a full life cycle analysis and not just physical performance.

When initiating this review, it became apparent that assessing building systems is not practically possible without comparative data on specific performance characteristics especially as alternative building technology tends not to conform to existing building norms and standards. Finding criteria and data on which to base a comparative survey of alternative building technology is therefore not practically achievable and to be able to concentrate on the latest trends for low-cost housing with building systems that have been tested and approved to a common standard, a survey of building systems certified by the 'Agrement South Africa, innovative construction product assessments' is conducted. The sample group of 41 Agrément certified building systems considered for this study, provided a data source of 17 systems.

Current Agrément certification requires the building system to meet minimum requirements without requiring stating the actual performance; it only has to "pass" a minimum performance. This can be confusing and misleading and does not stimulate competition between construction products in the market. Manufacturers or start-up companies are not stimulated to improve the quality and to offer a product with better performance than what is available. But rather limits themselves to just exceeding the minimum requirements to be awarded the certificate. This limits the possibility of reaching open competition in the market, based on encouraging manufacturers towards better-quality products and allowing customers to easily compare the quality of various products. This might constitute a factor which can hinder the introduction, advancement and large-scale implementation of sustainable building technologies in South Africa.

The emphasis in South Africa has been on producing housing at low cost and meeting the minimum specified building requirements with little emphasis on sustainability and residential home comfort. In the case of material properties, little information on their properties in terms of sustainability is available. It should be emphasised that the results of this survey are based upon data received from a questionnaire and qualitative responses are at the discretion of the building certificate holder, who may or may not be over-optimistic about his own products' performance.

In some cases, questions were not answered, either because the information was not available or lack of knowledge, time/interest to find the required information, resulting in a zero score for that specific sustainability indicator.

As an interesting overview, it was indicated by one respondent that the South African building regulations and specifically the Agrément certification has created a barrier for materials and systems. Excessive emphasis is put on the strength and “so-called” waterproofness of a material (i.e., cement-based products) at the expense of sustainability, health, resource efficiency and a more holistic understanding of how buildings perform as a whole system. The respondent further provided his opinion that the incredibly restrictive regulatory building framework continues to push our building trade away from sustainability and towards a heavily carbon-based fuel economy. This is despite the urgency of climate change and conversely natural buildings' potential to lead us on a different trajectory.

As a result, based on the information gathered and based on the survey findings, cement stabilised soil block system and cellular lightweight concrete provide the highest rating in terms of the sustainability criteria used by the study. The positive results for lightweight concrete are in line with expectations as one may hypothesise even without data that the following factors are favourable (1) reduction in cement usage and subsequent energy (2) improved integrity of poured concrete over blocks (3) Increased speed of construction (given the required facilities and design concepts for the integration of the concrete as the building structure) (4) improved thermal insulation. The survey results are in line with this. On the other hand, one may hypothesise that the compressed soil block may not fair highly due to the weight of the blocks and relatively high labour requirement, however on the positive side, very little cement (and thus energy) is required, also the high level of unemployment and relatively low labour cost in South Africa is a positive factor for job creation. One factor which is sometimes seen as a negative for the compressed soil block is the thermal insulation which on face value appears to be bad and even unacceptable, however, in practice, the 'thermal' mass of the heavy block acts as a heat sink reducing hot and cold peaks, especially in regions where day and night temperatures vary considerably such as the high inland areas.

The limited available data on sustainable building systems for low-cost housing is a clear indication of the lack of emphasis on the topic and suggests the validity and contribution to knowledge of this topic and research. Furthermore, the current scenario of having a high level of performance-regulated priorities for alternative building systems should perhaps be modified. Whereby the health and thermal comfort of a material, its embodied energy, environmental impacts, acoustic properties, biodegradability and the overall system performance are considered with a view to a full life cycle analysis and not just physical performance.

Current Agrément certification requires the building system to meet minimum requirements without requiring stating the actual performance; it only has to "pass" a minimum performance. This can be confusing and misleading and does not stimulate competition between construction products in the market. Manufacturers or start-up companies are not stimulated to improve the quality and to offer a product with better performance than what is already available. But rather limit themselves to just exceeding the minimum requirements to be awarded the certificate. This limits the possibility of reaching open competition in the market, based on encouraging manufacturers towards better-quality products and allowing customers to easily compare the quality of assorted products. This might constitute a factor which can hinder the introduction, advancement and large-scale implementation of sustainable building technologies in South Africa.

If one looks at the amazing skyscrapers of Dubai, London etc. appearing as works of art; removing the facades, we see, almost always, reinforced concrete. With this concept in mind, whether prefabricated or built on site by casting or even 3D printed by a robot, the outer surface can be a simple finish coating or, like the skyscrapers, can be an astatically pleasing whilst having the potential to have secondary functions, for example, solar panels, photoelectric and water heating, encapsulation of thermal insulation, plug-in windows and doors providing future options for home owners and even built-in plant pots. The options are mind-boggling and begin to make one think that the standard brick or timber frame house is a 'thing of the past'.

To make this type of building possible, we need to make available, the materials and technology. The technology to use CLC is already available and with continued use, the technology will advance with economies of scale, becoming more cost-effective.

It is put-forward, at this point, that the area for great research and development and growth, is the quest for advanced materials that meet the specific demands of this type of building process, whilst being sustainable and environmentally friendly.

Cement-based materials still offer the core binding properties of CLC but with time this could change and already geopolymers may be the first step to reducing the carbon footprint. However, regardless of the binder in the composite material (currently cement), the development of advanced composite materials specifically for this building process and final function opens a whole new field of technology for future research. Certainly, a better approach than flooding the market with carbon wasteful cement, which one could say is a resource that is squandered.

4.3 Incorporation of Industrial waste stream materials in concrete

This section discusses research into four waste stream materials incorporated in concrete mixes (part of ongoing research at the university of Kwa-Zulu Natal (UKZN).

Each year, the final year BSc Civil Engineering students need to author a dissertation based upon experimental work, this became a useful starting point or basis for building up data on the effect of incorporating waste into concrete. Guidance, supervision, reviewing and critiquing their dissertations formed this section of the thesis.

The materials sourced from all four of the waste streams considered were incorporated into concrete mixes, using common measuring and mixing equipment. Key physical performance tests: compressive strength, flexural strength and tensile strength were conducted utilising common physical test equipment. Furthermore, a critical assessment of the methodologies was conducted to determine the validity and consistency of data as discussed in section 3.2.5 of the Methodology chapter.

A Comparative review of the performance results of the four waste streams in concrete is provided in Figure 44

4.3.1 *Construction and Demolition (C&D) Waste in concrete*

An incremental increase in all performance tests was observed with the increased % of recycled aggregate see Figure 40. The increase in strength of the 40% large aggregate replacement (21%

total weight) level after 28 days of ageing was: compressive strength +11%; tensile strength +17% and flexural strength +64%.

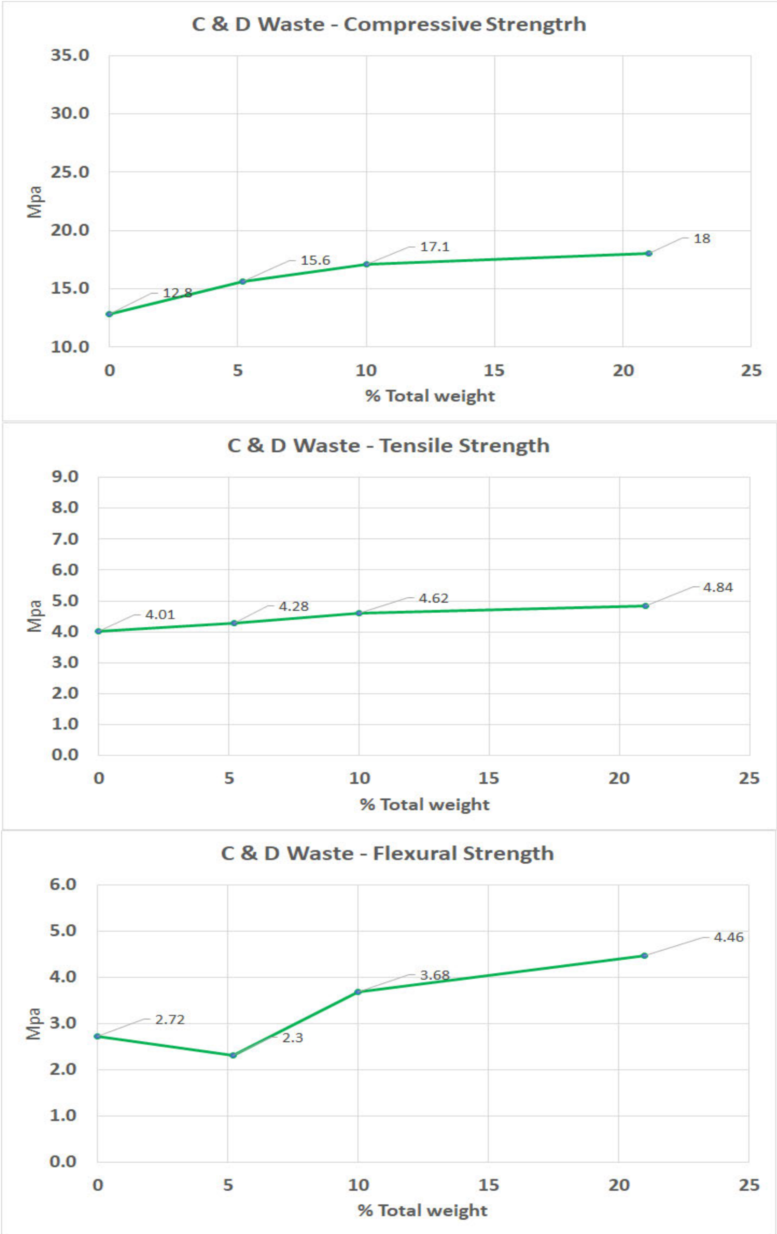


FIGURE 40. PHYSICAL STRENGTH OF CONCRETE CONTAINING CONSTRUCTION AND DEMOLITION WASTE (SMITH 2019)

The results, however, contradict research conducted by (Yehia, Helal et al. 2015) and as reported by the Portland Cement Association, who conclude that the flexural behaviour of recycled concrete substitution is similar to controlled samples. The use of crushed recycled 35MPa (crushed concrete), in a 14Mpa design mix, may have some influence on the results. Another possibility could be the manual method of crushing by hammer and sorting by hand, influencing the surface texture, form, and angularity as referred to by (Papagiannakis 2012) in the literature review. Future research should use recycled concrete that can be practically sourced in the construction and recycling environment.

4.3.2 *Glass cullet from recycled bottles in concrete*

The percentage of cullet substitution had a small but noticeable influence on workability. The average slump for the control (0% substitution) was 95mm and as the percentage of glass increased the workability decreased to 75mm for the 20% cullet mix, all within the target range of 50-100mm.

Strength results from the 20% cullet replacement are reviewed and displayed in Figure 41 Considering that each result represents one test sample the strength can be considered as approximately equivalent to the control. The strength of the 5% and 10% additions gave irregular results at all cure times and were typically lower than the control. Compressive strength was equivalent to the control sample after 28 days.

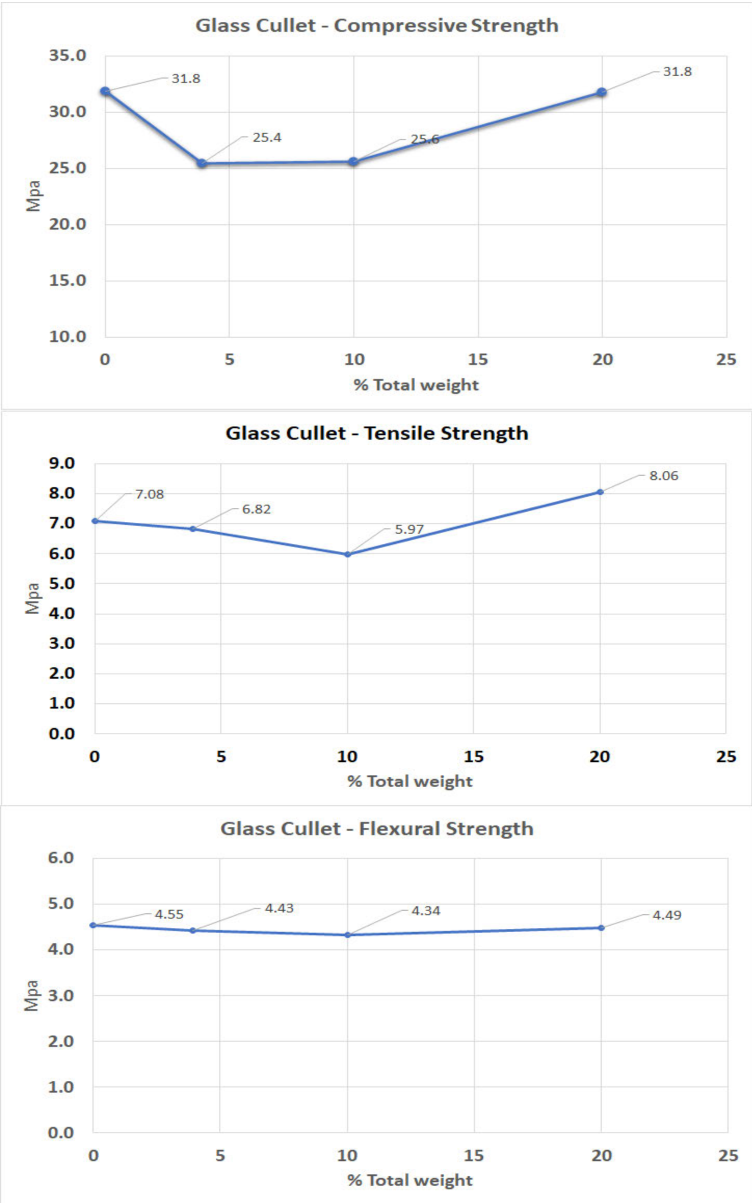


FIGURE 41. PHYSICAL STRENGTH OF CONCRETE INCLUDING GLASS CULLET FROM RECYCLED BOTTLES (SMITH 2019)

Flexural strength was equivalent to the control sample at all cure times (except for the 14-day cure sample). Tensile strength was equivalent to the control sample after 7, 14 and 21 days and higher with the 28-day cure sample.

4.3.3 *Paper pulp mill sludge in concrete*

With the addition of 0.8% (0.8% of total weight = dried paper sludge), compression strength, flexural strength and tensile strength all increased from the values of the control shown in Figure 42. Compressive +2%, Tensile + 27%, Flexural + 12% At 1.6% and 2.3% pulp addition all three performance tests gave progressively lower results with 2.3% addition giving results lower than the control value in all cases.

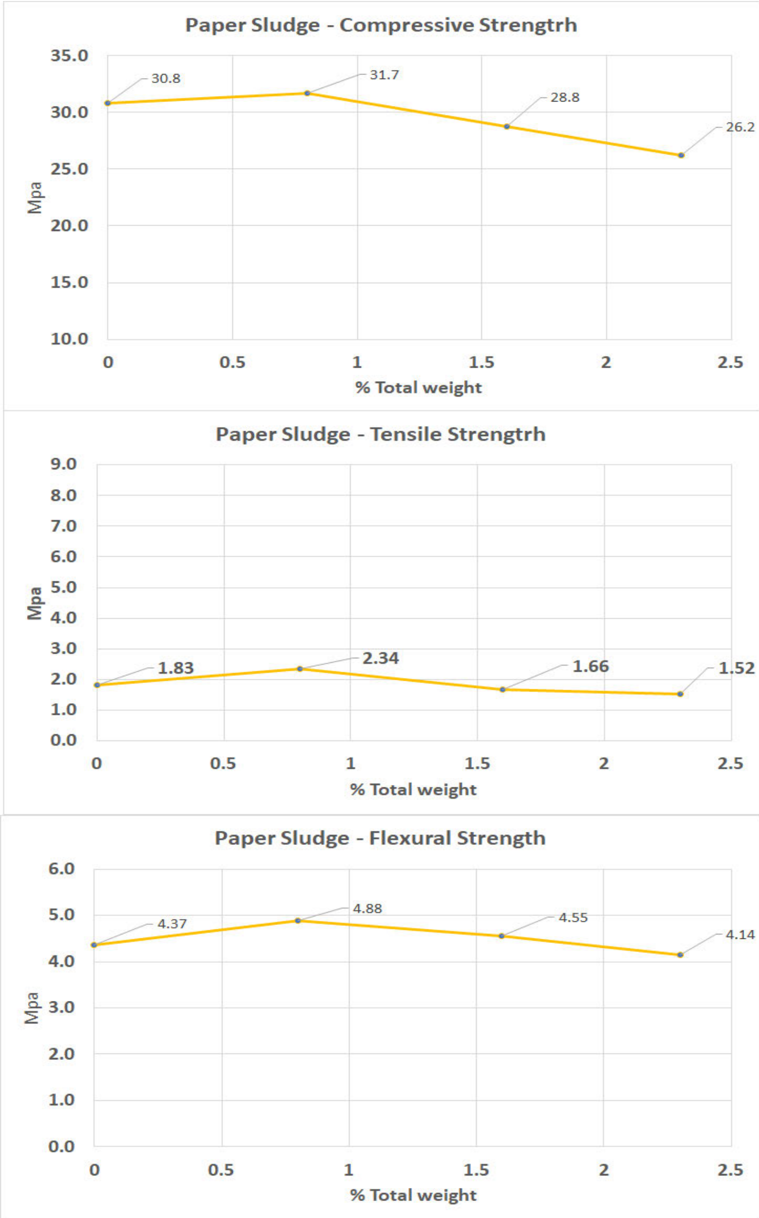


FIGURE 42. PHYSICAL STRENGTH OF CONCRETE INCLUDING PAPER MILL SLUDGE (SMITH 2019)

A notable point is a general improvement in performance at the lowest addition level, especially as the fibre was pulverised in a food blender.

4.3.4 *Fibre from recycled tyres in concrete*

The 5% substitution of fine aggregate with polymer fibre gave a significant reduction in workability. The average slump for the control (0% substitution) was 120mm, whereas the fibre-containing mix had a slump of only 10mm which, although well below the experimental slump for this mix of 75-150mm, meets the typical requirement for the category of ‘Kerbs and bedding for pipework of 10-40mm. Therefore, it was decided not to incorporate a workability agent at this stage of the research, to limit the changes of variables and more easily assess comparative results. A workability agent was incorporated in a subsequent trial.

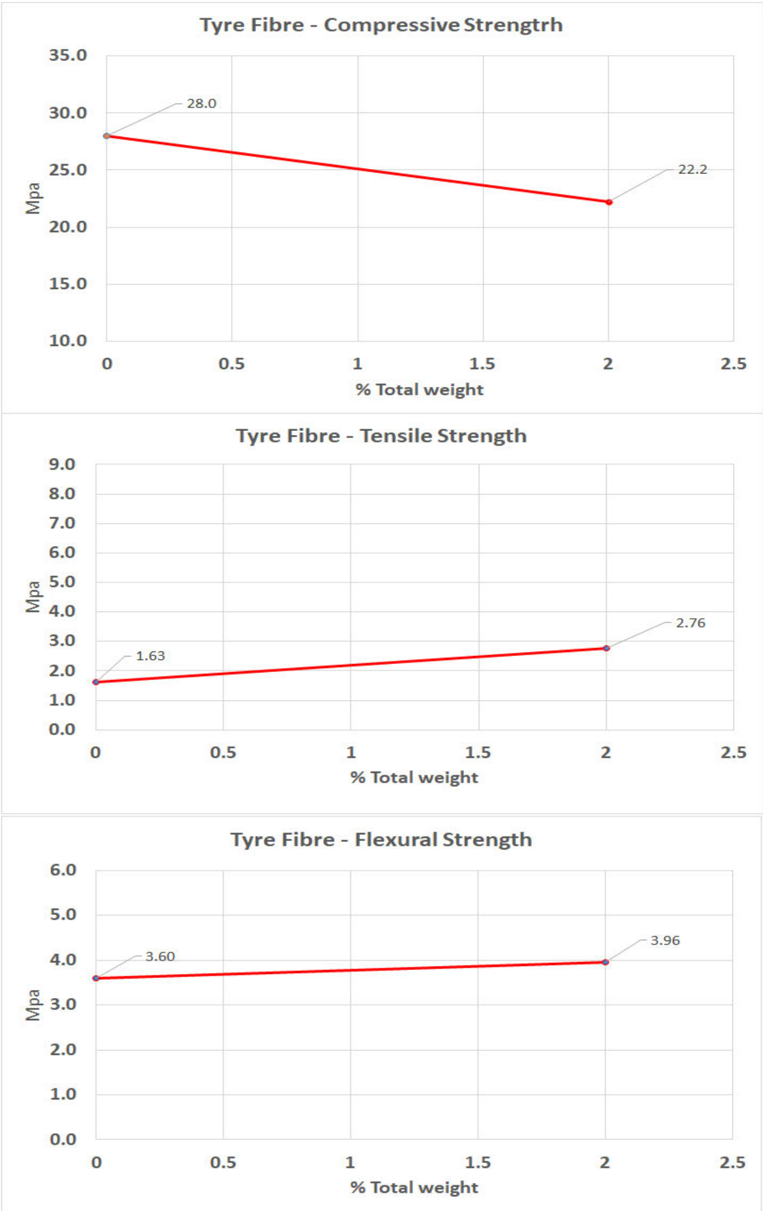


FIGURE 43. PHYSICAL STRENGTH OF CONCRETE INCLUDING FIBRE FROM RECYCLED VEHICLE TYRES (SMITH 2019)

Figure 43 shows that the fibre introduction resulted in a significant and consistent reduction in compression strength after each cure period (-17% average) but a converse increase in flexural strength (+10% average) and a substantial increase in tensile strength (+65% average). It is therefore clear that the addition of polymer fibre significantly changed the concrete from a brittle to a material behaving in a less brittle and more 'tough' manner.

Comparative review of the results of four waste streams in concrete. Shown in Figure 44 provides an overview of the performance of all four waste materials incorporated in concrete and tested. The addition level is shown on a common scale of the percentage of the total weight.

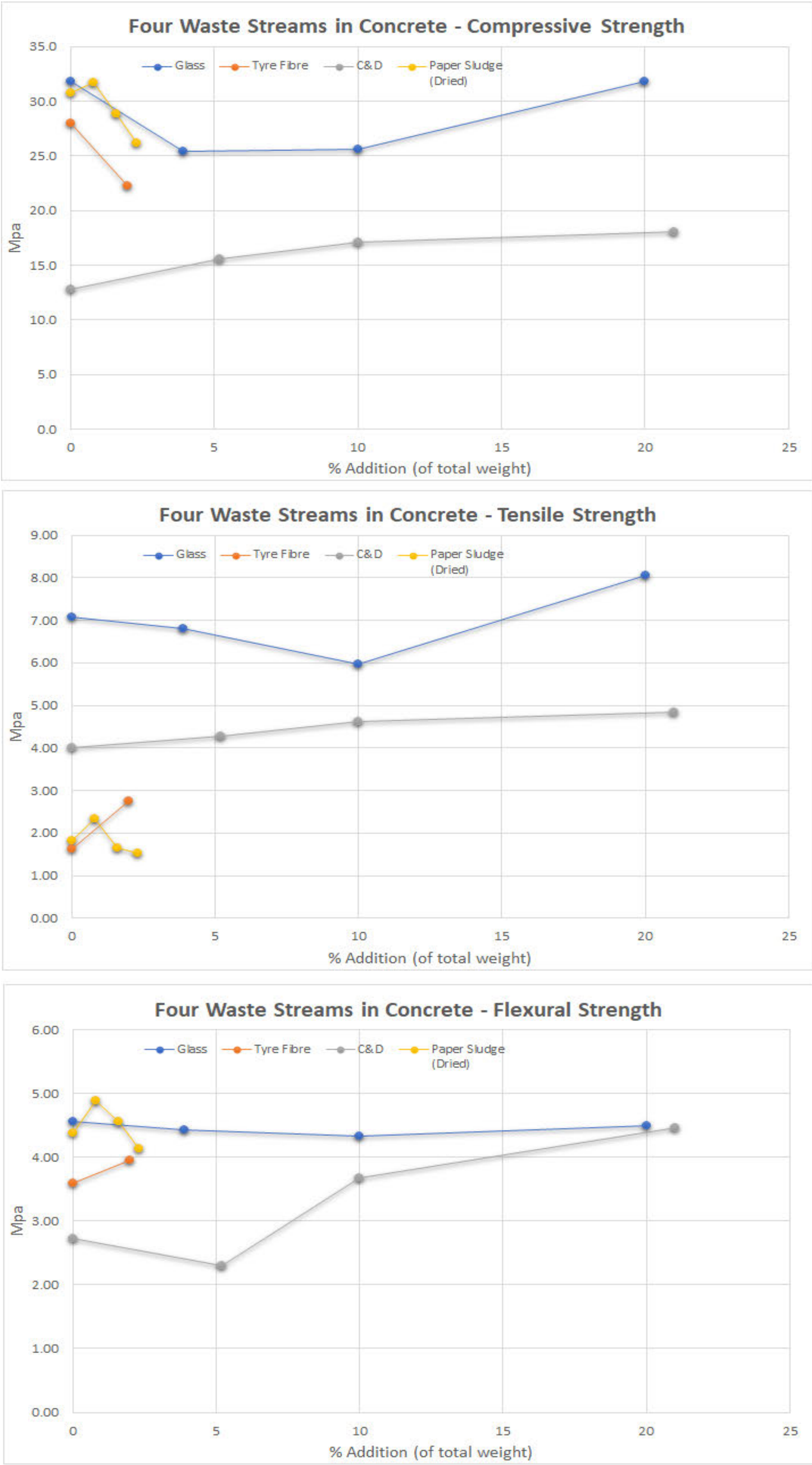


FIGURE 44. FOUR WASTE STREAMS IN CONCRETE - PERFORMANCE REVIEW (SMITH 2019)

Figure 44 provides an overview of the comparative physical performance of the concrete incorporating materials from four different waste streams. The percentage of the waste material incorporated relative to the total weight provides a good picture of the amount of waste material used in total. The construction and demolition waste and glass cullet are incorporated at a high percentage of the total concrete weight, up to 20% with the intention of substituting the aggregate with waste for environmental reasons. On the other hand, the tyre fibre and paper mill sludge are both used in small quantities, with the intention of improving the tensile performance whilst not using too much to significantly reduce the compressive or durability of the concrete, any performance improvements are generally not evident at addition levels of over 2% of the total weight.

Table 10 shows each material at its designed addition level relative to sand, stone or cement and the common percentage level relative to the total weight of all the materials in the concrete mix.

TABLE 10. MATERIALS FROM FOUR WASTE STREAMS IN CONCRETE - RELATIVE PERCENTAGE ADDITION BY WEIGHT (SMITH 2019)

Waste Stream	Relative waste percentages (weight) based on mix design - shaded values = design mix															
	Waste Addition % of sand				Waste Addition % of stone				Waste Addition % of cement				Waste Addition % of Total			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Glass	**10**	**25**	**50**		11	28	56		24	61	122		3.9	10	20	
Tyre Fibre Sachrin (contaminated)	**5**				5.0	0	0		6.9	-	-		2.0			
C&D	14	28	56	112	**10**	**20**	**40**		45	90	180		4.7	9	19	
Paper Sludge (Dried)	2.0	4.0	6.0	11.9	1.5	3.0	4.6		**5.0**	**10**	**15**		0.8	1.6	2.3	

This graph is intended to provide a better understanding of the levels of addition of the waste materials and the reasons. The grey-shaded cells of the table indicate the design level of addition. The glass waste, with fine regular particle sizes was added to replace fine aggregate i.e. river sand and to be consistent for comparative test purposes the tyre fibre addition was added in the same manner. The C&D waste 'chunks' had size and structure similar to the stone being used in the concrete and therefore it was logical to design based upon the replacement of stone aggregate. Former research on the incorporation of dried paper sludge was typically carried out by replacing a percentage of cement as a reference of addition.

4.4 Focus waste fibre from recycled tyres as a performance enhancer of concrete

4.4.1 *Introduction*

Based upon the outcomes from the 'four waste streams' studies, more extensive experimental work is continued with the incorporation of tyre fibre as a performance enhancer in concrete. For consistency and validity, the mixing method and basic testing remain constant but the analysis of the effect of the incorporated fibre on 'toughness' or crack mitigation is extended.

4.4.2 *Experimental test results of tyre fibre in concrete*

To provide a correlation between the data obtained from the four waste streams, testing was continued in the same way, compressive, tensile and flexural strength. See Figure 45.

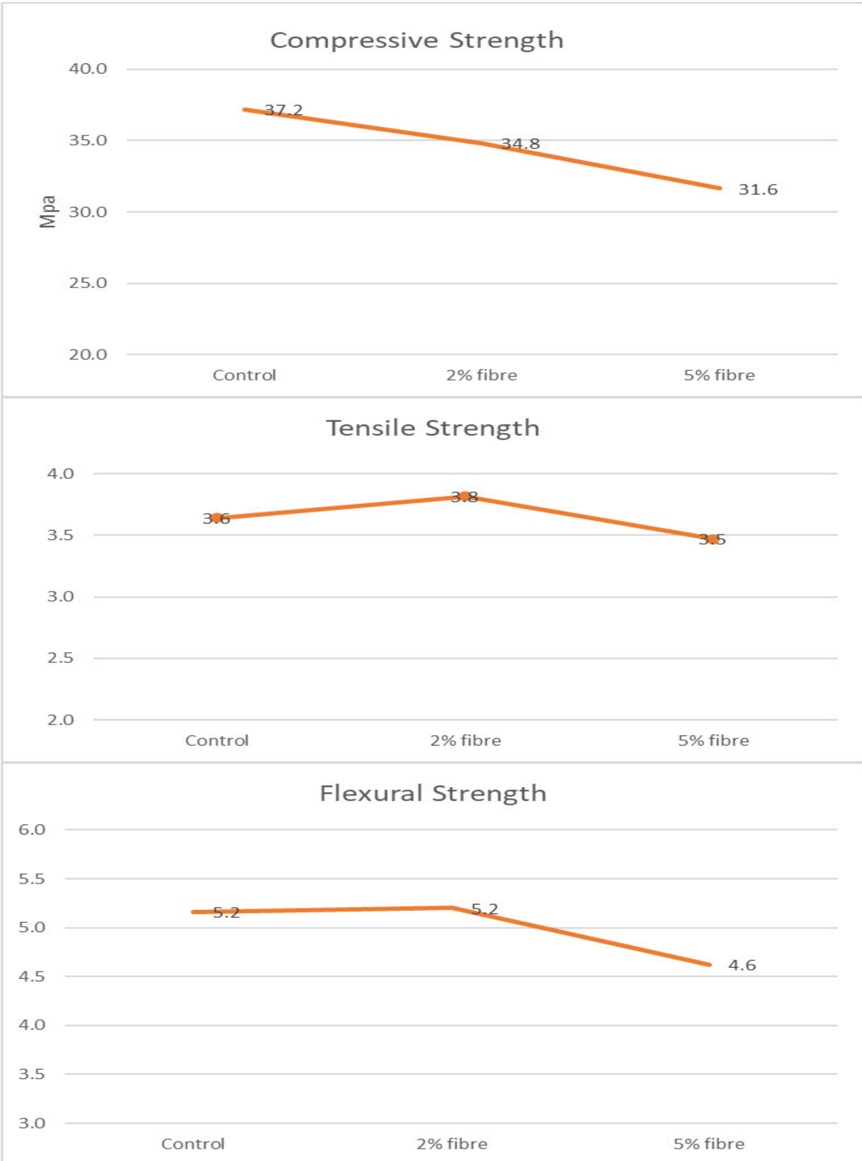


Figure 45. Extended testing of tyre fibre in concrete - Basic strength (Smith 2019)

More information is provided in the Discussion of Results. Based upon the initial results shown in fibre to the concrete mix. At an addition level of 5% of fine aggregate compressive, tensile and flexural strength are all noticeably reduced. At a 2% addition level, the only improvement is a minor increase in the tensile strength. These results therefore only indicate the traditional and standard strength; however, they are useful in terms of the requirement to meet existing specifications.

4.4.3 *Determination of fracture toughness of concrete incorporating tyre fibre*

4.4.3.1 Introduction to Determination of fracture toughness of concrete incorporating tyre fibre

As discussed in the methodology section 3.4.4.2 Additional testing to assess fracture is required to evaluate the effectiveness of any design change with this target performance improvement. For measuring the 'toughness' or resistance to cracking, ultrasonic crack detection at a stepped increase in the 4-point flexure test was performed; this is the recommended method by the UKZN University laboratory, as described in 3.4.4.2.1 of the methodology chapter. There were concerns with the implementation of this test method and two other tests were conducted plotting stress vs time (to simulate stress vs displacement) as described in 3.4.4.2.2. of the methodology chapter and plotting of stress vs deflection during 4-Point flexure, as described in 3.4.4.2.3 of the methodology chapter. This last test was done by an external laboratory and in the absence of the preferred stress vs deflection using 3-Point bending.

4.4.3.2 Results of ultrasonic crack detection – using four-point bending flexure

To provide an understanding of how the fibres introduced into the concrete affect the crack physical characteristics of crack formation, a flexural test vs ultrasonic pulse speed measurement was conducted as displayed in Figure 46. Flexural Stress vs Pulse Velocity (Smith 2019). It should be noted that the flexural stress level of this test, for a given displacement, is higher than the standard flexural strength test, this is due to the incorporation of steel reinforcing which is required to stop catastrophic failure from the first crack.

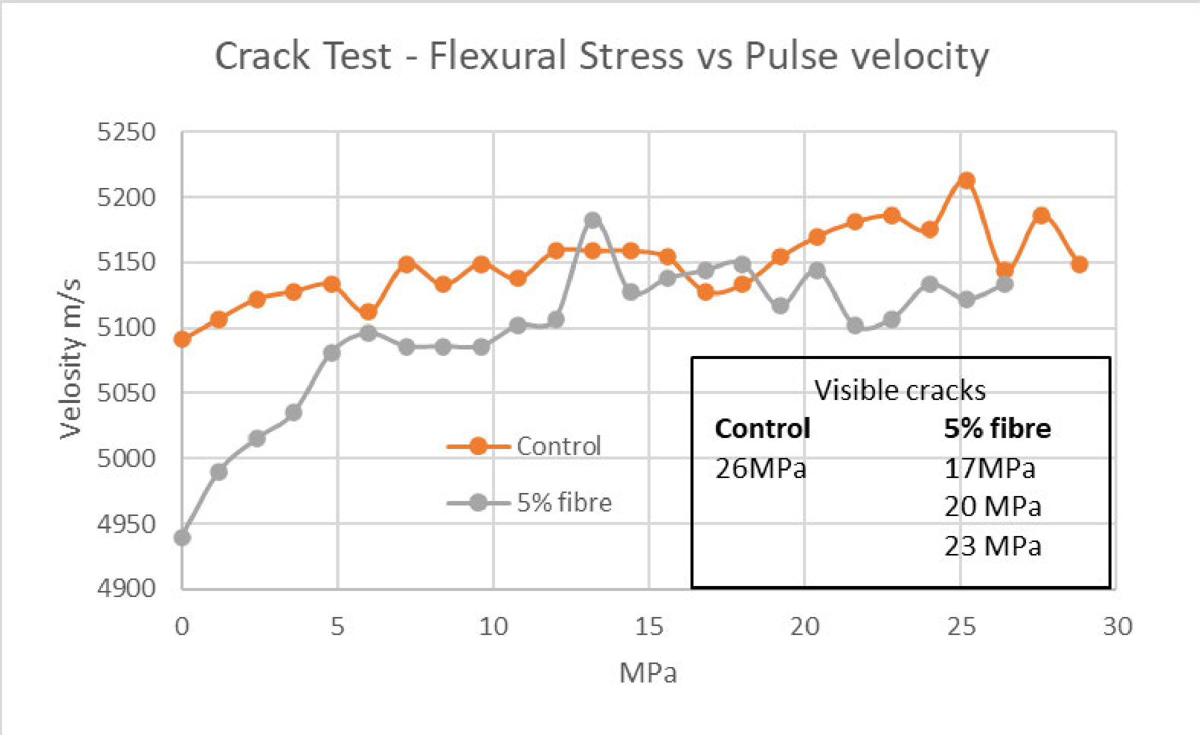


FIGURE 46. FLEXURAL STRESS VS PULSE VELOCITY (SMITH 2019)

4.4.3.3 Discussion of Results of Ultrasonic crack detection - four-point bending flexure test

The initial, stress-free, pulse velocity is higher for the beam without fibre (the control beam), possibly due to the reduction in density from the incorporation of the low-density fibre and the interruptions to the pulse caused by the interruptions at each mineral polymer interface.

In the section between 0MPa and 5MPa flexural stress, there is an almost linear relationship between stress and pulse velocity for both samples but the increase in pulse velocity with the tyre fibre test is approximately three times greater than that of the control sample without fibre. From 5MPa flexural stress onwards the relationship between stress and pulse velocity becomes more erratic, however, there is a relationship between the onset of visible cracks and drops in pulse velocity for both samples. These drops coincide with the visibility of new cracks at approximately 17MPa, 23MPa and 25MPa for the test beam with fibres and at 25MPa for the non-fibre test beam. Multiple small cracks were visible in the beam with fibre and only one crack in the non-fibre beam: this crack became large and propagated even with the support of the steel reinforcing. The distribution of load over many smaller cracks indicates that the beam will remain functional especially in the absence of the steel reinforcing and in situations where there is low-level repetitive stress as crack propagation is hindered by many fibres.

4.4.3.4 Results of the plotting of stress vs time during 4-point flexural test (to simulate stress vs displacement)

Test results are invalid due to test equipment capability.

4.4.3.5 Discussion of the results of the plotting of stress vs time during 4-point flexural test (to simulate stress vs displacement)

The concept of this test assumes that flexural deformation relative to the elapsed time is the same for each sample. In practice this was not the case as the hydraulic press performing the deformation was not able to maintain steady deflection without manually increasing the hydraulic supply pressure. The method and more information can be seen in methodology chapter 3.4.4.2.2

4.4.3.6 Results of the plotting of stress vs displacement during 4-Point flexure

4 Point bending stress vs displacement tests were conducted at the facility of an independent concrete test facility, the remaining control and 2% tyre fibre samples were tested, and results can be seen in Figure 47 with a discussion of the results following the graph.

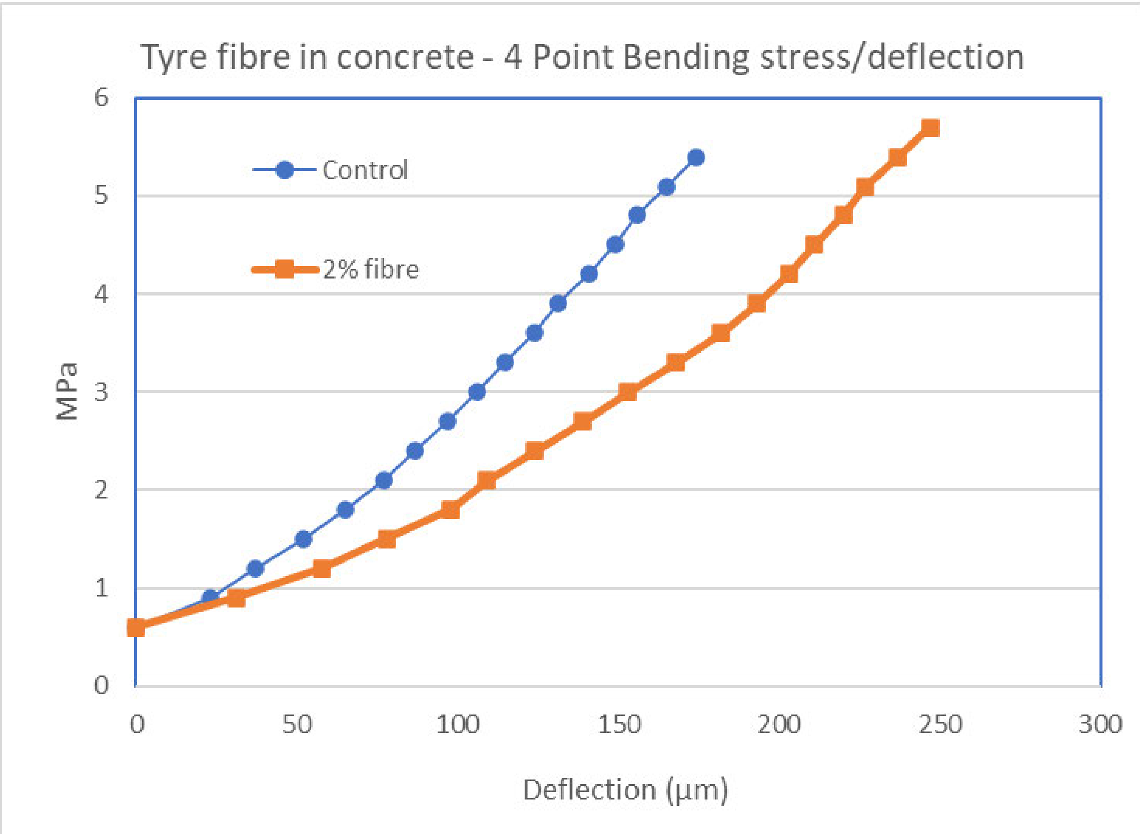


FIGURE 47. 4 POINT BENDING STRESS VS DEFLECTION (SMITH 2019)

The stress and displacement at the point of failure are:

Control bar 5.66 Mpa @ 174μm deflection

2% fibre bar 5.81 MPa @ 247μm deflection

The method and more information can be seen in methodology chapter 3.4.4.2.3

Notably, the test bar including 2% tyre fibre had >40% increased displacement at the ultimate failure stress with marginally higher maximum stress.

The shape of the curve is relatively straight (linear) for the control bar and more curved with the bar containing fibre, this is consistent with the fibre-containing bar being 'less stiff' at low loads and progressively stiffening with increased deflection.

4.4.3.7 Discussion of the results of plotting of stress vs deflection during 4-Point flexure

The performance at the point of maximum stress for the beam containing 2% fibre can be related to 3% higher stress and 42% greater extension than the control beam without fibre.

It should be noted that the results in table 11 are values of deflection by video and with load values provided verbally, hence the minor discrepancy in stress at the point of failure i.e. The final maximum stress value is recorded electronically whereas all the prior results are taken from a video of the displacement with a verbal record of the digital readout.

The beam with fibre can be said to be marginally stronger and clearly 'tougher' than the control beam without tyre fibre.

4.4.4 *Supplemental test results – Tyre fibre in concrete:*

4.4.4.1 Introduction to supplemental test results

The 'core' experimental test work for this thesis, is followed by initial test results by Sachrin Naidoo. To provide more data and to fill gaps in data, two more final-year BSc students undertook supplementary experimental work on tyre fibre in concrete

4.4.4.2 Supplemental test results – Tyre fibre in concrete

Supplemental (1) Initial concrete test results – Sachrin Naidoo (Fibre from recycled tyres in concrete (research from four waste streams, 4.3.4)

Supplemental (2) tyre fibre test results (Msize Mkise)

Supplemental (3) tyre test results (Yashay Basdaw)

The results from all four test programmes utilising tyre fibre including the supplemental testing as covered in the methodology section 3.3.6 (Fibre from recycled tyres in concrete - Methodology review) is summarised in Table 11

4.4.5 *Overview of test results of tyre fibre in concrete*

4.4.5.1 Introduction

This section provides comparative data from four different experimental concrete mixes containing tyre fibre from the same source waste source. In addition to the results using fibre contaminated with rubber particles (as received) two additional mixes were made after the removal of the rubber contamination (Cleaned fibre).

4.4.5.2 The comparative physical strength of concrete with the incorporation of fibre from automotive tyres

Data in this section is sourced from four different test programmes using the same tyre fibre source in each concrete mix.

For reference the four sources of data displayed in the comparative review of the data in Table 11 are from the following sources:

Core Data: Thesis Author

Supplemental 1: Sachrin Naidoo

Supplemental 2: Msize Mkise

Supplemental 3: Yashay Basdaw

TABLE 11. REVIEW OF PERFORMANCE CHANGE WITH TYRE FIBRE ADDITION (SMITH 2019)

Review of Performance change with tyre fibre addition

Sample	Fibre and Rubber	Rubber removed	% Total Weight	Compressive Strength Mpa	change %	Tensile Strength Mpa	change %	Flexural Strength MPa	change %
Core Test Rubber contaminated	X		0.0	37.2		3.63		5.16	
			1.0	34.8	-6.5	3.80	4.7	5.20	0.8
			2.6	31.7	-15.8	3.50	-7.9	4.62	-10.4
Supplemental 1 Rubber Contaminated	X		0.0	28.0		1.63		3.60	
			1.7	22.2	-20.6	2.76	69.5	3.96	-33.3
Supplemental 2 Cleaned		X	0.0	40.1		3.10		7.02	
			1.2	37.5	-6.5	3.10	0.0	6.00	12.0
Supplemental 2 Rubber Contaminated	X		0.0	40.1		3.10		7.07	
			1.2	34.8	-13.2	3.80	22.6	5.20	0.6
Supplemental 3 Cleaned		X	0.0	25.3		7.63		Not tested	Not tested
			0.7	20.3	-19.8	7.20	-5.6		
			1.7	12.8	-36.9	6.47	-10.1		
Supplemental 3 Rubber Contaminated	X		0.0	25.3		7.63		Not tested	Not tested
			0.7	25.6	-45.8	8.23	7.9		
			1.7	5.9	-122.3	4.83	-41.3		

Table 11 provides a review of the results of the four sources' experimental projects by rationalising the percentage of the tyre fibre relative to the total weight It then displays the performance of the control sample and the performance at each fibre addition level followed by the percentage change relative to the control sample for each test. Green shading indicates performance improvement and beige indicates performance reduction. Unfortunately, the flexural strength test results couldn't be provided for supplemental 3 test work as the student did not have enough time to complete the tests before his dissertation submission.

Reviewing Figure 48, the graphical results provide an improved understanding of the differences between not only the trends but the different performance levels for each experimental study. Tyre fibre mixed with rubber and other contamination is displayed with a data-point 'circle' whilst cleaned fibre is represented by 'triangle' data points. The initial design target for the control mixes was 32.5 MPa which was reduced to 25 MPa in supplemental test 3 to determine if there would be a greater increase in strength with a lower design strength concrete. See **Table 6** In fact, the opposite was the case, as supplemental test 3 suffered the greatest reduction in compression strength with increasing tyre fibre.

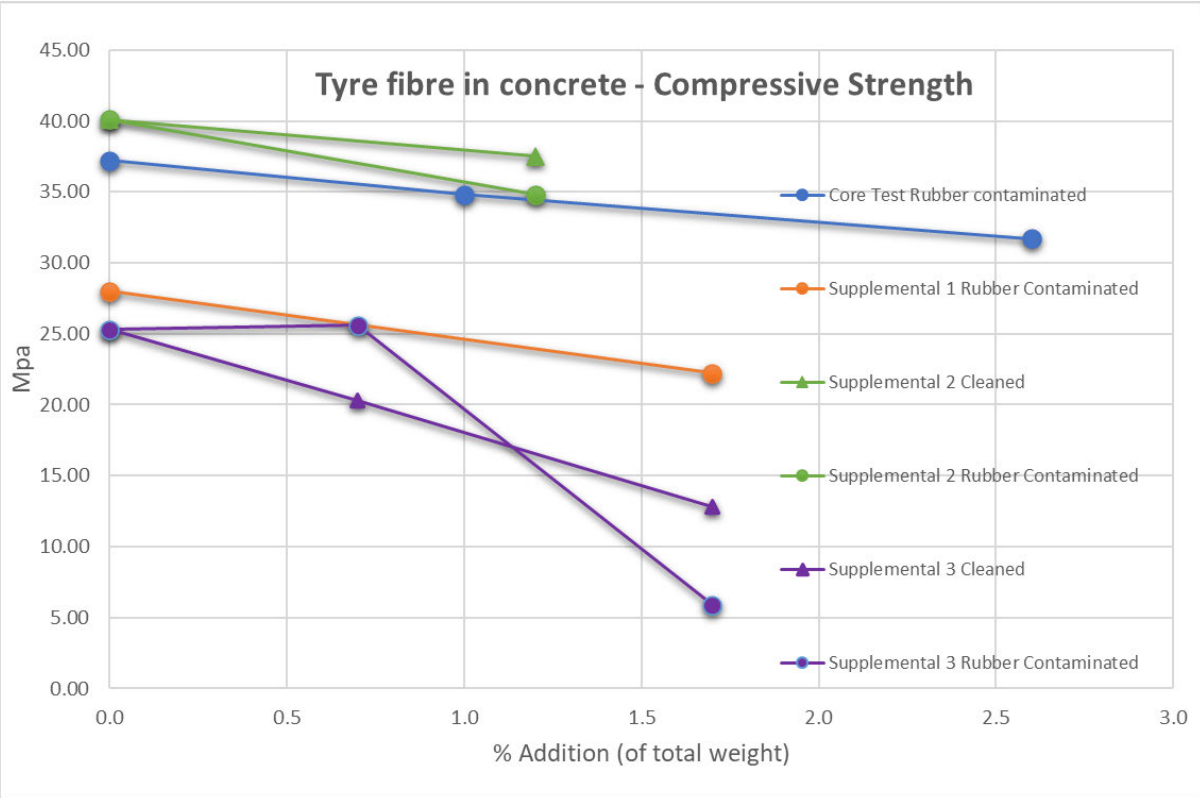


FIGURE 48. COMPARATIVE COMPRESSIVE STRENGTH OF CONCRETE INCLUDING TYRE FIBRE - FOUR TEST PROGRAMMES (SMITH 2019)

The first impression on viewing Figure 49 is that supplemental test 3 jumps from the lowest compression strength in all aspects to the highest by a factor of x2 for the control sample without tyre fibre.

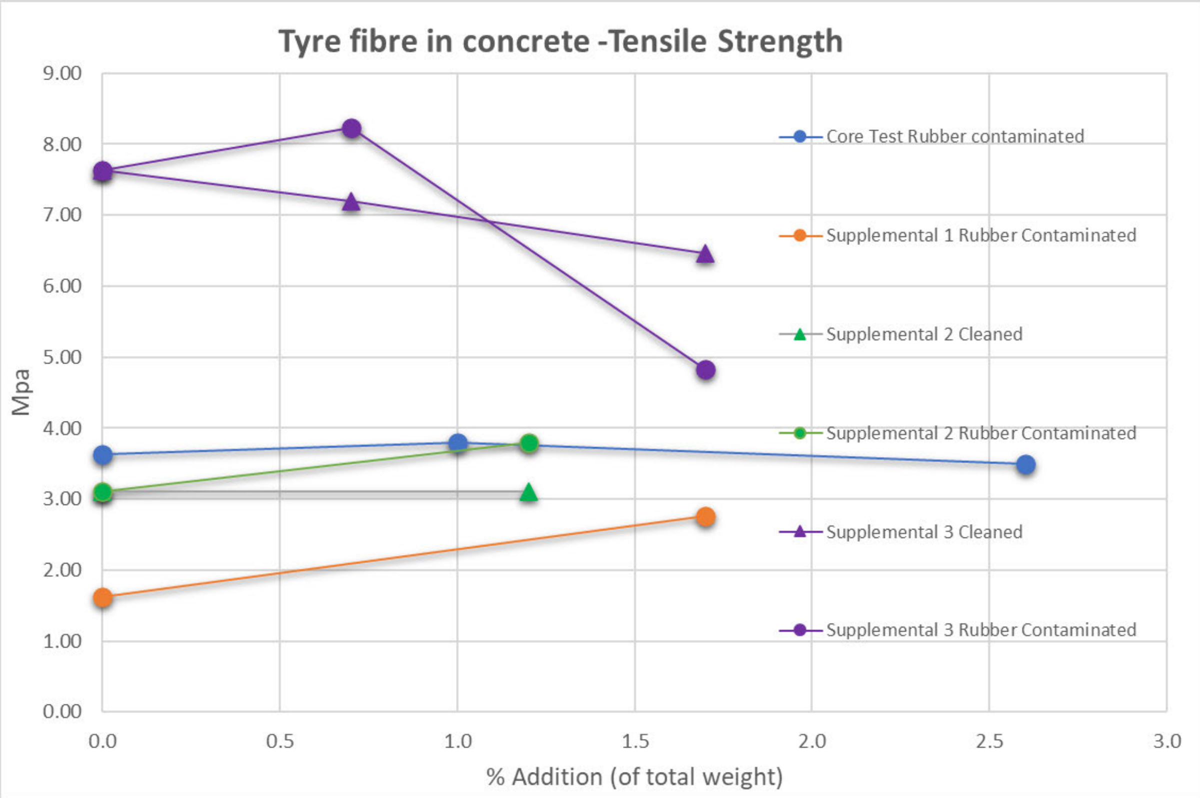


FIGURE 49. COMPARATIVE TENSILE STRENGTH OF CONCRETE INCLUDING TYRE FIBRE - FOUR TEST PROGRAMMES (SMITH 2019)

There is no indication that the cleaning of the tyre fibre is beneficial, the opposite is more often the case, as can be seen with the rubber contaminated (circular graph points) performing well in the tensile test.

Testing of flexural test for the supplemental 3 group and results are therefore absent from (Figure 50). Of the remaining three remaining samples the only one showing improved performance is the supplemental 1 concrete mix which as mentioned already, has already provided some suspicions regarding the result validity. The reason for the significant drop in flexure strength of the supplemental 1 samples is unclear but it is suggested that it is related to air inclusion from poor workability

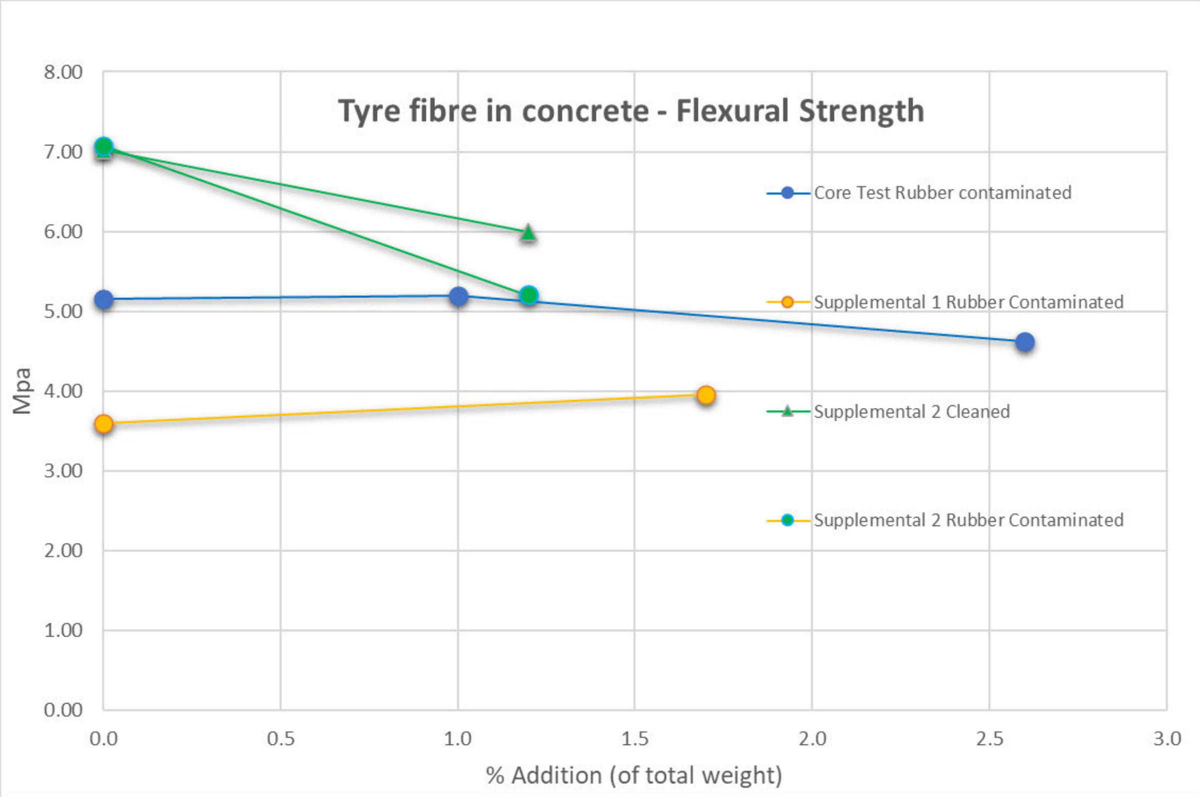


FIGURE 50. COMPARATIVE FLEXURAL STRENGTH OF CONCRETE INCLUDING TYRE FIBRE - FOUR TEST PROGRAMMES (SMITH 2019)

Discussion of the Overview of test results of tyre fibre in concrete

The first observation is that compressive strength reduces in every instance with the addition of tyre fibre.

Cleaning of the tyre fibre to remove the contamination of rubber particles and pieces of cord did not have a noticeable effect. This may be due to a neutral or positive effect of the contamination i.e., the rubber particles and tyre cord may be beneficial but at least do not appear to be detrimental to performance and therefore the benefit of difficult and costly removal should be reviewed.

4.4.6 *Failure analysis – Normal vision and Microscopy*

4.4.6.1 Introduction to Failure analysis – Normal vision and Microscopy

Gifted with the human senses of sight, sound, smell and touch, one may find that in our world of electronic technology, these senses are often overlooked. However, they are most helpful in guiding us in the 'right' or interesting direction for a more detailed investigation or line of research. If the mind is 'open' and 'switched on' to receive the multitude of senses arriving from the challenge in front of us, then one can make more meaningful research decisions and ultimate conclusions. The process of analysing something with one's 'naked eye' (sometimes termed bare eye or unaided eye) is often ‘overlooked’. The well-known detective character Sherlock Holmes pictured assessing evidence with his large magnifying glass, gives the impression of knowledge and importance, however, the use of a magnifying glass in a state-of-the-art laboratory today is likely to be mocked. However, the use of the naked eye can never be underestimated, and we now can use digital cameras and mobile phone cameras for magnifying the image of the item being assessed. This not only assists in assists in assessing the research but is recordable, essentially bringing the laboratory to the subject instead of the reverse.

In addition to the analysis of samples by the naked eye and camera, the use is made of

4.4.6.2 Test samples – Visible Images - review of failure faces

4.4.6.2.1 *Introduction to Test samples – Visible Images - review of failure faces*

Normal Visual examination of the fracture surface of the samples provided stunning examples of what can be termed brittle failure or tough failure (sometimes referred to as a ductile failure, strictly ductility refers to the softness of the material and its ability to be formed into a shape by force). This section provides the grounding for the more detailed optical microscope and SEM evaluation.

4.4.6.2.2 *Flexural test beams images after testing*

The following images show the flexural strength test beams, after the test, revealing the surface structure after the failure.

Microscopy samples removed from the surface of the flexural test beams were stored in boxes indicating the source location see Figure 23

Figure 51 shows the failure analysis sample source - flexural strength beam failure surface – close-up, the surface roughness and more ‘matt’ appearance increases with fibre addition.

FIGURE 51. FAILURE ANALYSIS SAMPLE SOURCE - FLEXURAL STRENGTH BEAM FAILURE SURFACE - CLOSE UP (SMITH 2019)

More 'ragged' crack surfaces are evident indicating that crack propagation has been hindered, whereas the control samples without tyre fibre have clean, smooth surfaces, indicative of brittle failure or 'catastrophic failure'.

4.4.6.2.3 *Tensile test cylinders after testing*

The tensile cylinder shown in Figure 52, after testing, has completely broken into two pieces. In the end view, one major crack is noticeable, the crack being clean with few deviations from its main course.

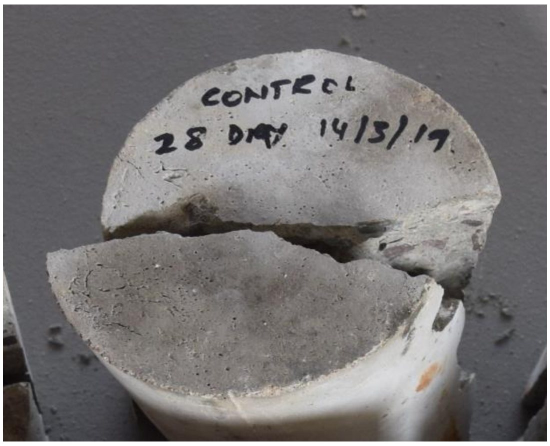


FIGURE 52. TENSILE TEST SAMPLE 0% FIBRE - CONTROL (SMITH 2019)

In contrast to the control sample without fibre, the sample containing 2% fibre shown in Figure 53, although having many cracks, remains in one piece. The cracks show signs of branching, indicating that the crack tip during propagation is being hindered and deviated, with the subsequent dissipation of energy over a greater surface area.

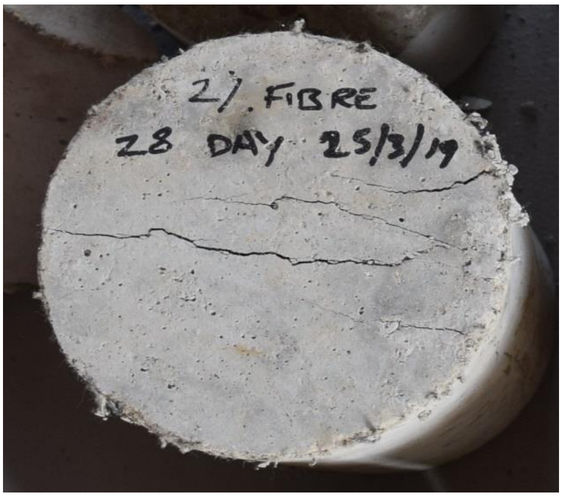


FIGURE 53. TENSILE TEST SAMPLE - 2% FIBRE (SMITH 2019)

The sample containing 5% fibre, Figure 54 has the characteristics of the 2% fibre sample but to a greater extent. On the right-hand side of the image, the passage of two cracks from the centre of the sample to the outside can be seen to be repeatedly broken down into a multitude of smaller cracks, arresting the movement of the crack propagation.

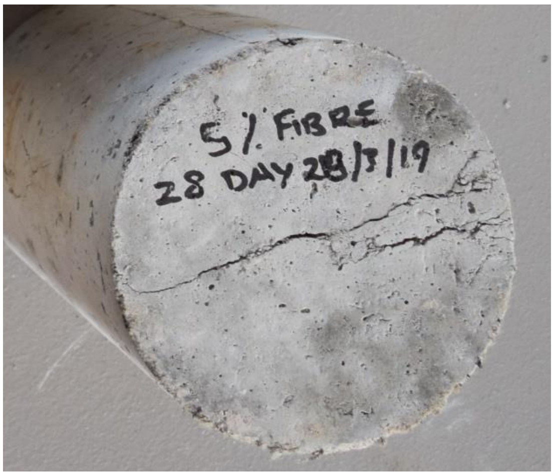


FIGURE 54. TENSILE TEST SAMPLE - 5% FIBRE (SMITH 2019)

A close-up image from a normal camera of the 5% sample was taken using a mobile phone camera, Figure 55 this image shows how the tyre fibre, in simple terms, has been holding the sample together under tensile stress.

FIGURE 55. TENSILE TEST SAMPLE - 5% FIBRE CLOSE UP {SMITH 2019)

4.4.6.2.4 *Optical Microscope evaluation of fibres received*

The Optical microscope magnification used in this study is generally in the region of x50 to x100 and can be verified by the calibration strip on each figure image.

Examples of the consistency of fibres received can be seen in Figure 56 example 1 and Figure 57.

FIGURE 56. FIBRE SAMPLE EXAMPLE 1 (SMITH 2019)

Figure 57 example 2. Example 1 provides an understanding of the complex form of the waste material being dealt with. Consisting of tangled fine fibres, which are the anticipated source of concrete reinforcing, woven 'cord' which appears to constitute a large percentage of the total weight, rubber particles attached to the fibre and cord. Example 2, although similar to example 1, has a greater percentage of fine but matted fibres and a smaller percentage of woven tyre cord.

FIGURE 57. FIBRE SAMPLE EXAMPLE 2 (SMITH 2019)

4.4.6.2.5 *Optical evaluation of fracture surfaces*

Optical and Scanning Electron Microscope Evaluation samples are taken from the failure face of each flexural test beam in the location shown in and as described in the methodology chapter The fracture faces of each test beam from where optical and SEM test samples are taken are shown in Figure 22 and Figure 51provides a closer view of the fracture surfaces.

The fracture surfaces of flexural strength test beams are assessed using an optical microscope Figure 58,Figure 59 and Figure 60 to show the bottom area of control samples. The bottom is in tension and the typical initiation area for cracks. The surfaces appear clean and smooth with little or no indication of applied stress, this can be the case where brittle failure occurs, as the rapid propagation of the crack takes the weakest interfacial path, leaving the smooth surfaces of the incorporated aggregate.

FIGURE 58. CONTROL SAMPLE FRACTURE BOTTOM A - OPTICAL MICROSCOPE (SMITH 2019)

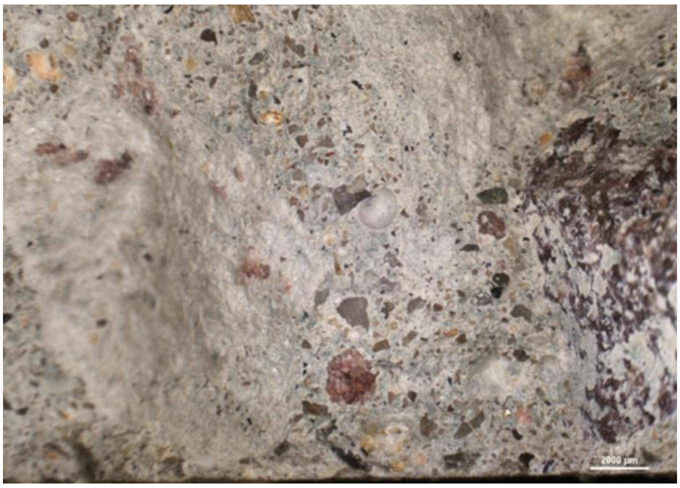


FIGURE 59. CONTROL SAMPLE FRACTURE BOTTOM B - OPTICAL MICROSCOPE (SMITH 2019)

FIGURE 60. CONTROL SAMPLE FRACTURE BOTTOM C - OPTICAL MICROSCOPE (SMITH 2019)

Figure 61 and Figure 62 are optical microscopic images of the bottom sections of test samples containing 2% fibre. The remains of tyre fibres are evident, although the fibres are clearly not well dispersed but are typically in the form of agglomerates or 'matted' together in clumps. A notable point and a factor that may be affecting the more 'matt' appearance of the samples containing fibre, is the apparent remains of cement paste on the aggregate surfaces. This may be due to a change in failure mode from 'adhesive' to a more favourable 'cohesive' failure mode as crack arrest increases, in this case, a greater amount of energy is required to propagate the crack; this being the definition of increased toughness.

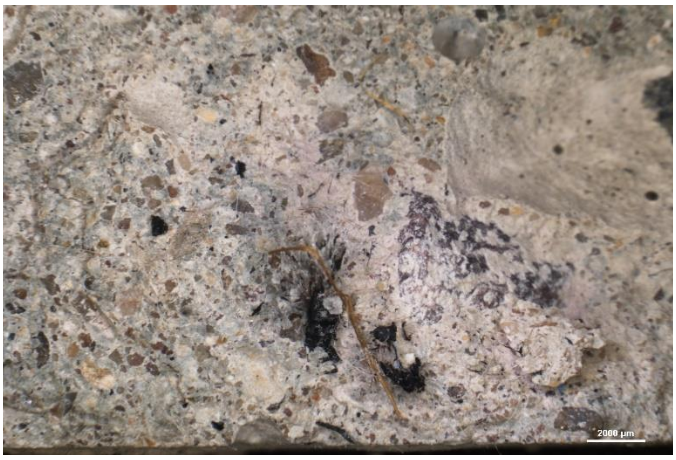


FIGURE 61. 2% FIBRE BOTTOM A - OPTICAL MICROSCOPE (SMITH 2019)

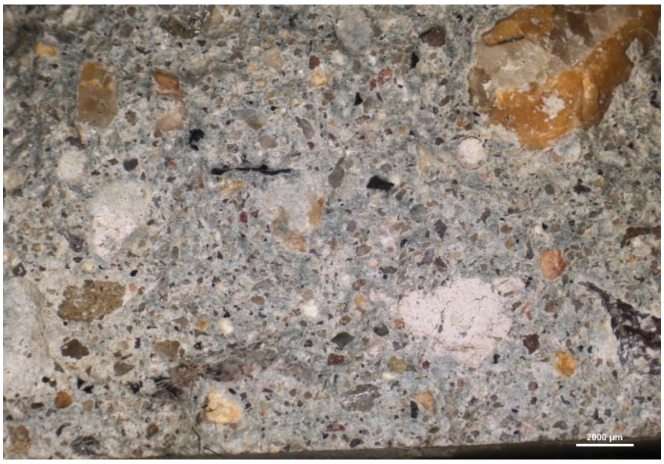


FIGURE 62. 2% FIBRE BOTTOM C - OPTICAL MICROSCOPE (SMITH 2019)

Figure 63, Figure 64, and Figure 65 Show optical microscope pictures of the bottom of the fracture surface of flexural strength beams with 5% fibre content.

FIGURE 63. 5% FIBRE FRACTURE BOTTOM A - OPTICAL MICROSCOPE (SMITH 2019)

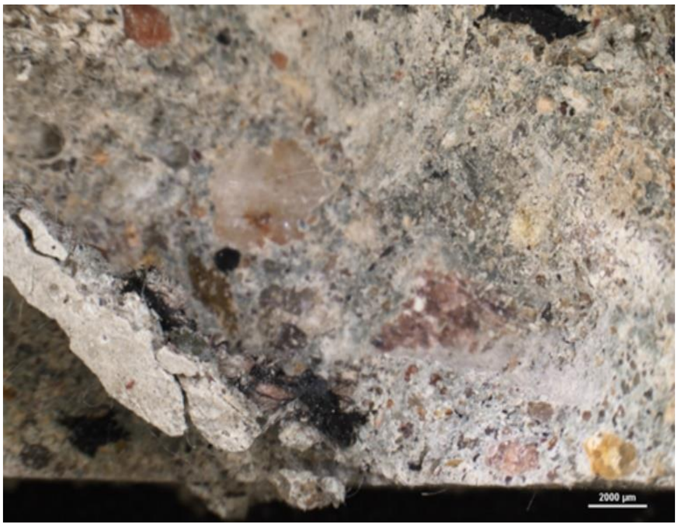


FIGURE 64. 5% FIBRE FRACTURE BOTTOM B - OPTICAL MICROSCOPE (SMITH 2019)


FIGURE 65. 5% FIBRE FRACTURE BOTTOM C - OPTICAL MICROSCOPE (SMITH 2019)

4.4.6.3 Scanning Electron Microscope (SEM) failure analysis

A review of the fracture surfaces indicates good bonding between the tyre fibres and the concrete, this is evident by the apparent affinity of the fibres to the concrete body and with some deposits remaining on the fibre surface.

SEM images were taken in all five locations requested however there were no noticeable differences in the failure mode at each crack surface. Therefore, for consistency, the bottom chip sample locations are selected for review i.e., the location under tension during the flexural strength test.

Figure 66 shows the typical fracture surface without the addition of fibre.

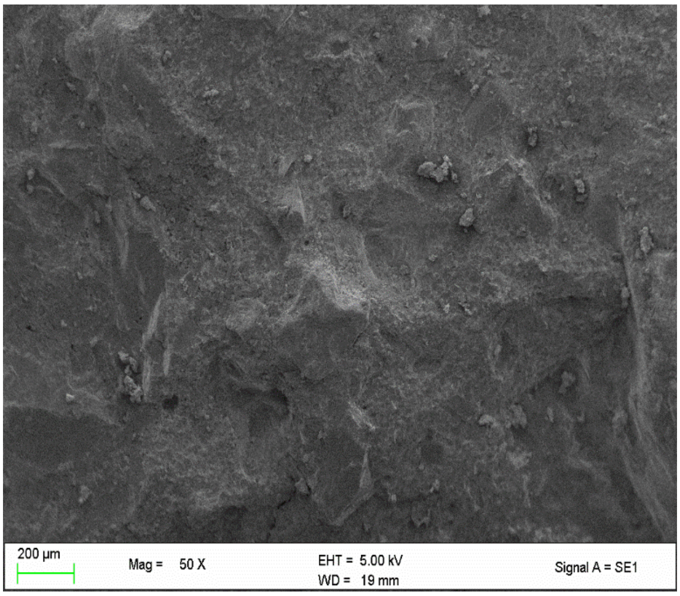


FIGURE 66. SEM CONTROL SAMPLE (SMITH 2019)

Microscopy sample specimens are chipped from the failure surface and Figure 67 provides an overview of the chip removed from a 5% fibre flexural test beam. The smooth outer surface is the surface that was chipped and the rough area in the centre is the fracture surface from the flexural strength test.

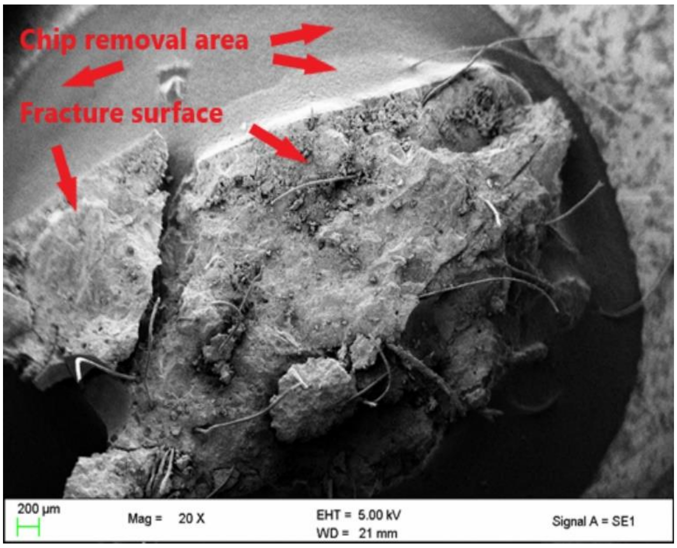


FIGURE 67. SEM CHIP SAMPLE (SMITH 2019)

Figure 68 shows a typical view of a 2% fibre addition fracture surface, although fibre distribution is not generally this consistent as the fibres are often clumped together.

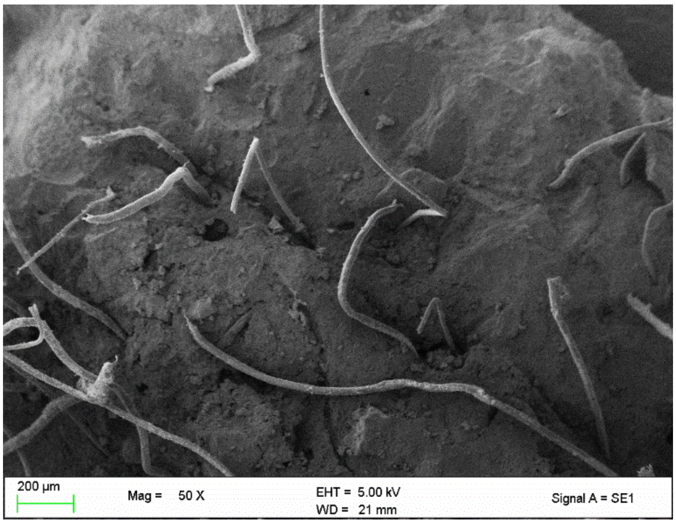


Figure 68. SEM 2% fibre (Smith 2019)

To verify that the fibres that we see are being pulled out of the concrete body, exit, or pull-out holes for the fibre are reviewed. **Figure 69** shows such holes and what appears to be a piece of the concrete body chipped off by energy transfer from a single fibre.

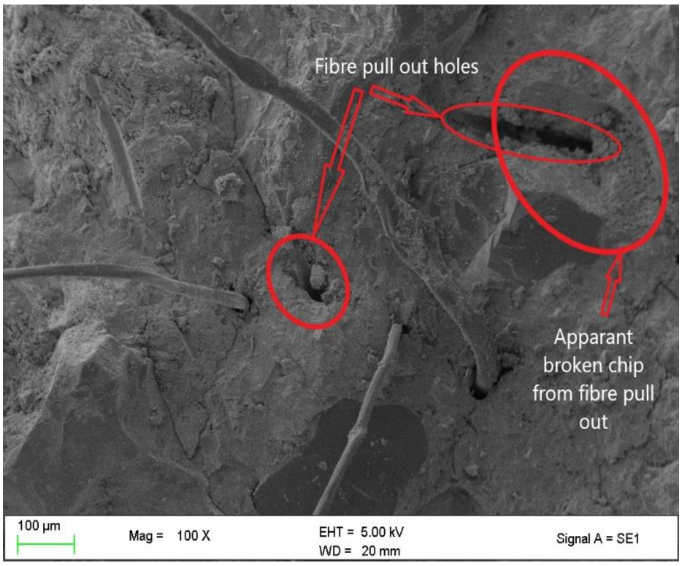


Figure 69. SEM 2% Fibre pull out (Smith 2019)

Figure 70 shows a lump of cement mix adhered to a single fibre, good wettability of the fibre surface by the cement mix is evident.

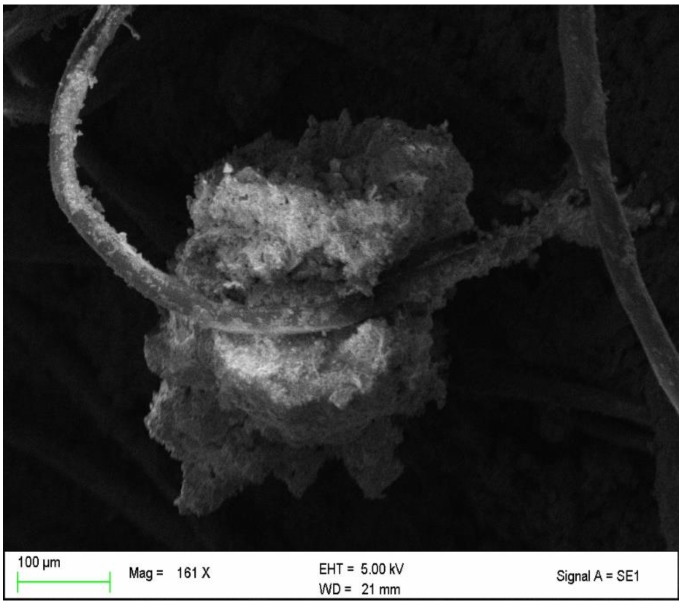


FIGURE 70. SEM 5% FIBRE ADHESION (SMITH 2019)

The red arrows in Figure 71 point to air pockets that were very evident as bubbles in the concrete test sample preparation. The bubbles continued to escape even after extended compaction.

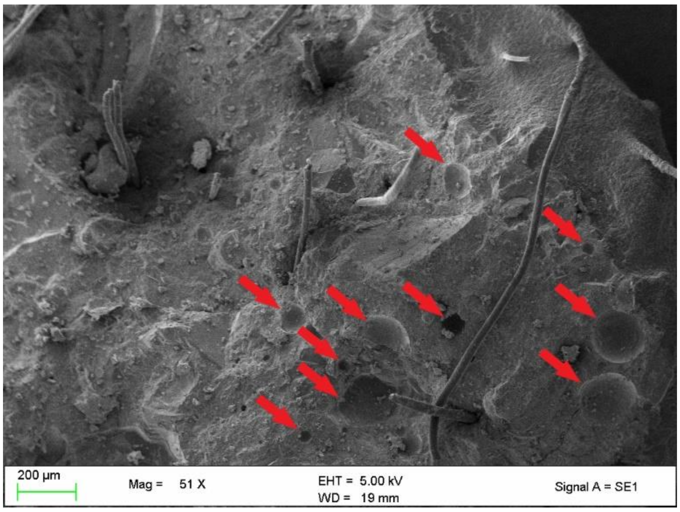


FIGURE 71. SEM 5% AIR POCKETS (SMITH 2019)

4.4.7 *Discussion of results of tyre fibre in concrete*

Experimental work on the incorporation of tyre fibre in concrete was initially conducted by one BSc student followed by two more students as the high potential for practical application was predicted. All students were given guidance and supervision throughout their projects, including the review and critiquing of their dissertations. Thus, in total four concrete mixes utilising tyre fibre were made and tested.

Before continuing, if one pauses for a moment and looks, thinking out of the box, in the image Figure 72 which dissipate energy and hinder the crack propagation.

FIGURE 72. TENSILE SPLITTING TEST CYLINDER - CONTROL AND 2% TYRE FIBRE (SMITH 2019)

(Figure 55 provides a closer view), a textbook example of a brittle failure and a tough failure. Yet, the test results, using the tried and tested concrete strength testing methods, Compressive, Tensile and flexural are showing little difference other than 'The addition of the waste material is making the concrete weaker in compression' and nothing very positive to speak of. However, visually, it appears to be a tougher material, even though the fibre is poorly dispersed, tends to remain in clumps and mixed with rubber particles and other contamination.

The Researcher needs to select (and sometimes create) test methods that either assess the material by simulating the final conditions OR by doing a test that directly relates to the practical ageing that the product will experience during its lifetime, such as is the case with the widely accepted concrete durability test, whereby the porosity of the sample relates to its long-term performance.

Following the completion of the standard concrete strength tests, a measure of the material toughness was required. The next section concludes the quest whilst leaving open ends for future research.

Test method for concrete toughness

Detailed information is provided in the methodology section 3.4.4.2 and results 4.4.3.3 to 4.4.3.6, here follows a summary and conclusions:

a) See 4.4.3.2 Ultrasonic crack detection – During 4- point bending.

   The final results, which were only conducted on the control and 5% fibre addition samples indicated the degree and type of cracking occurring:

   The distribution of load over many smaller cracks indicates that the beam will remain functional especially in the absence of the steel reinforcing and in situations where there is low-level repetitive stress as crack propagation is hindered by many fibres.

b) See 4.4.3.6 Plotting stress vs displacement during 4-point bending.

   The test bar including 2% tyre fibre had >40% increased displacement at the ultimate failure stress with marginally higher maximum stress.

   The method and more information can be seen in methodology chapter 3.4.4.2.3 and the stress vs displacement graph is displayed in the results section.

   Failure mode:

   The shape of the curve is relatively straight (linear) for the control bar and more curved with the bar containing fibre, this shows that the fibre-containing bar is 'less stiff' at low loads and progressively stiffens with increased deflection. This is consistent with the scenario of microcracks, initially beginning to open before being restricted by many fibres, distributing the load over many fibre-reinforced microcrack faces.

Normal optical assessment and microscopy

Already highlighted as important in 4.4.6.1, the visual assessment of samples during research and investigation is extremely important, together with the assessment of test equipment and test procedures during the process.

Visual Assessment

Images of compression test cubes are not shown, as there is not very much to see other than the fact that the cubes which include fibre tend to stay in one piece, whereas the control samples are more likely to crumble apart.

Interesting observations begin when reviewing the tensile cylinders, many small cracks become apparent on the end faces of the test cylinders during the test, allowing detailed visual assessment to be made immediately after testing see Figure 52, Figure 53,

Figure 54 and close-up Figure 55 provide classic images of a 'crack arrest' mode of failure of samples under tension. The multitude of cracks appear like rivers on a map, but in reverse as the passage of the cracks from the centre of the sample to the outside can be seen to be repeatedly broken down into a multitude of smaller cracks, arresting the movement of the crack propagation.

Going a step further, assessing the failure faces of the flexural strength test beams, the roughness (or smoothness) of the surface provides a good indication of the failure mode, whether brittle or tough. Figure 51provides an overview of all the samples together, it is evident that the surface roughness and more 'matt' appearance increases with fibre addition. More 'ragged' crack surfaces are evident indicating that crack propagation has been hindered, whereas the control samples without tyre fibre have clean, smooth surfaces, indicative of brittle failure or 'catastrophic failure'.

Optical Microscopy

Observations:

The fracture surfaces of the samples without fibre, appear clean and smooth with little or no indication of applied stress, this can be the case where brittle failure occurs, as the rapid propagation of the crack takes the weakest interfacial path, leaving the smooth surfaces of the incorporated aggregate.

The samples from both the 2% and 5% fibre addition fracture surfaces display the remains of tyre fibres, although the fibres are clearly not well dispersed but are typically in the form of agglomerates or 'matted' together in clumps. A notable point and a factor that may be affecting the more 'matt' appearance of the samples containing fibre, is the apparent remains of cement paste on the aggregate surfaces. This may be due to a change in failure mode from 'adhesive' to a more favourable 'cohesive' failure mode as crack arrest increases, in this case, a greater amount of energy is required to propagate the crack; this being the definition of increased toughness.

Scanning Electron Microscope (SEM)

SEM samples were taken from the same source as the optical microscopy samples.

To verify that the fibres seen are being pulled out of the concrete body, exit holes are determined, **Figure 69** shows such holes and what appears to be a piece of the concrete body chipped off by energy transfer from a single fibre.

In general, a review of the fracture surfaces indicates good bonding between the tyre fibres and the concrete, this is evident by the apparent affinity of the fibres to the concrete body, with deposits remaining on individual fibre filament surfaces, such as seen in Figure 70.

4.5 Summary of the Results and Discussion chapter

The results and discussion chapter bring together the entire output of the thesis.

Section 4.2 starts the picture with a positive note of how the Comprehensive Plan for Sustainable Human Settlement commonly referred to as "Breaking New Ground" or BNG RDP (reconstruction and development programme) house provides an improved environment compared with the original RDP house specification. Furthermore, the houses were built to a high-quality level efficiently, even in difficult terrain. The BNG houses being built in large numbers demonstrates that the critical assessment and redesign of the original basic RDP house has resulted in comfortable basic living accommodation. Furthermore, continuous assessment and improvement in the building technique by a proficient building contractor by improving build-efficiency can provide successful results.

Results from the survey of alternative building systems, confirm the high level of activity in designing and accrediting alternative building systems A wide range of 44 Agrement certified alternative building systems is assessed and although it is generally accepted that the construction industry should be moving away from the use of concrete due to the energy consumption of Portland cement, cellular lightweight concrete (CLC) provided high results in terms of sustainability ranking, possibly providing a stepping stone in the reduction of Portland cement usage. The other very different more traditional building system scoring the same ranking as CLC is Cement stabilised soil blocks (CSSB), which contains a small amount of cement. The CSSB Agrement certificate holder emphasised that the compressed soil blocks are fully functional without the addition of cement, as can be seen from the existence of many old buildings constructed from compressed soil, however, the strict Agrement 'waterproofness' test cannot be passed without some cement addition.

It should be noted that a response was provided from a reputable traditional building designer indicating 'the excessive emphasis is put on strength and "so-called" waterproofness of a material (i.e., cement-based products) at the expense of sustainability, health, resource efficiency and a more holistic understanding of how buildings perform as a whole system', a debate which may continue.

Section 4.3 provides data from the utilisation of four waste streams in concrete, indicating that both paper mill sludge and fibre from car tyres provide improved tensile and flexural strength with relatively small addition levels See Figure 44. Leading the direction of this research towards the modification of concrete with waste fibre which is otherwise destined for landfill.

The focused test results of concrete, incorporating fibre from car tyres, provided in section 4.4 clearly show the benefit of incorporating waste fibre for improving concrete crack resistance, making the concrete tougher or less brittle. Several attempts were made to quantify the improvement in toughness, which is visible in the microscopy results, but suitable equipment was not readily available for this research. However, a customised test was set up at an external test house, providing meaningful, 'increase in toughness' results. Furthermore, a recently developed test method has been specifically developed for this purpose, the 'round determinate panel' shown in Figure 4. This testing opens a pathway for further research work into more crack-resistant or tough concrete utilising industrial waste materials.

CHAPTER 5

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The South African Constitution, of 1996 enshrines the right of everyone to have access to adequate housing and makes it incumbent upon the State to take reasonable legislative and other measures within its available resources to achieve the progressive realization of this right (Department-of-Human-Settlements 2009). By conducting research into the most cost-effective and environmentally friendly building systems and building materials for the specific requirements of our country, this research assists in providing potential options for this challenge.

During the early stages of this research, it became apparent that, before developing radically new building materials, there is a gap, whereby industrial waste, which is a major environmental problem, can be utilised not only to fill and 'extend' concrete mixes and divert material from landfill but also provide enhanced performance of the concrete. During further research, the incorporation of recycled fibre from automotive tyres into the concrete mix was found to improve crack resistance. Hence, some of the objectives of the research pathway were shifted to more practical and achievable ones, whilst remaining in line with the original research aim.

Section 5.2 Affordable and sustainable building systems in South Africa

This section comprises two parts, as before, the RDP house case study and the survey of alternative building technology.

As the output from the two parts of section 2.2 literature review 3.2 methodology and 4.2 Results and Discussion, the outcomes from the RDP house case study and the survey of alternative building technology are concluded and based upon the findings. Recommendations for further research and development work are proposed.

Section 5.3 The application of industrial waste stream materials in concrete mixes: Research into four waste stream materials in concrete mixes (part of ongoing research at the university of Kwa-Zulu Natal (UKZN) based upon the output of previous chapters, the merits and limitations of the four waste streams are concluded with recommendations for potential avenues for further research.

Section 5.4 Tyre fibre as a performance enhancer in concrete

This core research has great potential in terms of the capability to have a win–win scenario, utilising waste in concrete in a way that reduces pollution to the environment, whilst at the same time providing enhanced specific performance characteristics (toughness). Quantifying the effect of the introduction of fibre becomes the key focus of this research opening avenues for future research.

5.1.1 *Reflection on the original Aim and Objectives of this research*

Aim – 'The main aim of the research is to evaluate alternative, more ecologically sustainable options of building materials, for use in the construction of affordable housing, in sustainable African cities, without compromising social acceptance and economic viability. A key focus is the utilisation of waste material and the minimisation of the dependence on traditional high-energy consuming Portland cement concrete. To conduct in-depth experimental test work on potential candidate materials and on the most promising way to determine the feasibility of the application, while ultimately proposing a pathway for future research.

Output – The starting point for this research, reviewed historical low-cost housing in South Africa followed by an assessment of the 'state of the art' construction of the latest government-specified low-cost house, giving a baseline to progress from, in line with Objectives 1 and 2. Output from Objective 3 provided a detailed assessment of certified alternative building systems with a focus on walling, using a sustainability indicator-based survey. Two systems are highlighted for further research, one of which, Cellular Lightweight Concrete (CLC) relates to Objective, 4 'To propose innovative and novel approaches to the building of low-cost housing with an emphasis on the utilisation of waste material' and Objective 5, 'Experimental investigation of one proposed building material'. The emphasis here is the continued use of concrete in building as a stepping stone on the road to more sustainable systems. The research presented is based on testing fibre-reinforced traditional concrete, with recommendations to utilise the output from this research to modify and enhance the performance of CLC.

Ongoing, research on the utilisation of industrial waste in building, within the Environmental Engineering facility of the College of Agriculture, Engineering and Science, forms the platform from which this research progresses, providing novel building material with guidelines for innovative practical and effective test procedures for further research.

5.2 Affordable and sustainable building systems in South Africa

5.2.1 *Introduction*

To 'kick-off' this research with some baseline grounding, a deep rural Government funded housing project was reviewed on-site, representing the specific needs of a significant percentage of the South African low-cost housing scenario.

Following this review, a survey is conducted using an 'indicator-based sustainability assessment tool' adapted for local conditions.

5.2.2 *Case study RDP (BNG) Low-cost housing 2016*

This case study provided a starting platform for this research. Reviewing this 'state of the art' re-design of the original poorly designed RDP house, combined with innovative contractor building methods, gave inspiration and confidence that, given good leadership and clear specifications, positive results are possible.

5.2.3 *Survey of alternative building systems*

At the onset of this research, a global survey was conducted concluding that our diverse world requires diverse solutions, dependent on a multitude of variables. Further research into alternative building systems in South Africa, to allow the assessment of measurable results, only Agrement certified building systems are assessed and to reduce the amount of data, the survey focussed specifically on the materials constituting the top-rated certified walling systems.

Two walling materials are rated above all others:

a) Cellular Lightweight Concrete (CLC)

The positive results for lightweight concrete are in line with expectations as one may hypothesise even without data that the following factors are favourable (1) reduction in cement usage and subsequent energy (2) improved integrity of poured concrete over blocks (3) Increased speed of construction (given the required facilities and design concepts for the integration of the concrete as the building structure) (4) improved thermal insulation. The survey results are in line with this.

CLC or other related building system has the potential to become the building system of choice for architects, environmentalists and the public.

Specifically, at this stage of this building material research, there is a requirement for the core building material to be tougher than traditional concrete, allowing the basic manufacture of load-bearing sections of buildings with minimal requirement for steel reinforcing and using the lowest amount of embodied and process energy. Hence the spotlight of this thesis is on the incorporation of fibrous materials to increase the toughness and the use of waste where possible and to use that waste to its best advantage and not just as an outlet.

b) Cement Stabilised Soil Blocks (CSSB)

Having read the previous section, another potential pathway is to modify an ancient method of building (compressed soil) i.e. back to the basics. If one is in an environment that, for whatever reason does not allow one the privilege OR right, to one's own home, then the building materials, given that labour is in surplus, are all around i.e., soil. Building houses from compressed soil has been normal practice for thousands of years and with the bonus of a little technology, the challenge can provide excellent robust results bearing a comfortable and homely environment. The challenge is awareness, and empowering people with the strength of mind to build their own homes or at least participate in their creation. Of course, the advantage of this type of structure, from a government and environmental perspective, is that there is almost zero carbon footprint.

Based on the survey, cement stabilised soil block system and cellular lightweight concrete provide the highest rating in terms of the sustainability criteria utilised by the study. Interestingly, these two systems both have positive aspects but in different ways, as discussed in section 4.2.4, lightweight concrete is new technology and ticks all the boxes for thermal insulation, reduced cement usage, and adaptability for high-speed casting (either on-site or prefabricated). However, for remote locations with difficult logistics, the cement-stabilised soil block method has environmental and cost advantages. For example, a higher level of manual construction may be beneficial in areas where job creation is a priority. Another aspect is the thermal insulation property; compressed soil block may not have the thermal insulation of lightweight concrete, but it does have a high 'thermal mass' which is beneficial for maintaining a comfortable indoor temperature, especially in regions with a high differential between day and night temperature. This also highlights another example, where the simple specification of minimum property performance may be detrimental to a material of a different type which has other beneficial aspects that outweigh the specified one.

As an interesting overview, it was indicated by one respondent that the South African building regulations and specifically the Agrément certification has created a barrier for materials and systems. Excessive emphasis is put on the strength and "so-called" waterproofness of a material (i.e., cement-based products) at the expense of sustainability, health, resource efficiency and a more holistic understanding of how buildings perform as a whole system.

This broad preliminary research provides a platform for further research into workable and meaningful sustainable building systems for low-cost housing while providing momentum for the drive towards more flexible building regulations. Potential routes for further research may include the selection and focus on a small group of favourable alternative building systems. Conducting an in-depth sustainability assessment or focusing on the potential benefits of a more holistic regulation and product certification system. A system which focuses on a clear performance-based approach and the declaration of the achieved performance, instead of just on the achievement of the minimum benchmark.

5.3 Application of industrial waste stream materials in concrete mixes: Research into four waste stream materials in concrete mixes

5.3.1 *Introduction to Conclusions the application of industrial waste stream materials in concrete mixes: Research into four waste stream materials in concrete mixes*

UKZN Civil Engineering and more recently the department of Environmental Engineering has been facilitating research into the use of waste material in concrete mixes. Materials have included: Fly ash, recycled rubber (rubber crumb), glass cullet, paper sludge from recycled paper, paper sludge from wood pulp, construction and demolition waste, fibre from recycled tyres and others. The UKZN Concrete laboratory has, in general, consistent materials and methods for concrete mix design, mixing and final performance testing, making this a good grounding for comparing the incorporation of different waste streams.

Each year, the final year BSc Civil Engineering students need to author a dissertation based upon experimental work, this became a useful starting point or basis for building up data on the effect of incorporating waste into concrete. Guidance, supervision, reviewing and critiquing their dissertations provided an excellent grounding for the final in-depth research of tyre fibre reinforced concrete concluding this thesis.

5.3.2 *Conclusions for the application of industrial waste stream materials in concrete mixes: Research into four waste stream materials in concrete mixes*

For an overall picture, of the concrete/waste material mix comparative performance Figure 44 ‘four waste streams in concrete - performance review’, should be reviewed.

5.3.2.1 C&D waste

Compressive, tensile and flexural strength all progressively increased with the percentage addition of waste.

The use of crushed recycled 35MPa (crushed concrete), in a 14Mpa design mix, may have some influence on the results. Future research should utilise recycled concrete that can be practically sourced in the construction and recycling environment.

5.3.2.2 Glass cullet from recycled bottles

The effect on compression strength was the most noticeable (a reduction of approximately 22%) and the effect on flexural is almost unnoticeable with the effect on tensile being approximately midway between the two. The reason for the dip in performance before returning to equivalency at 20% addition isn’t known, however, the mixing of two regular-sized and shaped particles (2mm and 5mm) together with the control standard of 13mm stone and river sand, may affect the efficient packing of the concrete matrix as fine particles are replaced.

5.3.2.3 Paper mill sludge

Considering the small addition level the increase in tensile and flexural strength is significant; furthermore, the concrete mix design involved replacing cement weight with dried paper mill sludge weight, equivalent to 5%, 10% and 15% weight of cement, making the increase significant. This data, therefore, confirms the literature review data predicting the strength emanating from the hindering of microcrack development.

An interesting point to note with this student’s work is the unusual practice of pulverising the dried paper mill sludge in a food blender to make it behave more like cement whereas one would anticipate that shorter cellulose fibres would have a negative crack-reinforcing effect, the small fibres may be more evenly dispersed and distributed in the concrete matrix making them more effective throughout the concrete body.

5.3.2.4 Tyre fibre

The physical results of this mix are very impressive in terms of increasing tensile and flexural strength. The fibre introduction resulted in a significant and consistent reduction in compression strength after each cure period but a converse increase in flexural strength and a substantial increase in tensile strength, it is therefore clear that the addition of polymer fibre significantly changed the concrete from a brittle to a material behaving in a less brittle and more 'tough' manner. The difficulty of separating or de-clumping the fibres only became apparent when trying to carry out the operation by hand; this being very difficult and time-consuming. However, impressive results are seen even with the poor dispersion and distribution of fibre in the concrete mix.

5.4 Focus on waste fibre from recycled tyres as a performance enhancer of concrete

5.4.1 *Introduction to the focus on waste fibre from recycled tyres as a performance enhancer of concrete*

The utilisation of waste fibre from end-of-life tyres to improve the crack resistance (or toughen) concrete is certainly novel and the output from this research has proved to be very innovative in the methods developed for the evaluation of the arrest of microcrack propagation i.e., creating characteristics of 'toughness'

5.4.2 *Conclusions for the focus on waste fibre from recycled tyres as a performance enhancer of concrete*

The utilisation of fibre from end-of-life or recycled tyres in concrete provides significant improvement in microcrack arrest with resultant improvement in the concrete 'toughness'. On a basic level Table 11. Review of performance change with tyre fibre addition (smith 2019) simple traditional concrete test methods. These test methods do not focus on 'toughness' but measure the yield or ultimate breaking strength of what is typically a relatively brittle material. However, even these basic tests clearly show an increase in toughness.
An interesting point to note is the increase in toughness with all additions of tyre fibre tested, whether cleaned or contaminated with rubber particles and larger pieces of woven cord.

To measure improvements in toughness, the field of 'fracture mechanics' is entered and a practical test method to monitor the degree of toughness is required.
Testing of stress vs deflection at an external facility, even with a primitive measuring method, provided excellent results seen in Figure 47.
This test method is relatively easy to set up based on existing concrete test facility equipment, providing a meaningful measurement of toughness.

5.5 Summary of conclusions and recommendations

Our diverse world.

The first conclusion drawn from this research is that the world is vast and diverse, its cultures, climates, natural resources, access to industry and technology, national monetary wealth, politics (with associated directives for sustainability and the utilisation of natural resources) and the list goes on.

For this reason, it is extremely unlikely that there will be a one-solution building system.

What we can do as Scientists and Engineers, is build up a 'toolbox' of environmentally friendly, sustainable building solutions which can be used or adapted depending on the specific requirements of the location and intended occupant.

5.5.1 *Survey of affordable and sustainable alternative building systems*

The survey undertaken, focusing on the South African affordable housing scenario and based upon existing certified, alternative building systems, provided two types of building system (Walling) that stood above all others.

- **Cellular Lightweight Concrete and**
- **Cement Stabilised Soil Blocks (CSSB)**

Strangely and perhaps fortuitously the two systems could not be further apart in terms of the raw materials used and the technology involved.

5.5.2 *Focus on waste fibre from recycled tyres as a performance enhancer of concrete*

Physical testing, assessment by eye, optical microscope and SEM images all conclude that the incorporation of tyre fibre in concrete inhibits microcrack propagation, hence increasing its toughness.

Additionally, there are potential positive 'spin-offs', with further research and development; the fibre-reinforced material could feed manufacturing systems such as Additive manufacturing (AM), or 3D printing where more crack-resistant (tougher) concrete is very beneficial. A reduction in the requirement for steel reinforcement for cast walling systems is another.

Cellular lightweight concrete (CLC) could be another application for automotive tyre fibre reinforced concrete, aptly, this was one of the two top-rated building system materials determined by the alternative building system survey and 'Indicator based sustainability assessment tool' proposed from Objective 3 of this research.

The emergence of room-temperature manufactured Geopolymer cement, which does not need the elevated temperature and high energy consumption needed for traditional Portland cement, would also further reduce the carbon footprint of this material building material.

Continuing the flow of this document, as with previous chapters, we conclude using the same structure as before but here we endeavour to merge the streams of data to emphasise and focus on the greater goal of 'optimal utilisation of material resources, in building a sustainable future for all' within each section we assess how the conclusions satisfy the objectives of this research and recommend further research as required.

5.5.3 *Recommendations for further research*

5.5.3.1 Tyre fibre cleaning and separation

Civil Engineering in conjunction with Mechanical Engineering

Positive results have been achieved by increasing the toughness of concrete with the incorporation of fibre from end-of-life-tyres. Greater performance improvement is anticipated if the fibre can be cleaned and 'de-clumped' A mechanised method for fibre separation is required.

5.5.3.2 As an extension to 5.5.3.1, optimisation of tyre fibre length

Concrete workability concerns with the incorporation of tyre fibre indicate that a shorter fibre length may be beneficial to reduce the clumping of fibres, whilst at the same time providing improved dispersion for a given weight of fibre.

5.5.3.3 Measurement of fracture toughness, to easily assess fibre-modified concrete

The assessment of the toughness of concrete is not a test normally associated with concrete technology. Concrete is typically considered and treated as a brittle material, and it is the compressive strength that is generally the driver for its functional applications. The poor toughness is compensated for by the incorporation of steel reinforcing.

The incorporation of fibre in concrete has several positive aspects, such as the improvement of fatigue resistance and crack propagation in unreinforced applications and potentially the replacement of steel reinforcing in applications with low toughness requirements toughness requirement. Other benefits include improved spalling resistance reduced costly long-term maintenance costs, reduced freeze-thaw cracking, and early-age shrinkage cracks (plastic shrinkage) (Hillerborg 1985). The recently developed ‘round determinate panel’ test has the potential to become an easy-to-use tool and, at the same time, a reliable procedure for the characterization of FRC, in terms of toughness and the post-cracking constitutive cohesive law. (Mitchell, Link et al. 2011). Details of such tests are analysed in a journal article (Martin, Seymour et al. 2010) and illustrated in Figure 4.

It is recommended that an investigation is conducted, to implement 3-point bending with displacement measurement or the round determinate panel at the UKZN concrete test laboratory, for the assessment of the toughness or fracture resistance of concrete.

5.5.3.4 Mix design for 3D printed concrete structures.

The determination of CLC mix design to optimise the process properties and ultimate performance for 3D printing of buildings. With a focus on sustainability and the use of waste materials. One output from this PhD research is the positive performance of dried paper mill sludge after chopping in a food blender. The pulverised paper sludge may provide useful thixotropic characteristics in addition to improved toughness.

5.5.3.5 Architectural design with 3D-printed concrete

3D-printed concrete has benefits and limitations when compared to normal brick laying or casting. These changes can create a change in thinking in the way we perceive our living space. For instance, the shape of the roof can be made to provide the specific form and strength required for each proposed design, covering part of the house with soil, or covering the roof with soil. Thus, providing thermal mass, and reducing the requirement for secondary insulation, heating and cooling.

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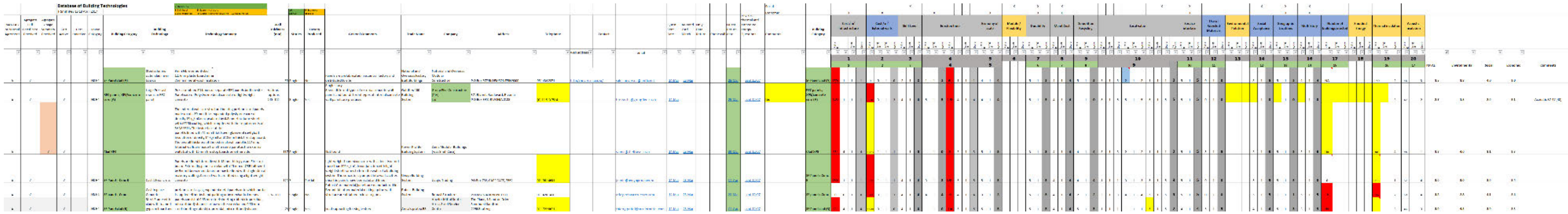
APPENDIX 1



Abbreviations:		Categories:	
XPS	Expanded Polystyrene	CSSB	Cement soil stabilisedblocks
LW	Light Weight	SF Panel clad	Steel Frame clad with Fibre panels / boards
Reinf	Reinforced	Cast Conc	Cast Concrete
Conc	Concrete	SF SC	Steel frame with sprayed concrete
SIP	Structural Insulated Panels	SF Clad XPS	Steel frame with clad expanded polystyrene
LSF	Lightweight Steel Frame	PUF + Board	PU foam encapsulated by solid board or coating
RTA	Ready to assemble	Hollow PVC	Hollow Polyvinylchloride
CSSB	Cement Soil Stabilised Block	CLC	Cellular lightweight concrete
ABT	Alternative Building Techgnology	Clad XPS	Expanded polystyrene with cladding
FC	Fibre cement	RFC Panel	Reinforced concrete panels
PB	Plasterboard	Hollow XPS + Conc	Hollow Expanded polystyrene blocks with concrete infill
RFCP	Reinforced concrete panels	Hollow conc+ conc	Hollow concrete with stabilising steel bar + conc infill each <1.5m
GFRC	Glass filled reinforced concrete	XPS + Plaster	Expanded polystyrene plastered
TF	Timber frame	Compressed soil	Compressed soil in frame
H3	domestic residence (flat and row houses)	SF Catenary arch	Steel frame catenary arch inner, external corregated steel, glass fibre insulation
H4	dwelling house (and related outbuildings)	Timber panels	Factory produced timber panels
SCCP are	Southern coastal problem area	Conc/XPS Blocks	Concrete blocks with Expanded polystyrene
PU	Polyurethane	CLC + FC board	Cellular lightweight concrete with fibre cement board
GRP	Glass reinforced plastic (polyester)	Cast Conc/XPS inserts	Cast conc encapsulating XPS blocks - forming concrete vert and horz beams
PUF	Polyurethane Foam	SF inside RFC Panel	Steel frame structure enacapsulated in light weight concrete (RFC panels)
GRC	Glass reinforced concrete	RFC/ XPS bead panels	reinforced, precast, polystyrene bead concrete panels,

NOTES:

Mantag certificates are a distinct type of Agrément certificate based on acceptable health and safety criteria for single storey houses and related out-buildings where the local authority is of the opinion that the type of construction is appropriate, given that in these areas it is of paramount importance that buildings be erected at the lowest possible cost.

MANTAG criteria permit a lesser level of performance than would be expected from buildings erected in accordance with the deemed-to-satisfy rules contained in SABS 0400-1990, The application of the National Building Regulations.

NOTES:

Thermal Insulation:
Agrément South Africa's opinion is based on the calculated likely maximum indoor air temperature in summer in a 53 m2 dwelling in Cape Town, Durban and Johannesburg, and the calculated energy required to maintain an indoor temperature of 16ºC in winter in Cape Town and Johannesburg
When assessing the thermal performance of a dwelling, the calculated performance of the subject is compared with that of the standard brick house. This is of similar size, orientation and fenestration. (Agrement 2010-372)

Alternative Building System - survey and assessment

Building system categories and Abbreviations used for the survey

APPENDIX 2

Case Study 2 Compressed Soil Blocks

Date	25 August 2015
Name	Rambrick
Source	http://www.useit.co.za/projects/rambrick Site visit to USE-IT Rambrick facility in Pinetown
General Overview	Compressed soil block containing optional inert builder's waste
Company	USE-IT
Link	http://www.useit.co.za/projects/rambrick
Video / Pictures	Case study pictures taken
Building category	Compressed soil block
Building process / Technology summary	*Raw material mix*: Locally available soil* 70%, cement stabilising agent 5% and inert builders waste 25% *Process*: Soil, waste and cement are automatically mixed in the required ratio using a blending machine. The mix is transferred to a hydraulic brick compressing machine which runs automatically producing 350 blocks per hour. **10 to 50% soil clay content required*
Mass production/ economy of scale	Traditional brick laying rate is limited by the number of machines and brick laying labour.
Building time	The blocks are quicker to lay than concrete blocks but are half the thickness and require twice as many rows.
Building height	Single story approved with two story potential
Raw materials	Soil with 10 to 50% clay content
Compressive strength	≥10.5MPa
Insulation 'U' value	
Recyclability	Yes, can be broken up and combined with soil for new bricks
Interface to services	Similar to standard concrete block
Social acceptance	Good – Similar to standard concrete block
CO_2 / m^2	350kg (Cement block = 750, Clay brick 1300)
Building skills / training required	Very minimal – The process is simple not requiring mortar
Local value Creation	
Projects	As at Aug 2016: The Crane Foundation chick rearing facility, an orphanage in Shongweni for New Horizons Trust, a recycling centre in Howick for Wildlands Conservation Trust, demonstration houses in Pietermaritzburg and Durban, and site offices and workshops. Will also be used in the R30 million waste beneficiation centre planned for Hammersdale
General Comments	Manufacturing machines are provided by Advanced Earthen Construction Technologies (Blocks are joined using a 20:80 cement/ soil slurry poured with a small jug. The small amount of slurry acts as an adhesive and bonds the bricks together. Overall building cost claimed to be 16-20% lower than conventional concrete blocks. Soil removed from building sites normally sent to landfill at high cost can be utilised to make bricks on site. Claimed CO_2 / m^2: Clay brick = 13 000, Concrete block = 750, Rambrick = 350 Concerns with adoption of the process: • The blocks are quicker to lay than concrete blocks but are half the thickness and require twice as many rows. • The bricks are heavy 7" = 11.5kg, 8" = 15kg and 10" = 18kg • Some contractors pay staff per block laid, causing difficulties when twice as many bricks are required. • Existing building specifications often include specific requirements that only allow concrete blocks

Site Visit to Rambrick Pinetown facility 23 Aug 2016

Hydraulic brick maker

Mixer / Blender

Compression moulded soil blocks

Building demonstration – compressed soil blocks laid together using cement/soil slurry

Compressed Block House

APPENDIX 3

Recycled materials in buildings – Global Review

Initial global survey August 2017

Part of initial global review of Recycled materials used in building, leading to the research work into car tyre fibre in concrete

	Useage category	Material source	Material type	Approximate cost (R/m³)	Conversion /Production Process	Commercial examples	Application	% Usage	Comment
A = Additive	GC = Green Concrete PW = Plastic waste O = Other	PrC = Pre consumer PoC = Post consumer CDW =							
R M	PW	General Plastic waste			Compressed and bound bale	Ubuntublox	Building walling	100	
A	GC	PrC or PoC	XPS		broken in a hammer mill, coated	Greenlite concrete	concrete with recycled XPS	TBC	
A	GC	Paper sludge	Paper pulp ash		Industrial waste		Partial cement replacement	TBC	Ref 136
A	GC	CDW	Concrete, bricks, stone			Cape Brick	Partial concrete agrement	TBC	
R	O	CDW	Wood		RE-Use		Cladding and	TBC	
	PW	PrC	**PET**						
	PW	PrC	**HDPE**						
	PW	PrC	**UPVC**						
	PW	PrC	**PVC (flexible)**						
	PW	PrC	**LDPE**						
	PW	PrC	**PP**						
	PW	PrC	**PS**						
	PW	PoC	PET		Bottle filled with water and bleach		Roof bottle lights	100	Works with open roof without ceiling
	PW	PoC	PET		Bottles filled with		Walls	100	
A	PW	PoC	PET				Add in concrete		
R M	PW	PoC	PET		Extrusion of fibre		Roof insulation		Polyester fibre matting
R M	PW	PoC	HDPE				Roof tile holding plants		Water proofing required below tile
	PW	PoC	PA		Car tyre	Life Refibre Life (EU)	Asphalt		
A	PW	PoC	PA		Car tyre recycling		Tough concrete	2 - 5%	Several reports - not commercialised
			Rubber		Car tyre	Life Refibre Life (EU)	Flooring (Sports)		
		PoC	Ceramic, glass			Life Ecotiles (EU)	Ceramic tiles		CDW ceramics, domestic bottles
			Rubber		Car tyre	Life Neriede (EU)	Asphalt - low		Mixed with bitumen
A	GC	PoC	Demolition waste and cement		3D printing		3D printed structural wall panels		In a first, a Chinese company has advanced the science of 3D printing by printing 10 houses entirely out of recycled materials, in just under a day.
A	GC	IW	Fly Ash				Concrete		
A	GC	IW	Slag from blast furnace				Concrete		GGBFS (Ground Granulated Blast Furnace Slag)
A	GC	IW	Chromite and 'red mud'				Concrete		
		IW	Fumed silica				Concrete		
		IW	Rice husk ash				Concrete		
		IW	Wood ash				Concrete		
			Sugar cane bagasse fibre				Concrete		SCBF

APPENDIX 4:

Data validity (Reported on 16 April 2018)

Review of test work completed at UKZN Environmental Engineering Section by final year 2016/2017 BSc students, on the use of four waste streams included into concrete mixes.

Waste streams evaluated:

- Construction and demolition waste
- Glass cullet from recycled bottles
- Paper processing sludge
- Tyre Fibre from recycled tyres

Objective

To evaluate the test work performed by BSc final year students and conduct a 'gap analysis' to determine if the data is usable for the publication of a conference papers and Journal articles.

Key findings of data validity analysis:

❖ Construction and demolition waste

The data and test work are considered to be acceptable for use.

The absence of saturated density testing is not considered to influence this study.

Recommendation: No further test work required to utilise the data on a comparative basis

❖ Glass Cullet

Further work is required relating to the mix design and glass cullet particle size and particle size distribution.

Extended literature review on the effect of ASR (alkali–silica reaction) is required as it has been demonstrated that ASR can be reduced when appropriate glass aggregates dimension are used, and when particular mineral admixture are used in the mix.

Although considerable further work is recommended, the test work provides reliable data for reporting the work done.

Recommendation: No further test work required to utilise the data on a comparative basis

- ❖ Paper processing sludge

The data and test work is considered to be acceptable for use.

Some test errors are noted in the measurement of saturated density, however, as with the C&D waste study, saturated density measurement is not considered essential to this exercise.

Recommendation: No further test work is required to utilise the data on a comparative basis

- ❖ Recycled tyre fibre

Samples strength was tested at 21 days only and not 28 days as intended, due to the limited timeframe, therefore, the final strength values are not consistent with the other waste stream testing. Furthermore, average test values were recorded (The author states that three test samples were used per test) however, only the mean value was recorded for each sample category and individual test results were not retained.

Recommendation: The data, although showing positive and interesting results is not considered reliable. However, the data can be utilised as part of a proposal for repeated and extended test work

Evaluation of Data validity

Relative review of concrete mix design

Relative review of test methodology

Review of data source sampling and RSD = Relative standard deviation (coefficient of variation)

Waste Stream	Sufficient Data	Data Validity	Saturated Density	Compressive Tensile and Flexural Tests	Comments
Glass	√	√	√	√	Further work is required relating to the mix design and glass cullet particle size and particle size distribution. However the test work does provide relable data for reporting.
Tyre Fibre Sachrin (contaminated)	X	X	X	√	a) Strength tested at 21 days only (not 28 days) b) Average test values were recorded (Author states that three test samples were used per test but individual test results were not retained)
C&D	√	√	X	√	The absence of saturated density testing is not considered to influence this study
Paper Sludge (Raw)	√	√	√	√	
Paper Sludge (Dried)	√	√	√	√	Dry paper sludge provided better performance than wet paper sludge. 5% (by wt cement) of dry sludge provided an improvement in Compressive, flexural and tensile strength. 10% (by wt cement) of dry sludge provided an improvement in flexural strength but a reductionj in compressive and tensile strength.

APPENDIX 5:

Uniform concrete mix design / processing for experimental study

This section provides details of the concrete mix design, casting, respective procedures used, curing and tests carried out to achieve experimental test results.

Determining Material Properties

To create a suitable mix design, certain material properties need to be predetermined. This includes the fineness modulus (FM), relative density of the stone and cement, and other empirical values.

Properties of Fine and Coarse Aggregate

The aggregates used were from the UKZN Civil Engineering laboratory, consisting of a fine aggregate of Umgeni River Sand and a coarse aggregate of 13mm or 19mm quartzite stone.

Fineness Modulus (FM)

In order to calculate the required volume of sand in the concrete mix, the FM needed to be determined. A test is carried out in accordance with TMH1 Method B4:

Compacted Bulk Density

The test procedure used to determine the CBD for stone is described in SANS 5845.

Relative Density (RD)

In order to calculate the volume of certain elements, the RD needs to be known. It is usually between 2.90 and 2.95. Two different methods are used to acquire the RD, one for particles greater than 4.75mm (coarse aggregate) and one for particles smaller than 4.75mm (fine aggregate), as per TMH1 (B14 and B15).

Properties of Cement Used

Natal Portland Cement (NPC) black, 42.5MPa was used in all of the mix designs. The relative density of which was provided by the supplier, which was 3.1.

Water

Potable, tap water is used in the mix design. This ensures that no harmful contaminants, such as chlorides, sulphates and oils will affect the concrete produced. Contaminants can cause voids in the concrete, affect the setting time and strength as well. The density was assumed to be 1000kg/m$_3$.

Concrete Mix Design

The mix design used to calculate the quantity of sand, stone, cement and water was done in accordance with Construction Materials for Civil Engineering (Van Amsterdam 2000), as well as UKZN recommended laboratory procedures.

The mix design process used for the experimental mixes is as follows:

Step 1: Choose target strength and select W:C ratio.

Step 2: Calculate the water requirement based on the nominal size of stone used and slump.

Step 3: Modify the water requirement for a required slump.

Step 4: Calculate the cement content.

Step 5: Calculate the stone and cement content required for the mix.

Step 6: Substitute a percentage of one of the Agrement ingredients with the proposed waste material (Glass, cullet, C&D waste, tyre fibre or paper mill sludge.

APPENDIX 6:

Test Sample Mixing and testing schedule

	Thu	Thu	Thu	Thu	Thu	Fri	Thu	Thu	Wed	Mon			
Date	14.2.19	21.2.19	28.2.19	7.3.19	14.3.19	21.3.19	28.3.19	04.4.19	17.04.19	**[15.05.19]**	**17.05.19**	TBC	TBC
Actual date						(25.03.19) Mon		(12.04.19) Fri					
Mix & Cast	**Control**	**2% fibre**	**5% fibre**	**Control (repeat beam)**	**x**	**x**	**x**	x	**2% fibre (repeat beam)**	x		x	x
Test		**7 day Control**	**7 day 2% fibre**	**7 day 5% fibre**	**28 day Control**	**28 day 2% fibre**	**28 day 5% fibre**	**28 day Control REPEAT**		**28 day 2% fibre REPEAT**	**28 day 2% fibre Flexural Strain**		
Compressive	-	3	3	3	3	3	3	-	-	-			
Tensile	-	1	1	1	3	3	3	-	-	-			
Flexural	-	1	1	1	3	-	-	-	-	-	3		
Flexural + video	-	-	-	-	**X**	3[*2]	3	3[*3]	-	**3**			
Crack test (Flex)		-	-	-	**1*[1]**	**1**			-	-			
Crack test Corrected	-	-	-	-	**X**	**X**	1	1	-	1			
Flexural Strain											3		
SEM													**45**
Optical Microscopy												**9**	

APPENDIX 7:

Mix design - Frazer Smith Experimental

Frazer Smith, Student Number: 216076117 PhD Research

Analysis of the effect of re-claimed tyre fibre in concrete

08-Feb-19

4 Beam mix

Test sample dimensions (m)		(m^3)	
Cube	0.15 x 0.15 x 0.15	0.00337	
Cylinder	0.15 Dia x 0.3 long	0.0053	
Beam	0.1 x 0.1 x 0.5	0.005	0.02

	Preliminary testing			**Current Test**											
	Control			**Control**						**2% Tyre fibre**			**5% Tyre fibre**		
	m^3	kg	%wt total	m^3	New **beam** m^3	kg	New **beam** kg	New beam adjusted for minimum mix size	%wt total	m^3	kg	% total	m^3	kg	% total
Water	0.0137	**13.73**	9.60	0.0180		**20.00**	**5.00**	**8.50**	10.67	0.0180	**20.00**	10.55	0.0180	**20.00**	10.55
stone	0.0177	**47.66**	33.33	0.0231		**62.49**	**15.62**	**26.00**	33.33	0.0231	**62.49**	32.98	0.0231	**62.49**	32.98
Cement	0.0114	**34.31**	23.99	0.0150		**44.98**	**11.25**	**18.75**	23.99	0.0150	**44.98**	23.74	0.0150	**44.98**	23.74
Sand	0.0182	**47.30**	33.08	0.0239		**62.01**	**15.50**	**26.00**	33.08	0.0234	**60.77**	32.07	0.0227	**58.91**	31.09
Tyre fibre	-	-	-	-		**-**			-		**1.24**	0.65		**3.10**	1.64
Total	**0.0610**	**143.00**	100.00	0.08	0.02	**187.48**	**46.87**	**79.25**	101.07		**189.48**	100.00		**189.48**	
Control Density	2.34			C/W ratio	0.44			0.44							

14-Feb-19

Control mix was very dry and not workable, Moses recommended adding 2 litre of water to mix, increasing to 20 litre. This gave a workable mix

21-Feb-19

Attempts were made to separate the fibre from the contamination but 2 people working for 2 hours only produced 30g of fibre, therefore uncleaned fibre was used.
Fibre mixed with sand only started to clump into agglomerated, adding stone and half water (10litre) broke apart the fibre mix.
Dispersion and distribution of fibre appeared to be good.

28-Feb-19

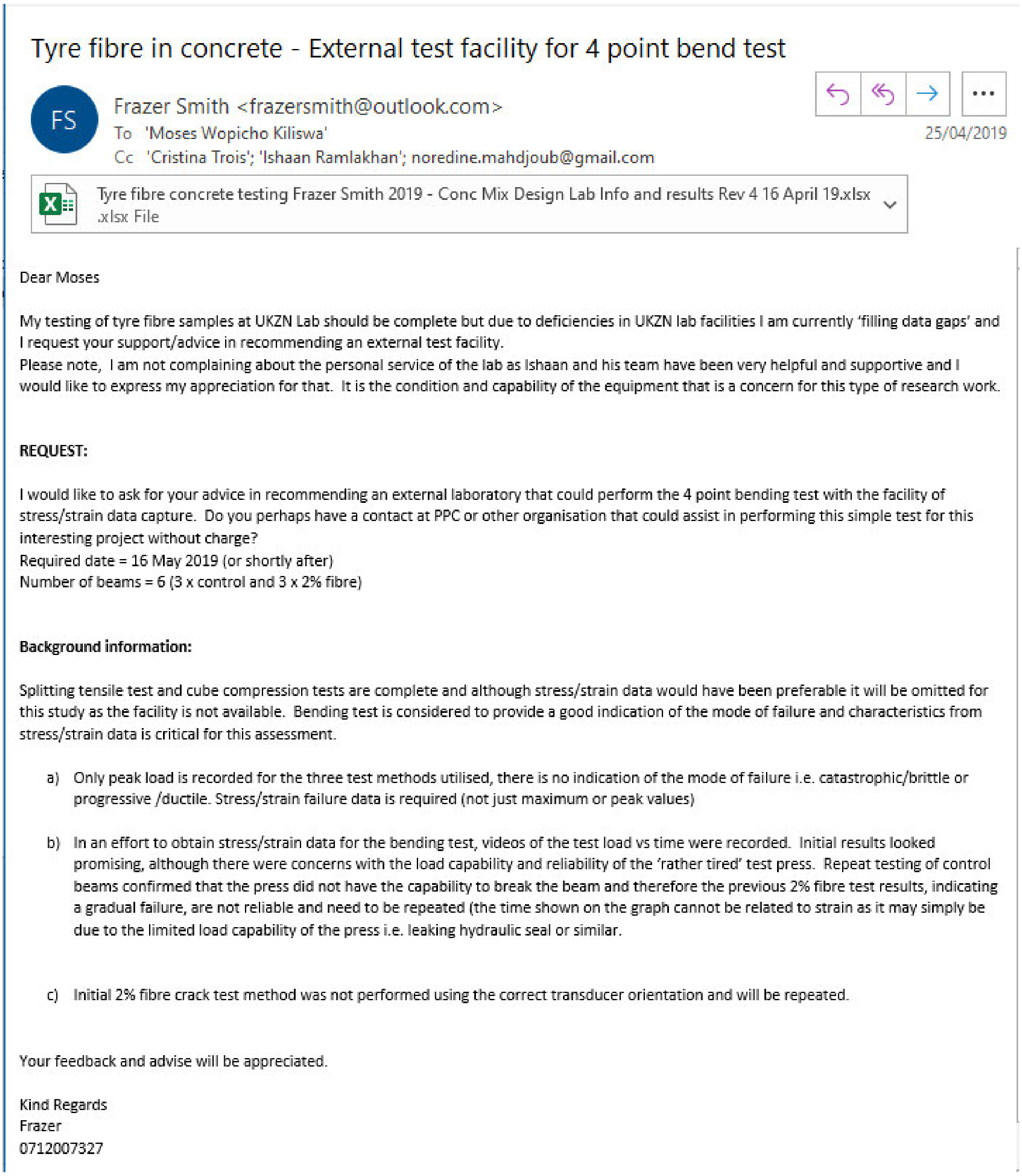
The mix was very stiff, like jelly.
Initial settling of mix in the moulds was very high but stopped at a point due to air entrapment …see below
One compression mould came undone on the vibrating table and the thin layer of mix was continuously bubbling over a long period (as the vibrator switch got stuck in the 'on' position.

17-Apr-19

New beams made to repeat the crack test which was performed incorrectly and the flexural strength to provide stress / strain graph.

APPENDIX 8:

Request for external test facility



Tyre fibre in concrete - External test facility for 4 point bend test

FS

Frazer Smith <frazersmith@outlook.com>

To 'Moses Wopicho Kiliswa'

Cc 'Cristina Trois'; 'Ishaan Ramlakhan'; noredine.mahdjoub@gmail.com

25/04/2019

Tyre fibre concrete testing Frazer Smith 2019 - Conc Mix Design Lab Info and results Rev 4 16 April 19.xlsx
.xlsx File

Dear Moses

My testing of tyre fibre samples at UKZN Lab should be complete but due to deficiencies in UKZN lab facilities I am currently 'filling data gaps' and I request your support/advice in recommending an external test facility.
Please note, I am not complaining about the personal service of the lab as Ishaan and his team have been very helpful and supportive and I would like to express my appreciation for that. It is the condition and capability of the equipment that is a concern for this type of research work.

REQUEST:

I would like to ask for your advice in recommending an external laboratory that could perform the 4 point bending test with the facility of stress/strain data capture. Do you perhaps have a contact at PPC or other organisation that could assist in performing this simple test for this interesting project without charge?
Required date = 16 May 2019 (or shortly after)
Number of beams = 6 (3 x control and 3 x 2% fibre)

Background information:

Splitting tensile test and cube compression tests are complete and although stress/strain data would have been preferable it will be omitted for this study as the facility is not available. Bending test is considered to provide a good indication of the mode of failure and characteristics from stress/strain data is critical for this assessment.

a) Only peak load is recorded for the three test methods utilised, there is no indication of the mode of failure i.e. catastrophic/brittle or progressive /ductile. Stress/strain failure data is required (not just maximum or peak values)

b) In an effort to obtain stress/strain data for the bending test, videos of the test load vs time were recorded. Initial results looked promising, although there were concerns with the load capability and reliability of the 'rather tired' test press. Repeat testing of control beams confirmed that the press did not have the capability to break the beam and therefore the previous 2% fibre test results, indicating a gradual failure, are not reliable and need to be repeated (the time shown on the graph cannot be related to strain as it may simply be due to the limited load capability of the press i.e. leaking hydraulic seal or similar.

c) Initial 2% fibre crack test method was not performed using the correct transducer orientation and will be repeated.

Your feedback and advise will be appreciated.

Kind Regards
Frazer
0712007327

APPENDIX 9:

Four Waste streams in concrete – Percentage additions and test validity summary

Waste Stream	Relative waste percentages (weight) based on mix design - shaded values = design mix												Sufficient Data	Data Validity	Saturated Density	Compressive Tensile and Flexural Tests	Comments
	Waste Addition % of sand			Waste Addition % of stone			Waste Addition % of cement			Waste Addition % of Total							
	A	B	C	A	B	C	A	B	C	A	B	C					
Glass	10	25	50	11	28	56	24	61	122	3.9	10	20	√	√	√	√	Further work is required relating to the mix design and glass cullet particle size and particle size distribution. However the test work does provide relable data for reporting.
Tyre Fibre	5.0			5.0	-	-	6.9	-	-	2.0	-	-	X	X	X	√	a) Strength tested at 21 days only (not 28 days) b) Average test values were recorded (Author states that three test samples were used per test but individual test results were not retained)
C&D	14	28	56	10	20	40	45	90	180	4.7	9	19	√	√	X	√	The absence of saturated density testing is not considered to influence this study
Paper Sludge (Raw)	2.0	4.0	6.0	1.5	3.0	4.6	5.0	10	15	0.8	1.6	2.3	√	√	√	√	Dry paper sludge provided better performance than wet paper sludge.
Paper Sludge (Dried)	2.0	4.0	6.0	1.5	3.0	4.6	5.0	10	15	0.8	1.6	2.3	√	√	√	√	5% (by wt cement) of dry sludge provided an improvement in Compressive, flexural and tensile strength. 10% (by wt cement) of dry sludge provided an improvement in flexural strength but a reductionj in compressive and tensile strength.

APPENDIX 10:

PhD Experimental Data – Mix Design

Frazer Smith, Student Number: 216076117 PhD Research

Analysis of the effect of re-claimed tyre fibre in concrete

08-Feb-19

4 Beam mix

Test sample dimensions (m)		(m^3)
Cube	0.15 x 0.15 x 0.15	0.00337
Cylinder	0.15 Dia x 0.3 long	0.0053
Beam	0.1 x 0.1 x 0.5	0.005

0.02

	Preliminary testing			Current Test											
	Control			Control						2% Tyre fibre			5% Tyre fibre		
	m^3	kg	%wt total	m^3	New beam m^3	kg	New beam kg	New beam adjusted for minimum mix size	%wt total	m^3	kg	% total	m^3	kg	% total
Water	0.0137	**13.73**	9.60	0.0180		**20.00**	**5.00**	**8.50**	10.67	0.0180	**20.00**	10.55	0.0180	**20.00**	10.55
stone	0.0177	**47.66**	33.33	0.0231		**62.49**	**15.62**	**26.00**	33.33	0.0231	**62.49**	32.98	0.0231	**62.49**	32.98
Cement	0.0114	**34.31**	23.99	0.0150		**44.98**	**11.25**	**18.75**	23.99	0.0150	**44.98**	23.74	0.0150	**44.98**	23.74
Sand	0.0182	**47.30**	33.08	0.0239		**62.01**	**15.50**	**26.00**	33.08	0.0234	**60.77**	32.07	0.0227	**58.91**	31.09
Tyre fibre	-	-	-	-		-			-		**1.24**	0.65		**3.10**	1.64
Total	**0.0610**	**143.00**	100.00	0.08	0.02	**187.48**	**46.87**	**79.25**	101.07		**189.48**	100.00		**189.48**	
Control Density	2.34			C/W ratio	0.44			0.44							

14-Feb-19 Control

Control mix was very dry and not workable, Moses recommended adding 2 litre of water to mix, increasing to 20 litre. This gave a workable mix

21-Feb-19 2% fibre

Attempts were made to separate the fibre from the contamination but 2 people working for 2 hours only produced 30g of fibre, therefore uncleaned fibre was used.

Fibre mixed with san only started to clump into agglomorated, adding stone and half water (10litre) broke apart the fibre mix.

Dispersion and distribution of fibre apperaed to be good.

28-Feb-19 5% fibre

The mix was very stiff, like jelly.

Initial settling of mix in the moulds was very high but stopped at a point due to air entrapment …see below

One compression mould came undone on the vibrating table and the thin laer of mix was continuosly bubbling over a long period (as the vibrator switch got stuck in the 'on' position.

17-Apr-19

New beams made to repeat the crack test which was performed incorrectly and the flexural strength to provide stress / strain graph

APPENDIX 11:

PhD Experimental Data – Test Schedule

	Thu	Thu	Thu	Thu	Thu	Fri	Thu	Thu		
Date	14.2.19	21.2.19	28.2.19	7.3.19	14.3.19	21.3.19	28.3.19	04.4.19	TBC	TBC
Actual date						(25.03.19) Mon		(12.04.19) Fri		
Mix & Cast	Control	2% fibre	5% fibre	Control (Repeat Beam)	x	x	x	x	2% fibre	x
Test		7 day Control	7 day 2% fibre	7 day 5% fibre	28 day Control	28 day 2% fibre	28 day 5% fibre	28 day Control REPEAT	-	28 day 2% fibre REPEAT
Compressive	-	3	3	3	3	3	3	-	-	-
Tensile	-	1	1	1	3	3	3	-	-	-
Flexural	-	1	1	1	3	-	-	-	-	-
Flexural + video	-	-	-	-	X	3	3	3	-	-
Crack test (Flex)		-	-	-	1	1			-	-
Crack test Corrected	-	-	-	-	X	X	1	1	-	1

APPENDIX 12:

PhD Experimental Data – Test Result Summary

Frazer Smith, Student Number: 216076117 PhD Research

Tyre fibre in Concrete - Physical Testing Feb / March 2019

Sample		Area	(kN) Force 7 Day	(kN) Force 28 Day	(MPa) Stength 7 Day	Ave 7 day	(MPa) Strength 28 Day	Ave 28 day
			Control Mix					
Compressive	A	0.0225	574.5	764.2	25.5		34.0	
(Force/Area)	B	0.0225	541.6	842.5	24.1		37.4	
	C	0.0225	578.5	903.8	25.7	**25.1**	40.2	**37.2**
Tensile	A		237.2	240.1	3.4	**3.4**	3.4	
(2P/π lD)	B			241			3.4	
P = N, l = length(mm)	C			290.9		**3.4**	4.1	**3.6**
Flexural (SANS 5864:2006)	A		12.7	17.3	3.81	**3.8**	5.19	
(PL/bD²)	B			17.5			5.25	
L = distance between rollers	C			16.8		**3.8**	5.04	**5.2**
Slump = 127mm								
			2% Fibre Mix					
Compressive	A		596.5	812.8	26.5		36.1	
	B		586.3	827.1	26.1		36.8	
	C		549	709	24.4	**25.7**	31.5	**34.8**
Tensile	A		235	285.5	3.3	3.3	4.0	
	B			267.8			3.8	
	C			256.1		**3.3**	3.6	**3.8**
Flexural	A		12.5	18.3	3.66	3.7	5.49	
	B			16.9			5.07	
	C			16.8		**3.7**	5.04	**5.2**
Slump = mm								
			5% Fibre Mix					
Compressive	A		514.2	669.6	22.9		29.8	
	B		514.4	710.9	22.9		31.6	
	C		501.2	755.4	22.3	**22.7**	33.6	**31.6**
Tensile	A		219	286.7	3.1	3.1	4.1	
	B			254			3.6	
	C			195		**3.1**	2.8	**3.5**
Flexural	A		12.2	14.5	3.66	3.7	4.35	
	B			16			4.80	
	C			15.7		**3.7**	4.71	**4.6**
Slump = 27mm								

APPENDIX 13:

Survey questionnaire : Agrement Building Systems

Frazer Smith (PhD) Researcher
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14 March 2017

Survey Questionnaire: Agrément Building System

Dear Sir or Madam

As part of my PhD research I am assessing the sustainability of alternative building systems in South Africa with a focus on the Agrément certified walling and building systems. CSIR (Agrément South Africa) provided me with Agrément certificate summaries, however, I find that I have gaps in the required data. I would greatly appreciate your support in providing information on your Agrément certified building system, using the attached questionnaire. Please be aware that Information provided will be treated and maintained as confidential and based upon the building system category. No reference to product brand or trade names will be disclosed.

The questions are generally multi-choice and typically have qualitative selections. In some cases, space has been provided for additional supportive or descriptive information. If information is not known or is not available, please tick 'N/A'.

The PDF questionnaire can be completed electronically and saved (For ease of reference please save the document using your agreement certificate number as the file name). Alternatively, the form can be printed, completed by hand and scanned; in either case please return to me at frazersmith@outlook.com

Any additional supportive information on the building system would be gratefully accepted.

Thank you in advance for your feedback

Kind Regards

Frazer Smith
MSc Advanced Materials (UK), PhD Researcher (Civil Engineering)

............Please turn over this page for the first question of the three-page questionnaire

Please return the completed form by 24 March 2017

Frazer Smith (PhD) Researcher
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Survey Questionnaire

Review of Agrément Walling and Building Systems

Agrément Certificate No ____________

You are kindly requested to provide information on your Agrément certified building system for a research study into 'Sustainable Materials for Low Cost Housing for the African City of the Future'. Information provided will be maintained as confidential.

Questions:

1. **Total Cost / m² for 40m² house based upon the National minimum standard 01 April 2014**

<R110 000 ☐
<R125 000 ☐
<R150 000 ☐
<R175 000 ☐
>R175 000 ☐

2. **Cost / m² External walls surface area based on 40m² house**

R/m² ___________

3. **Skill level required for construction workers**

Unskilled labour with no training ☐
Unskilled labour with short training (<2 weeks) ☐
Unskilled labour with intensive training (several weeks) ☐
Skilled workers ☐
Advanced skills or tools required ☐

.

4. Total time for erection of one 40m² house (assuming a 200 house project)

_______________Days

5. Economy of scale.

What effect will the number of houses being constructed have of the construction costs?

Immense price reduction ☐
Significant price reduction (or only viable for high production) ☐
Moderate price reduction ☐
Minor price reduction ☐
No significant price reduction ☐

6. Durability

>40 years ☐
>30 years ☐
>20 years ☐
>10 years ☐
<10 years ☐

7. Maintenance Requirements (costs and resources for corrective and preventative maintenance)

Seldom required ☐
Some maintenance required – low skill / low cost ☐
Moderate maintenance – medium skill / cost level ☐
Very frequent maintenance required ☐
Maintenance involving high cost required ☐

8. Material availability: Are materials available

In each local region ☐
Nationally ☐
Imported ☐

9. Interface to services (drinking water, drainage, electricity, ventilation)

- Fully integrated within the construction process ☐
- Some degree of integration in the construction process ☐
- Additional process required such as wall chasing ☐
- Large effort required for integration ☐
- Surface mounting of services required ☐

10. Are any recycled materials utilised in the building system?

- Yes ☐
- No ☐

If yes, please provide information

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11. How many buildings have been erected and where? Please provide comments.

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12. Thermal insulation of exterior wall panel

If tested please provide the measured R-value (m^2K/W) or U-value (W/m^2K) of the exterior wall.

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