DEVELOPMENT OF ‘GREEN’ RIGID PAVEMENTS INCORPORATING RECYCLABLE RUBBER AND PAPER MILL PRODUCTS

by

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ACKNOWLEDGEMENTS

"Almighty God Thank You …
...For Everything!!!"

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- Printing and binding services: Ingcweti ACE Technology

Lastly, many thanks to my family, friends and colleagues in industry for their continuous encouragement and unfailing support.

THANK YOU.

Senzo Brian Nhlabatsi

To Nester

For her love, her patience, and her faith.

“If we knew what it was we were doing,

it would not be called research, would it?”

-Professor Albert Einstein

ABSTRACT

Natural aggregate resources used as conventional fillers in concrete production are constantly diminishing. Several studies have suggested that there will be a lot of pollution in the degradation of waste rubber products. This research explores the potential use of waste tyre rubber crumbs in a concrete mixture for rigid (concrete) roads. The research also focuses on the possibility of using paper mill ash, a by-product of the paper mill industry, as a new innovative binder in a concrete mixture with rubber aggregate. Specifically, concrete mixtures with river sand partially replaced by crumbed rubber and Portland cement partially replaced by paper mill ash were produced for a new concrete. The objective was to optimise proportion and size of tyre rubber and paper ash particles to improve material performance. The sustainable mixes incorporated a constant 5% cement substitution with paper mill ash and river sand substitution with crumb rubber proportions of 5%, 10% and 15% by mass of sand. A class 40/19 control mixture comprised of crumb rubber particles of sizes ranging from 1mm-5 mm considered for a mix with 0.49 water/cement ratio was designed as per the C&CI design method developed by the Concrete Institute, South Africa. Laboratory tests were conducted, and the effects of the paper mill ash and crumb rubber inclusions were ascertained by comparing the results for mixtures containing the two waste stream materials to a control mixture only with the conventional materials (river sand, stone and Portland cement).

The concrete was tested for fresh and hardened properties including density, compressive strength, splitting strength and flexural strength. Hardened concrete samples were then extracted to carry out a durability analysis by performing a chloride conductivity, water sorptivity and oxygen permeability test. This research has uncovered that replacing conventional aggregate with waste paper mill ash and rubber lead to, on average, improvements in the durability of concrete, and a degradation of the mechanical strength. The loss of mechanical strength can be attributed to the sense that the resulting lower density and nature of waste tyre rubber weakens the interfacial bonding and thus resulting in a heterogeneous particle distribution within the concrete. However, the research reveals that the use of recycled rubber and paper mill ash-modified concrete in road pavements is feasible when low proportions of paper mill ash and crumb rubber are added. The marginal loss of strength with the offsetting improvements in durability implies that there exist an optimum combination of proportion and size of the rubber crumbs and paper mill ash that will improve the material performance under cyclical vehicle loads.

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CHAPTER 1

INTRODUCTION

1.1 Background and Problem

In the past decade, there have been stronger interest on the availability of natural resources and in how rapidly the world's growing population is depleting these reserves. Thus 'green' concrete is one very important aspect that needs to be incorporated in the field of structural engineering. Tiwari (2015) defines green concrete as the kind of concrete which is much similar to traditional concrete, however, producing this kind of concrete requires minimum amount of energy and causes least harm to environment.

Ahmad et al. (2013) states that the global cement production industry is one of the highest greenhouse gas emitting sources, contributing approximately 7 % of carbon emissions to the earth's atmosphere. Moreover, the concrete manufacturing industry is arguably the largest user of the world's natural resources. To attend to the environmental impacts related to discarded rubber products and the cement manufacturing sector, it is imperative to recycle waste tyre rubber to build a saving and green environment. A new type of concrete with rubber fragments shall be an effective technique to re-use waste rubber products. Likewise, the development of alternative binders is necessary to develop a sustainable concrete industry.

"Environmental Problem...or Engineering Resource?"

The increasing volumes of traffic on the road in developing and industrialised countries generate masses of scrap tyres each year. Presti (2013) reported that about 1,4 billion rubber tyres are sold globally each year, and ultimately as many falls into the category of scrap or end of life tyres. A large portion of the discarded rubber tyres ends up in stockpiles in a landfill without subjecting to some form of treatment prior to stockpiling (Pacheco-Torres et al., 2018). The increasing number of the waste sites may pose increasing possibility of fires, sanitary risks and exclusion of occupied spaces in relation to the surrounding environment. Discarded tyre sites are already an aesthetic and health problem.

At the same time, conventional cement concrete contains natural materials such as the aggregates, and thus the growing need for more concrete structures consequently place a burden on the remaining limited resources and the environment. Parolkar (2017) reported that the most widely consumed natural resource on the planet after water is river sand. According to the research, an estimated 15 billion tonnes of river sand are consumed annually across the globe, thus this excessive use consequently leads to scarcity of the resource.

One possibility to lessen these environmental issues is for the engineering and construction sectors to utilise these high amounts of scrap tyres gathered in stockpiles as a new innovative aggregate in concrete production. As a result, this research focuses on developing green resources with strong emphasis on new non-conventional and innovative utilisation of recycled resources. The research explores new inventions to improve concrete mixes by using discarded rubber tyre crumbs as a partial sand substitute and waste paper mill ash as a binder or cementitious material partly substituting cement in the construction industry. An example of a scrap tyre stock pile is shown in Plate 1- 1.

Plate 1- 1: Thousands of tonnes of scrap vehicle tyres are dumped every year in South Africa (after Fakhri, 2016).

From a South African viewpoint, there are potential economic benefits associated with moving up the waste management hierarchy (that is, towards recycling), as outlined by the National Waste RDI (*Research, Development and Innovation*) roadmap. The benefits would not only include the development impacts resulting from bringing back to life all the resources lost through waste disposal, but also a contribution to the concept of a ‘green’ South African economy.

Paper mill ash (or residuals) are solid residues drawn from paper mill chimneys or wastewater treatment plant prior to discharging emissions or treated water into the natural environment or salvaged for re-use in the mill. Paper mill sludge is burnt to produce electricity. The sludge ash is a residue or remains from the combustion, it is made up of primarily coal ash and small amount of paper sludge ash. Waste paper mill ash behaves like the normal cement because of the presence of magnesium and silica which help improve the setting of a concrete mix (Balwaik and Raut, 2019).

In the end, certain important concrete properties in rigid pavements may be improved. For example, the unique elasticity and strength of tyre rubber may improve properties such as level of noise produced, durability for cyclic efforts, and increasing the comfort and safety on the highways. Additionally, a pavement strengthening mechanism may occur where the rubber crumbs play a vital part in the bridging of cracks to control their propagation (Pacheco-Torres et al., 2018). Thus, the re-use of these materials in concrete pavements clearly will provide social and environmental benefits.

1.2 Research question

Future generations will be reliant on these very mineral aggregates and conventional concrete binders that are gradually becoming scarce. This research seeks to give response to the argument whether developments in pavement construction can finally be sustainable or not. A question arises as to whether there are existing alternative suitable resources that can be used instead of the conventional resources used in plain concrete production, in the event alleviating the global issue of pollution by pollutants that can be recycled and brought back to life, thus easing the pressure on landfills and waste stockpiles.

1.3 Research aim

The research aims to explore an optimum combination and proportion of recycled rubber crumbs and paper mill ash to be added in a concrete mixture to produce a new, innovative and sustainable concrete that is aimed to improve rigid pavements. The effects of the new mixture on the concrete properties shall be determined through a series of laboratory tests. The new concrete shall be compared with a control mix containing only conventional materials used in concrete production.

1.4 Research objectives

The research objectives are summarised as follows;

- To design a conventional concrete mix to use as a control mix.
- To design a ‘new’ concrete mix of incremental volumes of crumb rubber and a constant volume of paper mill ash. A partial natural sand replacement with crumbed rubber aggregate and partial Portland cement replacement with paper sludge ash were applied to produce the new concrete.

- To carry out a test on the fresh concrete (both new mix and control mix) properties including a slump test.

- To carry out a test on the hardened concrete (both new and control mix) properties including compressive strength, splitting strength and flexural strength at (7 and 28) days for all three tests.

- To ascertain the density of hardened concrete (both new and control mix).

- To assess the failure mode of the hardened concrete (both new and control mix)

- To extract hardened concrete samples and carry out a durability analysis by performing a chloride conductivity, water sorptivity and oxygen permeability test for durability.

- To analyse all sets of results and compare all incremental new mixes with the control (conventional) mix to determine an optimum new mix which will be ideal for sustainable rigid pavement construction.

1.5 Research Layout

This research presents a literature section on critical information on what researchers and experts have written in this field of research. The chapter starts by introducing the two categories of hard surfaced pavements namely; rigid and flexible pavements. The background of rigid pavement structures was explored as this research consider a rigid pavement system. Considerable advantages of a concrete pavement when compared to other pavement types are presented together with the issues associated with this type of pavement.

Then the literature section presents the incorporation of recyclable rubber and waste paper mill ash as it looks to alleviate rigid pavements issues. The two studied materials are described, and a life cycle assessment of vehicle tyres is presented. To inform this research, the chapter also presents similar previous investigations to establish the effects of paper mill ash and crumb rubber and on pavement concrete properties. The literature review ends by exploring the situation in South Africa in terms of waste tyre recycling industry and a profile of the paper mill sector.

As an innovative approach, the experimental program applied in this research considers each mix in constant paper mill ash proportions and varying crumb rubber proportions. The methodology describes each of the constituents used to manufacture the concrete mixtures. The experimental program ends by describing the sampling, specimen preparation, curing and the test procedures for each test method. The results of the laboratory tests are then presented and discussed to ascertain some of the mechanical and physical properties of a new mix when used in pavement concrete.

To conclude the research, an optimum material replacement rate was determined and the concrete mixture consisting of recycled materials was compared with plain concrete. It was anticipated that some experiments and tests will yield positive results, underlining the writer’s growing scientific interests in utilising alternative pavement materials. One limitation experienced on this research was the shortage of laboratory equipment in the department of civil engineering, thus some laboratory works were carried out using external facilities from partner companies mentioned in the acknowledgement section of this report.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review on critical information on what researchers and experts have written in this field of research is presented. The chapter introduces the two categories of hard surfaced pavements namely; rigid and flexible pavements. The background of rigid pavement structures shall be explored as this research consider a rigid pavement system. The chapter also present the incorporation of recyclable rubber and waste paper mill ash as it looks to alleviate rigid pavements issues. To inform this dissertation the chapter also presents similar previous investigations to establish the effects of paper mill ash and crumb rubber and on pavement concrete properties. The literature review ends by exploring the situation in South Africa in terms of waste tyre recycling industry and a profile of the paper mill sector.

2.2 Alternative pavement designs

2.2.1 Background

Hard surface pavements can be categorised into two types; flexible pavements and rigid pavements. Rigid or concrete pavement structures are made of a Portland cement concrete surface slab with an underlying subbase layer and any other layers (Liu et al., 2014). Flexible pavements are constructed with a bitumen bound surface layer overlaying an unbound base course and other courses if necessary. This paper shall consider a rigid pavement system as it aims to report an investigation on recycled waste materials to produce a new concrete for a sustainable rigid pavement construction as illustrated in Plate 2-1.

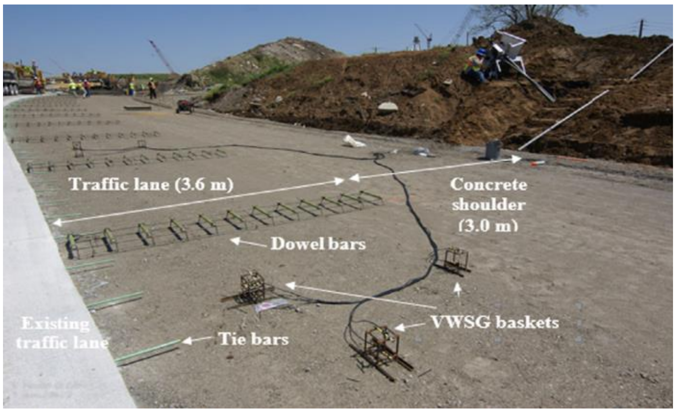


Plate 2- 1: A general view of a rigid pavement construction site (after Kujala, 2012).

A concrete pavement presents significant advantages when compared with other pavement kinds. The advantages include; a higher resistance to adverse weather conditions, high service rate with longer useful life, shorter maintenance delays, and lower requirements for supporting structure. Concerning energy efficiency, a concrete pavement reflects a higher radiation coefficient, reaching surface temperatures that are lower than that of asphalt and other traditional pavements (Pacheco-Torres et al., 2018). Hence, the concrete pavements clearly help reduce the ever more frequent heat effect on pavements. Outside urban areas, due to the lighter surface colour, this type of pavement may offer savings in the lighting or illuminating of highways. Nonetheless, due to high initial costs, concrete pavement construction may bring an important drawback.

2.2.2 Pathologies of rigid concrete surfaces

A flexible pavement may incorporate concrete as a reinforcing material to improve safety of vehicles on damaged flexible roads or to correct a profile of an existing road. A common phenomenon of a concrete surface is the appearance of corner fissures, shown in Plate 2-2. The fissures may extend vertically over the full depth of the concrete slab. A corner fissure can be caused mostly by stress or fatigue due to repeated heavy traffic loads. Deficiency in transmitting of traffic loads over joints between slabs can also contribute to the appearance of this phenomenon. To prevent a risk of appearance of corner fissures, increasing the concrete resistance to cyclic loading may be the most viable solution (Pacheco-Torres et al., 2018).

Plate 2- 2: Corner fissures in concrete pavements (after Pacheco-Torres et al., 2018).

2.3 Incorporating recyclable rubber and waste paper mill products

As mentioned in the introduction, the most widely consumed natural resource on the planet after water is river sand (Parolkar, 2017). According to the research, an estimated 15 billion tonnes of river sand are consumed annual across the globe. Excessive usage of river sand may lead to the banning of the use of the resource (for example, in some Indian states), subsequently leading to scarcity of the resource. Previous investigations on using discarded tyre rubber and paper mill ash in cement and asphaltic mixtures have are encouraging.

2.4 Paper mill sludge ash

A larger scale of environmental pollution is partly a result of developments in industrial activity. Wastes from pulp and paper and industry has turn out to be a major environmental problem and lead to high disposal costs. Waste paper mill sludge constitutes of organic compounds, water, small cellulose fibres, inorganic salts and mineral fillers. Parolkar (2017) estimates a formation of about 60kg of waste ash per tonne of paper mill sludge. The amount of mineral fillers in the sludge depends on the kind of paper produced. Plate 2- 3 below shows raw paper sludge.

Plate 2- 3: Wastepaper sludge (after JayrajVinodsinhSolanki, 2013)

2.4.1 Properties of paper mill ash and its effect on concrete

2.4.1.1 The incineration process and the cement-like behaviour of paper mill ash

To decrease the amount of the waste disposal and to recover heat, paper mill sludge is often incinerated (Parolkar, 2017). The incineration process can be achieved firstly by de-watering, applying evaporation by mechanical means at lower temperatures (less than 200°C), followed by an incineration process at higher temperatures (more than 800°C). The incineration process burns down organic compounds at high temperatures, where inorganic salts and mineral fillers are burnt and converted to oxides. The oxides resulting from the incineration of paper mill sludge include SiO_2, MgO, Al_2O_3 and CaO (Liaw et al., 1998; cited by Parolkar, 2017). It was shown that waste from pulp and paper industries also possess low amounts of silica and calcium and have a cement-like behaviour because of the magnesium properties.

2.4.1.2 Effects of incorporating paper mill ash on concrete

JayrajVinodsinhSolanki (2013) concluded that presence of the silica and magnesium make paper sludge ash behave like cement and help improve the setting of concrete. A comparison between cement and the sludge ash chemical properties is shown in Table 2-1. Incorporating paper mill sludge ash in a mix result in a concrete compressive and splitting tensile strength increase at (0-15)% ash added. Use of the product lead to major reductions in the cost of producing concrete (Parolkar, 2017). The material's moisture content, found to be 40%, also comprises of some constituents such as residual chemicals and calcium carbonate bound up with water. Another important observation was that incorporating the waste ash result in a lighter concrete, as showed by a weight reduction by approximately 5% with 20% replacement with the sludge ash.

Table 2- 1: Comparison of cement and paper mill sludge (after JayrajVinodsinhSolanki, 2013)

Constituents	Cement (%)	Paper mill sludge
CaO (Lime)	62,0	38,0
SiO_2 (Silica)	22,0	11,9
Al_2O_3 (Alumina)	5,0	0,67
MgO (Magnesium)	1,0	1,90
Calcium	4,0	0,57

2.4.2 A profile of the paper industry in South Africa

The FP&M SETA (*Fibre Processing and Manufacturing Sector Education and Training Authority*) (2017) states that South Africa is the 15th and 24th largest producer of pulp and paper (respectively) in the world. The main paper and pulp manufacturing industries are largely based in the Gauteng, KwaZulu-Natal and Western Cape provinces. The geographic location of paper mills across the country are displayed in Plate 2-4 by product.

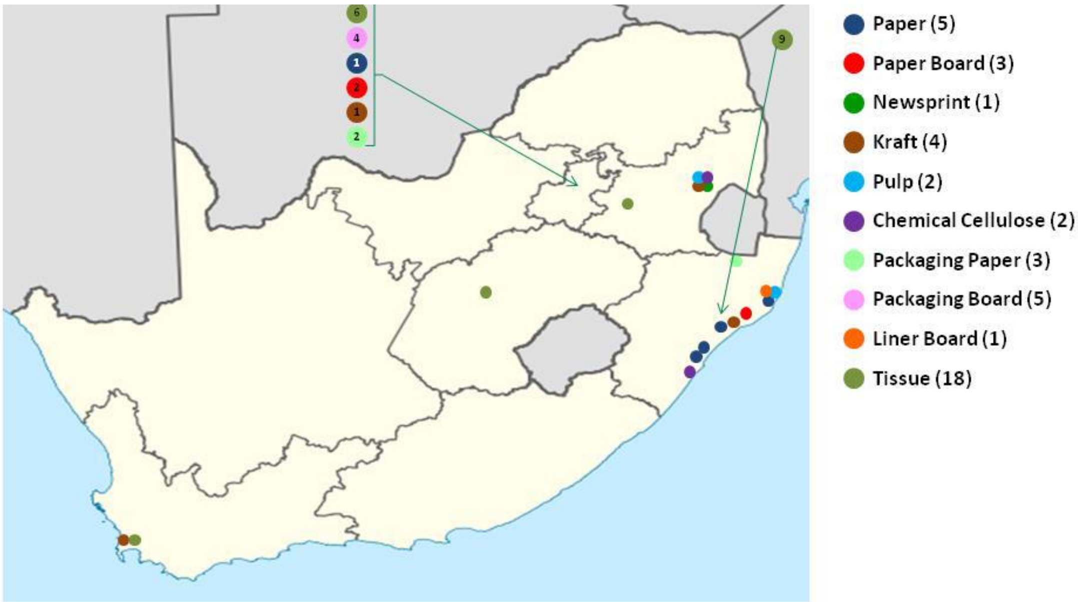


Plate 2- 4: paper and pulp mills in South Africa (after FP&M SETA, 2017)

An outline of the major players in the paper and pare industry in South Africa are presented in Table 2-2.

Table 2- 2: Major paper and pulp companies in South Africa (after FP&M SETA, 2017)

Producer	Core business	Factory location(s)
Kimberly-Clark	This company focuses on health and hygiene products. It has a professional and health care division, as well as three consumer products divisions – adult and feminine care, baby and child care, and family care.	Gauteng Western Cape
Mondi South Africa	Established in 1967, Mondi SA includes forestry, pulp, uncoated fine paper (UFP) and containerboard operations.	KwaZulu-Natal Mpumalanga
Mpact	Mpact is one of the largest paper and plastic packaging groups in Southern Africa. It has 24 manufacturing operations across Africa.	Gauteng KwaZulu-Natal Western Cape
Nampak	Africa's largest packaging company formed in 1968, offers a product range which includes paper, glass, metal and plastic. Nampak's paper products include cartons and labels, corrugated paper boxes and trays and paper sacks and trays as well as toilet tissue.	Gauteng KwaZulu-Natal Western Cape
Sappi	Sappi South Africa, established in 1936, provides locally produced fine, office and business papers, container board, newsprint, and many other pulp and paper products.	Gauteng KwaZulu-Natal Western Cape

2.5 Crumb rubber

2.5.1 Effect of rubber aggregate on concrete properties

When compared with conventional mixtures, outcomes show that rubberised pavements have reduced fatigue cracking, better skid resistance and prolonged life (Siddique and Naik, 2004). The outcomes also showed that discarded tyre rubber have the potential to be used as substitute material partially replacing the aggregates in concrete production. Crumb rubber can be used in concrete production for specific applications to yield a concrete with improved workability. The material selection process has to be adequately undertaken, and it includes decisions on shape, material grades and amount.

Regarding sustainability issues; industries, governments and the public are all very much concerned with green engineering towards sustainable development and better environmental quality. A comprehensive analysis that explores tyre rubber interaction with the environment is presented in a form of a Life Cycle Assessment as shown in Appendix J. Rubber crumbs comprises of fragments or particles of size range 0.075 mm to 4.75mm (Siddique and Naik, 2004). In general, a scrap vehicle tyre can be converted to crumbs using the procedures outlined in Appendix J. Plate 2- 5 shows the sizes in three stages of crushed rubber.

Plate 2- 5: Crushed rubber from waste tyre (after Sofi, 2018)

2.5.2 Waste tyre recycling industry in South Africa

Synthetic or natural discarded tyres are utilised in three major recycling industries, namely; craft-based uses of waste tyres (Kraftek), crumbing, and waste to energy (WTE) as illustrated in Figure 2-2. In the crumbing method, waste tyre shreds are transformed into rubber crumbs which can be used to produce rubber products or by other industries such as the construction sector. The crumbing process can bring about outputs that can therefore be possible replacements for virgin commodities conventionally used by industries in their production processes.

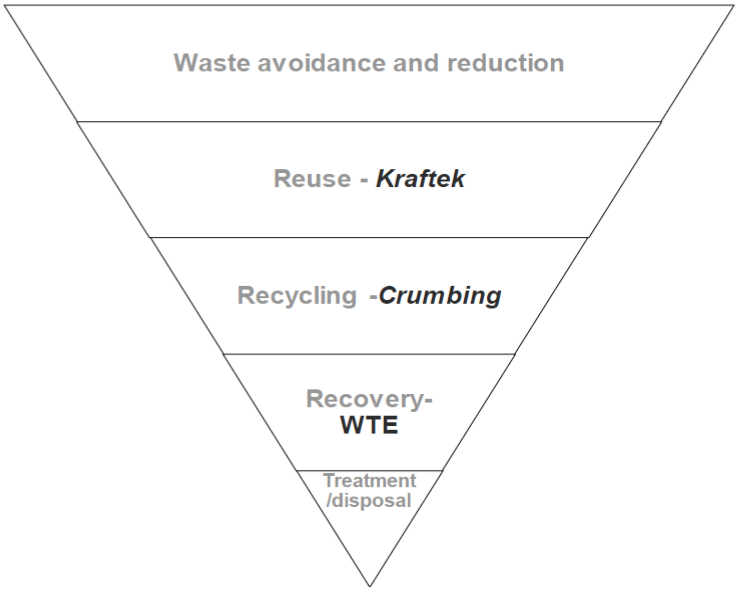


Figure 2- 1: Tyre waste hierarchy (after Hartley et al., 2016)

Between November 2012 and October 2016, South Africa has recycled about 170000 tonnes of waste tyres through the IIWTMP (*Integrated Industry Waste Tyre Management Plan*) and REDISA (*Recycling and Economic Development Initiative of South Africa*) (Hartley et al., 2016). Presently, the largest waste tyre markets are 16 percent - incineration, 18 percent- pyrolysis, 23 percent- shredding or cutting, and 25 pe cent- re-use). In 2014 approximately 31 448 tons of scrap tyres underwent recycling, 16 037 tonnes in 2013 and 71 806 tonnes in 2015 (Hartley et al., 2016). Table 2-3 shows the location of the current waste tyre processors in South Africa.

Appendix F show a list of tyre Depots in South Africa. It must be noted that not all Depots shown are necessarily in operation.

Table 2- 3: Waste tyre processors in South Africa (after Ministry environmental affairs, 2017)

Processor	**Processor type**	**Province**	**City**
Nettworth	Crumbing	Gauteng	Bronkhorspruit
Goswell	Crumbing	Kwa-Zulu Natal	Durban
Energia Recycling	crumbing	Gauteng	Johannesburg
Game Rubber	crumbing		
Mathe	crumbing	Kwa-Zulu Natal	Hammarsdale
SA Tyre Recyclers	crumbing	Western Cape	Atlantis
Dawhi Rubber Recyclers	crumbing	Gauteng	Germiston
Kabusha OTR	crumbing	Gauteng	Vereeniging

2.6 Civil Engineering applications: Rubber effect on pavement concrete properties

2.6.1 Unit weight

Oikonomou and Mavridou (2009) state that as the content of crumb rubber substituting aggregates increases, the unit weight of the tyre-modified concrete decreases. The reduction may be due to the lesser rubber unit weight when compared to that of conventional aggregates (about 2,65 to 2,67 grams per cubic centimetres for conventional aggregate compared with 0,9 to 1,16 grams per cubic centimetres for recycled rubber) (Khaloo *et al*., 2008; cited by Oikonomou and Mavridou, 2009). It was shown that the reduction in unit weight of tyre rubber is nearly negligible for rubber inclusions not exceeding an average of 15% of the total avolume of aggregate in the concrete mix.

2.6.2 Slump (Workability)

The ease with which mortar or concrete can be mixed, moved and placed is known as the workability. Raghvan et al., 1998; cited by Siddique and Naik (2004) carried out an investigation and reported that concrete incorporating waste rubber particles have a better workability than a control mix with no rubber crumbs. Conversely, Khatib and Bayomy, 1999; cited by Siddique and Naik (2004) examined the rubber modified concrete’s workability and stated that the slump of rubber-modified concrete reduces with an increase in the amount of rubber in a mixture. It was noted further that there was no slump at 40% aggregate replacement with rubber. Another observation was that rubcrete mixtures comprising finer crumbs are more workable when compared to coarser tyre particles.

2.6.3 Air content

Siddique and Naik (2004) investigated the air content in rubcrete without the use of air-entraining admixtures (AEA) and reported that the air content is higher in rubber-modified concrete than normal (control) concrete. This was attributed to non-polar nature of rubber crumbs and its tendency to entrap air within the rougher particle surfaces (Siddique and Naik, 2004). Moreover, the tendency of rubber to repel water, may attract air molecules to adhere to the rubber surfaces. Hence, an increase in rubber content in a mix may result in an increase in air content, in that way reducing the unit weight of the concrete.

2.6.4 Water absorption

The concrete's ability to resist water absorption often relate to its durability. Absorption can be defined as the primary transportation procedure by which water enters the capillarity of cementitious mixtures by suction. Durability generally improves with a lower mixture capillarity. Previous research show that cement mixtures modified with waste tyre rubber particles (replacing sand) can be described by a reduced amount of capillary absorption of water and porosity with an increase in the amount of tyre rubber. This results may be attributed to rubber's tendency to repel water, and the water may not easily reach the pores of the composite (Oikonomou and Mavridou, 2009).

2.6.5 Durability

In a laboratory research, the penetration of chloride ion was found to decrease with an increase in rubber proportion , observed in cement concretes containing waste rubber (Oikonomou and Mavridou, 2009). Penetration of chlorides further reduced when commercial products containing bitumen emulsions and rubber latex were added. On the contrary, according to Gesoglu and Güneyisi, 2007; cited by Oikonomou and Mavridou (2009), using rubber may increase the penetration of chlorides when using a specified water to cement ratio. The extent of ion permeability depends on the amount of added tyre rubber. Furthermore, after curing for twenty-eight days, the extent of penetration of chloride ion into the mortar decreased significantly.

2.6.6 Mechanical characteristics

2.6.6.1 Tensile and split tensile strength

Concerning the materials ability to resist tensile stresses, the findings from a previous investigation were that, compared to the compressive strength, the tensile strength degradation was marginal (Oikonomou and Mavridou, 2009). The dynamic modulus of elasticity (MoE) was also assessed for rubber-modified concrete, it was observed that the MoE decreased with an increase in rubber content in the concrete mixture. The decrease, however, resulted in an improved material as the new concrete was less brittle.

2.6.6.2 Toughness and impact resistance

Siddique and Naik (2004) define toughness as a material’s capacity to absorb energy. After a flexural test has been carried out, a load can be plotted on a graph against the deflection, the area under the resulting curve is the material’s toughness. Two sets of concrete mixtures were designed; a control mixture and a rubberised concrete (5% rubber) mixture to determine the toughness for each specimen. The toughness recorded for the rubber concrete mix was higher than that of the control specimen. It was reported that the rubberised concrete specimen was able to withstand additional loads after reaching the peak load. The rubber concrete mix designs were further assessed by using two different particle shapes; shreds and granules. The rubber shreds’ tendency to bridge cracks in the specimen delayed a complete separation, but specimens comprising granular rubber particles did not withstand extra loads as the specimen ruptured completely at the failure.

2.6.6.3 Compressive strength

Moustafa and ElGawady (2015) carried out a study to investigate the effect of incorporating waste tyre rubber (up to 30% replacement of fine aggregate) in a high strength concrete on the compressive strength. Two separate mixes of rubberised concrete were designed. A variable slump concrete (hereafter VS) was designed to examine the effects of replacing sand with rubber on the concrete homogeneity and workability. The other set of concrete mixture was designed to have a constant slump (hereafter CS) with an intention to maintain a constant workability. There was a resulting reduction in compressive strength of concrete when using rubber, with more severe loss of strength for VS than CS. The two sets of mixtures of rubberised concrete were designed to have 0% to 30% partial sand substitution (at 5% volume intervals) with waste rubber. Varying superplasticizers were used to set the CS with same slump at any rate rubber content. The used waste ground rubber is shown in Plate 2-6.

Plate 2- 6: Ground rubber used (after Moustafa and ElGawady, 2015)

The concrete performance in terms of its ability to resist compressive loads in CS and VS concrete mixtures was determined for 7 and 56 days of moist curing according to ASTM C192 is shown in Figure 2-2. The day 7 compressive strength show a very limited decrease for the CS mixture. There was a severe loss of strength at 15% rubber up to the maximum content of 30%. A significant degradation in compressive strength happened for all rubber percentages for the VS mixture. For corresponding number of days, it was observed that the CS mixtures had a higher strength than the VS mixtures for all rubber contents. Moustafa and ElGawady (2015) concluded that this trend can be ascribed to loss of slump for the concrete leading to difficulties in preparing the moulded mix hence the presence of voids and less strength, and also the freezing effect of hydration water due to added superplasticizers. The superplasticizer effect was visually noticed after de-moulding of the cylinders. The compressive strengths of the hardened concrete cylinders were also measured through axial loading on day 56, also shown in Figure 2-2. A trend similar to that of the 7 days was observed for compressive strengths.

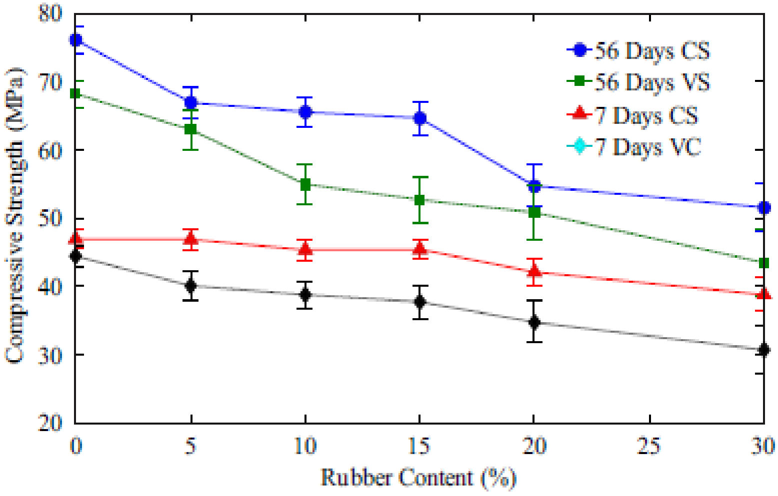
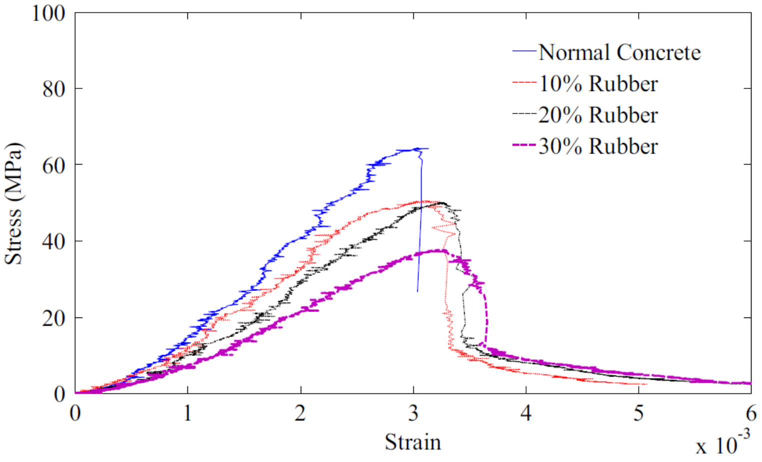
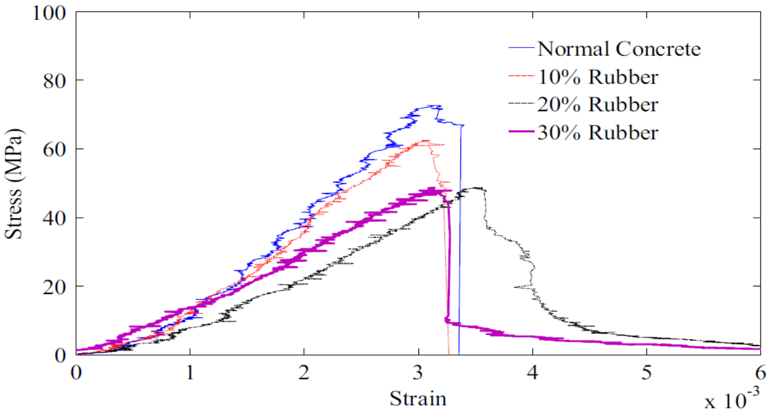


Figure 2- 2: A graph of the recorded compressive strength (after Moustafa and ElGawady, 2015).

Regarding the CS set of mixtures, the compressive strength decrease was significant at all replacement percentages. The VS mixture had a higher standard deviation than the CS mixture. According to Moustafa and ElGawady (2015), this difference in standard deviation can be attributed to the poor distribution of particles in the VS mixture when compared with the CS mixture.



(a)



(b)

Figure 2- 3: Stress–strain curves (a) VS and (b) CS (after Moustafa and ElGawady, 2015)

The stress vs strain curves for loading at day 56 are shown in Figure 2-3. The conventional mix was more brittle as the loading was approaching peak. Smaller rubber percentages in VS did not alter the behaviour of the concrete while larger contents of rubber increased the material ductility. The expansion of rubber particles during the cyclic loading was observed, but the subsequent unloading lead to particles returning to their original shape, a phenomenon that lead to an accommodation for compression for subsequent cycles. The differing ductility in the VS might be a result of rubber particles' poor concentration, thus causing the material to be more compressible, deeming such mixtures appropriate for applications where the material can resist impacts, such as road barriers and sidewalks (Moustafa and ElGawady, 2015).

(a) (b) (c) (d)

Plate 2- 7: Mode of failure: (a) control mix, (b) 10% replacement, (c) 20% replacement, and (d) 30% replacement (after Moustafa and ElGawady, 2015).

The addition of rubber lead to differences in the failure modes of on all specimens. When the maximum load was reached, the conventional mixture (without rubber particles) shattered due to its brittle nature. Rubberized concrete is able to withstand higher loads and it suffered a more ductile failure. The specimen shapes after failure for concrete with 0%, 10%, 20%, and 30% content of rubber are shown in Plate 2-7.

2.7 Civil Engineering applications: Effect of ash wastepaper on properties of concrete

Al Zubaidi et al. (2018) performed a research aimed to study the inclusion of wastepaper ash in a concrete mixture. The optimum percentage of wastepaper ash substituting cement was determined. In the work, 0%, 5%, 7% and 10% wastepaper ash partially replaced cement in a M-25 concrete mixture with water to cement ratio of 0.48 as per ASTM C 94: 2007. Four mixes incorporating wastepaper ash were prepared. The work examined the ash effects flexural, tensile and compressive strengths of concrete specimens tested at (7, 14 and 28) days of moisture curing. The outcome indicated that replacing Portland cement with 5%, 7% and 10% wastepaper ash increased the flexural, splitting and compressive strength by approximately 34%, 4% and 22% respectively at 28 curing days. The use of wastepaper sludge ash as a replacement of conventional cement with specific percentages resulted in a production of a concrete with reduced environmental impacts.

Printing waste paper was collected from libraries and schools. At temperatures 525 degrees celsius, the papers were burnt in a furnace for about 60 minutes, complying with ASTM D 586. Then the burnt wastepaper became ash and was passed through a sieve to attain wastepaper ash for use in the investigation. The chemical composition of wastepaper ash was ascertained by using an EDX (energy dispersive x-ray fluorescence). The results obtained are listed in Table 2-4.

Table 2- 4: A chemical analysis of wastepaper ash (after al Zubaidi et al., 2018)

Oxide composition	Percentage content %
CaO	90.99
SiO_2	4.379
Fe_2O_3	2.689
SO_3	0.025
K_2O	1.829
MnO	0.021
SrO	0.019
TiO_2	0.043
ZrO_2	0.002
Loss of Ignition	5.03

2.7.1 Slump

Figure 2- 4 show the results obtained for slump values for all four concrete mixtures including the control mix. An increment in wastepaper ash content brought about a decrease in concrete slump. Al Zubaidi et al. (2018) concluded that the wastepaper ash particles' tendency to absorb more water than equivalent cement particles led to a decrease in the workability of mixture as the ash wastepaper content increases.

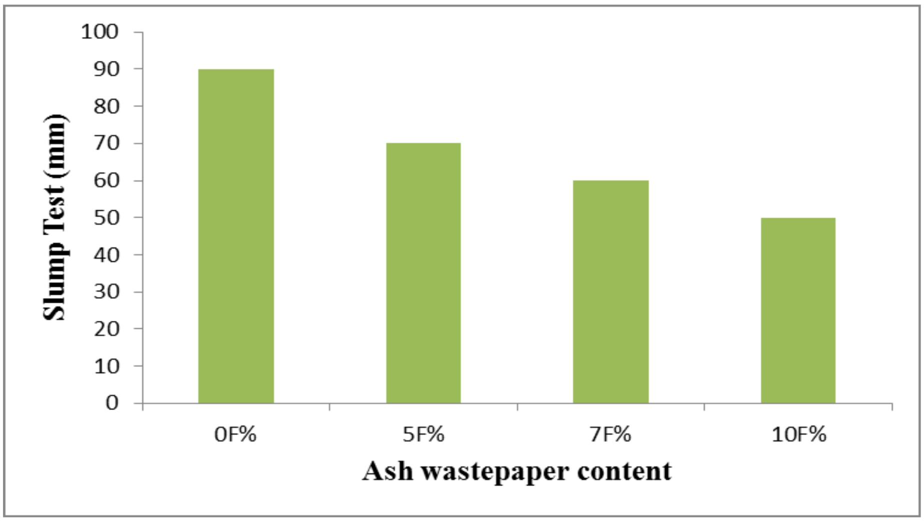


Figure 2- 4: Results of slump test (after al Zubaidi et al., 2018)

2.7.2 Compressive strength

The (7, 14 and 28) days compressive strength results for the four specimens of concrete comprising of varying wastepaper ash content by weight are shown in Figure 2-5. The 28 days specimens recorded the highest compressive strength. When 10% wastepaper ash was added to the mix, i.e. the 10F, a strength improvement of 12.49% was recorded at day 28, when compared with the corresponding normal mix with 0% wastepaper ash. The figure shows that there was a 16.22%, 4.12% and 1.62% strength increase in the mixtures 5F, 7F and 10F respectively, when compared to the corresponding conventional mixtures at day 7 of curing. Al Zubaidi et al. (2018) concluded that the amount of water in the wastepaper ash particles may promote a continuous hydration or internal water supply to the concrete by a process as water in a rubberised concrete have a tendency of filling the micro-cracks or pores to improve concrete properties.

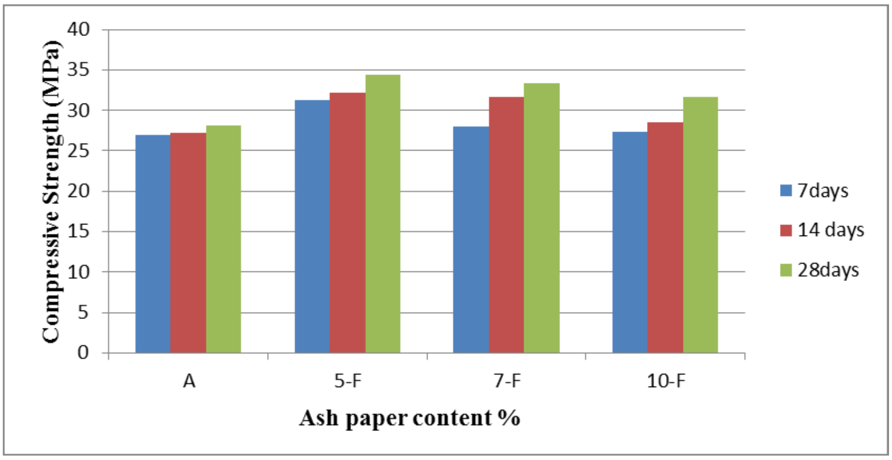


Figure 2- 5: A chart showing the compressive strength results (after al Zubaidi et al., 2018)

2.7.3 Splitting tensile strength

The results of the splitting tensile strength test were plotted on a chart shown in Figure 2-6. The chart shows the curing age and the corresponding tensile strength of the wastepaper ash modified concrete and the conventional mixtures. For all four sets of mixes, the results show that the tensile strength for wastepaper ash modified concrete improved at all increments when compared with the control concrete. In all curing ages, an increase in wastepaper ash percentage in the mixtures resulted in an increase in concrete strength. It was noted also, that the splitting tensile strength generally increases with an increase in curing days.

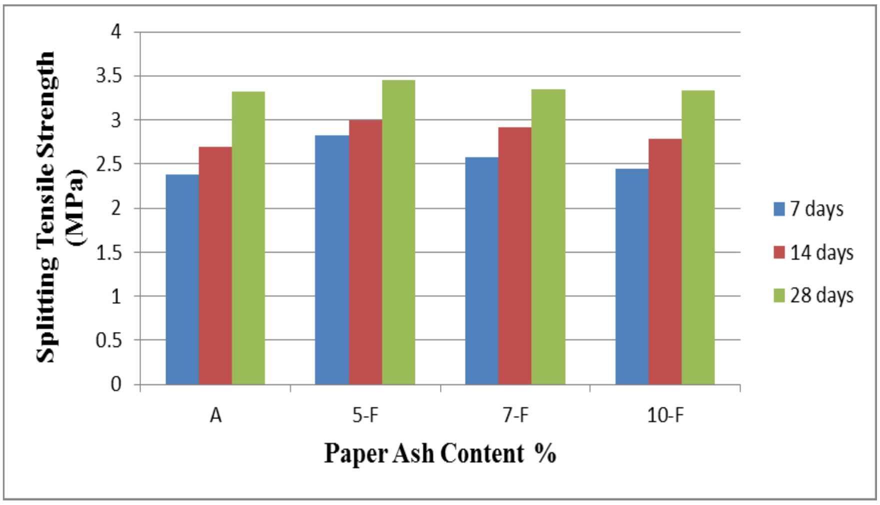


Figure 2- 6: A chart showing the splitting strength results (after al Zubaidi et al., 2018)

2.7.4 Flexural strength

A chart showing results of the flexural strength test for wastepaper ash modified concrete and that of the conventional concrete mixtures are presented in Figure 2-7. In all the test ages, there was a flexural strength improvement for the wastepaper ash modified concrete than the conventional mixture. It was noted also, that flexural strength for all mixes increased with curing age.

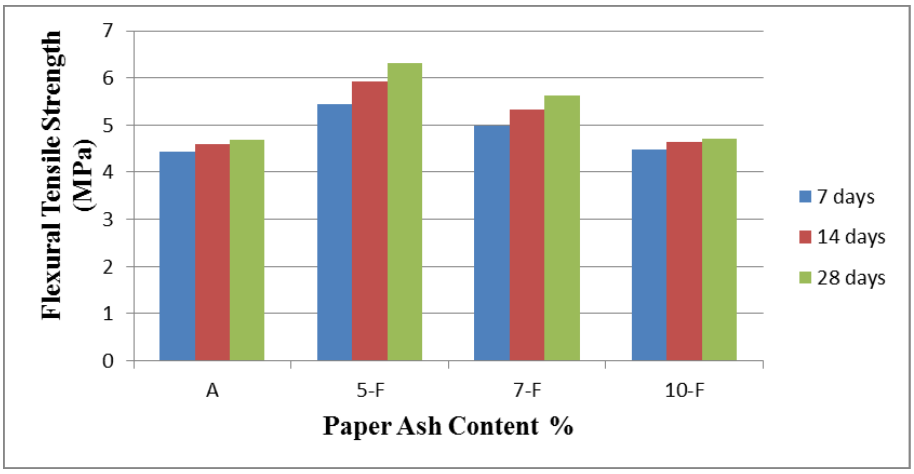


Figure 2- 7: A chart showing the flexural strength results (after al Zubaidi et al., 2018)

2.8 Literature review summary

The literature show that the construction sector can utilise these high amounts of waste tyres gathered in stockpiles as a new and innovative aggregate in concrete production. In both previous studies covered in the literature, each study utilised recycled resources and there was a comparison that followed a series of laboratory tests where there was a positive outcome regarding the maintaining of the structural integrity of concrete.

In the previous study carried out by Al Zubaidi et al. (2018) to investigate the use of wastepaper ash, an increase in the percentage of wastepaper ash caused slump decrease, meaning that concrete become less workable as more ash wastepaper is added in the mixture. However, the expectations were exceeded as the incorporation of the recycled material gave mechanical (splitting, compressive, and tensile) strength results that improve the ash wastepaper-modified concrete when compared with a conventional mix (one with no recycled material).

The previous study carried out by Moustafa and ElGawady (2015) to investigate the effect of incorporating waste tyre rubber in a high strength concrete relate with this research as the concrete was tested for application in a rigid pavement. Moustafa and ElGawady concluded that a constant slump (CS) mixture can be ideal for use in rigid concrete pavements and other structural elements subjected to dynamic loading. CS concrete uses an extender to maintain the same slump/workability in all designed mixtures. This previous research does not make use of an admixture so that the effect on workability of the inclusion of non-conventional materials can be ascertained.

This dissertation was informed in that the previous studies explored new inventions to improve concrete mixes by using discarded rubber tyre crumbs as a partial sand substitute and waste paper material substituting traditional cement. The strength of the literature was that the previous studies investigate the use of recycled material that would otherwise be disposed of in landfills, and samples on were tested for both fresh and hard concrete properties and came up with graphs and bar charts, thus estimated values could be compared. Deductions from the literature review do suggest that certain important concrete characteristics in rigid pavements may be improved, and the re-use of these recycled materials in concrete pavements clearly will provide social and environmental benefits.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

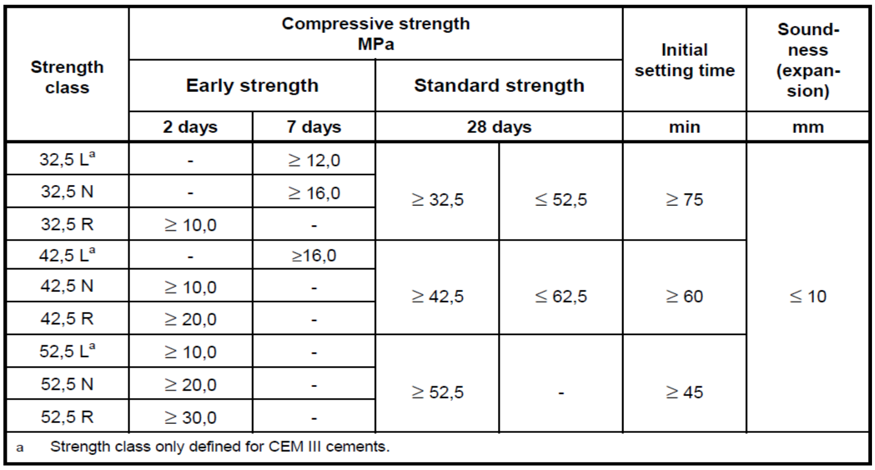
As an innovative approach, the experimental program applied in this research considers each mix in constant paper mill ash proportions and varying crumb rubber proportions. The methodology describes each of the constituents used to manufacture the concrete mixtures. The experimental program ends by describing the sampling, specimen preparation, curing and the test procedures for each test method.

3.2 Materials

3.2.1 Cement

Portland-Slag Cement (type GP) was used in this experimental research, in accordance with SANS 50197-1(2013) specifications. The descriptor *CEM II/B_S 42.5 N* type Portland-Slag cement with a density of 3.07 was manufactured in a SABS ISO 9001:2008 plant at NPC Newcastle, South Africa. The percentage composition by mass for this type of cement was, on average, 28% blast furnace slag and 72% clinker. The cement may also contain some minor additional constituents of up to 5%. The SANS 50197-1 (2013) guideline states that the (2nd or 7th) day compressive strength is taken as the early strength of a cement and shall conform to the requirements in Table3- 1. Appendix A show digital images of the Portland-Slag Cement and natural aggregates used in the research.

Table 3- 1: Characteristic values of cement requirements (after SANS 50197-1, 2013).



Strength class	Compressive strength MPa				Initial setting time	Sound-ness (expan-sion)
	Early strength		Standard strength			
	2 days	7 days	28 days		min	mm
32,5 L^{a}	-	≥ 12,0	≥ 32,5	≤ 52,5	≥ 75	≤ 10
32,5 N	-	≥ 16,0				
32,5 R	≥ 10,0	-				
42,5 L^{a}	-	≥16,0	≥ 42,5	≤ 62,5	≥ 60	
42,5 N	≥ 10,0	-				
42,5 R	≥ 20,0	-				
52,5 L^{a}	≥ 10,0	-	≥ 52,5	-	≥ 45	
52,5 N	≥ 20,0	-				
52,5 R	≥ 30,0	-				

a Strength class only defined for CEM III cements.

3.2.2 Recycled cementitious material- paper mill ash

Paper mill sludge ash from Mondi Merebank Mill, Durban, South Africa, complying with the requirements of concrete binders was used as a cement partial substitute in this experimental research. Mondi Merebank burns an amount of sludge (with coal) collected from the mill chimneys or wastewater treatment plant, which is then used in cement production. Mondi combusts the paper sludge together with coal and gas to generate steam and electricity. Paper mill sludge ash can be described as residues from the combustion, the ash is made up of primarily coal ash and small amounts of paper mill sludge ash. Plate 3- 1 (a) shows an amount of paper mill ash particles (used in this research) with size similar to that of cement particles. The chemical composition of paper mill ash is given in Appendix E.

(a) paper sludge ash (b) crumb rubber

Plate 3- 1: Digital images recycled material used in the research.

3.2.3 Recycled aggregate- Crumb Rubber

Recycled crumb rubber aggregate was obtained locally at Mathe Group (Pty) Ltd situated in Hammersdale town in the outskirts of the city of Durban, South Africa. The material was composed of recycled tyre rubber crumbs of sizes ranging from 1mm up to 5mm, as shown in Plate 3- 1(b). The particle grading was carried out at the company facility and the results are shown and discussed in the next chapter of this document. The tyres processed at the company facility are sourced from post-consumer/industrial tyres around South Africa. The manufacturing process involves reducing a tyre to a finer quality rubber, separation and refining. The technology applied is automated to ensure a high quality and consistent rubber crumb output (https://mathegroup.com/).

3.2.4 Natural aggregates

A 19mm crushed tillite stone having relative density of 2.65 and CBD of 1446 kg/m^3 was used as coarse aggregate material. Sand sourced from the *Umgeni* river was used as fine aggregate in this laboratory research. The sand has a relative density of 2.65 and comprises of 98.19% of material passing through the 4750μm (5mm) sieve size. The testing and sampling methods of the natural fine aggregate were done according to SANS 1083(2017) and SANS 3001-AG1(2014). The aggregates were dried and raked to ensure dust content of the coarse aggregate complied with SAPEM (*South African Pavement Engineering Manual*) standards shown in Appendix B.

3.2.5 Particle size analysis of fine aggregate by sieving

The distribution of particle size was determined for the fine aggregate material to determine compliance with applicable specifications for concrete including those shown in Table 3-2.

3.2.5.1 Apparatus

- A set of sieves that comprising a 4750μm, 2360μm, 1180μm, 600μm, 300μm, and 150μm sieve with pan and covers.
- Electronic balance
- Non-corrodible metal basins
- Drying oven and mechanical sieve shaker
- Brush with hard nylon bristles

(a) Sieve shaker (b) Measuring using a balance (c) Graded material

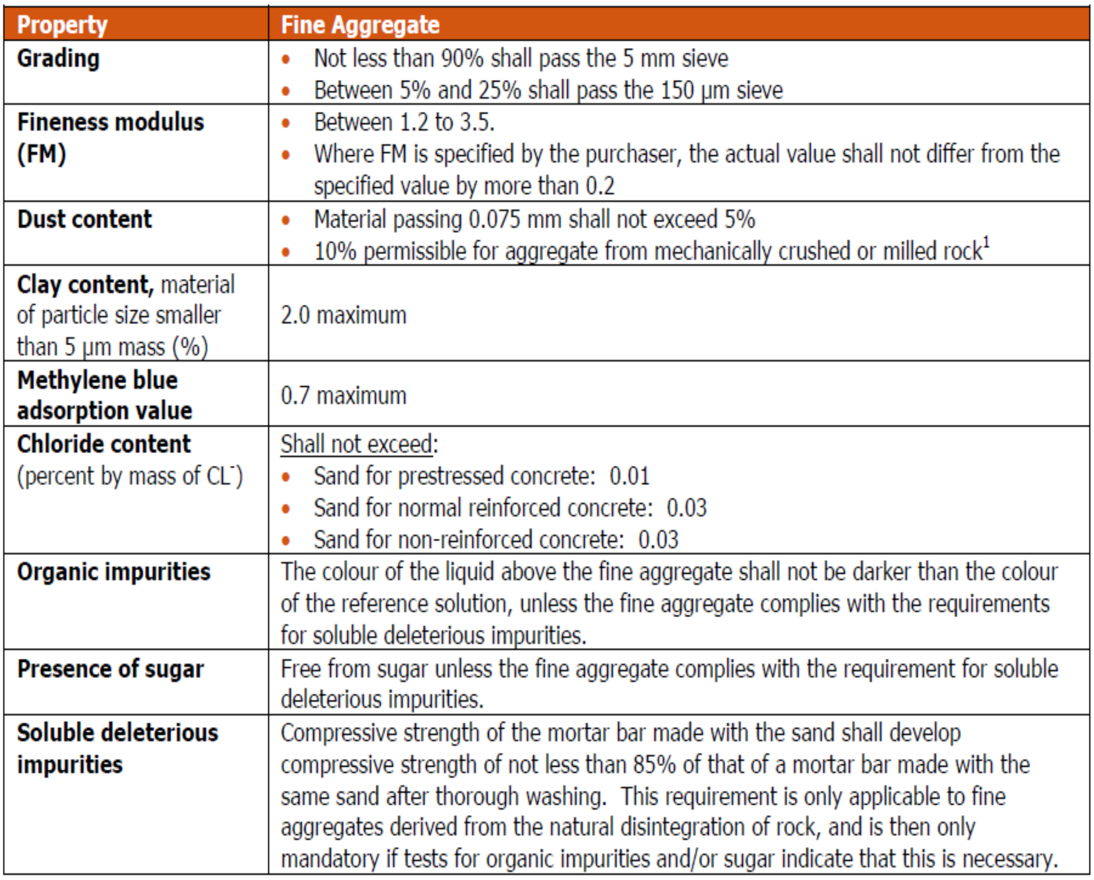
Plate 3- 2: Digital images showing the sieve analysis procedure during the research.

3.2.5.2 Procedure

The Particle size analysis of aggregates by sieving was carried out as described in the South African Concrete Institute manual (2013) and SANS 3001-AG1(2014) using an oven-dry test sample of aggregate of a constant mass 500g. The analysis procedure is illustrated in Plate 3-2. The size of tillite stones was found to be a constant 19mm with almost negligible dust content. Then for the Umgeni river sand, a tabled calculation method was used to ascertain the retained mass of sample on each sieve; the percent of total mass of sample (left below); and cumulative percentages of retained material. Finally, the fineness modulus (FM) was computed using the formula shown below. The results for grading and distribution of particles are shown in the next chapter of this document.

FM = (∑ cumulative percentage of material retained)/100

Table 3- 2: Important Requirements for Fine Aggregates (after SANS 1083, 2017)

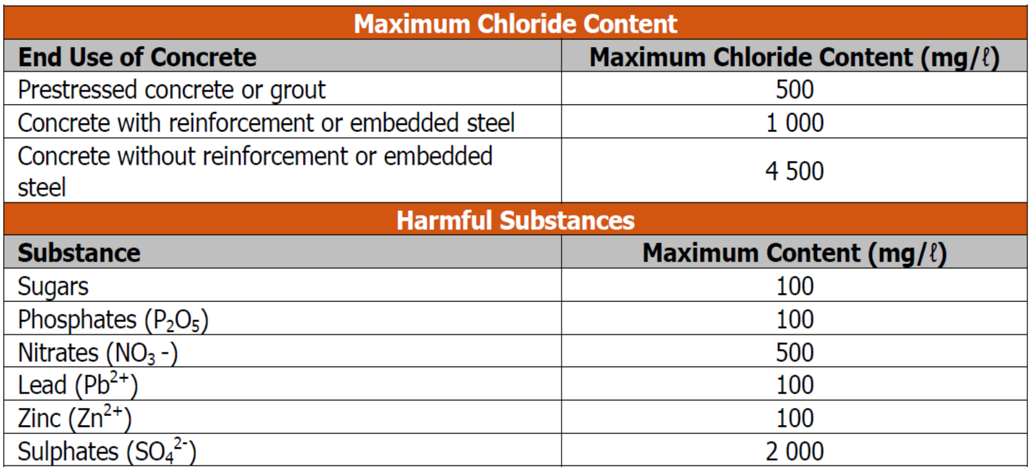


Property	Fine Aggregate
Grading	• Not less than 90% shall pass the 5 mm sieve • Between 5% and 25% shall pass the 150 µm sieve
Fineness modulus (FM)	• Between 1.2 to 3.5. • Where FM is specified by the purchaser, the actual value shall not differ from the specified value by more than 0.2
Dust content	• Material passing 0.075 mm shall not exceed 5% • 10% permissible for aggregate from mechanically crushed or milled rock[1]
Clay content, material of particle size smaller than 5 µm mass (%)	2.0 maximum
Methylene blue adsorption value	0.7 maximum
Chloride content (percent by mass of CL^-)	Shall not exceed: • Sand for prestressed concrete: 0.01 • Sand for normal reinforced concrete: 0.03 • Sand for non-reinforced concrete: 0.03
Organic impurities	The colour of the liquid above the fine aggregate shall not be darker than the colour of the reference solution, unless the fine aggregate complies with the requirements for soluble deleterious impurities.
Presence of sugar	Free from sugar unless the fine aggregate complies with the requirement for soluble deleterious impurities.
Soluble deleterious impurities	Compressive strength of the mortar bar made with the sand shall develop compressive strength of not less than 85% of that of a mortar bar made with the same sand after thorough washing. This requirement is only applicable to fine aggregates derived from the natural disintegration of rock, and is then only mandatory if tests for organic impurities and/or sugar indicate that this is necessary.

3.2.6 Mixing Water

The mixing water used in this experimentation was portable water in accordance with SANS 51008 (2006). The standard states that potable water can be deemed appropriate for use as mixing water in concrete. The standard further states that portable water would not require to be tested as such water is adequate for human consumption. The 4th chapter of SAPEM (2014) states that, generally, water to be utilised in concrete production must be clean and free from concentrations of detrimental sugars, salts, alkalis, acids, and other inorganic or organic constituents that could spoil the strength, durability, setting time of the concrete or any dowels or reinforcing steel in the concrete. Table 3-3 present some applicable requirements of the standard. SAPEM sates that water should be tested for compliance with SANS 51008/EN1008 if there are any doubts as to its quality.

Table 3- 3: Requirements for Mixing Water (after SAPEM, 2014)



Maximum Chloride Content	
End Use of Concrete	**Maximum Chloride Content (mg/ℓ)**
Prestressed concrete or grout	500
Concrete with reinforcement or embedded steel	1 000
Concrete without reinforcement or embedded steel	4 500
Harmful Substances	
Substance	**Maximum Content (mg/ℓ)**
Sugars	100
Phosphates (P_2O_5)	100
Nitrates (NO_3 -)	500
Lead (Pb^{2+})	100
Zinc (Zn^{2+})	100
Sulphates (SO_4^{2-})	2 000

3.3 Mixture proportions

A class 40/19 concrete was designed using the C & CI design method in accordance with the Concrete Institute (South Africa) along with the SAPEM guidelines presented in Table 3-4. The target hardened concrete flexural strength for the control concrete was 5 MPa after 28 curing days, and the size of nominal coarse aggregate (Tillite stone) used was 19 mm. The South African Pavement Engineering Manual states that for minor roads, a flexural strength of not less than 4 MPa at 28 days can be targeted.

In conjunction with this research, the AdCoM (*Advanced Concrete & Materials Research Group*) in the civil engineering department of University of KwaZulu Natal conducted a laboratory investigation about the possibility of using paper mill ash to partially replace cement in a concrete mixture. The outcomes show that inclusions (up to 10%) of paper mill ash in concrete generally result in improvements in the mechanical strength of concrete, Appendix I display an extract of the results.

Furthermore, the literature review section of this research presents an investigation carried out by Al Zubaidi et al. (2018), aimed to study the inclusion of wastepaper ash in a concrete mixture. In this past study, there was an impressive trend observed on the results; the wastepaper ash modified concrete showed that at 5% paper ash, the mechanical (splitting, compressive, and tensile) strength recorded were higher than those of the control concrete (0% wastepaper ash).

Through deductions from the AdCoM research outcomes, and an in-depth review of similar previous investigations, the material replacement percentages were determined. The sustainable concrete mixtures were designed to incorporate both non-conventional materials (crumb rubber and paper mill ash and) in the same mixture.

Thus, in the design mix of this research, the amount of paper mill ash was kept at a constant at 5% (by mass of Portland cement) throughout all the three new mixtures while (on the same mixtures) varying the crumb rubber at incremental and quite conservative proportions of 5%, 10% and 15% (by mass of river sand). This was done by reason of the presumption that a more practical solution could be achieved as opposed to designing and testing two sets of mixtures which would investigate separately each of the two non-conventional materials- a technique which would rather be uneconomical.

Table 3- 4: Recommendations for concrete exposed to the atmosphere (after SAPEM, 2014)

Concrete Specification	**Type of Environment**			
	Non-polluted	**Polluted**	**Corrosive**	**Highly Corrosive**
Minimum cement content (kg/m^3)	As dictated by strength requirements	340	380	420
Cement type	Any cement complying with SANS 5017-1 70% CEM I + 30% FA 50% CEM I + 50% GGBS			
Maximum water:cement	As dictated by strength requirements	0.55	0.50	0.45
Minimum cover to steel (mm)	25	30	40	50
Minimum strength	As per structural requirements			

The recycled tyre rubber aggregate (Crumb Rubber) used had sizes of 1mm-5mm. A control mix of 0,49 w/c (water to cement) ratio with a 467 kg/m3 cement content was designed. Table 3-5 presents the mix proportions per cubic meter and Table 3-6 show the adjusted mixture proportions as per requirement of this research.

Table 3- 5: Design mix per cubic meter

Material	**MIX - Per m^3**					**Units**
	Mix	**Control**	**1**	**2**	**3**	
	Paper sludge ash	0%	5%	5%	5%	
	Crumb rubber	0%	5%	10%	15%	
Water		210	210	210	210	litres
Cement		467	444	444	444	kg
paper mill sludge ash		0	23	23	23	kg
Umgeni sand		581	552	523	494	kg
crumb rubber		0	29	58	87	kg
Stone		1113	1113	1113	1113	kg

Table 3- 6: Design mix required for this research.

Material	**MIX - Required**					**Units**
	Mix	**Control**	**1**	**2**	**3**	
	Paper sludge ash	0%	5%	5%	5%	
	Crumb Rubber	0%	5%	10%	15%	
Water		24	24	24	24	litres
Cement		54	51	51	51	kg
Paper mill sludge ash		0	3	3	3	kg
Umgeni sand		68	64	61	58	kg
crumb rubber		0	4	7	10	kg
Stone		130	130	130	130	kg

3.4 Specimen Preparation

In this laboratory procedure, preparation of the concrete specimens was achieved using a mechanical concrete mixer in compliance with SANS 5861-1:2006. For the new mixtures; sand, stone and cement, stone and paper mill ash were loaded on a concrete drum mixer and mixed for approximately 4 minutes. Crumb rubber and water were then added, and mixing was resumed up until a uniform fresh mixture was achieved.

3.5 Fresh concrete test method: A slump test

3.5.1 Apparatus (Plate 3-3)**:** ruler, tamping rod, base plate, and mould

3.5.2 Procedure

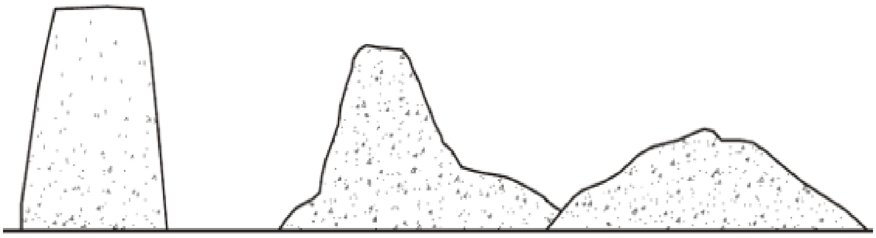
The fresh concrete was checked if it possesses the necessary cohesiveness and plasticity through a slump test carried out in accordance with SANS 5862-1:2006. Each concrete layer (of three equals layers) was poured on the mould and tampered 25 times using a tamping rod and carefully demoulded. The slump was measured to the nearest 5 mm immediately after demoulding.   Using the tamping rod, the side of the concrete was tapped gently to check how well the concrete was proportioned and if the mixture had an appreciable slump. Figure 3-1 shows the types of probable slump shapes.

Plate 3- 3: A digital image showing the slump test apparatus used in the research.

The slump was calculated using the formula below;

Slump = $h_m - h_s$

where; h_m - height of mould (mm)
h_s - height of slumped specimen (mm)



(a) true slump (b) shear slump (c) collapse slump

Figure 3- 1: Types of slump (after SANS 5862-1, 2006)

The SAPEM guidelines presented in Table 3- 7 show the minimum and maximum target slump values for different types of concretes. For this research, a target slump of about 75mm was aimed, which is somewhat the average slump given by SAPEM chapter 4 in the case concrete is to be used in the construction of road pavements.

Table 3- 7: Slump values specified in the standard specifications (after SAPEM, 2014).

Type of Construction	**Slump (mm)**	
	Minimum	**Maximum**
Prestressed concrete	25	75
Concrete nosings and prefabricated units	50	75
Mass concrete	25	100
Reinforced concrete walls, footings, cast in situ piles (except dry-cast piles), slabs, beams and columns	50	125

3.6 Specimen Sampling and Curing

3.6.1 Sampling

For each of the four mixtures shown in Table 3- 6, the specimens for each mix were prepared in accordance with SANS 5861-2:2006 and SANS 3001-CO3-1:2015. The specimens included 11 cubes (150x150x150) mm made for compression and the durability tests, and six specimens of each mix were prepared with prism moulds of size (100x100x500) mm for flexure tests. Six cylinder specimens for the splitting test specimens of size (150dia. x 300 ht.) were also prepared. Compaction for all specimens was achieved by using a vibrating table.

3.6.2 Curing

Twenty-four hours after casting, all moulds were removed and specimens were dipped in a controlled water curing room for the required number of days. The curing temperature range was (22 – 25) °C in accordance with SANS 5861-3:2006.

3.7 Hardened concrete test methods

A larger portion of the hardened concrete samples were used to test the materials mechanical strength. From the remaining samples, concrete disks were extracted to carry out a durability analysis by performing an oxygen permeability, chloride conductivity and water sorptivity tests for durability. The relevant SANS procedures were adhered for each of these laboratory tests. The following sections of these chapter describe the general methodology that was followed when performing the tests.

3.7.1 Compressive Strength (SANS 5863: 2006)

3.7.1.1 Apparatus: A compression testing machine.

Appendix D show images of the compression testing machine and other machines and testing apparatus used for determining the mechanical strength and durability indexes.

3.7.1.2 Test procedure

The bearing platens surfaces of the machine were wipe cleaned and the specimen was placed as per the SANS guidelines. The compressive load was applied at a rate of (0,1 ± 0,3) MPa/s until failure. The compression load was recorded for each specimen, and images of the appearance of cube after failure were taken. The compressive strength was calculated using the formula below;

$$\mathrm{fcc} = \frac{\mathrm{F}}{\mathrm{Ac}}$$

where; f_{cc} - compressive strength (MPa)
F - load at failure (N)
A_c - cross-sectional area of cube (mm^2)

The compressive strengths were recorded and checked as per the guidelines.

3.7.2 Flexural strength

As the concrete for road pavements will be subjected to bending, the flexural strengths were specified for the designed control mix in compliance with SANS 5864:2006. The South African Pavement Engineering Manual states that for minor roads, a flexural strength of not less than 4 MPa at 28 days can be targeted. The two-point loading standard method was followed in this research.

3.7.2.1 Apparatus: compression testing machine

3.7.2.2 Test procedure

The bearing rollers of the machine were wipe cleaned and the specimen was placed as per the SANS guidelines. The compressive load was applied at a rate of (0,01 ± 0,03) MPa/s until failure. The maximum load was recorded for each specimen, and images of the appearance of prism after failure were taken. The flexural strength was calculated using the formula below;

$$\mathrm{fcf} = \frac{\mathrm{F\ x\ l}}{\mathrm{bx\ d.\,d}}$$

where;

f_{cf} - flexural strength (MPa)
F - load at failure (N)
L - distance between the axes of rollers (mm)
b - width of specimen (mm)
d - depth of specimen (mm)

The parameters used in the above equation are shown in Figure 3-2. The flexural strengths were recorded and checked as per the guidelines.

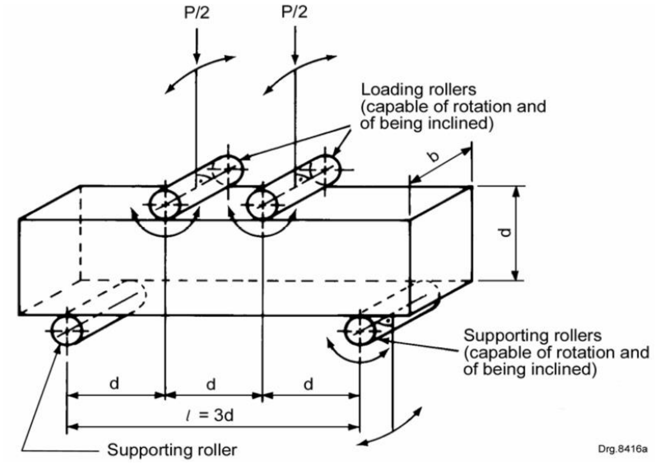


Figure 3- 2: Arrangement of the flexural strength testing apparatus (after SANS5864, 2006).

3.7.3 Tensile splitting strength (SANS 6253:2006)

3.7.3.1 Apparatus

- Compression testing machine
- Jig to locate the application of the test load and the test specimen and at the centre
- Wood or hardboard to support specimen on the bearing plate

The rate of force application (N/s) was calculated using the formula;

$$\frac{(0.02 \text{ to } 0.04) \text{ x } \pi}{2 \text{x l x d}}$$

where;

l - length of specimen (mm)
d - diameter of specimen (mm)

3.7.3.2 Test procedure

Immediately after removal from curing, each specimen was centrally positioned, platens cleaned and the load was applied at a rate of (0,01 ± 0,03) MPa/s until failure. The splitting strength (f_{ct}) was calculated for each specimen in MPa, applying the formula;

$$\text{fct} = \frac{2\text{F}}{\pi \text{ x l x d}}$$

where;

f_{ct} - splitting strength (MPa)
F - load at failure (N)
l and d - as before

Some of the parameters used in the above equation are shown in Figure 3-3. The tensile splitting strengths were recorded and checked as per the guidelines.

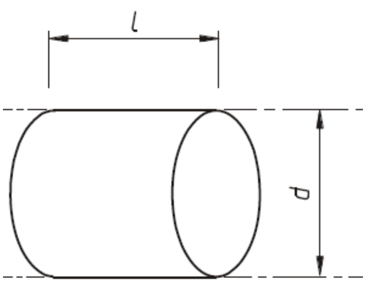


Figure 3- 3: Plane of loading (after SANS 6253, 2006).

3.8 Durability index tests

The durability index testing for the concrete specimens of this research is discussed. The oxygen permeability and chloride conductivity tests were adopted as per SANS 3001-CO3-1:2015. The adopted procedures followed when performing the water sorptivity testing are outlined in the UCT-WITS DI Manual:2018.

3.8.1 Preparation of specimens extracted from cubes

3.8.1.1 Apparatus

- A 70 mm diameter water-cooled core barrel
- Holding device able of securing and accommodating cubes of sizes required.
- Water cooled bed saw.

3.8.1.2 Procedure

Circular specimens, diameter (70 ± 2) mm and thickness of (30 ± 2), were cut and cored from the 28-day cube specimens, as per the guidelines. Immediately after cutting, the durability index conditioning was started. Four specimens were prepared for each of the three test.

3.8.2 Oxygen permeability test (SANS 3001-CO3-2:2015)

3.8.2.1 Apparatus

- An oven
- A permeability cell
- Rubber collars
- Pressure transducers or pressure gauges of accuracy of at least 0.5 kPa
- Oxygen supply capable of regulating pressures of up to 120 kPa
- Vernier calliper
- Desiccator

3.8.2.2 Conditioning of specimens

Specimens were placed in the oven for 7 days maintained at 50°C to dry uniformly.

3.8.2.3 Test procedure

A more detailed version of the methodology can be accessed on the SANS 3001-CO3-2 guidelines. The following steps were followed during the oxygen permeability index test;

- Removed specimen from the oven
- Specimen placed in the desiccator to cool
- Recorded specimen dimensions
- Specimen, collar and sleeve placed on permeability cell. A ring and cover plate were placed to tighten the apparatus
- Opened oxygen inlet and outlet valves, waited 5 seconds
- Closed oxygen valve
- Increased pressure to about 100 kPa, and inlet valve closed
- Time and pressure readings recorded
- Terminated testing when pressure decrease to 50 kPa

3.8.2.4 Calculations

calculations for the oxygen permeability index were carried out in accordance with the guidelines. Amongst other equations described in the standard, the following relationship was used to determine the Darcy coefficient of permeability for each specimen:

$$\mathrm{k} = \frac{\omega\,\mathrm{V\,g\,d\,z}}{\mathrm{R\,A\,T}}$$

where;

k - coefficient of permeability (m/s)
ω - molecular mass of oxygen of. 0,032 kg/mol
V - volume of the permeability (m^3)
g - acceleration due to gravity of 9,81 m/s^2
d - specimen thickness (m)
z - slope of the linear regression line (s^{-1})
R -universal gas constant of 8,313 Nm/K mol
A - cross-sectional area of specimen (m^2).
T - temperature, (K)

The average of the individual oxygen permeability index (OPI) values of the specimens gave the concrete's OPI.

3.8.3 Chloride conductivity test

The method used on the concrete samples to test for chloride conductivity is described in SANS 3001-CO3-3:2015.

3.8.3.1 Apparatus

- An oven
- A vacuum saturation facility
- A conduction cell
- Direct current power supply
- A digital ammeter and voltmeter
- Measuring scale
- NaCl of 99 % purity
- A desiccator

3.8.3.2 Preparation of the chemical solution

About 2.93 kg of NaCl was mixed with 10 litres of potable water until the NaCl melted. The container was sealed and stored for 1 day at a temperature of about 23°C.

3.8.3.3 Conditioning of specimens

Specimens were placed in the oven for 7 days maintained at 50°C to dry uniformly.

3.8.3.4 Procedure

- Removed specimen from the oven
- Specimen placed in the desiccator to cool
- Recorded specimen dimensions and mass
- Specimen placed in the 75 kPa vacuum saturation tank for 3 hours
- Tank isolated
- Vacuum re-set to75 kPa for an hour, then released air to enter the chamber
- Specimens soaked for 18 hours
- Specimens removed from solution, dried and weighed

- Specimen placed within the collar, anode, cathode, ammeter, and voltmeter were connected.
- Current and voltage readings were recorded

3.8.3.5 Calculations

The specimen chloride conductivity was determined by applying the following formula:

$$\sigma = \frac{\mathrm{id}}{\mathrm{VA}}$$

where;

σ - chloride conductivity (mS/cm)
i - current (mA)
d - specimen thickness (cm)
V - voltage (V)
A –specimen’s cross-sectional (cm^2)

3.8.4 Water sorptivity

Ludwig (2018) outlines some procedures for determining the water sorptivity. The described method also allows the water-penetrable porosity of the specimen to be determined.

3.8.4.1 Apparatus

- An oven
- A vacuum facility
- Plastic tray
- Absorbent paper towel
- A Vernier calliper
- A measuring scale
- A water and calcium hydroxide solution
- A stopwatch
- Sealant to provide a watertight seal
- A desiccator

3.8.4.2 Conditioning of specimens

Specimens were placed in the oven for 7 days maintained at 50°C to dry uniformly.

3.8.4.3 Procedure

- Removed specimen from the oven
- Specimen placed in the desiccator to cool
- Recorded specimen dimensions and mass
- Curved sides of specimen sealed
- 10 layers of paper towel placed in the tray
- Removed samples from the desiccator, waited 30 minutes and recorded the dry mass
- Specimen placed on the wet paper and the stopwatch was started at time t_0 and weighed and recorded the mass at 2 min intervals
- Specimen placed in the 75 kPa vacuum saturation tank for 3 hours
- Tank isolated
- Vacuum re-set to75 kPa for an hour, then released air to enter the chamber
- Specimens soaked for 18 hours
- Specimens removed from solution, dried and weighed

3.8.4.4 Calculations

For a specimen, the water sorptivity (in mm/√h) was determined using the equation:

$$S = \frac{Fd}{Msv - Ms0}$$

Where;

F - slope of best fit line (g/√hr)
d - specimen thickness (mm)
Msv, Ms0 -Mass (saturated and at t_0 respectively)

The average of the individual water sorptivity values of the specimens gave the concrete's water sorptivity index.

3.9 Program summary

A description of the laboratory procedures followed in the research are presented in the flow diagram (Figure 3-1) below;

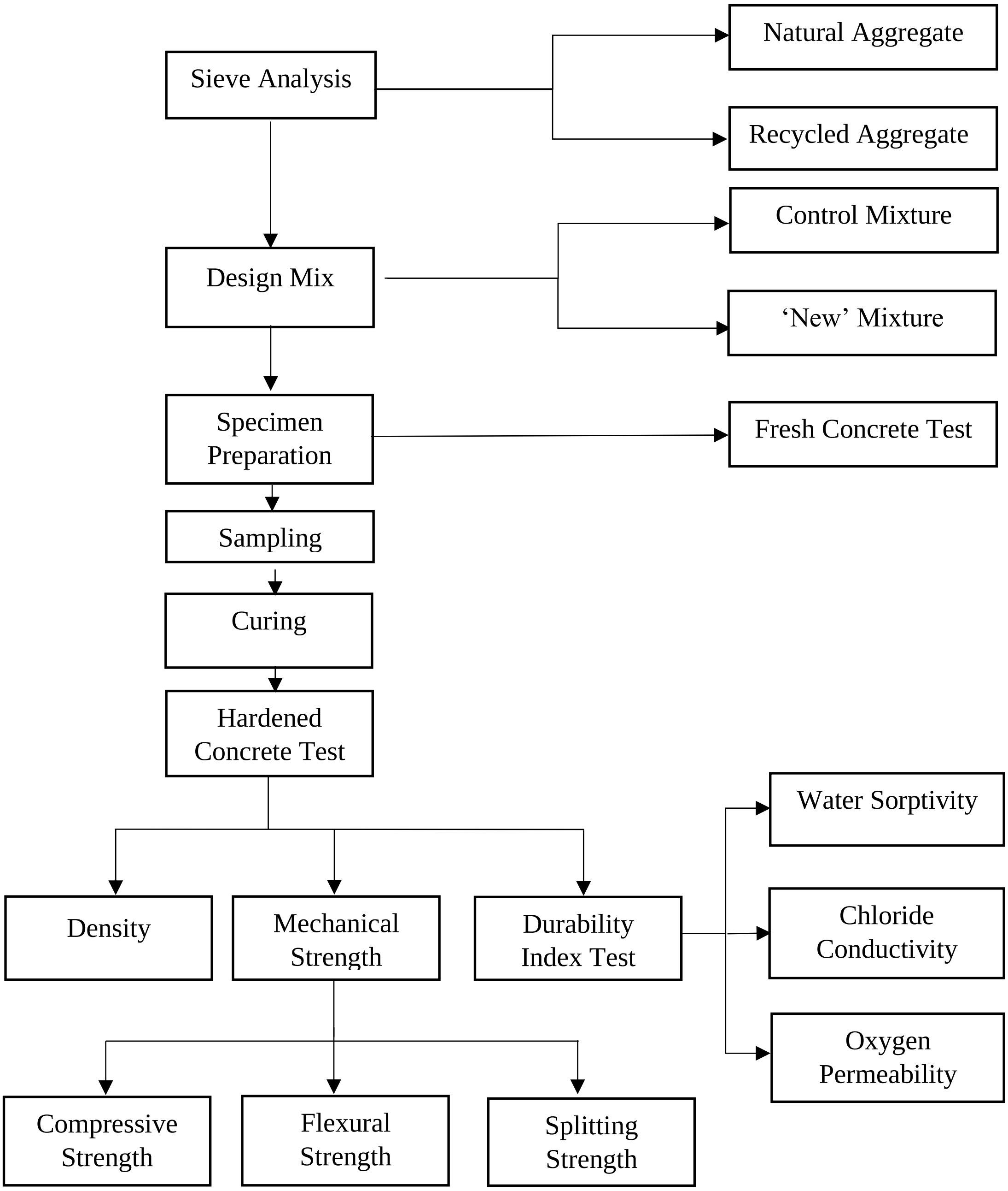


Figure 3- 4: A diagrammatic representation of the research methodology

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Introduction

The results of the laboratory tests are then presented and discussed to ascertain some of the mechanical and physical properties of a new mix when used in pavement concrete.

4.2 Particle size analysis of fine aggregate by sieving

4.2.1 Sieve results

A particle size analysis was performed to ascertain the percentage of the distribution of different particle sizes comprised by the studied fine aggregate materials. The tables below show the recorded particle size distribution based on the sieve analysis performed for both kinds of fine aggregate used in the research, namely: Crumb rubber and Umgeni sand. The grain sizes range between 1.25 mm and 6 mm for crumb rubber (Table 4-2). Particles ranging between dust and 6 mm were recorded for Umgeni sand (Table 4-1).

Table 4- 1: The results of a sieve analysis performed on a mass of Umgeni sand.

Fineness modulus calculation total mass = 500g				
Size of sieve (microns)	Retained mass (g)	Percentage of total mass retained	Cumulative % retained	Cumulative % passing
4.750	9	1,81	1,81	98,2
2.360	22	4,42	6,22	93,8
1.180	52	10,44	16,67	83,3
0.600	109	21,89	38,55	61,4
0.300	216	43,37	81,93	18,1
0.150	80	16,06	97,99	2,0
Passing 150	10	2,01		
Totals	**498**	**100,00**	**243,17**	
Fineness modulus = (cum % retained)/100 = 243.17/100 = **2.43**				

Table 4- 2: The results of a sieve analysis on a mass of crumb rubber, performed by Mathe Group at Hammarsdale, KwaZulu Natal, South Africa.

Sieve size (mm)	% Material Retained	Cumulate % passing
1.00	0	0
1.25	1	0
1.60	5	1
2.00	14	6
2.50	30	20
3.35	30	50
4.00	17	80
5.00	3	97
6	0	100

4.2.2 Grain-size distribution

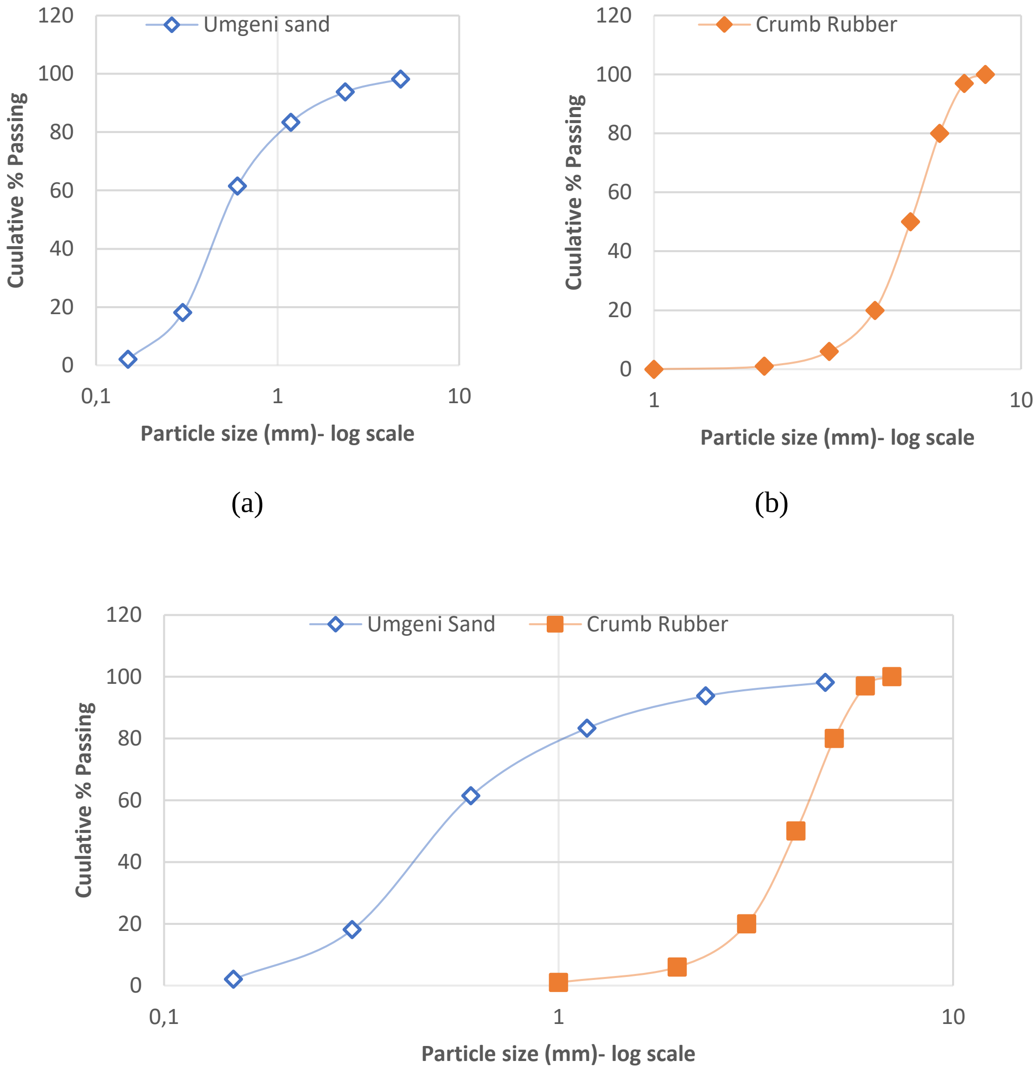
Data from the sieve analysis measurements can be plotted in different ways. Logarithmic scales for particle sizes are used in the graphs presented in this section to respond to skewness and to clearly show percentage changes. Data from the sieve analysis can also be a base for further analysis. For example, a sieve analysis may be important for analysing a material for the reason that the assessment of the performance or quality of a material can be influenced by the sieve analysis. A sieve analysis may also affect surface area properties, the solubility of a mixture and the strength of concrete. Aggregate quality may also be important regarding potential usage in an engineering project as it influences how well the aggregate will function in the engineering usage, being pavement applications for this research.

4.2.3 Limitations of a sieve analysis

Although the requirements for different material usages may be based to a larger extent upon grain size distribution established from a sieve analysis, however, the sieve analysis is not sensitive to variations in particle shape. Two studied fine aggregates may have the same sieve size but have completely different shape characteristics. The aggregate used in this research comprises of non-spherical particles, thus they may have some trouble fitting through the mesh of a sieve.

4.2.4 Cumulative fine aggregate percentage retained

The graphs below show traditional particle size distribution curves showing ‘Cumulative percentage passing vs Particle size’ based on the sieve analysis performed for both kinds of fine aggregate used in the research, Umgeni sand- Figure 4- 1(a) and Crumb rubber- Figure 4-1 (b). A direct comparison between the two fine aggregate materials used in the research was also represent by means of a graph as shown in Figure 4- 1 (c). Overall, it was observed that a significant portion of sand particles were less than 1mm in size while the rubber curve shifts to the right and have particles sized at 1mm and above. Appendix C displays graphs of ‘Percentage material retained vs Particle size’ for the fine aggregate.



(a) (b)

(c)

Figure 4- 1: Cumulative % passing vs Particle size for (a) Umgeni sand; (b) Crumb rubber; and (c) comparison between the two materials.

4.3 Fresh concrete test method: Slump test

The slump test results are listed in Table 4-3. There was a reduction in slump from the control mix (no waste rubber) to a marginal (5%) addition of crumb rubber and paper mill ash as a fraction of the total mass of fine aggregate and cement respectively. However, further increments of waste rubber content brought about a better workability than the control concrete with no rubber crumbs nor waste paper mill ash, as displayed by the more upward slopping bars from 5% to 15% rubber content as shown in the Figure 4-2. This concrete behaviour may be attributed to the notion that the wastepaper ash particles absorbed more water than equivalent cement particles and thus there was an initial decrease in the workability of the concrete mixture at 5% ash. Furthermore, a balance between keeping a constant ash content while further increasing waste rubber content improved the workability of the mixture.

Table 4- 3: Results of the slump test

Crumb Rubber content	Paper mill ash content	Slump (mm)
Control (0%)	0%	70
5%	5%	50
10%	5%	63
15%	5%	71

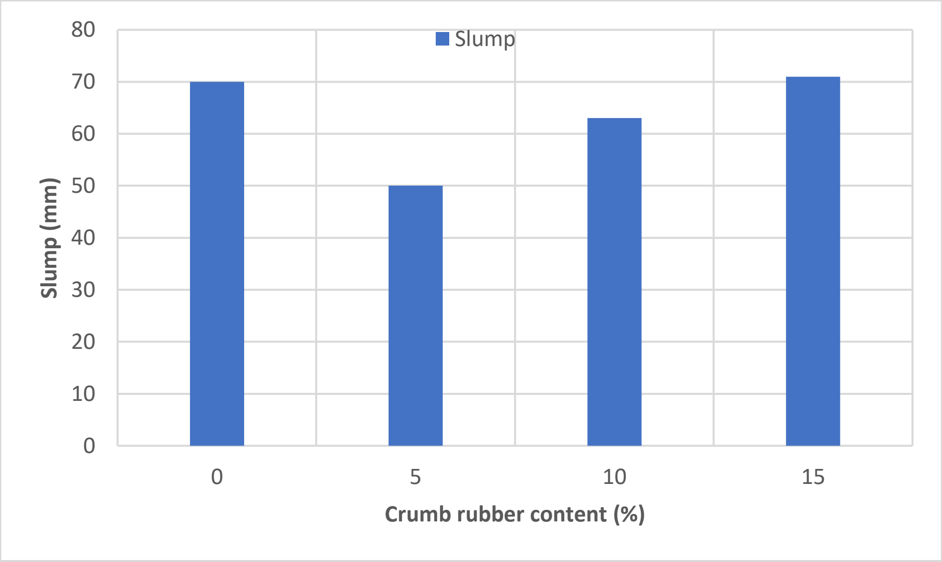


Figure 4- 2: Slump of the rubber and ash modified concrete

4.4 Failure modes of modified hardened concrete

It should be noted that reinforcing bars were not considered when designing and preparing the samples in this research. A prototype of the concrete pavement would require some reinforcement, thus the crack width shown by the samples in Plate 4- 1(a) can further be improved when incorporating reinforcement. Again, the concrete resistance to bending or flexure (shown in Plate 4- 1(c)) can be improved with having a reinforced concrete pavement, an action which can lead to high flexure loads at fracture and reduced tension crack widths. The failure modes of modified hardened concrete are shown in Plate 4-1. The failure modes of concrete with rubber aggregates generally had smaller crack widths than that of normal concrete. It was noted also, for rubber concrete, that the propagation of the cracks into the concrete was improved.

(a) splitting failure mode (b) compressive failure mode

(c) flexural failure mode

Plate 4- 1: (a, b, and c): Failure modes of modified hardened concrete

4.5 Hardened concrete test methods

4.5.1 Density

The measured concrete densities are listed in Table 4-4. As the extent of replacement of the fine aggregate with scrap tyre rubber crumbs increases, the density of concrete decreases. The reduction may be ascribed to the weight per unit volume of the crumb rubber being lesser than that of the conventional river sand being substituted. Figure 4- 3 displays that density reduction occurs in a linearly manner from a value of 2373 kg/m^3 at 0% crumb rubber to a value of 2279 kg/m^3 at 15% sand substitution. Nevertheless, even though the vertical scale is exaggerated, the bars in Figure 4- 3 show that the reduction in density is nearly insignificant at 5% crumb rubber content. Due to its low specific weight, the 5% paper mill ash content also contribute positively to the concrete density reduction. Rubber and ash modified concrete may be favourable in applications where a low-density concrete is required.

Table 4- 4: Results of concrete density

Crumb Rubber content	Paper mill ash content	Sample mass (kg)	Sample volume (m^3)	Density (kg/m^3)
Control (0%)	0%	8,01	0,003375	2373
5%	5%	7,94	0,003375	2353
10%	5%	7,77	0,003375	2302
15%	5%	7,69	0,003375	2279

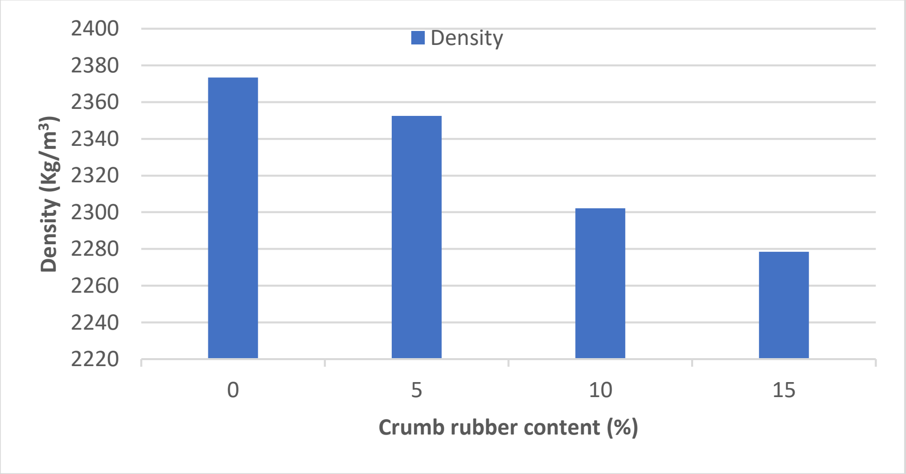


Figure 4- 3: A chart showing the concrete density trend

4.5.2 Compressive Strength

The measured concrete's ability to resist compression results at (7 and 28) days are listed in Table 4- 5. The table reveals that partially substituting conventional aggregate with rubber aggregate was found to decrease the strength of concrete. The reduction varies from one percentage replacement to another. The compressive strength for 'rubber and ash'-modified concrete is higher for waste tyre rubber incorporated in smaller proportions. The curves displayed by Figure 4-4 demonstrates that both the day 7 and day 28 compressive strengths decrease in a very similar fashion.

Table 4- 5: Compressive strength test results

Crumb rubber Content	Paper mill ash content	Compressive strength	
		Day 7 (MPa)	Day 28 (MPa)
Control (0%)	0%	27	40
5%	5%	26	39
10%	5%	19	33
15%	5%	18	27

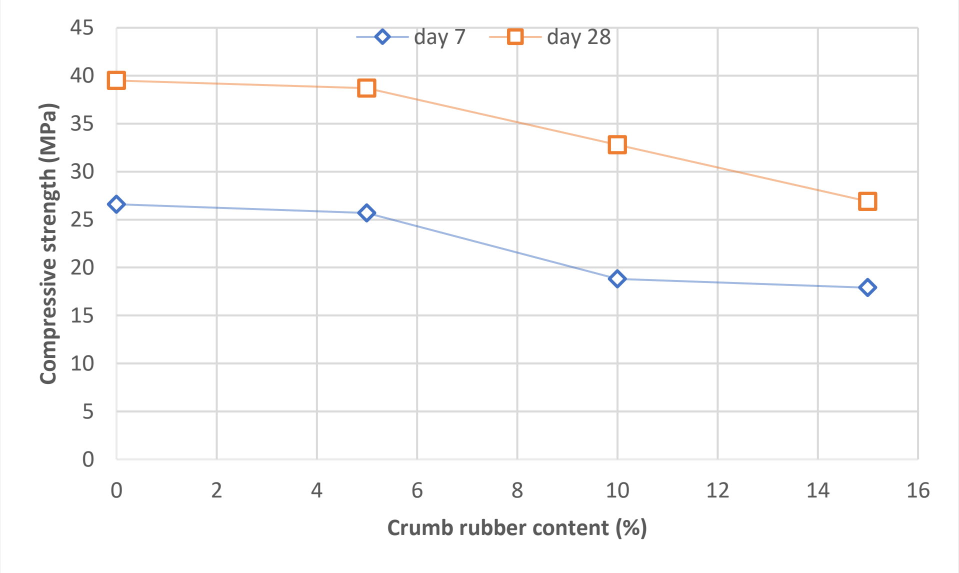


Figure 4- 4: The compressive strength curves

Each of these curves show a very limited strength decrease for the mixture when smaller amounts of crumb rubber are added to substitute sand, but (keeping the paper mill ash proportion at a constant 5%) a severe loss of strength was observed at 10% substitution through the maximum content of 15%. Oikonomou and Mavridou (2009) concluded that the strength reductions may be ascribed to the idea that there is a weaker chemical bond between the cement matrix and rubber crumbs. This trend can be ascribed to the initial loss of slump for the concrete leading to difficulties in preparing the moulded mix hence the presence of voids and less strength (Moustafa and ElGawady, 2015).

4.5.3 Flexural strength

The results of the flexural strength testing for all concrete mixtures are presented in Table 4-6. Generally, the the concrete's resistance to bending was lower for the mixtures modified with wastepaper sludge ash and crumb rubber than the conventional concrete. An increase in tyre rubber percentage in the mixtures resulted in a degradation of the flexural strength. When 5% crumb rubber was added in the mix, a drastic decrease in flexural strength (approximately 39%) was recorded at day 28 when compared to the corresponding control concrete with 0% paper sludge ash and 0% crumb rubber. However, the graph shown in Figure 4- 5 reveal that as the percentage substitution with rubber increase to 10% and 15%, the further strength decrease at 28 days was marginal.

Table 4- 6: Flexural strength test results

Crumb rubber Content	Paper mill ash content	Flexural strength	
		Day 56 (MPa)	Day 28 (MPa)
Control (0%)	0%	6.5*	5.6
5%	5%	5.3*	3.4
10%	5%	4.5*	3.1
15%	5%	4.0*	2.8

***Note**: due to inconveniences caused by test machine breakdowns, the numbers with an asterisk (*) were results recorded on day 56 (curing happened during the first 7 days).*

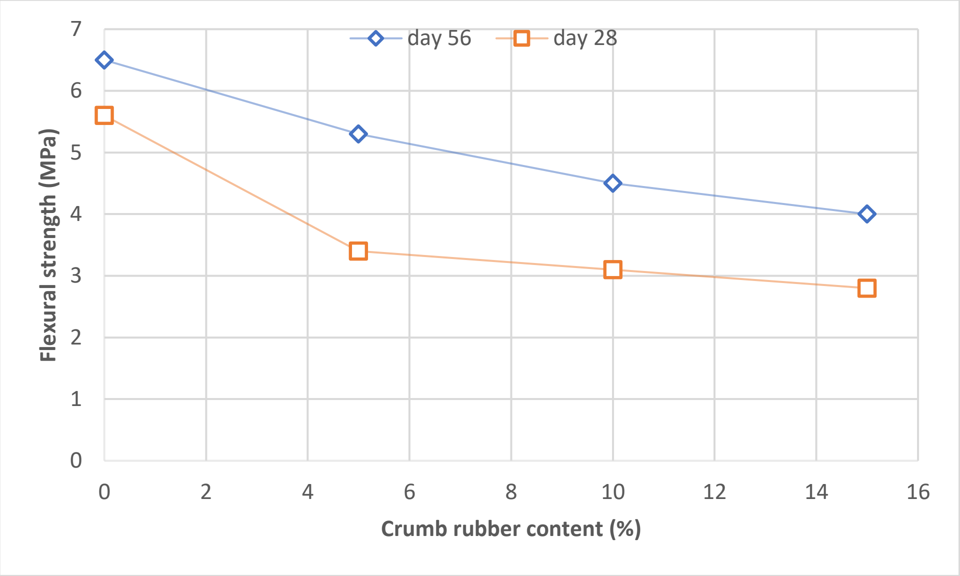


Figure 4- 5: Flexural strength vs rubber content after (56 and 28) days of curing

4.5.4 Tensile splitting strength

The measured results for the concrete's ability to resist splitting at (7 and 28) days are listed in Table 4-7. For all four sets of mixes, the results show that the splitting strength degrades for the modified concrete when compared with the conventional concrete mixture. Nonetheless, one exception is the flattening 28-day strength curve on the right-hand side of Figure 4- 6 which show the same value of 1.9 Mpa for both (10 and 15) % rubber content. For the mixtures, the test results present that a 5% increase in crumb rubber percentage by mass caused a 27% strength decrease when compared with the relevant conventional mixture at 28 days, while a 10% increase in crumb rubber percentage by mass caused a 37% strength reduction. There was no further loss of strength from 10% to 15% substitution, a positive trend that may be useful in predicting the tensile strength results at greater proportions of rubber (higher than 15%).

Table 4- 7: Tensile splitting strength test results

Crumb rubber Content	Paper mill ash content	Tensile splitting strength	
		Day 7 (MPa)	Day 28 (MPa)
Control (0%)	0%	2.3	3.0
5%	5%	2.0	2.2
10%	5%	1.5	1.9
15%	5%	1.3	1.9

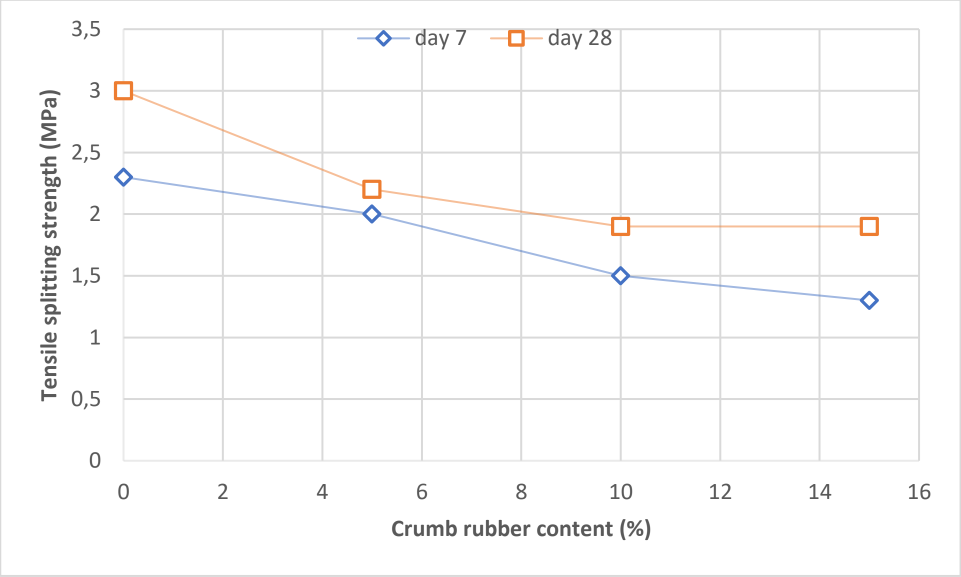


Figure 4- 6: Tensile splitting strength vs rubber content

***Chapter 4 notes:**

- *Though paper mill ash is incorporated in the mix as seen in the design mix (Table 3-11), the horizontal title axis on the plotted graphs of all concrete tests (fresh, hard, and durability) show 'Crumb rubber content' to avoid a clustered and long wording.*

- *For flexibility and clarity purposes, not all the decimal places or significant figures for results values comply with the expression and recording of results stipulated by the relevant standards.*

4.6 Durability index tests

4.6.1 Oxygen permeability test

An oxygen permeability index (OPI) is a logarithmic value. SANS states that for concrete, oxygen permeability index values generally range from 8,0 (more permeable concrete) to 11,0 (less permeable concrete). The results obtained are in agreement with this range of indexes outlined by SANS. Appendix H show the comprehensive durability test results obtained in this research. Table 4- 8 show that there is no significant difference between the OPIs in all four mixes. However, the exaggerated vertical scale in Figure 4- 7 show that the ability of concrete to resist permeating oxygen decreases with an increase in rubber content. The likely cause of this behaviour may be bleeding or inadequate compaction. Improved oxygen permeability index values may be obtained by reducing the water to cement ratio or prolonging the duration of concrete curing (Gouws et al., 2001).

Table 4- 8: Results of the oxygen permeability test

Crumb Rubber content	Paper mill ash content	OPI
Control (0%)	0%	10,46
5%	5%	10,42
10%	5%	9,91
15%	5%	10,04

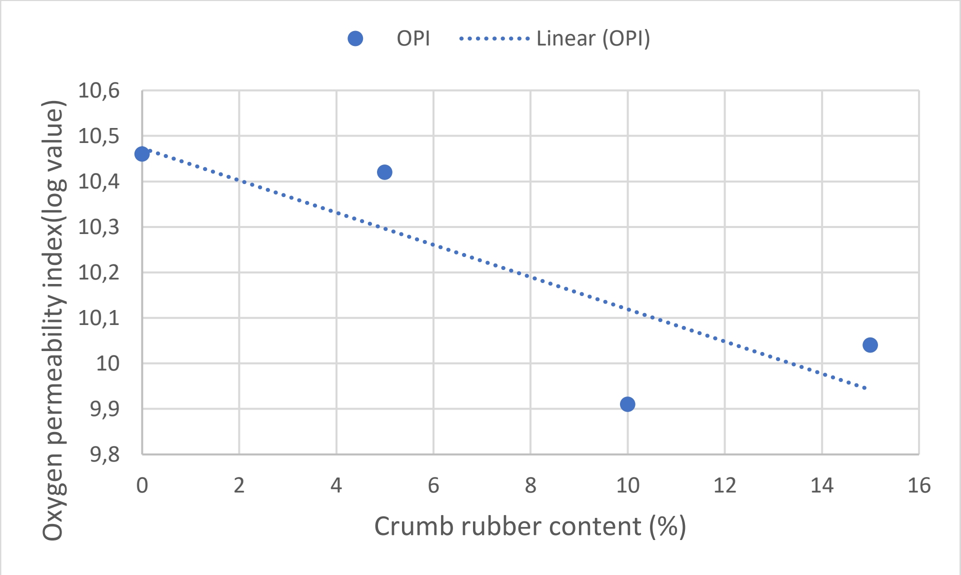


Figure 4- 7: Graph of oxygen permeability index vs crumb rubber content

4.6.2 Chloride conductivity test

The chloride conductivity test was carried out to study the process by which chlorides diffuse or enter a concrete specimen, the results were listed in Table 4-9. Generally, the chloride conductivity indexes lie within a fairly narrow band, as demonstrated by a scatter plot (Figure 4-8) showing that the indexes range from 0.18 to 0.25 millisiemens per centimetre (mS/cm). For concrete, chloride conductivity index values range from <0.75 mS/cm (excellent) to > 3 mS/cm (very poor). Table 4- 9 show that all chloride conductivity index values are less than 0.75 and they generally decrease as the rubber content increases, which indicate that tyre rubber concrete improves the material's resistance to chlorides. Gouws et al. (2001) reported that the chloride conductivity test is sensitive to changes in cement chemistry and the pore structure of the concrete. The results suggest that paper mill ash and crumb rubber had a positive effect on altering the chemistry and refining the pore structure of the concrete.

Table 4- 9: Results of the chloride conductivity test

Crumb Rubber content	Paper mill ash content	Chlorides (mS/cm)
Control (0%)	0%	0,25
5%	5%	0,18
10%	5%	0,25
15%	5%	0,19

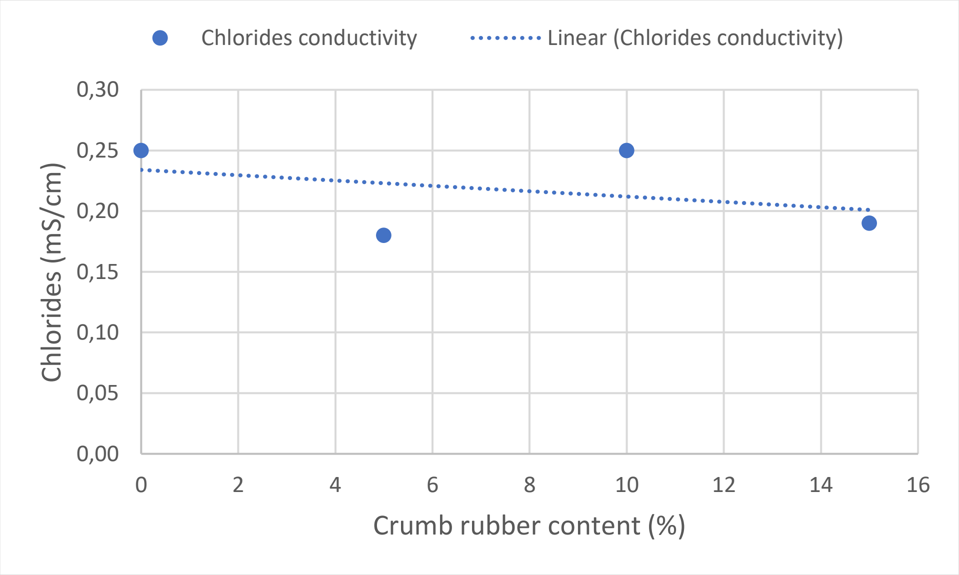


Figure 4- 8: Graph of chloride conductivity vs crumb rubber content

4.6.3 Water sorptivity test

A wetting front was applied on the concrete specimens to measure the water movements through the material. The results of the water sorptivity indexes are shown in Table 4-10. A better potential for concrete durability is denoted by a low water sorptivity index. Clearly, the line of best fit show a downward (negative) slope, demonstrating that the potential durability improves with the incorporation of crumb rubber in a concrete mixture. Figure 4- 9 show a scatter plot of the indexes to best describe the distribution. The vertical axis on the figure were exaggerated to show even slight changes in water sorptivity index. The band within which the indexes lie is relatively narrow as the indexes range from 5.30 to 5.74 mm/√hr. However, one exception is the outlier index of 5.74 mm/√hr in the scatter at 10% rubber content, which can be attributed to discrepancies in moulding or compaction of the concrete specimens.

Table 4- 10: Results of the water sorptivity test

Crumb Rubber content	Paper mill ash content	Sorptivity (mm/√hr)
Control (0%)	0%	5,48
5%	5%	5,40
10%	5%	5,74
15%	5%	5,30

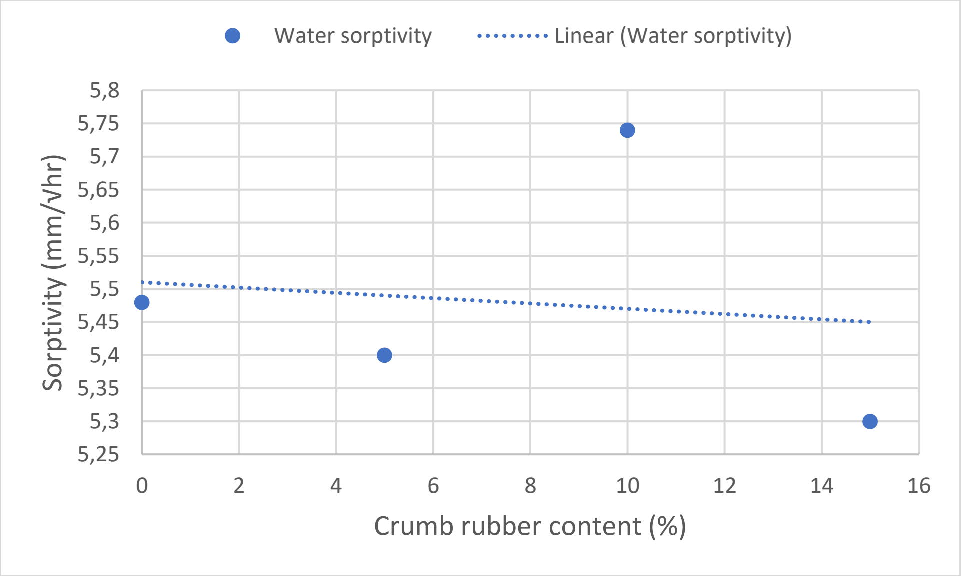


Figure 4- 9: Graph of water sorptivity vs crumb rubber content

CHAPTER 5

RECCOMENDATIONS AND CONCLUSIONS

5.1 Introduction

This chapter presents the writer’s closing remarks together with suggested recommendations. During the initial stage of the dissertation, it was anticipated that some experiments and tests will yield positive results, underlining the writer’s growing scientific interests in utilising alternative pavement materials.

5.2 Viability of rubber and paper mill ash-modified concrete

5.2.1 Optimal combination

This research aimed to determine an optimal combination of proportion and size of discarded tyre crumbs and waste paper ash particles added in a concrete mixture for pavement construction. Though certain limitations have been ascertained through this research, the writer believes that the use of waste rubber and paper mill ash-modified concrete within the road construction sector is feasible when low proportions of paper mill ash and crumb rubber are added. The research has shown that at 5% crumb rubber content and 5% paper mill ash content, there is a marginal loss of mechanical strength of the pavement concrete, with particle sizes ranging from 1mm to 5mm for crumb rubber, and paper ash powder size similar to that of cement (<5 micrometres). In spite of this tolerable outcome, a more positive and offsetting aspect is that the average durability results show a significant improvement in the durability of concrete at the same level of substitution (5%) for both materials.

It is worth noting that this combination equals to an equivalent of about 10% (by mass of fine aggregate and cement) incorporation of waste material in a concrete road pavement, which is a large proportion. For example, to put this into perspective, chapter 3 of this research show that a cubic meter volume of pavement concrete comprises of a minimum total of 53 kg of waste material at 5%, up to 110kg of waste material at 15% (by mass of fine aggregate and cement). These numbers will generally balloon when big projects involving vast volumes of concrete are executed.

Clearly, at lower volume fraction, the rubber crumbs or fragments are distributed evenly and easily in the spaces between other aggregates in the concrete. A pavement strengthening mechanism may occur where the rubber crumbs contribute in bridging of cracks to control their propagation. Furthermore, as stiffness/modulus is lower for tyre rubber than the other surrounding aggregates, the rubber crumbs are more likely to act as a soft core which introduces absorption of stress concentrations under cyclic vehicle loads. Concrete with higher proportions of crumb rubber may serve well in applications where the mechanical strength is not significant.

This research set forth the feasibility of using discarded vehicle tyres for concrete pavement construction and the environmental benefits associated with the option. Incorporating waste rubber in rigid concrete pavement mixtures may be considered as value added material for sustainable development. The incorporation of waste paper mill ash and tyre rubber in pavements is a viable option for recycling of waste and reduction of the demand for the depleting conventional raw materials (such as sand). The improved modulus of elasticity brings about a reduction in vehicle noise pollution as the use of crumb rubber improves the pavement’s ability to absorb and thus reduce vehicle noise level, thus contributing positively to the quality of life in areas where there is large traffic volume on roads (such as urban areas or cities).

5.2.2 Problems associated with this innovative concrete

The application of this technology may present some issues as the concrete production industry may be lacking properly trained personnel mainly for accuracy in areas such as laboratory analysis of raw material and final mixtures, which are necessary for achieving optimal modifications and final product performance. A definite environmental performance cannot be currently drawn about one of the products used in the research, paper mill ash. The concrete production industry currently lacks appropriate mix standards and a specific binder for rubberised concrete.

Training and education are necessary to perform some improved laboratory designs of these new concrete mixtures. To help decrease the implementation costs and solving the several issues pointed out in this report, there is a dire need for all stakeholders (including governments and professional bodies) to invest on training and research to achieve long term substantial savings. There is a need to develop new procedures as a key aspect for applying these innovations successfully. It is therefore necessary to ensure involvement of national or local governments to pioneer programs that support these new trends in the concrete production industry.

5.2.3 Recommendation to improve mechanical properties of concrete with rubber crumbs

Previous studies have shown that to counter the negative impact of rubber crumbs on the mechanical strength of concrete, the following may be considered;

5.2.3.1 Crumb rubber pre-treatment

To solve the issue of interfacial bonds weakened by incorporating waste paper mill ash and waste rubber in concrete, Li et al. (2016) presented a new approach involving treatment of the rubber crumbs with CSBR (*Carboxylated Styrene Butadiene Rubber*) latex and an SCA (*Silane Coupling Agent*) for stronger rubber-cement bonds. An experiment was carried out to study the effect of this surface treatment on the concrete durability and mechanical strength. The results showed that treated crumb rubber improves the mechanical strength of concrete by up to 13%, when compared with a control mixture of concrete with untreated crumb rubber. The concrete's resistance chloride penetration was also improved by 35%. Furthermore, CSBR is able to bridge some cracks and seal the voids of cement matrix by forming a uniformly distributed polymer film inside the hardened cement to enhance durability and strength of concrete.

5.2.3.2 Water-soaking method

The water-soaking method is another rubber treatment method that can be applied. According to Mohammadi and Khabbaz (2015), this method improves the mechanical characteristics of concrete containing crumb rubber. Though the mechanical strength can be improved, the is a need to further investigate this method's effects on other concrete properties such as the concrete's durability. Further research may also be necessary to enhance the knowledge of the drying shrinkage property of rigid rubber-modified pavements. Finally, to come up with more accurate standards, further research is necessary to model fatigue performance and hydration/bleeding behaviour of concrete.

5.3 Recommendations for future research based on this study

Regarding the recommendations mentioned in section 5.1.3, future laboratory work is necessary to study the effects of the surface treatment procedures on the concrete durability and mechanical strength. Further laboratory tests can be performed to rubberised concrete by using models to subject the concrete to cyclic/vehicle loads to study the behaviour of the pavement structure and the riding quality of vehicles. It may be useful to incorporate reinforcement on the concrete and redo all the tests on all samples for a more realistic assessment of this innovation.

5.4 Conclusions

The management of waste tyres is an important environmental concern. Due to their strong and durable nature, scrap vehicle tyres are not easily biodegradable naturally. This may present continual environmental hazard as they remain in the disposal areas with very low degradation rate over time. Moreover, the disposal sites accessible for dumping of scrap tyres are getting lesser by the day, with an increase in tyre generation. Therefore, finding alternative ways to re-use waste tyre rubber by means of recycling is imperative.

Rubber-modified concrete have desirable properties such as better sound insulation, enhanced ductility, toughness resistance and lower density. The environmental impacts from generated waste can be reduced and the concrete manufacturing industry may produce at lower costs. For the concrete with higher rubber volume, the paper mill ash and tyre rubber concrete results recorded on this research show that the innovative concrete may be used in other engineering applications requiring structural concrete where the mechanical strength is not of prime significance, for example, in the construction of barrier or boundary walls, light vehicle parking or other concrete platforms subjected to light loads, paving on open enclosed areas, for example, within or around a prison compound, large house or factory.

The literature review section of this report reveals that sections of pavements made of rubberised concrete have improved resistance to fatigue cracking, rutting and skidding. For economic feasibility, this new concrete may be used by governments in projects involving the construction of temporary shelters for disaster relief. The use of tyre crumbs may be advantageous in geotechnical applications due to their thermal insulation properties, shear strength, high durability, and low density.

In conclusion, this research has uncovered that replacing conventional aggregate with waste paper mill ash and rubber lead to, on average, improvements in the durability of concrete, and a degradation of the mechanical strength. These recycled materials have a good potential for contribution to infrastructural developments, however, there is need for construction designers to play a role in persuading developers and the relevant authorities of the benefits of these environment-saving applications. Though collaboration is needed among all the above-mentioned sectors for the establishment of necessary standards and guidelines, the addition of small volumes of paper mill ash and tyre rubber in some construction projects may lead to conservation of natural resources while great amounts of stockpiled scraped tyres are salvaged.

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APPENDICES

Appendix A: Conventional materials used

1. Portland cement

Plate A-1: A digital image of Portland-Slag Cement used in the research.

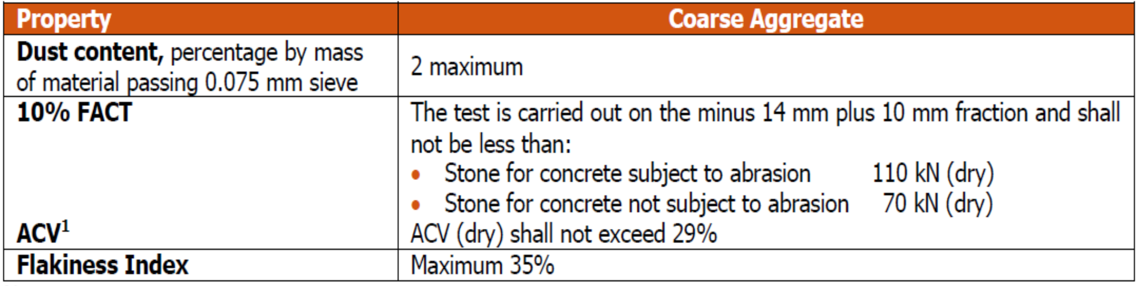
2. Natural aggregates

(a) Umgeni sand (b) Tillite stone

Plate A-2: A digital image of the natural aggregates used, (a) sand and (b) stone

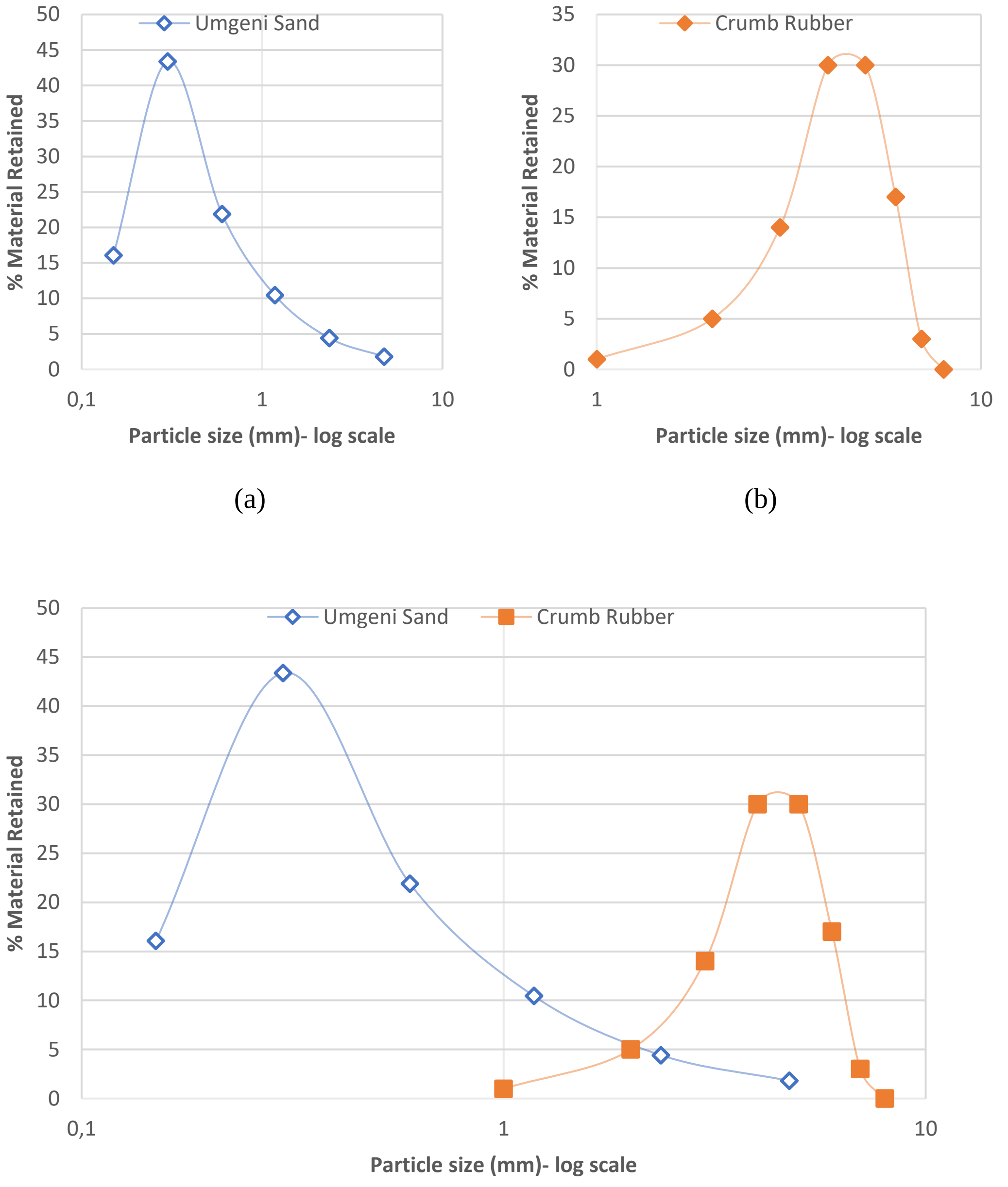
Appendix B: Coarse aggregates requirements in South Africa

Table B-1: Properties of Coarse Aggregates (after SAPEM, 2014)



Property	Coarse Aggregate
Dust content, percentage by mass of material passing 0.075 mm sieve	2 maximum
10% FACT	The test is carried out on the minus 14 mm plus 10 mm fraction and shall not be less than: • Stone for concrete subject to abrasion 110 kN (dry) • Stone for concrete not subject to abrasion 70 kN (dry)
ACV[1]	ACV (dry) shall not exceed 29%
Flakiness Index	Maximum 35%

Appendix C: Percentage fine aggregate material mass retained on each sieve



(a)

(b)

(c)

Figure C-1: Graph of 'Percentage material retained vs Particle size' for (a) Umgeni sand; (b) Crumb rubber; and (c) comparison between the two materials.

Appendix D: Testing apparatus

1. Mechanical strength testing

(a) beam flexure-testing machine (b) Compression-testing machine

(c) tensile splitting strength-testing machine

Plate D-1: A digital image of the machines used to measure (a) flexural, (b) compressive, and (c) tensile strength.

2. Durability testing

(a) Chloride conductivity-testing apparatus (b) Oxygen permeability-testing apparatus

Plate D-2: A digital image of the durability-testing apparatus used in the research to perform the (a) chloride conductivity and (b) oxygen permeability tests

Appendix E: Chemical properties of paper mill ash used in this research

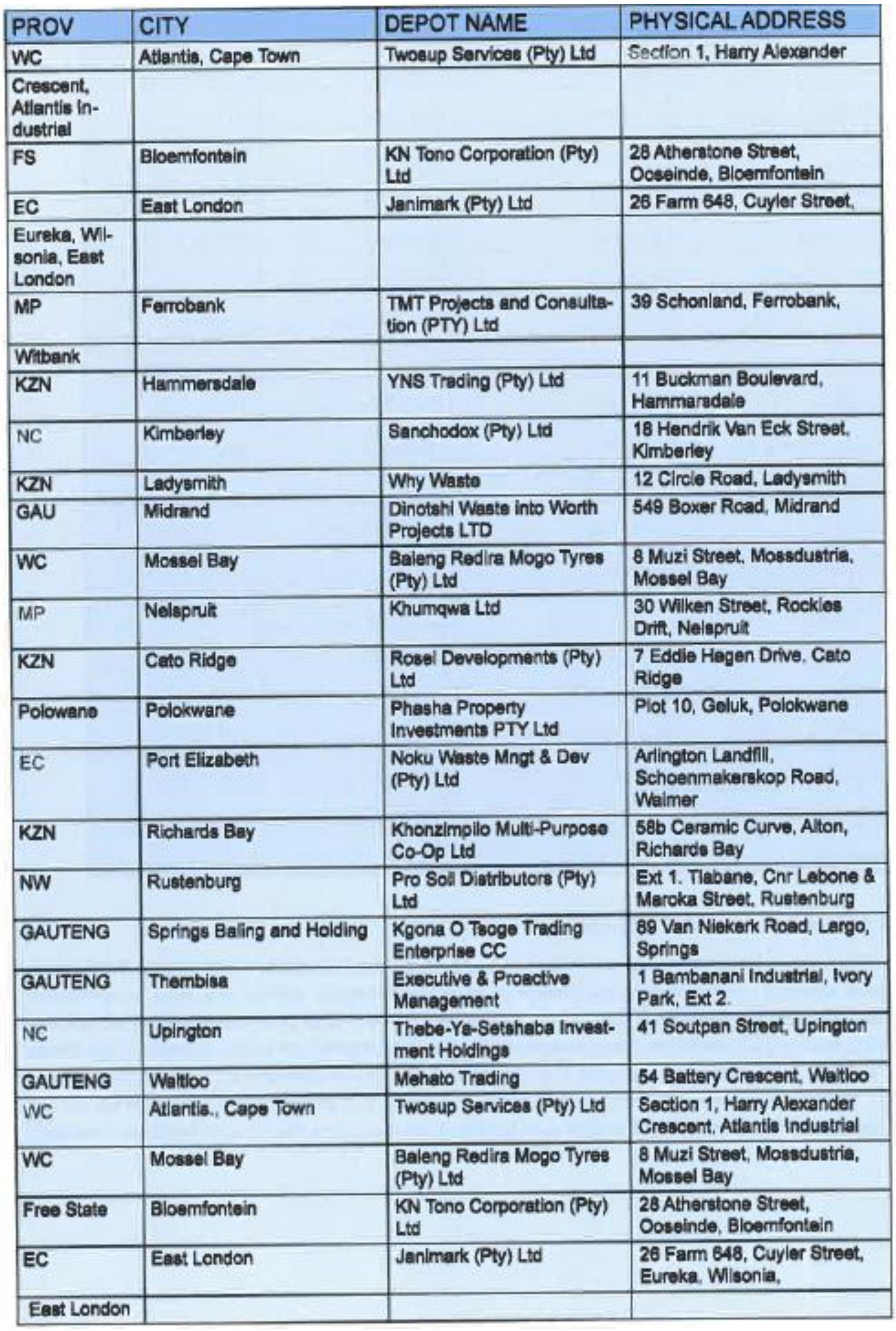
Table E-1: An (SEM) chemical properties of paper mill ash as supplied by Mondi Group

Oxide compound	Percentage (by weight)
MgO	1.55
AL_2O_3	22.41
SiO_2	35.83
SO_2	4.93
K_2O	0.43
CaO	32.58
TiO_2	1.16
Fe_2O_3	1.11

*SEM - scanning electron microscope

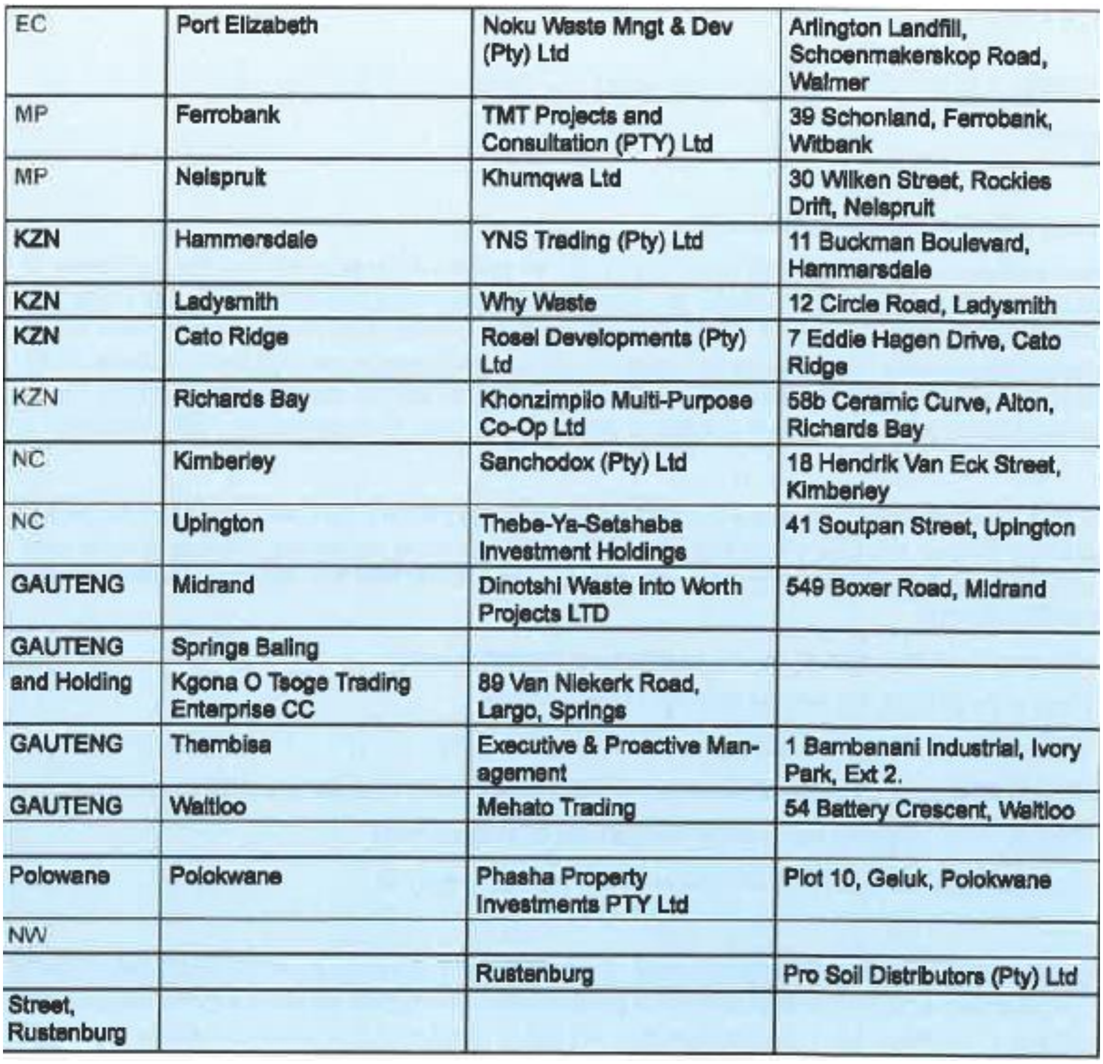
Appendix F: tyre Depots in South Africa

Table F-1: Existing tyre Depots in South Africa (after Ministry environmental affairs, 2017)



PROV	CITY	DEPOT NAME	PHYSICAL ADDRESS
WC	Atlantis, Cape Town	Twosup Services (Pty) Ltd	Section 1, Harry Alexander
Crescent, Atlantis Industrial			
FS	Bloemfontein	KN Tono Corporation (Pty) Ltd	28 Atherstone Street, Ooseinde, Bloemfontein
EC	East London	Janimark (Pty) Ltd	26 Farm 648, Cuyler Street,
Eureka, Wilsonia, East London			
MP	Ferrobank	TMT Projects and Consultation (PTY) Ltd	39 Schonland, Ferrobank,
Witbank			
KZN	Hammersdale	YNS Trading (Pty) Ltd	11 Buckman Boulevard, Hammarsdale
NC	Kimberley	Sanchodox (Pty) Ltd	18 Hendrik Van Eck Street, Kimberley
KZN	Ladysmith	Why Waste	12 Circle Road, Ladysmith
GAU	Midrand	Dinotshi Waste into Worth Projects LTD	549 Boxer Road, Midrand
WC	Mossel Bay	Baleng Redira Mogo Tyres (Pty) Ltd	8 Muzi Street, Mossdustria, Mossel Bay
MP	Nelspruit	Khumqwa Ltd	30 Wilken Street, Rockies Drift, Nelspruit
KZN	Cato Ridge	Rosel Developments (Pty) Ltd	7 Eddie Hagen Drive, Cato Ridge
Polowane	Polokwane	Phasha Property Investments PTY Ltd	Plot 10, Geluk, Polokwane
EC	Port Elizabeth	Noku Waste Mngt & Dev (Pty) Ltd	Arlington Landfill, Schoenmakerskop Road, Walmer
KZN	Richards Bay	Khonzimpilo Multi-Purpose Co-Op Ltd	58b Ceramic Curve, Alton, Richards Bay
NW	Rustenburg	Pro Soil Distributors (Pty) Ltd	Ext 1. Tlabane, Cnr Lebone & Maroka Street, Rustenburg
GAUTENG	Springs Baling and Holding	Kgona O Tsoge Trading Enterprise CC	89 Van Niekerk Road, Largo, Springs
GAUTENG	Thembisa	Executive & Proactive Management	1 Bambanani Industrial, Ivory Park, Ext 2.
NC	Upington	Thebe-Ya-Setshaba Investment Holdings	41 Soutpan Street, Upington
GAUTENG	Waltloo	Mehato Trading	54 Battery Crescent, Waltloo
WC	Atlantis., Cape Town	Twosup Services (Pty) Ltd	Section 1, Harry Alexander Crescent, Atlantis Industrial
WC	Mossel Bay	Baleng Redira Mogo Tyres (Pty) Ltd	8 Muzi Street, Mossdustria, Mossel Bay
Free State	Bloemfontein	KN Tono Corporation (Pty) Ltd	28 Atherstone Street, Ooseinde, Bloemfontein
EC	East London	Janimark (Pty) Ltd	26 Farm 648, Cuyler Street, Eureka, Wilsonia,
East London			

Table F-1: Existing tyre Depots in South Africa *(continued)*

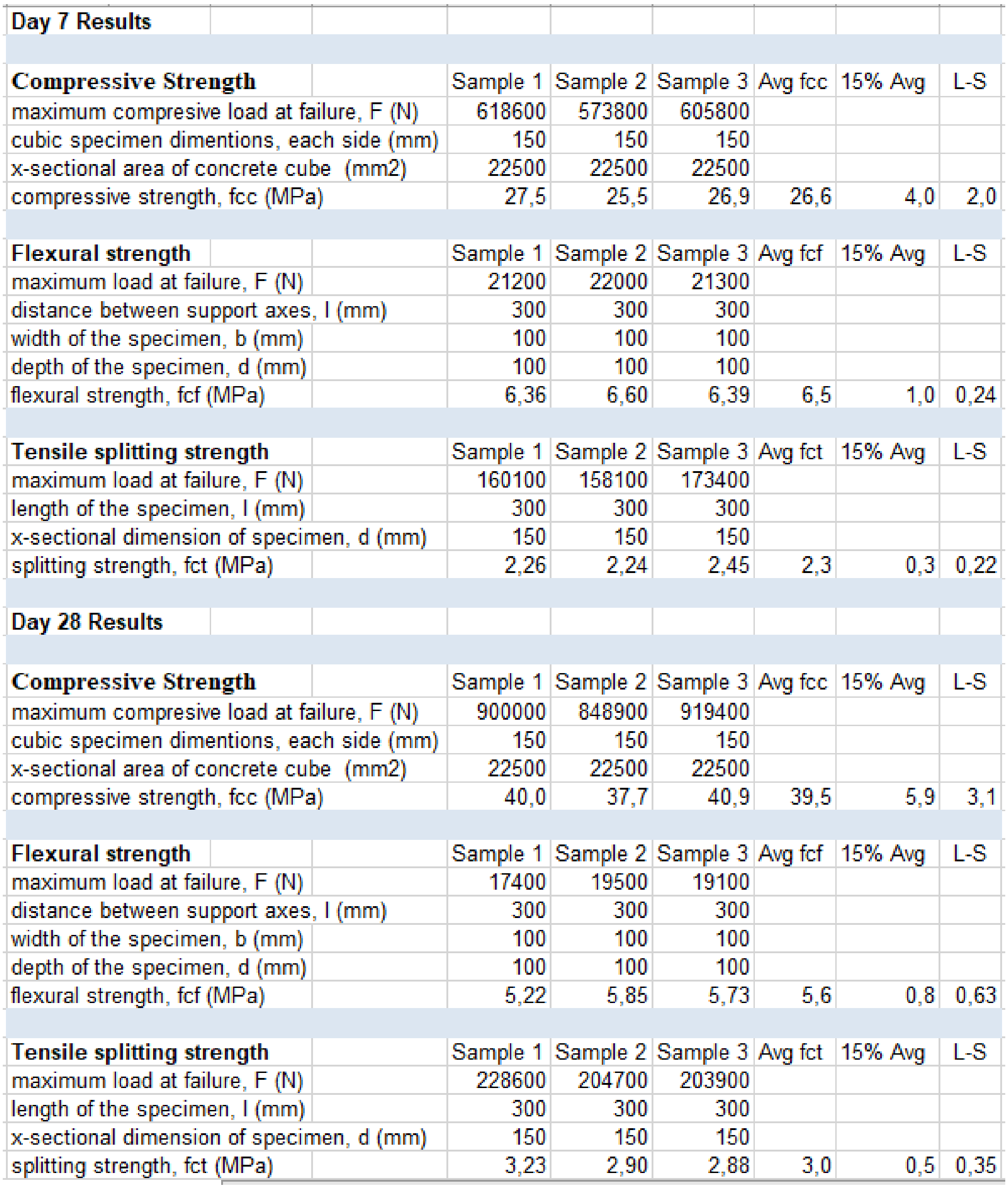


EC	Port Elizabeth	Noku Waste Mngt & Dev (Pty) Ltd	Arlington Landfill, Schoenmakerskop Road, Walmer
MP	Ferrobank	TMT Projects and Consultation (PTY) Ltd	39 Schonland, Ferrobank, Witbank
MP	Nelspruit	Khumqwa Ltd	30 Wilken Street, Rockies Drift, Nelspruit
KZN	Hammersdale	YNS Trading (Pty) Ltd	11 Buckman Boulevard, Hammarsdale
KZN	Ladysmith	Why Waste	12 Circle Road, Ladysmith
KZN	Cato Ridge	Rosel Developments (Pty) Ltd	7 Eddie Hagen Drive, Cato Ridge
KZN	Richards Bay	Khonzimpilo Multi-Purpose Co-Op Ltd	58b Ceramic Curve, Alton, Richards Bay
NC	Kimberley	Sanchodox (Pty) Ltd	18 Hendrik Van Eck Street, Kimberley
NC	Upington	Thebe-Ya-Setshaba Investment Holdings	41 Soutpan Street, Upington
GAUTENG	Midrand	Dinotshi Waste Into Worth Projects LTD	549 Boxer Road, Midrand
GAUTENG	Springs Baling		
and Holding	Kgona O Tsoge Trading Enterprise CC	89 Van Niekerk Road, Largo, Springs	
GAUTENG	Thembisa	Executive & Proactive Management	1 Bambanani Industrial, Ivory Park, Ext 2.
GAUTENG	Waltloo	Mehato Trading	54 Battery Crescent, Waltloo
Polowane	Polokwane	Phasha Property Investments PTY Ltd	Plot 10, Geluk, Polokwane
NW			
		Rustenburg	Pro Soil Distributors (Pty) Ltd
Street, Rustenburg			

Appendix G: Comprehensive test results

Mechanical strength test results

Table G-1: Control Mix



Day 7 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	618600	573800	605800			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	27,5	25,5	26,9	26,6	4,0	2,0
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	21200	22000	21300			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	6,36	6,60	6,39	6,5	1,0	0,24
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	160100	158100	173400			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	2,26	2,24	2,45	2,3	0,3	0,22
Day 28 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	900000	848900	919400			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	40,0	37,7	40,9	39,5	5,9	3,1
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	17400	19500	19100			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	5,22	5,85	5,73	5,6	0,8	0,63
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	228600	204700	203900			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	3,23	2,90	2,88	3,0	0,5	0,35

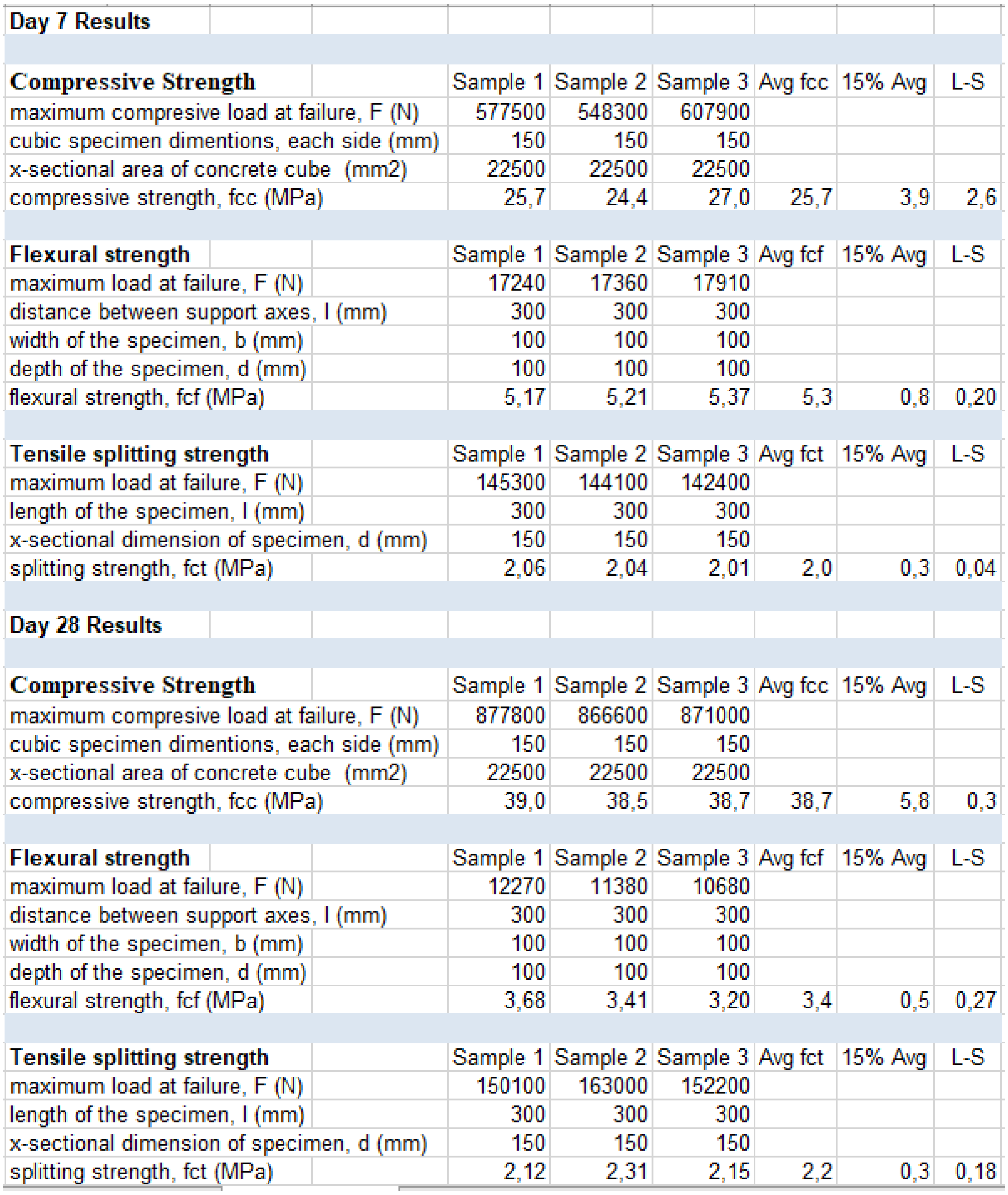
*__Notes__:

AVG- Average

H- Highest result

L- Lowest result

Table G-2: Crumb rubber content - 5%



Day 7 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	577500	548300	607900			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	25,7	24,4	27,0	25,7	3,9	2,6
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	17240	17360	17910			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	5,17	5,21	5,37	5,3	0,8	0,20
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	145300	144100	142400			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	2,06	2,04	2,01	2,0	0,3	0,04
Day 28 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	877800	866600	871000			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	39,0	38,5	38,7	38,7	5,8	0,3
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	12270	11380	10680			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	3,68	3,41	3,20	3,4	0,5	0,27
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	150100	163000	152200			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	2,12	2,31	2,15	2,2	0,3	0,18

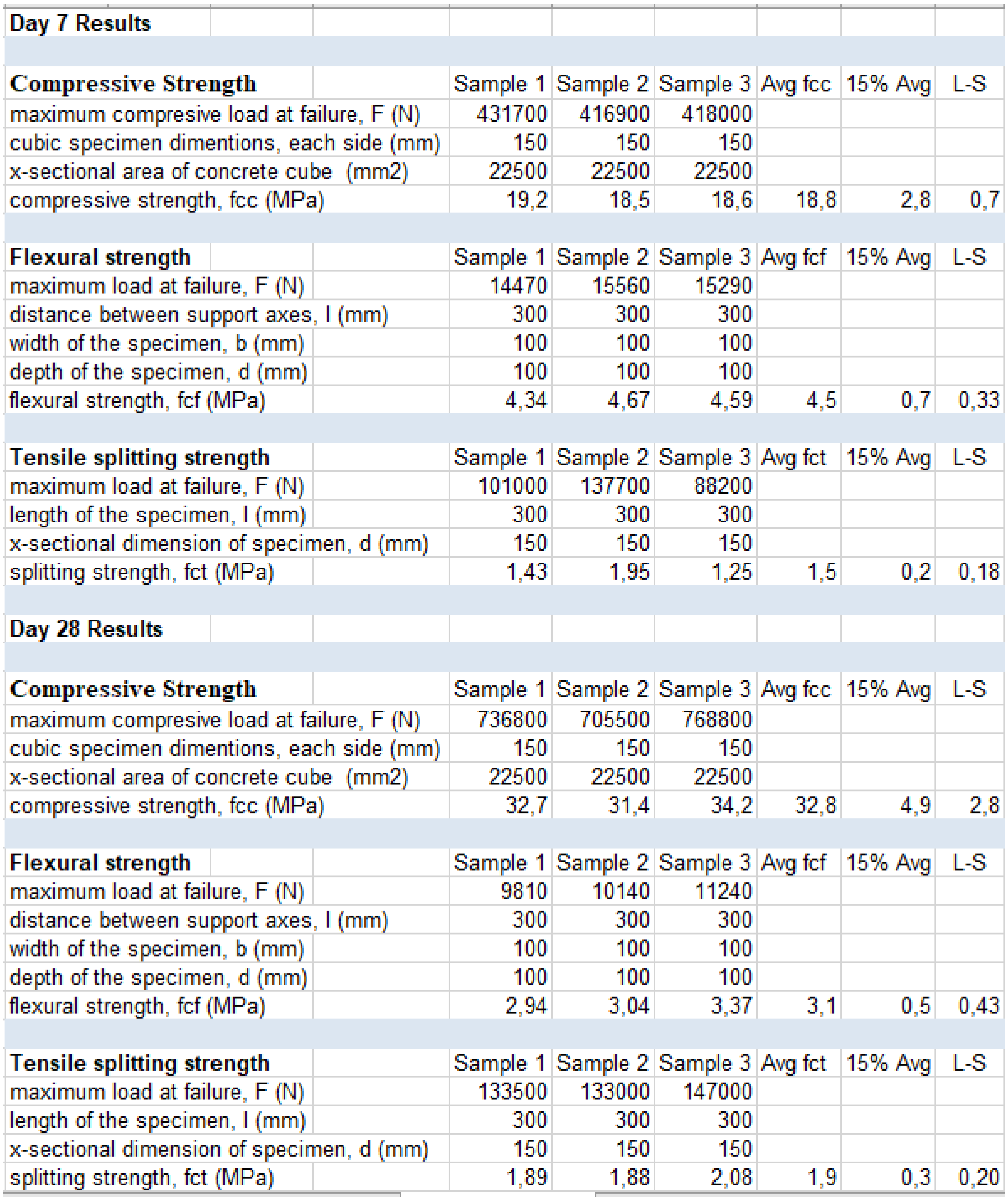
***Notes**:

AVG- Average

H- Highest result

L- Lowest result

Table G-3: Crumb rubber content - 10%



Day 7 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	431700	416900	418000			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	19,2	18,5	18,6	18,8	2,8	0,7
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	14470	15560	15290			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	4,34	4,67	4,59	4,5	0,7	0,33
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	101000	137700	88200			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	1,43	1,95	1,25	1,5	0,2	0,18
Day 28 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	736800	705500	768800			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	32,7	31,4	34,2	32,8	4,9	2,8
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	9810	10140	11240			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	2,94	3,04	3,37	3,1	0,5	0,43
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	133500	133000	147000			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	1,89	1,88	2,08	1,9	0,3	0,20

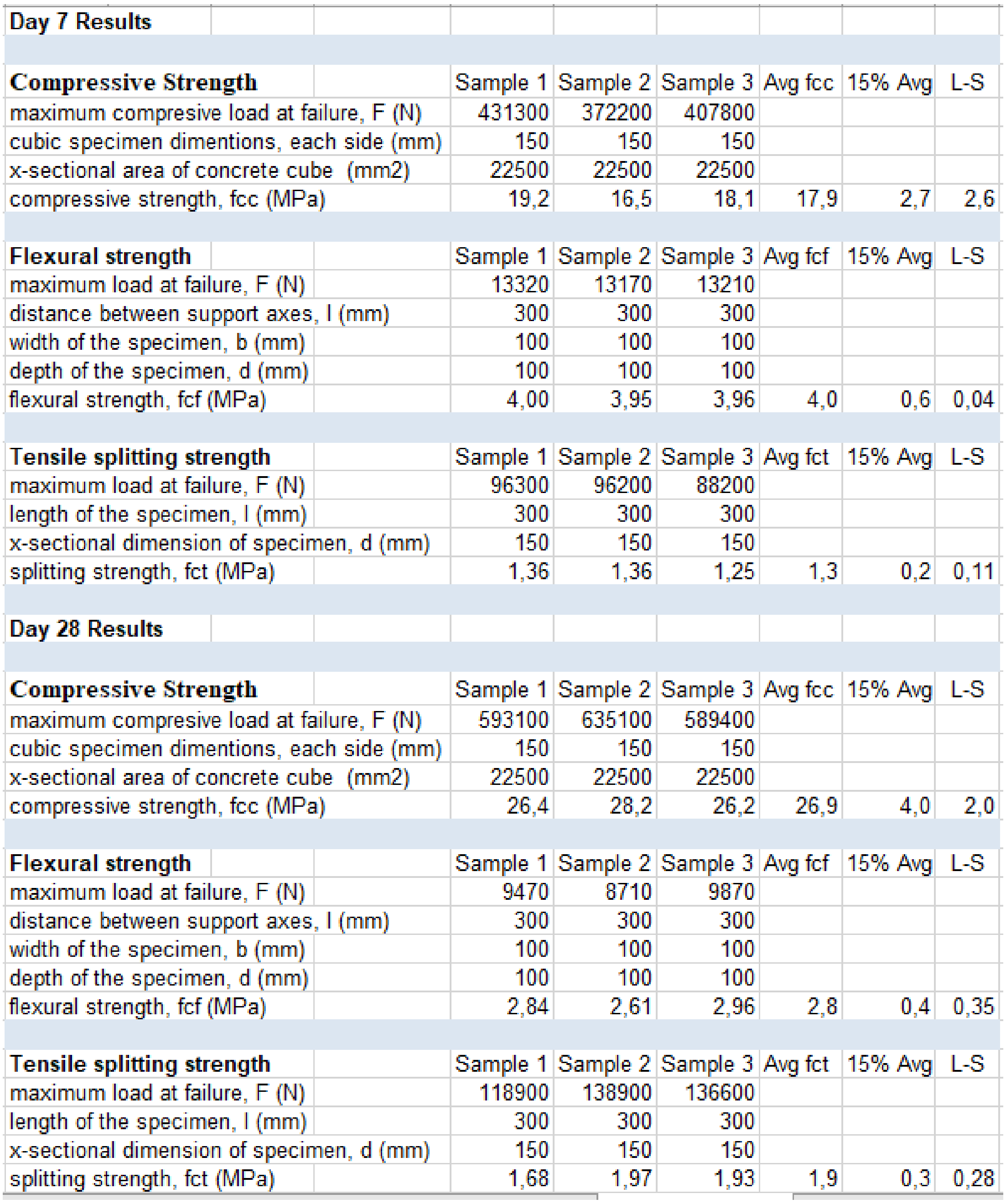
***Notes**:

AVG- Average

H- Highest result

L- Lowest result

Table G-4: Crumb rubber content - 15%



Day 7 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	431300	372200	407800			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	19,2	16,5	18,1	17,9	2,7	2,6
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	13320	13170	13210			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	4,00	3,95	3,96	4,0	0,6	0,04
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	96300	96200	88200			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	1,36	1,36	1,25	1,3	0,2	0,11
Day 28 Results						
Compressive Strength	Sample 1	Sample 2	Sample 3	Avg fcc	15% Avg	L-S
maximum compresive load at failure, F (N)	593100	635100	589400			
cubic specimen dimentions, each side (mm)	150	150	150			
x-sectional area of concrete cube (mm2)	22500	22500	22500			
compressive strength, fcc (MPa)	26,4	28,2	26,2	26,9	4,0	2,0
Flexural strength	Sample 1	Sample 2	Sample 3	Avg fcf	15% Avg	L-S
maximum load at failure, F (N)	9470	8710	9870			
distance between support axes, l (mm)	300	300	300			
width of the specimen, b (mm)	100	100	100			
depth of the specimen, d (mm)	100	100	100			
flexural strength, fcf (MPa)	2,84	2,61	2,96	2,8	0,4	0,35
Tensile splitting strength	Sample 1	Sample 2	Sample 3	Avg fct	15% Avg	L-S
maximum load at failure, F (N)	118900	138900	136600			
length of the specimen, l (mm)	300	300	300			
x-sectional dimension of specimen, d (mm)	150	150	150			
splitting strength, fct (MPa)	1,68	1,97	1,93	1,9	0,3	0,28

*__Notes__:

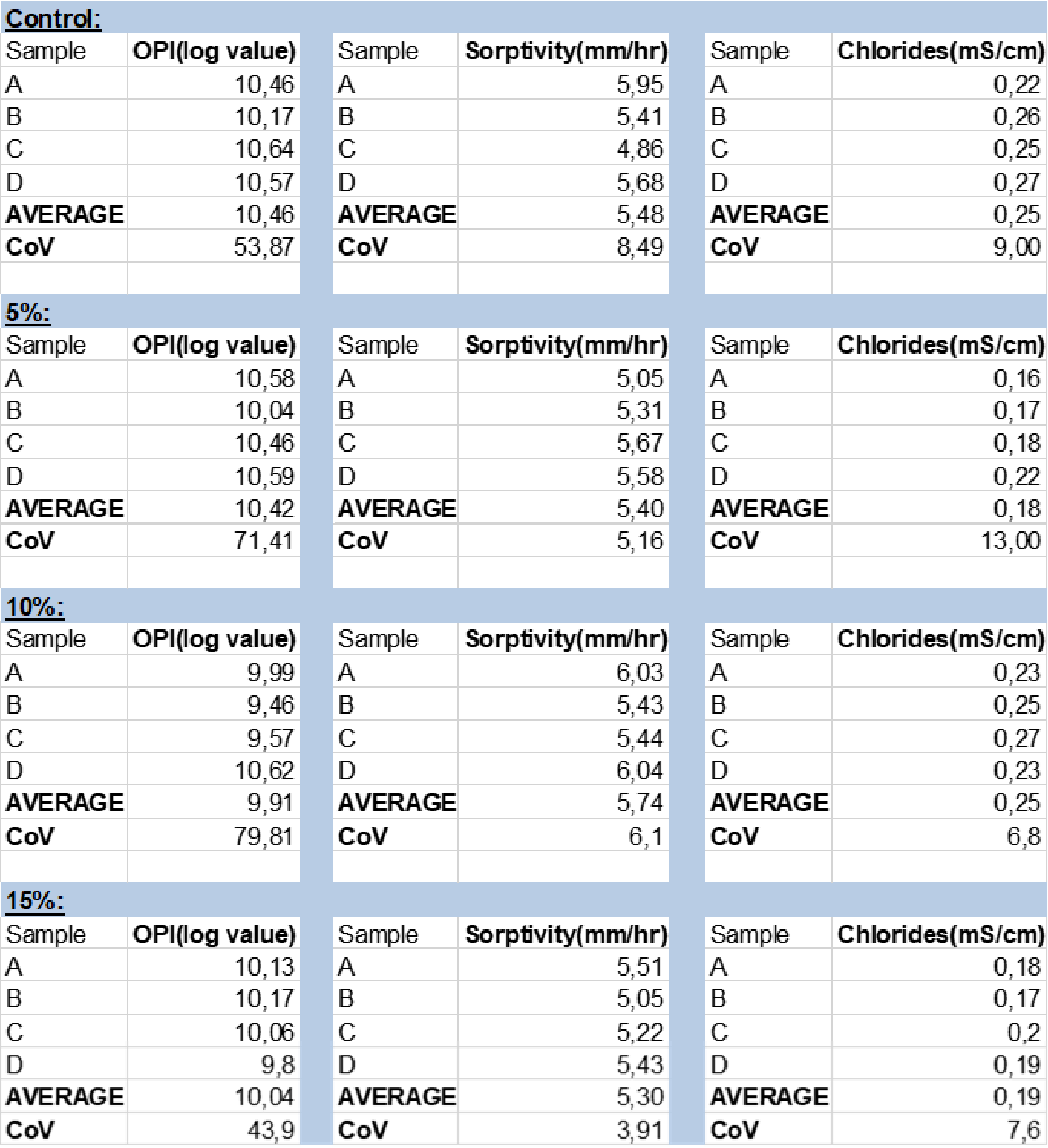
AVG- Average

H- Highest result

L- Lowest result

Appendix H: Comprehensive durability test results

Table H-1: Durability index test results



Control:

Sample	OPI(log value)	Sample	Sorptivity(mm/hr)	Sample	Chlorides(mS/cm)
A	10,46	A	5,95	A	0,22
B	10,17	B	5,41	B	0,26
C	10,64	C	4,86	C	0,25
D	10,57	D	5,68	D	0,27
AVERAGE	10,46	**AVERAGE**	5,48	**AVERAGE**	0,25
CoV	53,87	**CoV**	8,49	**CoV**	9,00

5%:

Sample	OPI(log value)	Sample	Sorptivity(mm/hr)	Sample	Chlorides(mS/cm)
A	10,58	A	5,05	A	0,16
B	10,04	B	5,31	B	0,17
C	10,46	C	5,67	C	0,18
D	10,59	D	5,58	D	0,22
AVERAGE	10,42	**AVERAGE**	5,40	**AVERAGE**	0,18
CoV	71,41	**CoV**	5,16	**CoV**	13,00

10%:

Sample	OPI(log value)	Sample	Sorptivity(mm/hr)	Sample	Chlorides(mS/cm)
A	9,99	A	6,03	A	0,23
B	9,46	B	5,43	B	0,25
C	9,57	C	5,44	C	0,27
D	10,62	D	6,04	D	0,23
AVERAGE	9,91	**AVERAGE**	5,74	**AVERAGE**	0,25
CoV	79,81	**CoV**	6,1	**CoV**	6,8

15%:

Sample	OPI(log value)	Sample	Sorptivity(mm/hr)	Sample	Chlorides(mS/cm)
A	10,13	A	5,51	A	0,18
B	10,17	B	5,05	B	0,17
C	10,06	C	5,22	C	0,2
D	9,8	D	5,43	D	0,19
AVERAGE	10,04	**AVERAGE**	5,30	**AVERAGE**	0,19
CoV	43,9	**CoV**	3,91	**CoV**	7,6

***Notes**:

OPI- Oxygen Permeability Index

CoV- Coefficient of Variation

Appendix I: AdCoM results

Table I-1: An extract of an AdCoM research (courtesy: Damian Ramrajh)

Paper mill ash content	Compressive strength	
	Day 7 (MPa)	Day 28 (MPa)
Control (0%)	23	35
5%	24	34
10%	25	38
15%	23	38
20%	20	36

Appendix J: Life Cycle Assessment (LCA) of vehicle tyres

Regarding sustainability issues; industries, governments and the public are all very much concerned with green engineering towards sustainable development and better environmental quality. Life Cycle Assessment (hereafter LCA) can be defined as a comprehensive analysis that explores a product interaction with the environment. Particularly, LCA estimates, through calculations, the energy and raw materials utilised in producing a product (that is the inputs) and any undesirable impact of the consequential pollutants released to the environment, including any impact on the health of humans (that is the outputs). Krömer *et al*., 1999; cited by Oikonomou and Mavridou (2009) conducted an LCA focusing on passenger vehicle tyres in order to contribute in the production green products with minimal negative effects on the environment. This was achieved by firstly studying, in each phase of the LCA, the impacts on the environment. The resulting tyre cycle was illustrated in a simplified version shown in Figure J-1.

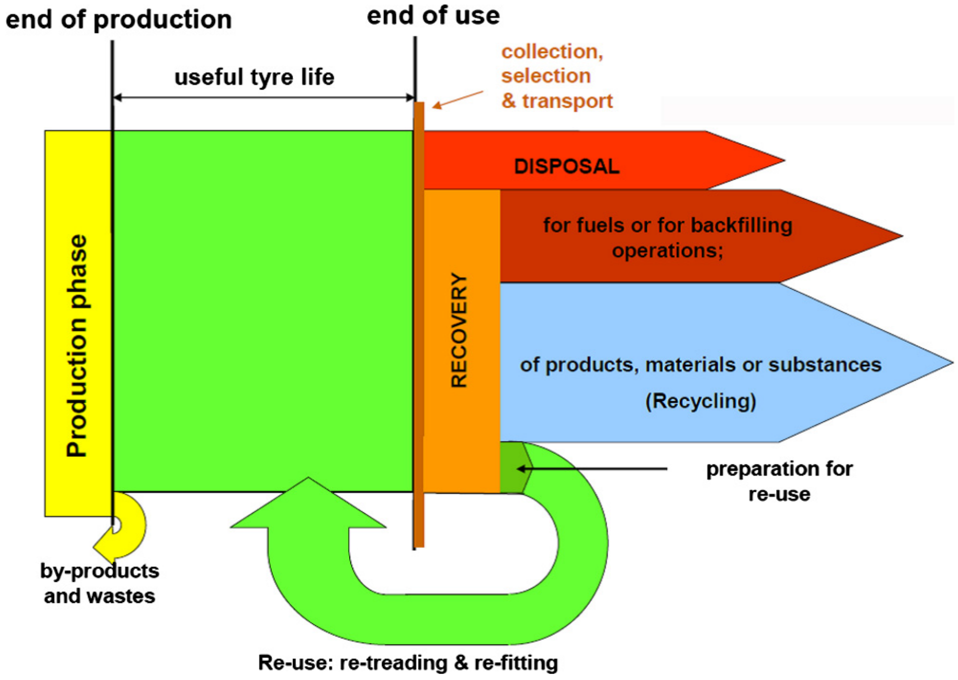


Figure J- 8: The life cycle of waste vehicle tyres (after Presti, 2013)

J-1: Stages in the LCA of motor vehicle tyres

Generally, the study concluded that there are five stages in the LCA of motor vehicle tyres;

Extraction of raw materials: The components making up a tyre come from diverse sources such as petroleum (chemicals, carbon black, synthetic elastomers), minerals (metal reinforcements, silica) and plants (natural rubber). About 6,9% of the total resource requirements in a tyre life is used in the extracting of raw material stage.

Tyre plant (production): The production phase uses about 4,8% of the entire resources in a tyre life cycle.

Distribution: tyres need to be transported between all the different life phases. About 0,2% of the total resources are utilised in this stage of the life cycle.

Use by vehicles on the road: A tyre's function in a vehicle is to absorb irregularities on road surfaces. In the process, the rubber compounds making the tyre are deformed due to heat and friction. A part of the energy produced in the engine dissipates to the external environment. Tyres are also exposed to recurring wear because of abrasion of the treads. The ultimate result is the lack of satisfactory depth of treads, the vehicle tyre forfeits its functional value. Generally, a truck tyre has a service life of about 180 thousand to 200 thousand km, and car tyres are removed from service after approximately 35 000 to 45 000 km. Concerning energy consumption, about 88% of the total resources used in the tyre life are required for the service live of the tyre on the car.

Recycling of worn tyres and waste management: Incineration of a light vehicle tyre may provide enough power for a 60-watt light bulb for approximately 40 days. The total life cycle energy may be reduced by re-treading to extend the service life and in the event displacing raw material use.

To eliminate negative impacts on the environment, the following is recommended at each stage of the LCA;

- Tyre steel cord may be replaced with the use synthetic fibres to decrease the quantity of generated waste
- Tyres can be used in cement kilns in place of traditional fuels

- Use of tyres during the waste-to energy combustion process
- Utilising scrap tyres as a filling material in construction.
- Granulate recovery (explained in the following section)

J-2: Granulate recovery.

Presti (2013) states that the recovery granulate involves a tyre chipping and shredding process using big machines that reduce tyres by cutting them into smaller fragments of varying sizes. The fabric and steel components are removed at a particular stage. The produced materials can be used in civil engineering as: roofing materials, paving blocks, as shock absorbing mats, flooring for sports stadiums and playgrounds, rubberised asphalt pavements, et cetera. The tyre particle size may differ, ranging up to 460 mm depending on the application. There are several methods and technologies used to reduce vehicle tyres to smaller fragments, namely; Cryogenic grinding, Wet-grinding, Hydro jet size reduction, and Ambient grinding. Ambient or mechanical grinding make use of knives and rotating blades to separate rubber fibres with the normally included steel fibres. The metallic material is removed, and the grinder's technology normally produces rubber crumbs of size ranging from 0,5mm to 5mm. Plate J-1 depicts an SEM (*Scanning Electron Microscope*) analysis of rubber processed with the ambient method.

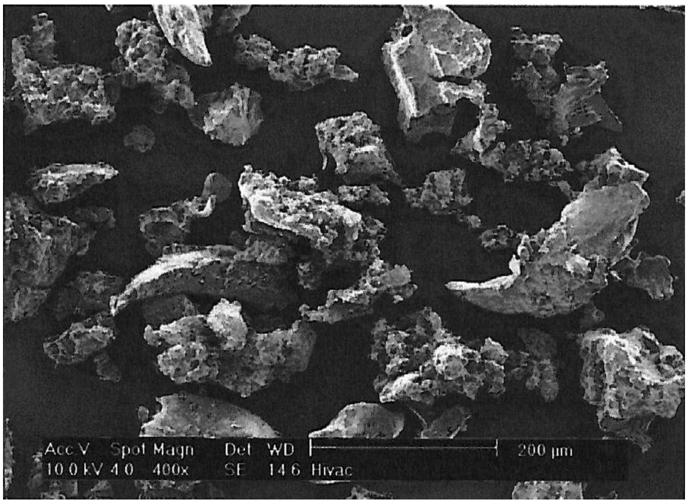


Plate J-1: An SEM analysis of rubber processed with the ambient method (after Presti, 2013).