FEASIBLE USE OF RECYCLED CONCRETE AGGREGATES AS UNBOUND ROAD BASE MATERIAL IN SOUTH AFRICA

By

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DECLARATION

I hereby declare that the dissertation submitted by me for fulfilment of Master of Engineering degree in Civil Engineering at the Central University of Free State is my original work and has not been submitted at another University as partial fulfilment for a degree. I have not given permission to other parties to copy my work and I have referenced and acknowledged other people`s work that was used in this dissertation.

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ABSTRACT

Sustainability is one of the biggest challenges facing the world today. Construction and demolition waste (C&DW) has become a financial burden globally. Landfills are reaching maximum capacity earlier than expected and one of the biggest contributors to this phenomenon is C&DW. This is generated by the need for new infrastructure, refurbishment and demolition of existing infrastructure as a result of urbanisation that is sweeping through the world. New avenues have to be explored to reduce the financial costs and environmental effects instead of the old-fashioned way of hauling C&DW to landfills.

There is uncertainty with regards to defining CD&W in the world: every country has its own definition, and there is no exact amount available for the total of CD&W generated worldwide. The composition of C&DW varies based on site activity and is, usually, mainly made up of concrete. The United States alone generates about 100 million tons annually of C&DW, and roughly more than 50% of the landfill volume is used for C&DW. About 5 to 8 million tons of C&DW is generated annually in South Africa, where the community is not keen to recycle and few organisations are involved in recycling.

C&DW is produced by crushing and screening of material from old infrastructure and may be produced by processing the material on site or off-site. There are mobile processing machineries available in the market which gives flexibility to production of C&DW. The material is crushed and screened for production and there is technology available to assist with the removal of detrimental substance and steel.

The recycling of C&DW is still in its early stages. Although the European Union and several American States have high expectancy in C&DW material as a commodity, it took ISO 9000 until 1996 to come up with standards for recycled material. In South Africa there are currently no local standards for C&DW and there is consequently a need to develop standards to promote the use of C&DW. The introduction of standards will give environmental value to the construction industry and eradicate financial losses, and will also assist to overcome barriers.

The South African experience regarding C&DW is not totally different to the world. The South African construction industry is not keen to recycle and uses mainly virgin aggregates from natural reserves. There are some similarities such as differences among local authorities with regards to the definition of C&DW. Most local authorities define C&DW as a waste generated through demolition, excavation and building activities. The Environmental Conservation Act, Act 73 of 1989, and the National Water Act, Act 36 of 1998 define waste as unwanted or surplus material, with potential to create pollution. The South African construction industry views the restrictive definition of waste as one of the barriers for implementation of recycling of C&DW. The C&DW in South Africa is mainly made of concrete. The concrete industry comprises cement manufacturers, aggregates producers, admixture suppliers,

cement extender suppliers, precast and readymix concrete producers, structural engineers, building contractors and small-scale concrete consumers such as home builders. This use of virgin aggregates has adverse effects on the environment. It also leads to more extraction and less usage as a result of availability of resources, towering energy consumption, pollution of the environment by $C0_2$ emissions, lack of rehabilitation, ecosystem disturbance and generation of waste and neglectful disposal.

The sieve analysis and densities of C&DW obtained from returned readymix concrete aggregates for the purpose of this study indicated the material was well graded and dense, which indicated the material could easily be compacted on site. The plasticity index test indicated that the material was non-plastic, which indicated in turn that the material would not be susceptible to big volumetric changes as a result of changes in moisture content.

It was found that the optimum moisture content was on the higher side and the maximum dry density was on the lower side when compared to virgin aggregates usually used as base course material in South Africa. The high optimum moisture content was due to absorption of water by the cementitious paste from previous concrete. The lower maximum dry density was due to loss of aggregates stiffness since C&DW was subjected to secondary crushing. The California bearing ratio (CBR) for C&DW was on the lower side resulting in loss of aggregates stiffness due to secondary crushing; the results were also inconsistent as a result of different classes of concrete blended to obtain C&DW.

It was found that the UCS met COLTO requirements for C3 and C4 material and it increased as the cement content increased. Contrary to unconfined compressive strength (UCS), the indirect tensile strength (ITS) was less than that of C3 and C4 material. The ITS increased as the cement content was increased which was a positive indication that higher ITS could be achieved. The maximum dry density of stabilised C&DW increased as well and the increase may be attributed to addition of cement and cementitious properties from crushed concrete aggregates which also contributed in the hydration process.

Physical and chemical test results obtained in this study indicated that C&DW could be successfully recycled, which correlates with the literature review. European countries and Japan have successfully recycled C&DW; ISO 9000 was established in 1996 for C&DW. South Africa has to change its perception towards C&DW and develop a local standard to be used by the industry to promote the use of C&DW.

CONTENTS

LIST OF ABBREVIATIONS

AADTT	Average annual daily truck traffic
ASR	Alkali-Silica Reactivity
ASTM	American Society for Testing Materials
ATC	Automatic Temperature Compensation
BS	British Standard
BSRM	Bench Scale Resilient Modulus
C&DW	Construction and demolition waste
CBD	Compacted Bulk Density
LBD	Loose Bulk Density
CBR	California Bearing Ratio
COLTO	Committee of Land Transportation Officials
CTE	The coefficient of thermal expansion
EIA	Environmental Impact Assessment
EWC	European Waste Catalogue
FWD	Falling weight deflectometer
GHG	Greenhouse gas
M	Grading modulus
GW	Well graded gravel
ICC	Consumption of Cement
IRI	Internal roughness index
ITS	Indirect Tensile Strength
LL	Liquid limit
LS	Linear shrinkage
LSME	Large scale model experiment
MDU	Maximum dry unit weight
MEPDG	Mechanical Empirical Pavement Design Guide
NEMA	National Environmental Management i
OMC	Optimum moisture content

pH	Potential Hydrogen
PI	Plasticity index
RAP	Recycled Asphalt Pavement
RCA	Recycled Concrete Aggregates
RMC	Ready Mix Concrete
RPM	Recycled Pavement Material
RSA	Republic of South Africa
RSG	Road surface gravel
SANS	South African National Standard
SN	Structural number
SP	Poorly graded sand
SRM	Summary Resilient Modulus
SRPM	Stabilized road pavement material
SRSG	Stabilized road surface gravel
TMH	Technical methods for highways
UCS	Unconfined compressive strength
UK	United Kingdom
USA	United States of America
USCS	Unified soil classification system
WGR	Waste generation
XRD	X-ray diffraction

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CHAPTER 1: INTRODUCTION

1.1 Background

Concrete is one of the most important and most used construction materials. The usage is estimated at one ton per capita per year throughout the world. This huge dependence on concrete is compelling economic justification to look for ways of using this material more than once by recycling the material (Elias-Ozkan & Duzgunes, 2002). Concrete is manufactured and consists of cement, aggregates, water and admixture. The aggregates such as granular materials like sand, and crushed stone form the bigger part of concrete. Traditionally aggregates were easily available at affordable prices, but recently the use of aggregates from natural resources has been challenged by academia and industry at international level (Limbachiya et al., 2004).

Construction and demolition waste (C&DW) is undergoing a dramatic change in the world. It has become one of the biggest budget costs for local government (Samton, 2003). Landfills are reaching maximum capacity and most are scheduled to close a few years down the line. There is a need for recycling of CD&W (Samton, 2003). The construction industry has to find alternatives for using C&DW instead of the old-fashioned way of hauling C&DW to landfills. Reduction of waste, waste material reuse and recycling are among the alternatives to be considered. The environmental impact of the construction industry is huge and therefore necessitates a need to find alternatives to hauling C&DW to landfills (Smith-Pursley, 1997).

The need to recycle concrete is more than cost-orientated. The advantages include reduced environmental harm and protection of natural resources by not using the valuable land fill space. The recycled concrete aggregates may also be more durable than virgin since they have already been exposed to freeze-thaw cycles (Elias-Ozkan & Duzgunes, 2002). Recycled concrete aggregates can be obtained from concrete that has failed due to structural reasons, chemical attack or unsuitable cements and aggregates or one obtained from structures that have reached the end of their life-span (Wilcken & Fleischer, 1999).

Recycled concrete aggregates may be used as water-bound or unbound base course in pavement layers. The unbound base course in pavement layers can contain 20% of asphalt without the performance and durability being affected (Wilcken & Fleischer, 1999). Wilcken and Fleischer (1999) state that "*Being able to recycle 100% of old road concrete into new concrete roads can be described as ‘state of the art’ today. Depending on the condition of old concrete pavement, old road concrete can be reprocessed several times over to form recycled aggregates for new road concrete or for unbound base courses".*

1.2 Problem statement

The construction industry produces 5 to 8 million tons of construction and demolition waste (C&DW) per annum in South Africa (Kutegeza & Alexander, 2004). The South African community is not keen on recycling, and there are no recycling paths, although a small number of people do actually recycle, according to the Cement and Concrete Institute (2011), as cited by Immelman (2013).

There are no up-to-date figures regarding the quantities of recycled concrete in South Africa because the construction and demolition waste (C&DW) is not subdivided into its constituents. The figures of the general C&DW are also not accurate or up to date.

The lack of accuracy in quantities of C&DW in RSA emanates from lack of consistency in defining C&DW and lack of national information centre for C&DW. There is intermingling of C&DW, illegal dumping and lack of weigh bridges and no recording of C&DW in some of the dumping sites which leads to wrong C&DW statistics (Macozoma, 2008).

The construction industry in South Africa does not believe that recycled aggregates can produce the same performance as virgin aggregates. The practitioners do not want to change from virgin aggregates which have been tried and tested. The construction industry is not adopting techniques which encourage the use of recycled concrete which will result in recovery of construction and demolition waste (Macozoma, 2002).

There is limited information and technical publication on the use of recycled concrete aggregates as pavement base layers in South Africa. Research which has been conducted in other countries indicates a success in the use of recycled concrete aggregates as base in pavement layers (Macozoma, 2002).

1.3 Significance of research

There is a need for research to be done on the use of recycled concrete aggregates to make more technical information available the general public, which will encourage the use of recycled concrete aggregate in pavement base layers. The significance of this research is to explore and encourage the use of C&DW as base course material in the construction industry, this is important when considering the shortened lifespan of landfills due to C&DW and the pollution of the environment when extracting and producing virgin aggregates. The information obtained from this research will assist the construction industry with technical information required to incorporate C&DW in the new infrastructure.

1.4 Research Aim

The purpose of this research is to get technical information on C&DW in order to reduce illegal dumping of C&DW, increase the life span of dumping sites and reduce consumption of virgin aggregates.

1.5 Hypothesis

It is feasible to use recycled concrete aggregates as unbound pavement base course material, more research has to be done to assist the construction industry with technical information for using C&DW in new infrastructure.

1.6 Objectives

To test C&DW for application as unbound road base material in South Africa with an objective of using them as replacement for virgin aggregates.

1.7 Thesis layout

The thesis layout is as follows:

- Chapter 1 Introduction

This chapter covers the background, problem statement, significance of research, research aim, hypothesis and objectives.

- Chapter 2 Literature review

This chapter covers the review of the feasible use of recycled concrete aggregates as unbound road base material.

- Chapter 3 The South African Experience

This chapter covers the feasible use of recycled concrete aggregates as unbound road base material in South Africa.

- Chapter 4 Materials and methodology

This chapter covers the sampling of materials and laboratory test methods that were used for the experimental work.

- Chapter 5 Discussion of results

This chapter covers the physical and chemical properties of recycled concrete aggregates when used as base course material as observed during the experimental work in relation with literature review.

- Chapter 6 Concluding remarks

This chapter is a summary of the study, the conclusion and recommendations for the future.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature review concerning C&DW as base course material. It starts with a definition of the term C&DW, followed by issues concerning generation of C&DW.

2.2 Definition of C&DW

There is limited unanimity with regards to the definition of C&DW. C&DW is generally defined as waste which originates from construction, renovation and demolition activities. This may include additional damaged products and materials generated by the construction work and temporary on-site activities. Similar definitions of C&DW can be obtained in Hao et al. (2007), Shen et al. (2004) and Fatta et al. (2003).

The European Waste Catalogue (EWC, 2002) as cited by Bertram *et al*., (2002) gives an all-inclusive classification of C&DW in relation to its constituent materials. Different perspectives about C&DW result in different philosophies. The Japanese regard C&DW as a by-product instead of waste and much emphasis is placed on reuse and recycling (Nitivattananon & Borongan, 2007). Most studies define C&DW according to the characteristic of its research since only defining the waste specifically is likely to result in a study that is meaningful for disparate practices (Lu & Yuan, 2011).

There is an increase in the use of C&DW in literature. From a landfill point of view, this term is used for all solid waste even though construction waste and demolition waste are significantly different in terms of their quantities, according to Li (2006), US EPA (2002), Bossink and Brouwers (1996).The concept of C&DW should represent the material from absolutely only construction activities irrespective of whether its origins are construction or demolition activities (Lu and Yuan, 2011).

Although some studies tend to define C&DW by regarding it as appreciable wasted materials, there is also another study which suggests that C&DW waste should be valueless construction work, according to Serpell and Alacrcon (1998) as cited by Lu and Yuan (2011).This perspective goes back to an early study by Skoyles (1976), who differentiated between direct and indirect waste in terms of money loss, as may happen if the thickness of the concrete slab is greater than that specified. This perspective, which is also supported by Formoso et al. (2002) and Alarcon (1998), makes it possible to take into consideration both the material loss and the non-value adding work. The most recent studies have overlooked this approach, probably due to the ease with which waste materials can be seen and measured, according to Formoso et al. (2002) as cited by Lu and Yuan (2011).

Although C&DW is defined differently, there is a common understanding that the waste comes from various processes such as construction and demolition. The various definitions are used for carrying out individual researches. The constituents of C&DW usually include concrete, asphalt, wood, metals, gypsum, wallboard and plastic (Yuan, 2011).

C&DW should be defined by how it is generated and how it is intended to be used, this will give more information regarding the origin of the recycled material, which will assist with traceability which in return will give technical information with regards to properties of virgin materials initially used. The intended use of recycled material will also add more value to the material and change the current negative perception of C&DW in South Africa, since C&DW won't be perceived as waste but rather as re-usable material which will open more avenues for C&DW.

2.3 C&DW generation

There are many studies with regards to the quantity of C&DW in different countries and regions. The USA generates over 100 million tons of C&DW annually, according to Mills et al. (1999), and about 29% of solid waste in the USA is generated by the construction industry. More than 50% of the landfill volume is used by C&DW, according to Ferguson et al. (1995) and 70 million tons of C&DW is discarded annually, according to Sealey et al. (2001). About 20-30% of all waste ending up in Australian landfills is generated by construction activities, according to Shen et al. (2004).

About 38% of the solid waste in Hong Kong is generated by the construction industry, and the amount of annually generated C&DW between 1993 and 2004 has doubled ,according to Tam (2008), as cited by Lu and Yuan (2011).The above statistics paint a picture of the proportion of C&DW as a percentage of the total solid waste in some economies. It should be noted that when the waste from new construction and that from demolition is separately considered, it becomes evident that the volume of waste generated by demolition activities is greater than that of construction activities. The information according to Bossink and Brouwers (1996) gave an indication that the annual volumes of C&DW in Germany was about 30 million tons for demolition and 14 million tons from construction waste and the report by the US EPA (2002) indicated that the majority of C&DW was generated by demolition and renovation, which was estimated at 48% and 44% on an individual basis.

It is challenging for the public to realise challenges facing society and the industry due to inaccurate data with regards to C&DW. Over the past few decades, the research about C&DW and its untoward impact on the environment has intensified. However, countries such as China (according to Wang et al., 2008), Malaysia (according to Begum et al.,2007), Turkey (according to Esin and Cosgun, (2007) and Thailand (according to Kofoworola and Gheewala, 2009) are lagging behind with regards to reporting the quantity of C&DW they are generating.

2.4 Origins of C&DW

The C&DW emanates from different sources in the life cycle of the construction projects, from the start to construction and demolition (Shen et al., 2004). Researches classify the origins of C&DW into the following ten categories: contractual, design, procurement, transportation, on-site management and planning, material storage, material handling, site operations, residual, and others (Osmani et al., 2008; Kulatanga et al., 2006; Gavilan & Bernold, 1994). These origins are illustrated in Table 2.1 below

Table 2.1: Origins and causes of C&D waste

Origins of waste	**Causes of waste**
Contractual	Errors in contract documents
	Contract documents incomplete at commencement of construction
Design	Design changes
	Design and detailing complexity
	Design and construction detail errors
	Unclear/Unsuitable specification
	Poor coordination and communication (late information, last-minute client requirements, slow drawing revision and distribution)
	Selection of low-quality products
	Lack of attention to standard sizes available on the market
	Designers` unfamiliarity with alternative products
Procurement	Ordering errors (i.e., ordering items not in compliance with specification
	Over-allowances (i.e., difficulties to order small quantities)
	Supplier errors
	Purchased products that do not comply with specification
Transportation	Damage during transportation
	Difficulties for delivery vehicles accessing construction sites
	Insufficient protection during unloading
	Inefficient methods of unloading
On-site management and planning	Lack of on-site waste management plans
	Improper planning for required quantities
	Delays in passing information on types and sizes of materials and components to be used
	Lack of on-site material control
	Lack of site supervision
Material storage	Inappropriate site storage space leading to damage or deterioration
	Improper storage methods
	Materials stored far away from point of application
Materials handling	Materials supplied in loose form
	On-site transportation methods from storage to the point of application
	Inadequate material handling
	Damages during transportation
	Unfriendly attitude of project team and labourers
Site operation	Accidents due to negligence
	Unused materials and products
	Equipment malfunction

	Poor craftsmanship
	Use of wrong materials resulting in their disposal
	Time pressure
	Poor work ethics
Residual	Waste from application processes (i.e., over-preparation of mortar)
	Off-cuts from cutting materials to length
	Waste from cutting uneconomical shapes
	Packaging
Other	Weather
	Vandalism
	Theft

(Osmani et al., 2008; Kulatunga et al., 2006: Gavilan & Bernold,1994)

Origins such as contractual, design and procurement cause indirect C&DW since their effects will be checked only during the construction stage. This gives a suggestion that the C&DW can be effectively reduced by implementing strategies that embrace life-cycle thinking instead of merely focusing on the construction stage (Yuan, 2011).

Changes in the design that happen during construction are widely considered as major sources of C&DW (Ekanayake & Ofori, 2004; Faniran & Caban, 1998). This is in agreement with the study from Osmani et al. (2008), which found that about 33% of on-site waste related directly or inversely to the design of the project. The changes in the design of the project can cause waste in two ways. The first one is if the construction materials have already been bought based on the original design, meaning the material cannot be resold or returned to the supplier and therefore has to be dumped. The second one is if the change in the design of the structure which has already been built is likely to result in that part of the structure being dismantled, so that the material cannot be saved or reused (Faniran & Caban, 1998).

2.5 Measuring C&DW

There have been efforts to report C&DW as a percentage of total municipal solid waste (MSW), so that the comparison can be made to establish high or low waste generation (WGR). Tam (2008) established that C&DW contributes about 19% and 14% of the waste that ends up at landfills in Germany and Finland respectively, and about 38% in Hong Kong. The comparisons should be cautiously handled since the percentages are not only influenced by construction activities but by the size of a country`s economy and population and the social conduct as well. Table 2.2 gives a summary of previous research into WGR.

Table 2.2: A summary of previous studies on WGR

Author	**Country**	**Measurement of WGR**	**Methodology**	**Main conclusions**

Skoyles (1976)	UK	Percentage by weight (of the amount required according to design)	Direct observation and comparing contractors` records	2%-15% by weight according to the amount purchased for 37 materials
McGregor et al. (1993)	USA	Weight and percentage of total waste from an individual project	Questionnaire and telephone survey	Varied with construction type and project cost
Bossink & Brouwers (1996)	Netherlands	Percentage by weight (of purchased materials)	Sorted and weighed the waste materials	1%-10% by weight of the amount purchased for 7 materials, with an average of 9%
McDonald & Smithers (1998)	Australia	The volume (m^3) of waste generated per m^2 of gross floor area	Sort in waste bins and delivery records of bins	Total waste rate: $0.084m^3/m^2$
Forsthe & Marsden (1999)	Australia	Waste-ordered materials - in-situ quantities	In-situ quantities were from drawing or site measurement; ordered materials were from delivery and order documents	Maximal and minimal generation rate for 8 materials by percentage in two projects
Poon et al. (2001)	Hong Kong	Percent by weight or volume according to different materials	Site observation and questionnaire	1-8% for public housing; 1-100% for private housing
Morris Specification Inc. (2001)	Canada	N/A	N/A	WGRs for main construction materials (wood, drywall, metal, concrete, other) are given
Formoso et al. (2002)	Brazil	Waste% = [(Mpurchased-Inv)-Mdesign]/Mdesigned;Where Inv indicates the final inventory materials	Direct observation and contractor`s records	19.1%-91.2% by weight according to the amount purchased for 8 materials
Treloar et al. (2003)	Australia	Not clear	Consultation with construction employees	3%-10% for eight materials
Poon et al. (2004)	Hong Kong	The volume (m^3) of waste generated per m^2 of gross floor area	Visual inspection, tape, measurement, truck load records	Total waste generation rate: $0.176m^3/m^2$(C); 0.4-$0.65m^3/m^2$(D)
Lin (2006)	Taiwan	The volume (m^3) of waste generated per m^2 of gross floor area	The Neutral Network Method	$0.85m^3/m^2$ for factory (D); 0.54-$0.66m^3/m^2$ for residential (D)
Tam et al.(2007)	Hong Kong	Wastage level (%T)=(Mp-Mu)/(Mu x 100; where Mp is the purchased material and Mu is the used material (in m^3 for concrete, in ton for reinforcement, in m^2 for formwork, in m^2 for brick/block, in m^2 for tile)		Different sub-contracting arrangement

(Yuan, 2011)

2.6 Production of C&DW aggregates

It is very important to know alternatives available to generators of C&DW. The options are source separation on-site which is done according to the progress of the work, and off-site separation which is done by a recycling facility and off-site separation which is done by waste haulers (Smith-Pursley, 1997).

The production C&DW is crushed to create lumps and transported to the site where it is crushed and screened. The lumps are fragmented down and screened to form aggregates. Up to 250 tons per hour of old concrete can be crushed and about 200 tons per hour of high-grade concrete aggregates can be produced (Wilcken & Fleischer, 1999).

There are number of different processes for crushing and sieving of C&DW since such material often contains foreign materials such as metals, wood, hardboard, plastics and paper. Therefore, the processing has to involve removing large pieces of these foreign materials mechanically or manually before the product is crushed and cleaned (Limbachiya et al., 2004).

The recycling process is still at a young age, although the European Union and several American States, like California, have a high expectancy in recycled material content in the new commodity. It took ISO 9000 and 1400 until 1996 to have standards for recycled commodities. Specifications in South Africa have to be determined before the product can be used, and this is a complicated process which involves various stages (Integrated Waste Management Board [IWMB], 1999).

The recycling process which requires specification of the product will add economic and environmental value to the construction industry. The specification of the product will include factors such as colour, texture, dimension and strength. The absence of the specifications hampers the innovative use of the product by architects and construction practitioners (IWMB, 1999).

2.6.1 Crushers

The new technology can provide some sites with machines to crush and sort recycled concrete aggregates. The mobile concrete plants can be set up near sites that are removing concrete, and the recycled concrete can be used which will reduce the filling of landfills and the use of virgin aggregate

(Bolden, 2013) (Figure 2.1).

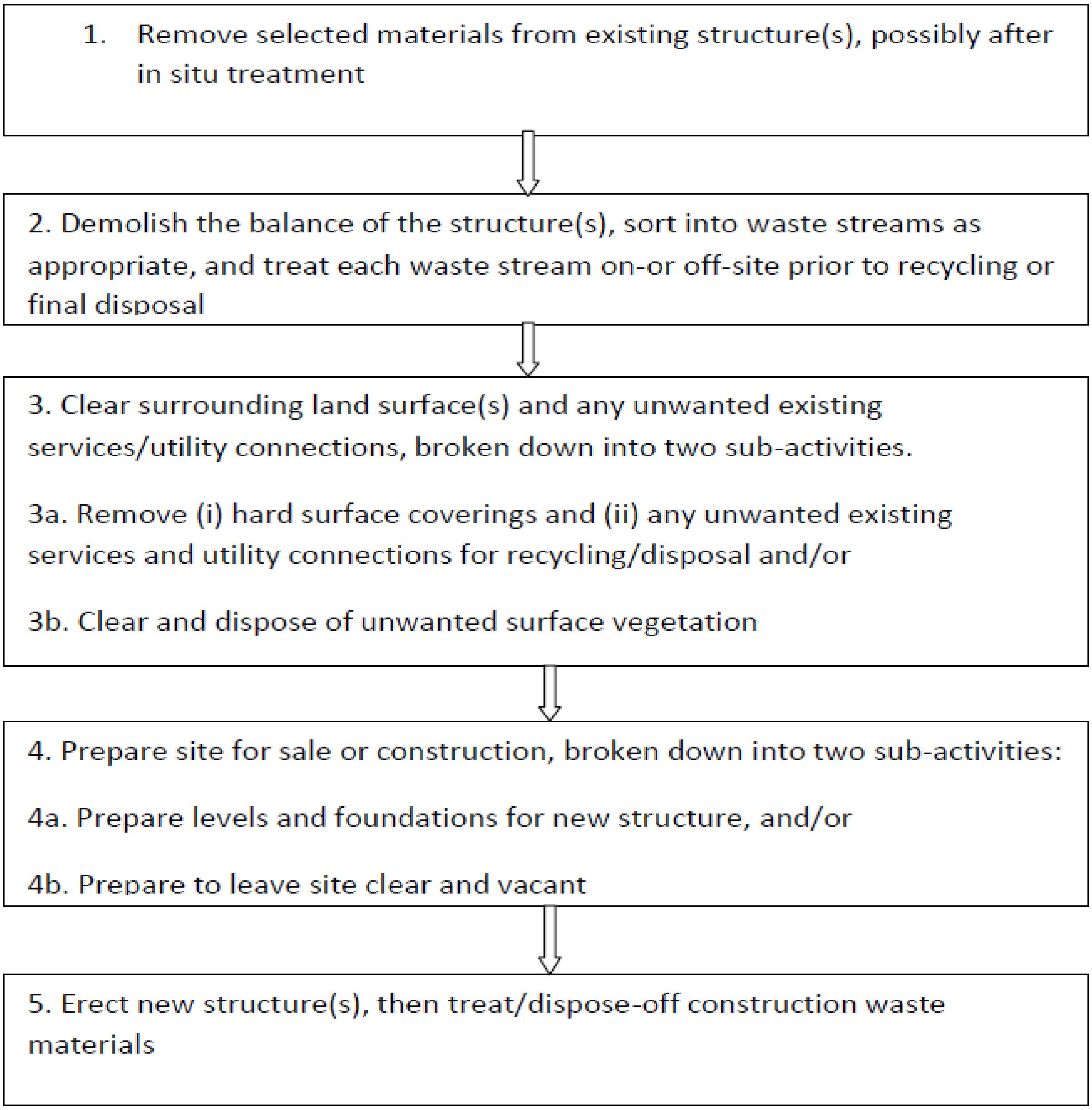
Figure 2.1: Mobile crushing plant (Texas Lone Star Materials. 2013. Available from: www.txlsm.com [Accessed 2013])

Portable crushing plant can be used for crushing concrete rubble to a certain size and properly screening it, similar to natural aggregates. The machines use magnets to separate steel from concrete. Most of the time the steel is recycled at steel plants and recycled concrete is used in construction (Bolden, 2013) (Figure 2.2).

Figure 2.2: Mobile crushing plant (Texas Lone Star Materials. 2013. Available from: www.txlsm.com [Accessed 2013])

There are five elementary activities found on recycling sites as illustrated in figure 2.3. The recycling can be done on- and off-site; the choice of whether crushing and sorting should be done on- or off-site is based on the following factors (Symonds and COWI, 1999):

i) The attainability of varying types of machines
ii) The quality of aggregates to be produced on site
iii) The accessibility and availability of time on site
iv) The distance between collection site, the processing site and final place.



1. Remove selected materials from existing structure(s), possibly after in situ treatment

2. Demolish the balance of the structure(s), sort into waste streams as appropriate, and treat each waste stream on-or off-site prior to recycling or final disposal

3. Clear surrounding land surface(s) and any unwanted existing services/utility connections, broken down into two sub-activities.

3a. Remove (i) hard surface coverings and (ii) any unwanted existing services and utility connections for recycling/disposal and/or

3b. Clear and dispose of unwanted surface vegetation

4. Prepare site for sale or construction, broken down into two sub-activities:

4a. Prepare levels and foundations for new structure, and/or

4b. Prepare to leave site clear and vacant

5. Erect new structure(s), then treat/dispose-off construction waste materials

Figure 2.3: Basic activities found on demolition and construction sites (Symonds & COWI, 1999:p11)

Larger off-site crushing and sorting facilities work like normal aggregates quarries by building stocks of varying specification materials which gives them the ability to supply big contracts without delays. Some operations mix virgin aggregates and C&DW derived aggregates;and this practice is increasing in UK, Italy and Spain (Symonds & COWI, 1999).

Off-site facilities are effective with regards to removing wood, plastic wastes and other contaminants and this is helpful with regards to ensuring the final products meet the acceptance criteria. Off-site operations are those at which material is dropped and their operation makes C&DW aggregates very fast (Symonds & COWI, 1999).

Off-site operations which take C&DW from third parties are likely to have challenges with irregular and unpredictable product performance which may contain hazardous substances as a result of the manner inf which the structure was demolished. Some operations overcome this by controlling the demolition process and by intensifying the inspection of incoming material before and during the processing stage (Symonds & COWI, 1999).

Table 2.3 is a summary of key factors which determine whether crushing and sorting facilities should be on site or off site (Symonds & COWI, 1999).

Pros and Cons of On and Off-site crushing and sorting	
Advantages of on-site crushing and sorting: lower materials handling and transport costs lower machinery capital costs less transport disruption to surrounding areas (if recycled materials can be used on-site)	Disadvantages of on-site crushing and sorting: conflicts between site operations and space demands for materials and machinery higher machinery operating costs per tonne of C&DW more local noise and dust nuisance less flexibility about where/when recycled materials can be used construction may be delayed
Advantages of off-site crushing and sorting: easier to reduce and/or mitigate adverse environmental impacts on surrounding areas more practical to use a wider range of higher capacity equipment lower machinery operating costs per tonne of C&DW easier to control quality of recycled materials possible to hold stocks, thereby making positive marketing of recycled materials easier	Disadvantage of the off-site crushing and sorting: proper control of demolition process essential (to avoid arrival of unknown quality materials) higher materials handling and transport costs higher machinery capital costs fixed costs of recycling the site (land etc)

Table 2.3: Factors which determine whether crushing and sorting facilities should be on site or off site (Symonds & COWI, 1999)

2.6.2 Sorting techniques

The sorting of materials is very important when recycling C&DW. Waste materials have to be sorted before they proceed to the production stage. Sorting can be done by separating larger different materials and this will decrease the amount that proceeds to the production stage. Material such as scrap, ferrous metals, cables, asbestos, gypsum and wood should be separated during the sorting stage. The quality of the end product drops if sorting of materials is omitted. The deconstruction and of the building should be considered in the design stage in order to make it easier for C&DW to be sorted once the building reaches its life span (Mulders, 2013).

The description that follows is mainly based on the presentation in a meeting in the UK (the 1997 AAS seminar, May 1997, London) by Deutang Remex, one of the leading German operations of C&DW recycling facilities, and the information was supplied by manufacturers of C&DW equipment. It is generally accepted that German C&DW facilities give a good representation of the best technology; Remex are not demolition contractors, but take C&DW from plenty of contractor of similar nature (Symonds & COWI, 1999).

The incoming material is weighed and checked, and separated into a series of disparate stockpiles for:

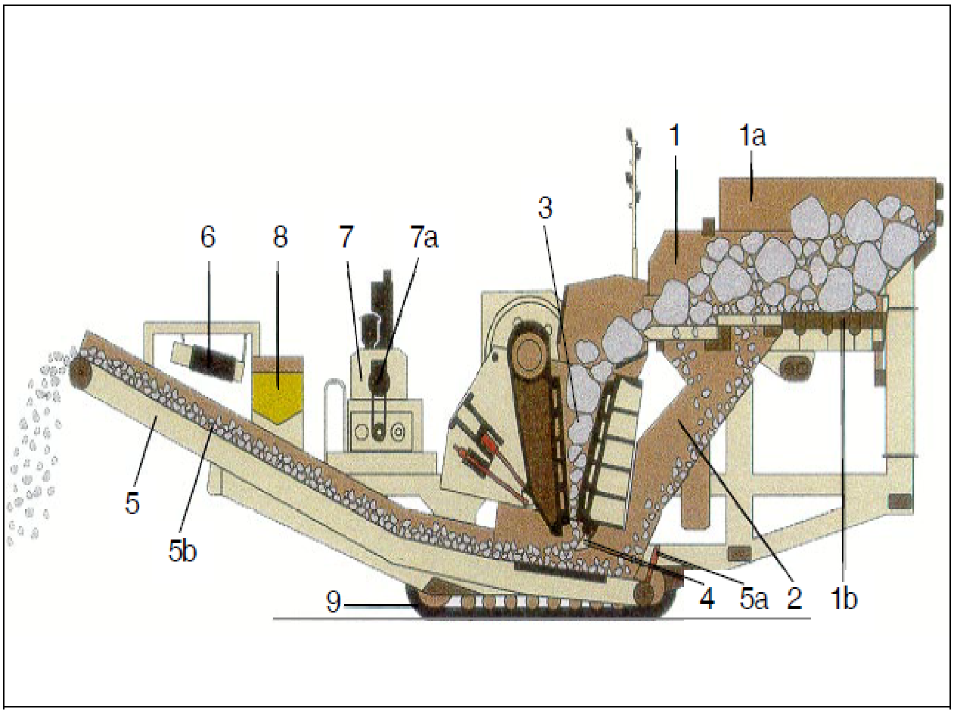
a) Fragmented bricks and tiles
b) Concrete with embedded rebar
c) Concrete without embedded rebar
d) Assorted C&DW.

Fragmented bricks, tiles, concrete with embedded rebar and concrete without embedded rebar are screened on a pre-sieving process to eliminate the 0-45mm fraction (Symonds & COWI, 1999). The material proceeds to crushing, sifting with or without washing after sorting. The most used crushers are the cone and the jaw crusher (Mulder, 2013). The residual material is then subjected to an impact crusher as shown in the figure below. The material from the impact crusher goes through a magnetic separator to remove the steel before being sieved to separate it from 0-45mm and >45mm. The fraction that is greater than 45mm is placed onto a temporary stockpile to be re-crushed, the 0-45mm fraction is screened into subdivisions of 0-4mm, 4-8mm, 8-16mm, 16-32mm and 32-45mm. The sub-divisions can be re-blended to form products which meet specific requirements of end users (Symonds & COWI, 1999).

The impact crusher is chosen over a jaw crusher because of the fact that it produces a more consistent and predictable aggregate which has sharper edges on particular granules. Impact crushers have a high-speed rotor inside a container in which the material is crushed. There are about four to six hammer plates fixed on the rotor which breaks the material against the face plates (Symonds and COWI, 1999).

Jaw crushers are usually shaped similar to a wedge; the other faces move in relation to the others, which produce a chewing action that grinds the material into smaller pieces towards the restricted end. The restricted end can be adjusted to a range of openings to establish the end product (Symonds &COWI, 1999).

The choice between the impact or jaw crusher is that of the operator and the application of the crushed material. Impact crushers produce aggregates with a narrow size range. Even though they are much cheaper to buy, their running costs are much higher, especially with very hard materials such as some concrete with embedded rebar. Generally impact crushers are used for high throughputs compared to jaw crushers (Symonds & COWI, 1999).



Key:

1. 1 Feed hopper with extension 1(a).
2. 2 By-pass chute
3. 3 Jaw crusher
4. 4 Belt protection plate
5. 5 Main conveyor
6. 6 Magnetic separator
7. 7 Engine unit
8. 8 Fuel and oil tank
9. 9 Tracks

Figure 2.4: Cross-section of a jaw crusher (Symonds &COWI, 1999)

Figure 2.5 shows the operations and processes executed in different types of plants, as well as operations in relation to the classification, transfer and the treatment of the dormant fraction (Mercante, 2012).

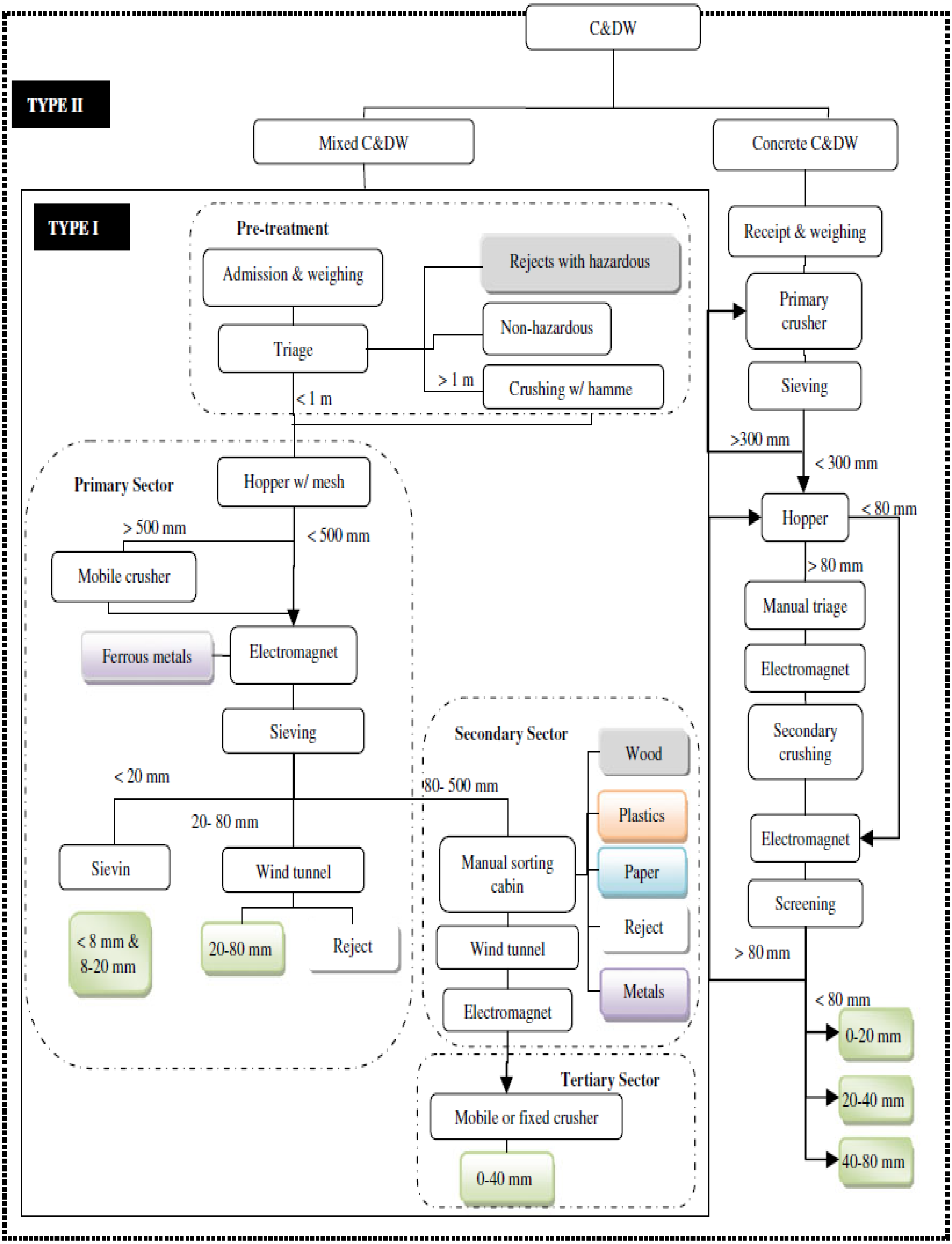


Figure 2.5: Flow chart and system boundaries for type I and type II Plants (Mercante et al, 2012)

2.7 Advanced Concrete Recycling Technology

A method for producing high-quality recycled aggregates by heating and rubbing has been developed. The concrete rubble is broken to sizes less than 50mm and heated to about 300° C to dehydrate old concrete paste and make it brittle. The quality of aggregates is not affected by heating. There are no changes in density, absorption, and other properties of recycled aggregates due to high temperatures and the quality of coarse aggregates heated up to 500° C do not deteriorate. The heated aggregates are transferred to a primary rubbing equipment and are rubbed by steel balls to remove the adhered mortar.

The removed mortar and coarse aggregates are transferred to the secondary rubbing equipment to remove the adhered mortar on fine aggregates by rubbing fine aggregates against coarse aggregates. The coarse and fine aggregates are separated by transferring them into a 5mm vibrating screen for separation. The average proportions of aggregate recovery and fine powder to the original concrete by weight are about 35% of coarse aggregate, about 30% of fine aggregate and about 35% of fine powder. There are also reports that coarse aggregates obtained by this method can used to make concrete and fine powder can also be used as raw material for cement, cement admixture and soil stabilizer. The disadvantage of this method is high energy consumption by heating and rubbing equipment. Figure 2.6 below depicts the process involved in this method (Akentuna, 2013).

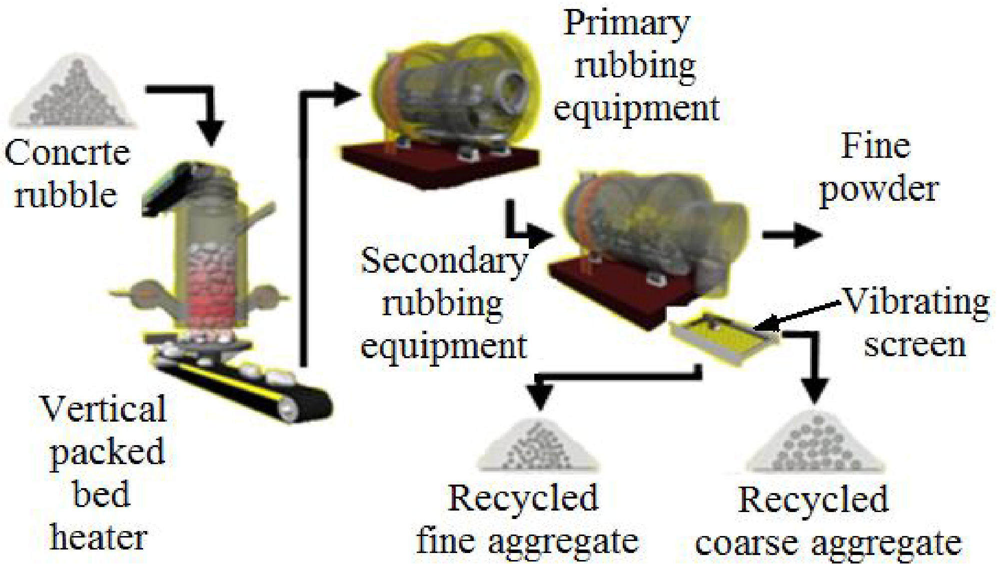


Figure 2.6: Process flow for high-quality recycled aggregates manufacturing process (Akentuna, 2013)

2.8 C&DW categorisation

C&DW has four main categories, which are as follows:

2.8.1 Demolition debris

Demolition debris is waste generated from the demolition of buildings or civil infrastructure (Limbachiya & Roberts, 2004). Waste can also be generated by a disaster, which is the same as demolition and is more frequent in certain areas. There are different characteristics and composition for construction waste. Waste from road construction generates large amounts of few items and building construction generates a variety of small and large amounts and construction wastes are primarily non-hazardous (Henry, 2005).

According to Macozoma, many buildings are demolished because their owners no longer have a use for them, not because they have reached the end of their design lives (Macozoma, 2002:3). The shortcomings with regards to this are as follows (Viljoen, 2010):

a) The building lacks flexibility
b) There is lack of design for deconstruction
c) The building is demolished without planning for material recovery
d) The forfeiting of incorporated energy that is integrated in materials.

2.8.2 Materials and product manufacturing

According to Macozoma, the manufacturing process used to extract virgin material in construction is responsible for the following (Viljoen, 2010):

a) Towering energy usage rates
b) Pollution of the environment by emissions
c) The generation of generic and toxic waste by-products
d) The use of packaging that generate waste.

2.8.3 Construction

The construction waste can be divided into structure and finishing waste.

According to Macozoma, the construction process most often results in avoidable waste due to labour practice, poor design and construction methods such as (Viljoen, 2010):

a) Poor procuring of material and site practice
b) Human factor
c) Not planning for waste management.

2.8.4 Operation and maintenance

According to Macozoma, a building requires certain maintenance once occupied. The inefficiencies with regards to operation and maintenance are as follows (Viljoen, 2010):

a) Lack of planning for material recovery and secondary use
b) Flexibility of building to different use requirements over time

2.9 Use of recycled concrete aggregates as base course material

It is important to check the gradation, angularity, soundness and solubility when using recycled concrete aggregates as a base course. The ability of the base to drain water depends on the gradation, a drainable base requires an additional handling of fines to ensure that the base does not have excess fines which will lead to clogging. The soundness should be checked to ensure the base has sufficient strength to meet the load-bearing requirements for the specified design period. The angularity will affect the compaction effort required to meet the specified density.

The solubility will determine whether the material will dissolve in rain water passing through the base which will raise the pH of ground water, with a negative effect on vegetation alongside the road. The carbon dioxide from the atmosphere may also react with dissolved concrete to form a precipitation of calcium carbonate which will clog the draining systemn according to Forster (1997) as cited by Robinson (2004).

2.10 Properties of recycled concrete aggregates

The composition of construction and demolition waste varies and critically depends on the type of activity. Although wood is also generated at construction and renovation sites, the largest component of building and demolition debris is concrete. Table 2.4 below gives an illustration of typical components of construction waste (Henry, 2005).

Table 2.4: Typical components of construction waste

Project Category	**Typical Components**
Construction	Mixed rubble, wood, roofing, wall board, insulation, carpet, pipe, plastic, paper, bricks
Demolition	Mixed rubble, concrete, steel beams, bricks, wood, pipe
Excavation	Earth, sand, stones, wood
Roadwork	Asphalt, concrete, earth
Site clearance	Trees, brush, earth, concrete, mixed rubble, sand, steel, paper, plastic

(Source: Henry, 2005)

A thorough understanding of recycled concrete aggregates is important for determining the suitability for different applications. The use of C&DW is limited by the following major intrinsic properties (Robinson et al., 2004):

2.10.1 Specific gravity

The specific gravity of C&DW is 10-15% less than that of natural aggregates. The lower specific gravity is likely to reduce transportation costs compared to transporting natural aggregates. The specific gravity of RCA varies between 2.29 to 2.51 for parent concrete with different quality and grade (Robinson et al., 2004). The lower specific gravity of C&DW emanates from an average density of 2400Kg/m^3 for concrete compared to 2800Kg/m^3 for most natural aggregates and C&DW is mainly made of concrete, hence lower specific gravity.

2.10.2 Absorption

The Portland cement in C&DW absorbs more water than natural aggregates. It can absorb nearly double the amount of water when compared with natural aggregates. The higher water absorption can be beneficial by minimising water infiltration into underlying road base material (Robinson et al., 2004). The water absorption and void ratio of fresh crushed recycled concrete aggregates is slightly higher with lower maximum dry unit weight when compared with RCA which has been stockpiled for a longer period. This phenomenon is due to the cementing of unhydrated cement phase and consolidation of the stockpile over time. The fines in RCA contain unhydrated cement which fills up the voids when the stockpile is exposed to water (Akentuna, 2013).

2.10.3 Coefficient of thermal expansion

The ability of material to expand in higher temperatures and contract in lower temperatures is measured by the coefficient of thermal expansion (CTE). The coefficient of expansion of C&DW is one or two times more than that of natural aggregates. The higher CTE results more expansion, shrinking and cracking of C&DW products. The fine aggregates fraction of C&DW is also different compared with natural aggregates because of the lower specific gravity and greater water absorption of C&DW as a result of larger paste content (Robinson et al., 2004).

2.10.4 Soundness

The ability of aggregates to resist various environmental conditions like heating and cooling or wetting and drying (similar to CTE) is referred to as its soundness. The cement binder portion in C&DW is susceptible to sulphate attack compared to natural aggregates, therefore more tests have to be done to assess the soundness of C&DW (Robinson et al., 2004). The sulphate soundness is the most frequently test in the United States to predict the freezing and thawing durability of aggregates by simulation of freezing and thawing cycles.

The aggregates are immersed in a sulphate solution, dried and re-immersed in the sulfate solution. The sulfate soundness degradation of RCA after cycles ranges from 18.4 to 58.9% for original concrete of different grades. It has been determined that the sulfate soundness test is inappropriate for RCA as a result of the chemical attacks which occur on concrete materials exposed to the environment over time (Akentuna, 2013).

2.10.5 Grading, texture and particle shape

The gradation of C&DW needs to be checked since it will assist in determining the particle percentage of the material that can be used for an intended application (Robinson et al., 2004). The research work done on size distribution stipulates that the crushing characteristics of hardened concrete are similar to those of natural rock and are not affected that much by the grade of original concrete. A jaw crusher with an opening of 33mm produces approximately 20% by weight of fine RCA below 5mm irrespective of the quality and grade of concrete. The fines of RCA become 14.1, 10.6 and 7% if the jaw openings are adjusted to 60mm, 80mm and 120mm respectively (Akentuna, 2013).

Flakiness and elongation indices are important and should be considered. The shape of RCA is angular as a result of adhered mortar. The optical and electronic microscopic scanning study also indicates that the particle shape of recycled concrete aggregates is more angular when compared to natural aggregates (Robinson et al., 2004).

2.10.6 Contaminant solubility

Material such as asphalt overlay, patch, join filling, or sealing materials or chloride ions from de-icing salts and sulphates from sulphate-rich soils and alkali-reactive aggregates needs to be minimised in C&DW. Chlorides lead to steel deterioration and alkali aggregate reactivity leads to expansion and cause cracking. It is suggested that maximum replacement of 20% by mass of conventional fine aggregates should be maintained for use of C&DW as base material, and the deleterious substances should not exceed 5% of the material by weight (Robinson et al., 2004).

2.10.7 Potential groundwater contamination

C&DW is susceptible to dissolution when exposed to ground water due to a greater surface area. The dissolution raises the pH of contact water, which is likely to have an effect on the vegetation. The dissolution of fines is also likely to result in clogged drainage systems (Robinson et al., 2004).

2.10.8 Alkali-Silica Reactivity (ASR)

ASR is the reaction which takes place over time between highly alkali cement and reactive silica in aggregates. The reaction forms an alkali silica gel which swells as it absorbs water which in turn results in expansion, then to spalling and loss of strength in concrete. RCA obtained from concrete which has undergone active alkali silica reaction is equally susceptible to ASR. The reasons for susceptibility are as follows (Akentuna, 2013):

a) The alkali on the adhered mortar contributes to the reaction.
b) The existing ASR gel expands when exposed to moisture in RCA concrete.
c) The fresh exposed faces which occur when the original aggregates are crushed during demolition of concrete.

The fine RCA is less susceptible to ASR compared to coarse RCA as a result of less reactive alkali component. The ASR for RCA used in concrete does not only depend on the alkali present in cement, it also depends on alkali content in RCA concrete. The use of supplementary materials such as fly ash, silica fume and blast furnace slag minimises the possibility of ASR. Alkali silica reactivity can be effectively mitigated by 25% replacement of cement by fly ash.

2.10.9 Adhered mortar and cement paste

The mortar in the original concrete remains in the RCA and becomes part of the RCA when old concrete is crushed. The lumps of mortar embedded with varying proportions of natural aggregates may be present and mortar may be present as a binder joining two or more natural aggregates. The nature of properties of parent concrete and crushing equipment determine the properties and amount of attached mortar. An average percentage of adhered mortar differs between 25% and 35% for 16 to 32mm size, 40% for 8 to 16mm proportion, and 60% for 4 to 8mm proportion of recycled aggregates. Compressive strengths of 24 MPa were also reported for recycled concrete aggregates with 35.5% of adhered mortar in 5 to 25mm proportion, 41 MPa for 36.7% and 51 MPa for 38.4% (Robinson et al., 2004).

2.10.10 Mechanical properties of RCA

RCA are weaker in comparison with virgin aggregates when subjected to repeated impact action such as impact load, which is tested by the aggregate impact value test, gradually applied load such as aggregate crushing value test and wearing and abrasive action such as Los Angeles abrasion test. Lower mechanical strengths are due to adhered mortar which creates weakness between the original aggregate and cement paste. The Los Angeles abrasion value for 16 to 32mm proportion is 22.4% for RCA from high strength concrete and 41.4% for 4 to 8mm proportion produced from low-strength concrete. The aggregate impact value for RCA from low-strength concrete is 31% and 26% for high-strength concrete. The abrasion test results vary between 37.2 and 40.8% and the quality of original concrete increases the mechanical strength of RCA marginally (Robinson et al., 2004).

2.10.11 External factors

The use of C&DW is also affected by external factors. The amount of concrete produced in the United States annually is 100 million tonnes. Most of this material is not recycled for use as aggregates. A report issued by the University of Massachusetts Transportation Centre stipulates that C&DW is used as granular fill material in 22 states, as an aggregate subbase material in eight states. The cost of processing C&DW may be more expensive than that of natural aggregates due to small quantities involved and labour intensive operation requirements such as removal of reinforcement steel. An Antonio study found C&DW is mostly used in urban areas where 5-10% cost saving is due to decreased transportation costs and avoidance of disposal tipping costs which assist to cover processing costs (Robinson et al., 2004).

2.10.12 Impurities and Fines Content

The impurities present in RCA and RAP differed between the samples. The most prominent impurities for RCA were, generally, asphalt aggregate, aggregate with plastic fibres and wood chips; they were less than 1% for different states. The prominent impurities for RAP were pavement markings which were also less than 1% for most states, with an exception of 1.7% for New Jersey (Edil, 2011).

The existing asphalt pavement is removed from roadway structures during the production process of RCA and RAP, during which some of additional material such as wood chips or pavement markings mix with the recycled aggregates. The stockpiling of recycled aggregates creates more impurities. There may be stones, brick, asphalt pieces, decorative concrete and higher soil fraction in RCA obtained from buildings (Edil, 2011).

2.10.13 Compaction characteristics

The maximum dry unit weight (MDU) had a narrow variance of about 1 KN/m^3 with optimum moisture content (OMC) of about 3% for RCA and RAP respectively. The average MDU for both RAP and RCA was about 19-20 KN/m^3 and the average OMC for RCA was about 10% and RAP was about 7% as a result of higher absorption capacity of RCA. An empirical estimation of OMC as a function of uniformity coefficient and absorption percentage, and MDU as a function of optimum moisture content can estimated for RCA and RAP respectively (Edil, 2011).

2.10.14 Resilient Modulus and Plastic Strains

The primary design property of pavement materials is the resilient modulus. Previous studies conducted indicated that the resilient modulus of RCA and RAP are equal or higher than that of virgin aggregates. The representative modulus was calculated for base course referred to as Summary Resilient Modulus (SRM). The resilient modulus for a corresponding bulk stress of 208KPa was 627 to 989 for RAP and 549-715Mpa for RCA, class 5 virgin aggregates obtained the lowest SRM of 525 Mpa. There are studies which indicate that RAP has greater plastic strains (about 10 times) than virgin aggregates and RCA which becomes a concern for potential contribution towards rutting (Edil, 2011). RCA has higher resilient modulus compared to virgin aggregates due to residual cementing properties from C&DW, since it is mainly consist of concrete which has cement as one of its main components.

2.10.15 Scaling

Resilient modulus is a non-uniform function of stress circumstances (e.g. bulk and octahedral stresses). The present models of resilient modulus consider this dependency on the state of stress in the base course but do not take the effect of strain amplitude on resilient into consideration. Put differently, the deformation of a thicker base course on the same granular material under the same wheel loader would be less than even if the difference in stress is accounted for because the thicker layer would have lower strains, resulting in higher modulus (Edil, 2011).

2.11 Specifications and recommendations

There are no approved specifications in South Africa for recycled concrete aggregates. The United States has come up with a solution to this situation by introducing specifications in ASTM subcommittee D18.14 Geotechnics of Sustainable Construction which was established in 2007 to encourage sustainability. A guideline titled “Standard Guide for Recycled Aggregates As Unbound Road base” has been reviewed in the subcommittee and there is ongoing research on some aspects of this guideline such as the content of allowable deleterious materials.

2.12 Design

The appropriate pavement thickness has to be determined in the design stage of pavements. The determination of the pavement thickness is more challenging when recycled concrete are used. A methodology that incorporates granular recycled concrete aggregates as base course material in pavement design has been developed. Laboratory bench scale resilient modulus (BSRM) and large scale model experiment (LSME) tests were carried out to determine the mechanical behaviour of recycled concrete aggregates.

Tests such as the falling weight deflectometer (FWD) were done to obtain field modulus properties in some illustrations. LSME and FWD results were compared to incorporate the resilient modulus scale and test settings. The pavement design methodology for recycled concrete aggregates was established with plastic deformation and resilient modulus acquired through LSME. (Edil, 2011)

The modulus of a granular material does not only depend on the stress level, it also depends on the strain level, thus layer thickness. Figure 2.7 shows an example of SRM as a function of layer thickness. The SRM of a typical base course thickness of 0.1 to 0.4m for unstabilised base materials is consistently higher for thicker base course as a result of lower shear strain amplitude and is constant for cementitiously stabilised materials.

2.13 Design Using AASHTO 1993

There are two design approaches for flexible pavements using unstabilised and stabilised recycled concrete aggregates as base. The first one uses AASHTO-1993 design guide and the second one uses the Mechanical Emperical Pavement Design Guide (MEPDG) based on lifetime expectancy. The method was developed using SRM and LSME to simulate field conditions (Edil, 2011).

The structural number (SN) is used to describe the structural capacity and contribution of each pavement layer in the AASHTO-1993 *Guide for Design of Pavement Structures.* The SN is controlled mainly by layer thickness and layer coefficient, the latter reflects the stiffness of the layer which is the function of the SRM. The SN of the entire pavement is taken as the sum of the SN of the pavement layers, according to AASHTO 1993 (Edil, 2011).

$$SN = \frac{[SN1+SN2M2+SN3M3]}{25} = \frac{[b1t1+b2t2M2+b3t3M3]}{25}$$

Equation (1)

where m1 is for drainage factor, b1 is for the layer coefficient, and t1 is for the thickness of the layer in (mm) i (i=1 for asphalt, i=2 for base course, i=3 for subbase). There is an empirical relation of the layer coefficient (b2) of granular material to the resilient modulus by (Edil, 2011):

$$b2 = 0.249 logSRM - 0.44$$

Equation (2)

where the summary of resilient modulus of the granular base material in MPa is SRM.

It is assumed that base course material stabilised with cementitious materials follow Equation 2. Equation 2 is used to calculate the layer coefficients (b2) by employing the SRM which is corrected for scale. The calculated layer coefficients are typically within the range of layer coefficients for base course material as presented in AASHTO-1993. The layer coefficient of materials without cementitious stabilisation varies with thickness because the lower strain amplitude in thicker layers gives higher SRM.

The typical layer coefficient of 0.3m thick RPM is 0.20 and the typical layer coefficient for a 0.2m RPM is 0.17 due to higher strains in thinner layer of RPM. The layer coefficient for stabilised material does not vary based on the thickness of the base course, because the SRM of stabilised materials is not stress or strain dependent on the base course layer, which is contrary to unstabilised materials. Stabilised materials have higher layer coefficient than unstabilised materials, which gives an indication that stabilised base course materials have a higher structural capacity (Edil, 2011).

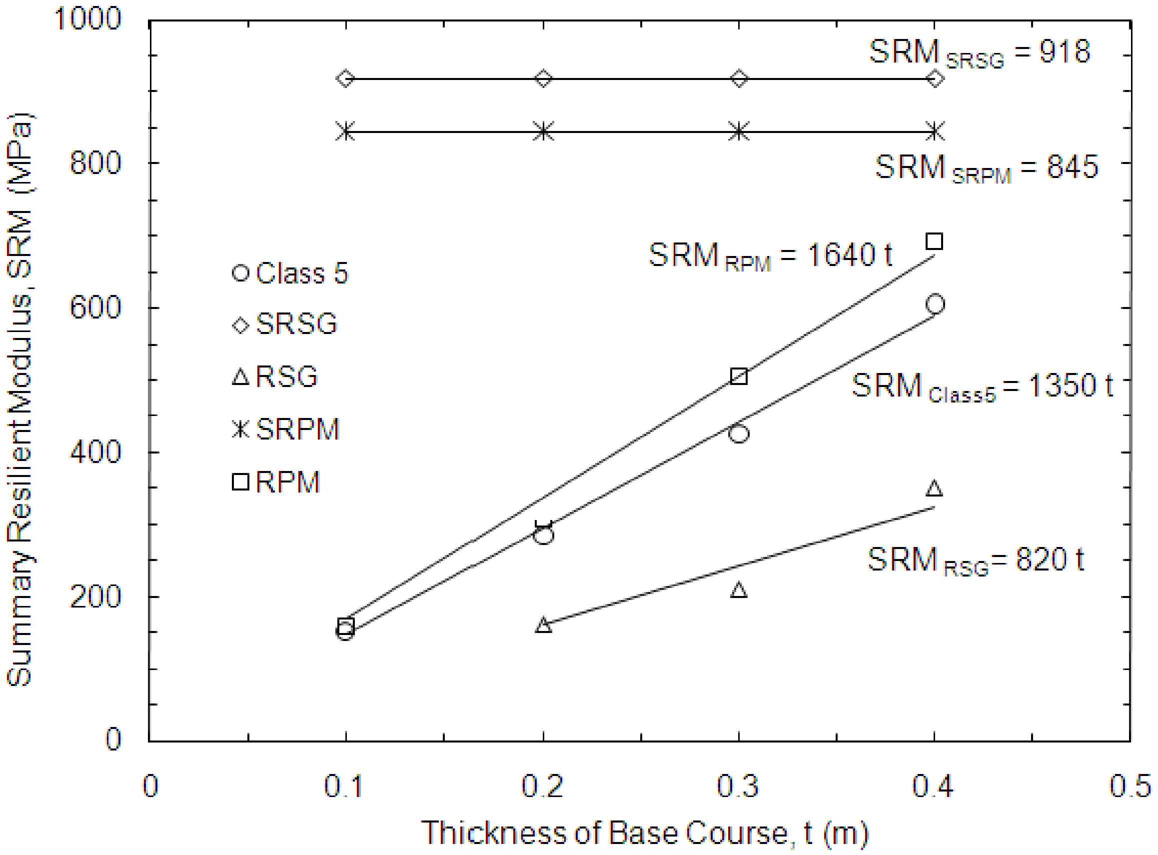


Figure 2.7: Summary resilient modulus (SRM) of Class 5 base, RPM, RSG, stabilised RPM and RSG (SRPM and SRSG) as a function of base course thickness (Edil, 2011).

2.14 Designing with MEPDG

The AASHTO MEPDG design guide is the latest product which was developed to improve current design procedures. It necessitates a change from current empirical pavement methods to mechanistic empirical pavement design methods which uses a combination of analytical modelling and practical performance. The models are calibrated with practical results and they are critical in the accuracy of design results (Souliman *et al.*, 2010).

The design guide is a notable new approach with regards to the way pavement design is done (Velasquez *et a.l*, 2009). A design is undertaken by use of the Mechanistic Emperical Pavement Design Guide (MEPDG) in order for the plastic deformation of base course to be accounted for categorically in the design (plastic deformation is not implied in the AASHTO-1993). The mechanistic-empirical models are used for the prediction of damage accumulation over determined service life of a pavement. The traffic, climate, materials and pavement structure are used as input (Edil, 2011).

The performance estimations are made with regards to deterioration and ride characteristic (Velasquez *et al.*, 2009).

The input data for MEPDG is the strain corrected SRM for the intended thickness of the base course and base course thickness together with traffic information, thickness of the surface layer and properties, subgrade modulus and the assumed thickness, environmental data based on the location of the project, and the factor for rutting calibration.

The MEPDG uses the plastic deformation obtained from LSME to predict the rut depth and the internal roughness index (IRI) of a pavement. The LSME data is inverted to determine the rutting calibration factor (Bs1). (The plastic deformations from LSME are compared with MEPDG predictions.) Bs1 is typically set at 1.71 for RSG, 1.41 for RPM or RAP, 1.0 for virgin aggregates and RCA base course with 0.1 m thickness, and 0.1 for cementitiously stabilised base materials. The depth of rut and international roughness index (IRI) are then determined for pavement structures made of different base course materials. There are two categories for determining the service life of stabilised and unstabilised recycled aggregates as base course: the rut depth limit of 12.7mm and IRI limit of 2.7m/km (Edil, 2011).

2.15 The environmental justification for recycling of C&DW

Despite depleting natural resources, the quarrying and processing of virgin aggregates involves the generation of obvious environmental impacts, mostly to the local area surrounding the quarry. The transportation of aggregates from the quarry to the site also generates a separate and more widely dispersed environmental impacts mostly associated with bulk transportation. There are also environmental impacts associated with bulk storage facilities at railheads (Symonds & COWI, 1999).

The scale and detail of the environmental impact of quarrying depends mostly on the product being quarried. The digging of sand is much quieter, less dusty than blasting and crushing of virgin aggregates. Marine dredging at a carefully determined area has substantially less problems than land based quarrying. The environmental impacts associated with land quarrying are as follows (Symonds & COWI, 1999):

a) Dust and noise.
b) Air pollution (from blasting, but mostly from the use of internal combustion engines)
c) Vibration (from blasting which is likely to open fissures in the underlying rock, which is likely to change the drainage patterns and allow pollution to contaminate groundwater).
d) Pollution of groundwater by fuels and lubricants used by the machinery and plant.

e) Land form change (which affects the surface water drainage and has a visual impact.
f) Natural habitats change and a possibility of destruction of historical artefacts
g) Aesthetic and visual impacts

Certain environmental impacts are primarily environmental; however, others depending on people's presence are typically known as amenity impacts. There is less amenity impact for quarries in remote areas than those in urban or suburban areas. Contrarily, quarries in remote areas depend on transportation links to deliver aggregates to end users and the transportation whether by land or train has a visual and detachment impact in relation to the existing infrastructure. The transportation of aggregates by boat or barge is less damaging; however, its application is limited (Symonds & COWI, 1999).

2.16 Barriers and benefits

The recycling option seems to be a great solution for the enormous mountain of C&DW generated annually. However, contamination of C&DW, transportation arrangements for both on and off site separation, lack of assistance from government with incentives, affordable landfill fees, lack of knowledge regarding C&DW as recycled material and oscillation of recyclables market seems to be a challenge (Smith-Pursley, 1997). These barriers may be surpassed as it has been done in other countries. The physical challenges to recycling C&DW start in the way it is collected. C&DW is most of the times collected in about 30m^3 containers. C&DW comes assorted in containers, which makes it a challenge for C&DW to be sorted at a different location. The contractors cannot separate the material on site and the containers do not have compartments for different types of C&DW (Cochran, 2006).

The economic challenges that come with recycling include low tariffs of disposing C&DW at landfills. The low disposing tariffs make it a challenge to create an economically viable option to disposing the material at the landfills. The landfill disposal options do not include the environmental cost that C&DW poses such as groundwater contamination, virgin aggregates that complete with C&DW are also affordable which makes it a challenge in certain areas to compete with virgin aggregates (Cochran, 2006).

The political challenges transpire in a situation where local policies do not promote recycling programmes. Haulers are most of the time paid only to collect C&DW, not to recycle it. A further political barrier occurs when government officials fear the impact C&DW will impose on the recycling policies (Cochran, 2006).

The psychological barrier of C&DW results from burdensome challenges to transit from mindset concerning disposal. People are at ease with the contemporary system and sceptical to change due to lack of information concerning the environmental impact of disposal (Cochran, 2006).

The quality control seems to be very vital and the main barrier to market acceptance is the potential buyers are doubtful about the quality and consistency although there is lack of standards for recycled materials. Other countries are moving among C&DW producers to establish external quality control measures by cooperating independent material testing facilities which will allow their products from a quality token (Symonds & COWI, 1999).

The International Recycling Federation (FIR) has made a comparison between existing national quality systems for recycled aggregates (for countries such as Germany, France, Netherlands and Austria) and recommended the structure which these systems should be in line with. Table 2.7 below summarises the recommendations and holistically better product management leads to a better end product (Symonds and COWI, 1999).

Table 2.5: Quality systems for recycled C&DW (Based on the FIR Recommendation)

Heading	**Sub-Heading**	**Notes**
Resources	Determination of sources of input materials Avoidance of contamination/purity	Sources might include unbound C&DW, hydraulically bound C&DW To be attained by selective demolition and collection of mineral and other C&DW
Storage	Pre-treatment storage Post-treatment storage	Raw materials should be stored separately to achieve good product quality Treated materials should be stored separately according to quality classes
Preparation	Achieving the required properties	Preparation should be carried out in such a way as to ensure that the material(s) fit specified quality classes
Type (quality classes)	Classification according to the envisaged end use	Recycled materials should be classified according to their intended use(s)
Engineering tests	Particle size distribution Frost resistance Stiffness Compactability	These and any other test should (for the time being) be conducted according to national standards

Composition	Percentage of other minerals Mixing ratio Detrimental components Dangerous components	Other minerals would be those which differ from the main product (i.e. concrete in asphalt granulate) Mixing ratio gives the variability of percentage of different mineral products in the granular mix Detrimental components are materials which adversely affect the mechanical behaviour of the material Dangerous components are organic or inorganic contaminants which create a risk for the environment
Environmental	Leachability	For recycled materials the parameters and limit values should be defined according to the quality class
External monitoring	Determination of parameters and frequency of testing	To be conducted by a laboratory or testing organisation licensed or recognised by the government
Internal monitoring	Determination of parameters and frequency related to volume of production and quality classes	To be conducted by either an in-house laboratory or an external organisation

(Source: Symonds & COWI, 1999)

Chapter 3: The South African experience

3.1 Building and demolition waste in South Africa

Waste concrete in South Africa is defined as the waste generated during construction, alterations, and repairs or demolishing of structures which incorporate concrete, earth, rock and wood that is replaced during construction (Gauteng Provincial Building & Demolition Waste Guidelines, 2009).

Some local authorities have different definitions as indicated in Appendix 1. Most authorities basically define C&DW as the waste that is generated through demolition, excavation and building activities. Building activities may be referred to as construction, alterations and building repairs (Gauteng Provincial Building & Demolition Waste Guidelines, 2009).

There is an ongoing debate regarding definition of waste is South Africa. The internationally acceptable waste hierarchy, according to the European Community in the Framework Directive of 1975, is given in Table 3.1. The intention is to prevent waste by measures such as re-using, recovering and recycling. One of the main challenges regarding the implementation of the definition is that the definition depends on translation to policy, strategy and legislation (Oelofse and Godfrey, 2008).

Table 3.1: Defining waste in South Africa

Clear production	Prevention
	Minimisation
Recycling	Re-use
	Recovery/Reclamation
	Composting
Treatment	Physical
	Chemical
	Biological
Disposal	Landfill

(Source: Oelofse and Godfrey*,* 2008)

There is a challenge that comes with defining something as waste which creates a thin line between what are resources and waste. There are currently two legal definitions of waste in South African legislation according to Oelofse and Godfrey (2008). The legislation for Environmental Conservative Act, (ECA), Act 73 of 1989, defines waste as unwanted or surplus material. The National Water Act, Act 36 of 1998 defines waste based on protection by defining it with regards to the potential of creating pollution. It is assumed that waste is hazardous until proven otherwise in the preventative principle approach.

The construction industry views the restrictive, protection-based definition of waste as adopted by the South African Legislation as the obstacle for implementation of successful waste hierarchy (Oelofse

& Godfrey, 2008). Figure 3.1 gives an indication of the current move towards waste management and waste re-use in South Africa which is driven by the current legal definition of waste.

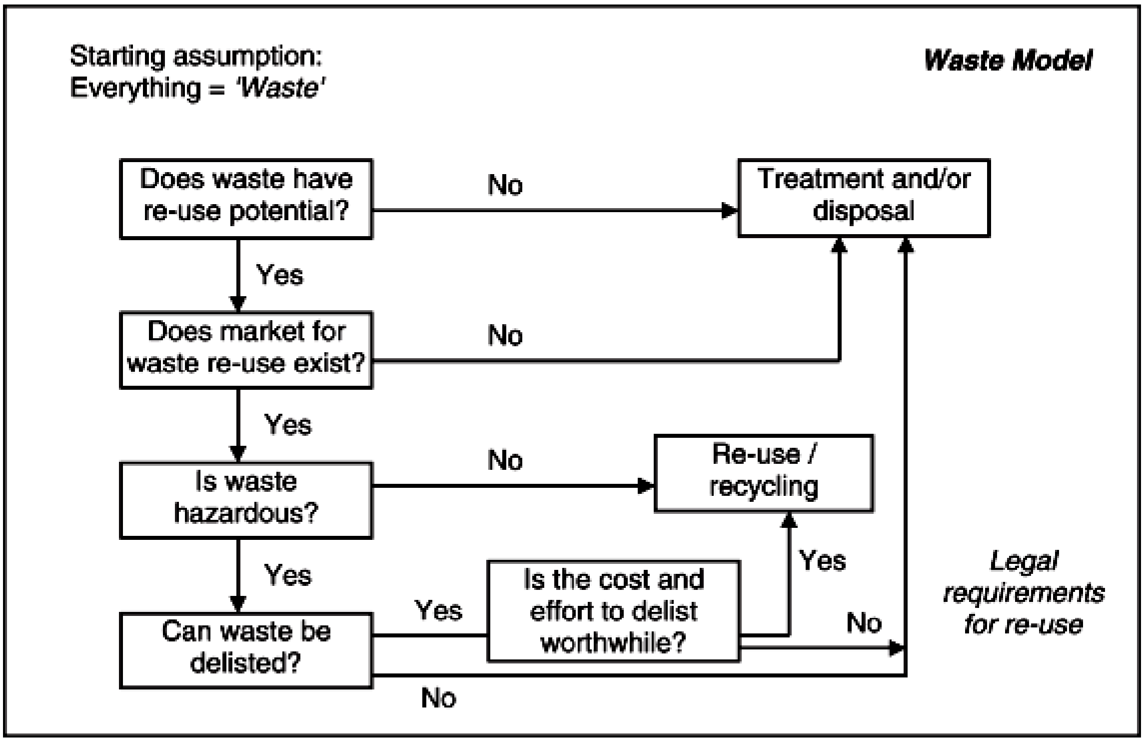


Figure 3.1: Managing waste through a 'Waste Model' (Viljoen, 2010)

There is a risk of construction and demolition waste being disposed of, despite a possibility of being re-used due to lack of economic incentives and technical information.(Oelofse & Godfrey, 2008)

The South African concrete industry is made up of cement manufacturers, aggregates producers, admixture suppliers, cement extenders suppliers (which are typically fly ash and slag), precast and readymix concrete producers, structural engineers, building contractors and small-scale concrete consumers such as home builders (Muigai et al., 2013).

The activities of the concrete industry in South Africa have mainly been due to government and private industry investment as a result of new and replacement stadia for the 2010 FIFA World Cup and certain infrastructure projects like Gautrain Rapid Link and airports (Muigai et al., 2013).

3.2 The Life-cycle of concrete

Contemporary concrete is made of a mixture of aggregates (65%-80%v/v), cement (10%-12%v/v) and water (14%-21%), and other constituents like mineral elements (cement extenders/additives) and chemical admixtures (e.g air-entrainers, water reducers and accelerators), and sometimes fibres (<1%). Pre-stressed and reinforced and unreinforced concrete structures are usually constructed with concrete. The life-cycle of concrete takes into consideration activities such as extraction and processing of raw/recycled materials up to the last one which is the final decommissioning and demolition of the structure for waste and recycling of its materials. The life cycle of phases of a concrete structure are illustrated in Figure 3.2 below (Muigai et al., 2013).

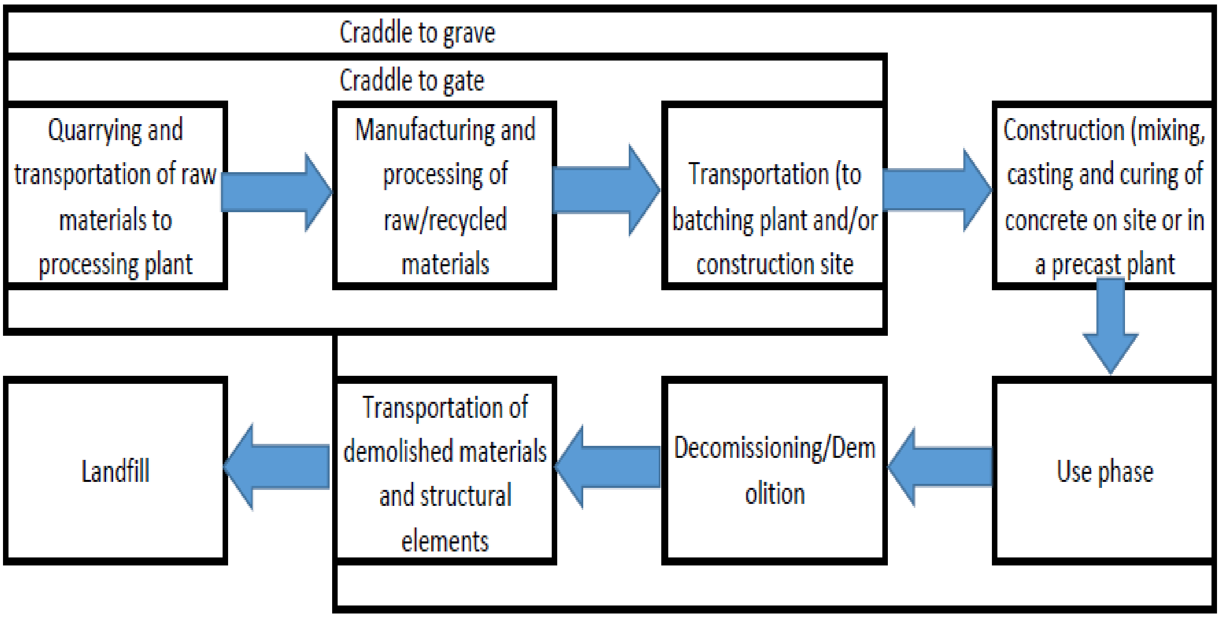


Figure 3.2: Life cycle phases of a concrete structure (Muigai et al., 2013)

The cradle-to-grave phases cover activities such mixing of concrete, structure construction, on-site transportation, operational phases, demolition and disposal of material. The grave-to-cradle covers the end-of-life and recovery plan which include recycling and re-use of the demolished materials (Muigai et al, 2013).There has been a linear chain consisting of input (raw material), processing (Construction), and output (waste), according to Macozoma (2002). This gives an impression of unlimited supply of resources that give an input to the process and a bottomless pit which does not yield output. Unfortunately our plant is experiencing consequences of such an approach with examples such as global warming and pollution. Figure 3.3 illustrates inefficiencies with regards to building materials which extends throughout the phase of a building`s life cycle (Viljoen, 2010).

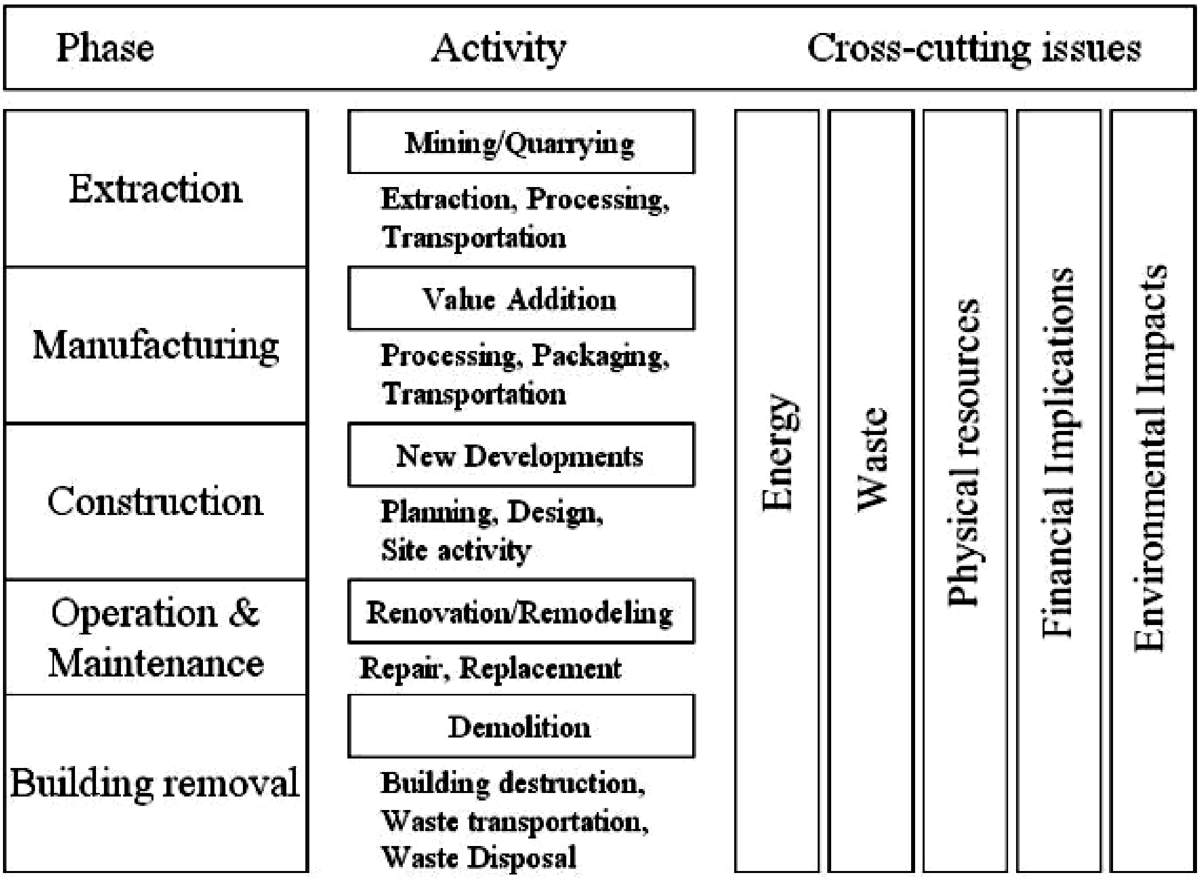


Figure 3.3: Life cycle of materials in building construction (Macozoma, 2002)

Young and Sachs (1994) made a call for closure of the loop of material flow. They focused on two main elements, namely: reduction of the extraction of raw materials and reduction through minimisation of waste by reduction and recovery for secondary usage. The life cycle of materials in the building and construction industry depicts inefficiencies which contribute to the poor performance by the industry.

3.3 The environmental impact of concrete and its constituent materials

Despite large carbon emissions of cement, concrete is not made with 100 percent cement. Cement acts as a binder in concrete as illustrated in figure 3.4 for a typical 30Mpa concrete. Cement is not the only determinant of the concrete strength, the rather depends on water to cement ratio. Water is used for consistency of concrete and admixtures are used to reduce the water. The total CO_2 of a typical South African 30Mpa concrete is 356 Kg CO_2 e/m^3, which is equivalent to 148g CO_2/kg of concrete, which is drastically less than 100 percent cement, however it is still a huge amount when considering the total volume of concrete produced globally (Boshoff, 2015).

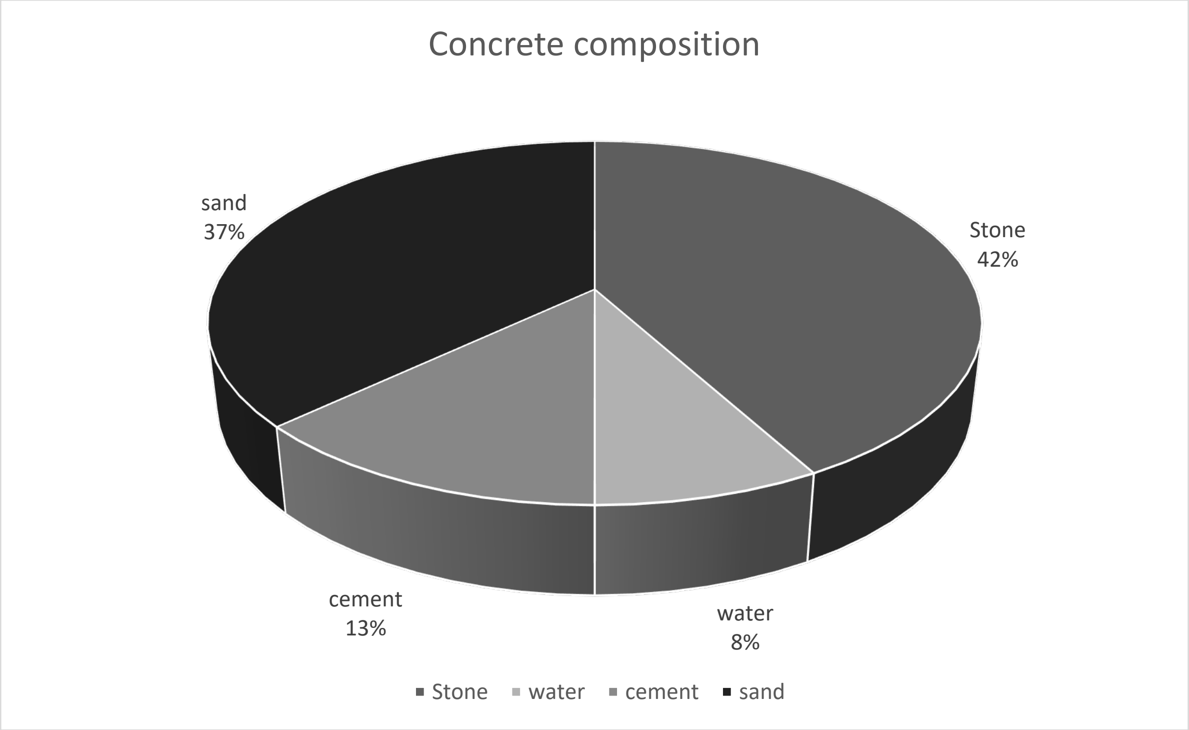


Figure 3.4. Composition by weight of a typical 30Mpa concrete (Boshoff, 2015)

3.3.1 Cement

The cementitious sales in South Africa are denoted by four producers (as of 2009) and new producers are expected to enter the market in the near future. The term *"cementitious products"* is used for cements complying with SANS 50197-1 (which is derived from EN 197 specifications) and it also refers to cement extenders sold direct to end users such as ready-mix suppliers. About 20.4 Mt of raw materials per year were used between 2005 and 2008 to produce cementitious materials. Averages of 12.8 Mt of binders were produced annually.

Ordinary Portland cement and extended cements like CEM IIA, CEM IIB, CEM III, CEM IV and CEM V were produced in line with SANS 50197-1 (Muigai et al., 2013). Approximately 37% of the total 12.8 Mt of binders produced annually between 2005 and 2008 was used in the production of concrete. Figure 3.5 is made of 17% readymix producers, 16% concrete product suppliers and 4% for civil engineering construction (Muigai et al., 2013).

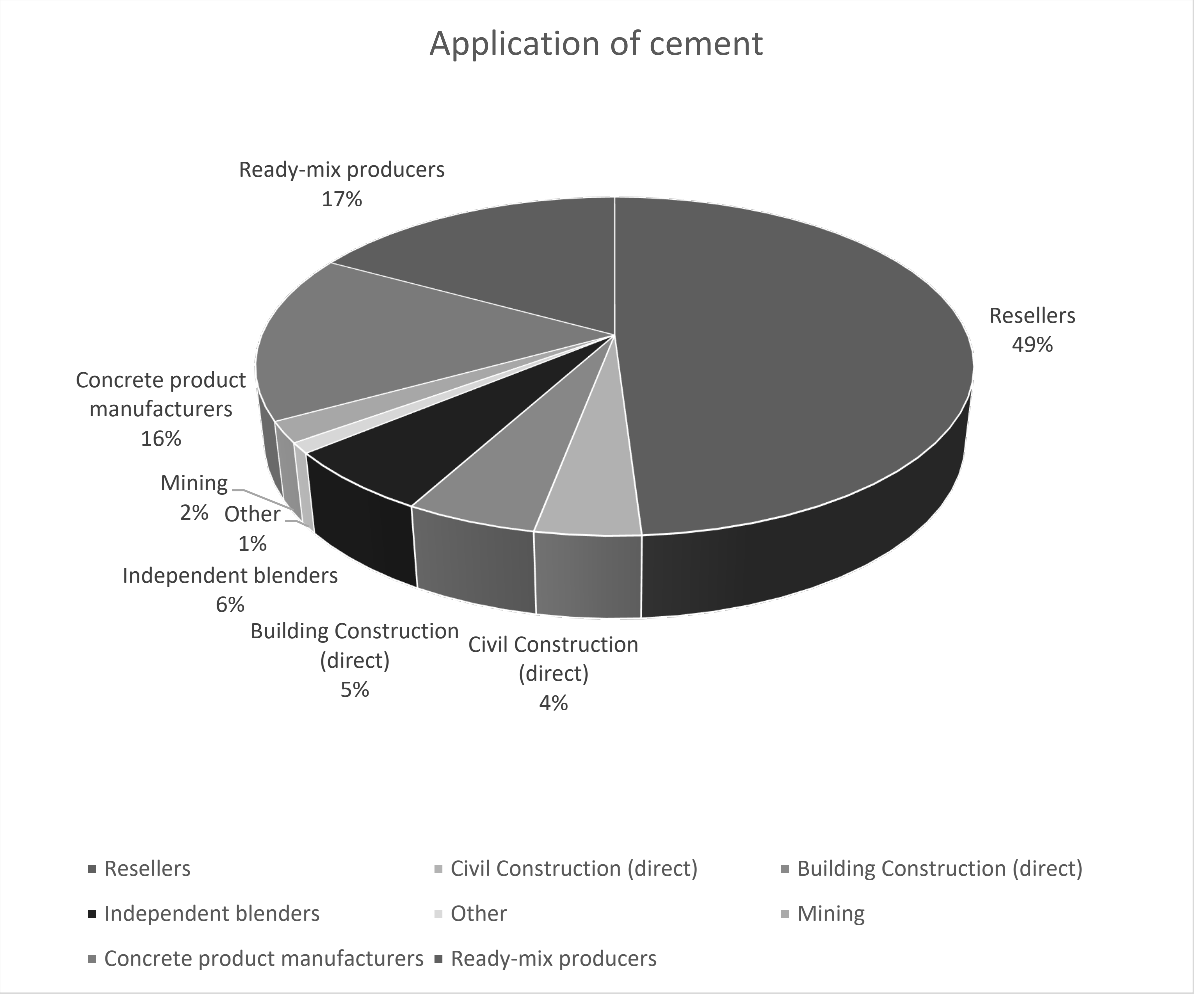


Figure 3.5: Four year [2005-2008] average values of the application of cement in South Africa (Muigai et al., 2013)

There is a possibility of the percentage value for concrete being higher than 37% since it does not include 55% of cement sales of 6% consumed by independent blenders and 49% percent for re-sellers (Muigai et al., 2013).

The production of Portland cement requires chemical transformation of raw materials: calcium oxides (63%-69% by mass in cement), silica (19%-24%), alumina (4%-7%) and iron oxide (1%-6%) into various types of cementitious products, by-products and waste materials. The manufacturing of Portland cement is made of the following five processes (Muigai et al., 2013):

a) Mining and transportation of raw materials: Explosives are used in the quarrying process and fuel is also used for the transportation of raw materials.

b) “Raw meal” preparation: The raw meal is prepared for the Pyro-processing stage by blending crushed limestone with iron ore, clay and shale.

c) Production of cement: Cement may be produced by wet or dry pyro-processing of the raw meal. The dry wet processing entails heating of the raw meal before feeding it into the kiln and the dry processing usually uses approximately 2.9 GJ to produce one tonne of cement. The wet process entails crushing of raw materials, grounding and blending. The South African cement industry uses dry processing since it consumes twice less energy than wet processing.

d) The final grinding of clinker and the grinding together of clinker with a small proportion of gypsum to manufacture cement. Waste products such as fly ash from power stations and blast furnace slagment from manufacturing of iron/steel can be used in small proportions by separate grinding and mixing together at a later stage.

e) Bulk or bags transportation of the final product to the customer site. The transportation distance of cement in South Africa varies, an average of 100Km is assumed in the review.

Coal fly ash and slagment may be mixed with raw material which will lead to low emissions. A typical kiln processes about 3000 tonnes of clinker per day. The most critical part of cement manufacturing process in relation to the environmental pollution is the clinker burning stage known as the calcinations (Stajanča et al, 2012).

The calcinations stage is the main contributor of CO_2, the clinkering starts at a temperature above 1 250˚C and cement is actually formed at this stage and material is heated to a temperature of 1 500˚C for full clinkering to occur (Boshoff, 2015). The CO_2 emissions from cement are as a result of (1) calcinations or decomposition of limestone ($CaCO_3$) to calcium oxide (CaO), which liberates CO_2; and (2) burning of coal in the pyro-processing. The secondary sources of CO_2 emissions is from fossil fuel needed for electricity generation required by the cement manufacturing operations and hauling of raw materials and transportation of the end product to clients (Muigai et al., 2013). The cement manufacturing process is illustrated in figure 3.6 (Boshoff, 2015).

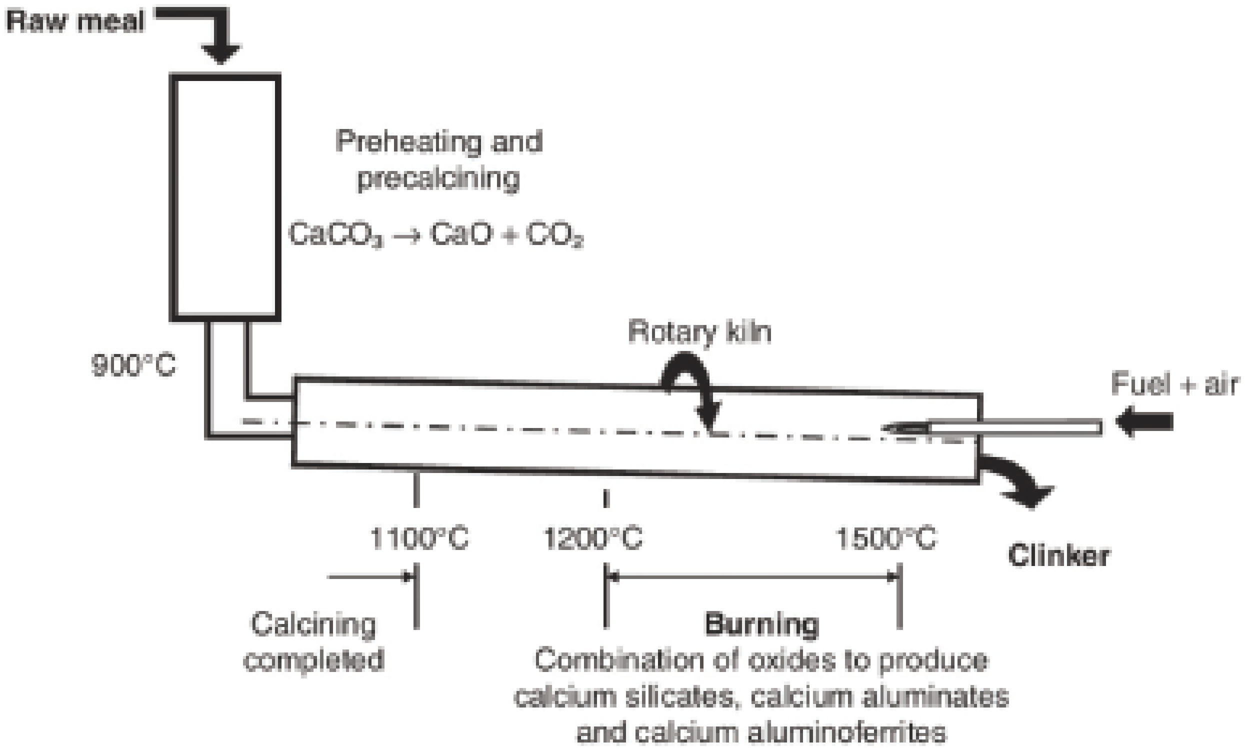


Figure 3.6: Cement manufacturing process (Boshoff, 2015)

The CO_2 emissions data illustrated in Table 3.2 below is reported according to the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) Protocol. Three sets of emissions from different processes are illustrated. The scope 1 (direct) refers to emissions from calcinations of raw materials, combustion of fuel, transportation of raw materials and personnel on site and explosives for mining in the Quarry, scope 2 (Indirect) emissions are from usage of purchased electricity and scope 3 emissions are from off-site activities such as transportation of raw materials such as cement extenders (Muigai et al., 2013).

Table 3.2: The CO_2 emissions data

Year	Cement for concrete production (tonnes)	Kg CO_2-e emissions			
		Scope 1	Scope 2	Scope 3	Total emissions (Kg CO_2-e)
2005	1.15E+07	9.38E+09	1.67E+09	2.50E+08	1.13E+10
2006	1.27E+07	1.04E+10	1.84E+09	2.76E+08	1.25E+10
2007	1.37E+07	1.12E+10	1.98E+09	2.98E+08	1.35E+10
2008	1.33E+07	1.09E+10	1.94E+09	2.90E+08	1.31E+10
Four year average kg CO_2-e					1.26E+10
Contribution from the concrete industry (37%) kg CO_2-e					4.7E+09

(Muigai et al., 2013)

There are mitigation options available to reduce carbon emissions for the cement industry. The cement industry may change from use of fossil fuels to options that are more environmentally friendly such as biofuels and municipal waste. Emissions may be further reduced by reducing the clinker content by increasing supplementary cementitious materials. Further reduction of carbon emissions may be achieved by using carbon capture and storage technology. It is estimated that carbon emissions may be reduced by about 80 percent by combining these mitigation options and by about 50 percent without carbon capture and storage technology (Arp *et al.,* 2018).

3.3.2 Coarse and fine aggregates

There is conflicting information presented by Stone Producers Association of South Africa (ASPASA) and for the Department of Mineral Resources (DMR). ASPASA reported a total of 114Mt of aggregates and sand produced in 2008, DMR reported total industry sales of 50% of that reported by ASPASA as per Figure 2.13.

The total sales reported by DMR were only for registered operating quarries and sand extractors. ASPASA made estimates based on conversion factors for total sales of cementitious materials that goes into production of concrete. ASPASA estimated that 30% of aggregates and sand produced in South Africa (estimated at 32.1Mt for 2005-2008) is used for production of concrete. The remainder of aggregates sales goes into non-concrete products such as railway ballast and filters for the water treatment industry. Figure 3.7 gives an illustration of the usage of aggregates for different applications in construction (Muigai et al., 2013).

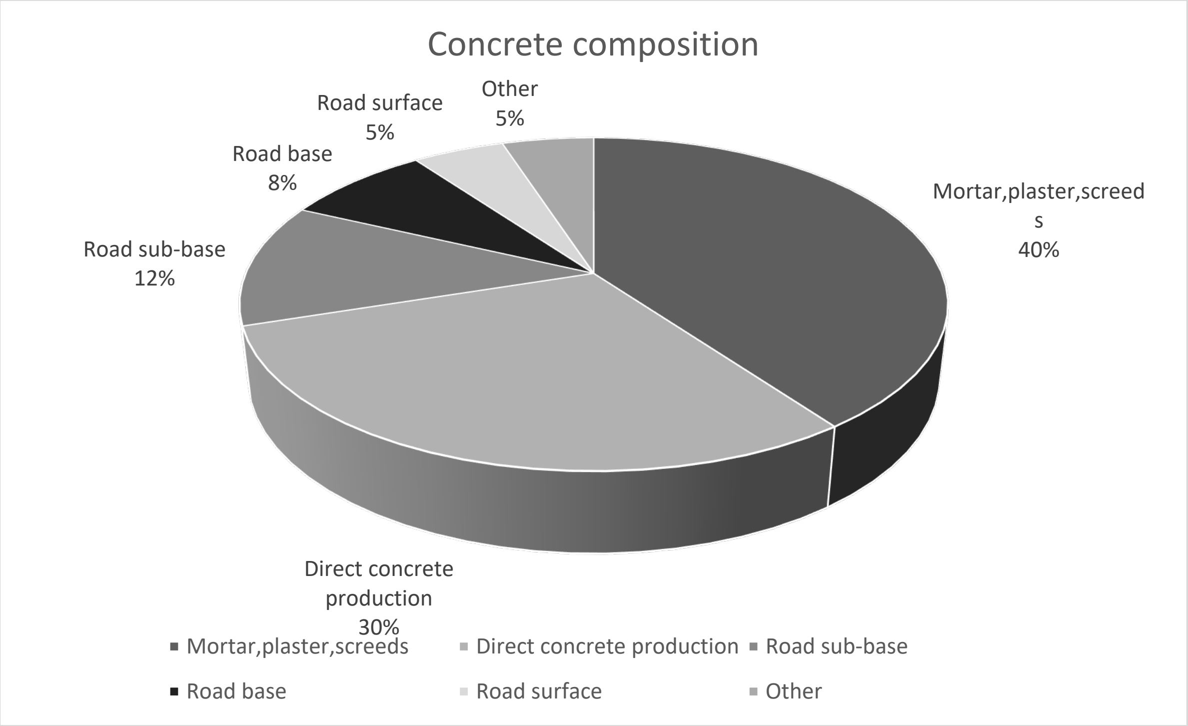


Figure 3.7: Application of aggregates in construction (Muigai et al, 2013)

Extraction of materials from natural reserves has adverse environmental effects such as the following (Macozoma, 2002):

a) Mining more than the required quantity.
b) High consumption of energy
c) Environmental pollution by CO2 emissions
d) Disturbance of the ecosystem with rehabilitation
e) Waste being generated without proper disposal measures

Approximately 65%-80% of the volume of concrete is made of fine (<4.75mm) and coarse (>4.75mm). Coarse and fine aggregates can be obtained from quarries, alluvial sources like river sands and gravels, or recycled materials such as construction and demolition wastes). The current main suppliers of aggregates for concrete are natural resources such as gravel and sand pits and rock quarries and coarse aggregates are mainly sourced from crushed rock.

There is a small usage of recycled aggregates mainly for pavement base construction. The challenges for use of recycled for structural purpose is the recycling facilities and equipment requires high costs. There is also lack of regulatory policies and strategies on recycling of concrete. Besides waste management aspects, recycled concrete aggregates tend to show large variances in quality, especially if they are sourced from different sites. The local standards for design of concrete structures such as SANS 10100-1:2000 do not have provision for use of recycled aggregates in concrete (Muigai et al., 2013).

There is no readily available local information which distinguishes the impact for production of natural quarried coarse and fine aggregates. Table 3.3 indicates that the extraction and processing of a tonne of both aggregates generates 8.1Kg of CO_2 equivalent emissions on average.

Table 3.3 : Extraction and processing of a tonne of coarse and fine aggregates

Activity	**Energy Source**	**Energy MJ/tonne**	**Kg CO_2-e/MJ**	**Kg CO_2-e/ tonne (In Energy Report 2010)**
Quarrying	ANFO^{c}	0.045^{a}	0.044	0.002
Onsite transportation	Diesel	26.41^{a}	0.073	1.928
Crushing, sieving and sorting	Electricity	28.80	0.119	3.43
Transportation to construction site (50Km)^{b}	Diesel	38	0.073	2.774
Total		**93.3**		**8.1**

a Based on the assumption that diesel oil constitutes 99.9% of the energy and explosives are 0.1% during quarrying
b Typical transportation distances of materials to site, the capacity of the truck is estimated to be 25 t for aggregates (Mclintyre et al., as cited in Muigai et al., 2013)
c ANFO – Ammonium Nitrate Fuel Oil

(Muigai et al., 2013)

Table 3.4 indicates a total of CO_2-e emissions based of ASAPA data between 2005 and 2008. There has been a steady increase in the production of aggregates used in concrete for 2005 to 2008. An average of 32.1 Mt of aggregates used in concrete resulted in 3.0 X 10^6 GJ of energy and 260 X 10^6 Kg CO e emissions (Muigai et al., 2013).

Table 3.4: Total CO_2 e emissions based of ASPASA

Year/Units	**Amount of fine and coarse aggregates consumed in concrete production in SA based on ASPASA data**	**Total kg CO_2-e emissions**
	Tonnes	Kg CO_2-e
2005	28.4 X 10^6	230 X 10^6
2006	31.9 X 10^6	258 X 10^6
2007	33.9 X 10^6	275 X 10^6
2008	34.1 X 10^6	276 X 10^6
Average	**32.1 X 10^6**	**260 X 10^6**
ASPASA – Aggregates and Stone Producers Association of South Africa		

(Muigai et al., 2013)

3.4 Emissions in the concrete industry

About 90% by weight of concrete is consist of a combination of water, sand, stone or gravel. The mining, processing and combining of materials at the concrete plant and transportation to the construction site emits small amount of CO2 since it requires little energy. The amount of CO2 in the concrete depends on the cement content in the concrete mix design. A typical concrete mix design contains about 7% to 15% of cement by weight with an average cement content of about 250Kg/m^3 and weighs about 2400Kg/m^3 which results in about 100 to 300Kg of CO2 embodied per cubic metre of concrete produced which is about 5% to 13% of the total weight of concrete produced (National Ready Mix Concrete Association, 2012).

3.4.1 Raw materials for concrete production in South Africa

Approximately 39.7 million tonnes of raw materials were produced annually for concrete production between 2005 and 2008, about 32.1 Mt were coarse and fine aggregates and about 7.6 Mt were raw materials used in the manufacture of cement (limestone, silica, iron ore and clay used to produce 4.73 Mt of binders). An average of 61% by mass of coarse and fine aggregates is used in the concrete production (Muigai et al., 2013).

3.4.2 Carbon equivalent emissions generated

The use of non-renewable energy to manufacture concrete constituent materials in RSA has resulted in the production of global greenhouse gas (GHG) emissions. The average GHG per year in SA between 2005 and 2008 is 49.2 X 10^8kg CO2-e. The main contributor of CO_2-e emissions is cement and contributes an average of 94.7% of total emissions in the SA concrete industry (Muigai et al., 2013).

3.4.3 Production of concrete in Republic South Africa

Figure 3.4 indicates that an average of 8.69 million m^3 (20.9Mt) of ready-mix concrete was produced annually between 2005-2008 of which 8.17 million m^3 (19.6Mt) of concrete was used to produce concrete products such as paving blocks, roof tiles, masonry, floor slabs, retaining blocks and infrastructure products and 2.04 million m^3 (4.9 Mt) was used for construction in the civil engineering industry. The total concrete produced in SA between 2005 and 2008 is 18.9 million m^3 (45.4 Mt). RSA consumed 0.58% of the global concrete consumption and this estimate is based on an assumption that all the global cementitious products are used to produce concrete (Muigai et al., 2013).

3.4.4 Solutions for reducing the environmental impact of the concrete industry

The South African concrete industry uses about 61% by mass of raw materials which is consist of coarse and fine aggregates. There are incentives in RSA by the Waste Management Act (2008) to encourage the use of alternative aggregates, such as C&DW and discourage the use of primary aggregates. The use of primary aggregates may be significantly reduced by replacement with C&DW whenever possible and this will result in conservation of primary aggregates and reduction of waste that ends up in landfills.

The main challenge with the use of C&DW in RSA is lack of research to encourage the use of C&DW. There should also be taxes and charges to discourage the use of primary aggregates similar to countries such as Denmark and UK. In the UK there`s a tax of £2.1 for one tonne of mined aggregates. The South African aggregate and sand industry makes it impossible to put tax systems in place due to disaggregation. The disaggregation is evident on production reports from ASPASA and DMR. The RSA cement industry is the main contributor of CO2 –e emissions and contributes approximately 94.7% of total emissions (Muigai *et al.,* 2013).

3.5 Waste Management Hierarchy

The process for managing waste revolves around material reduction in the design and planning stages. The important processes in reducing waste are reducing waste at building sites, re-using and recycling of materials which cannot be re-used by the contractors (Viljoen, 2010).

The most important step in the waste management process according to Advanced Construction and Demolition Waste Management of Florida Builders is to reduce waste management burden by reducing waste. The hierarchy of waste management is illustrated in Figure 3.8 which indicates that the most important step in waste is to reduce waste by re-using and recycling (Viljoen, 2010).

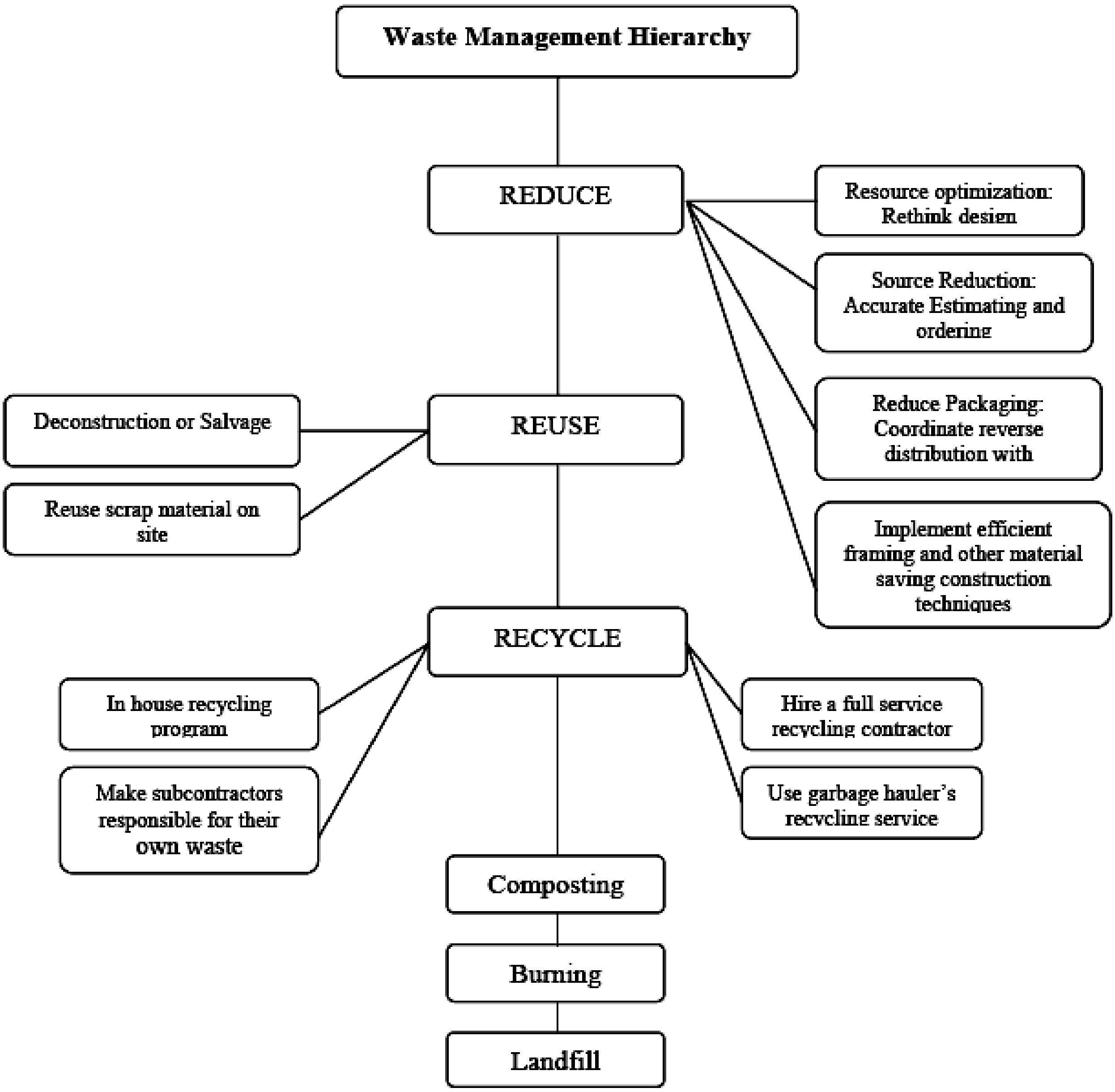


Figure 3.8: Waste Management Hierarchy (Viljoen, 2010)

3.5.1 Reduce

Reducing entails elimination or reduction of the amount of the materials to be used on site, before entering the solid stream. The architect can design structures on modular basis, which results in the use of standardized materials which help by reducing waste on construction site. Planning is the key to reduction. Thoroughly planning of the entire construction process reduces waste magnificently (Viljoen, 2010).

3.5.1 Re-use

Re-use is the second level of waste management hierarchy of which is the next step in materials efficiency and prevention of waste. Materials extracted from demolition/reconstruction project or left-over material can be re-used for future or current projects at other sites (Viljoen, 2010).

3.3.3 Recycling

The recycling process involves separating of waste into recyclable and non-recyclable materials. Virgin materials can be preserved by producing new materials with recycled content. Second World countries suffer most when it comes to waste and pollution. Measures need to be put in place to prevent illegal dumping of waste materials. Act 107 2008, of the National Environmental Management is described in section 16(1) (NEMA) which covers the generic duty with regards to waste management and waste classification.

There are number of laws which govern the establishment of waste management facilities. Act 107 of 1998, of the National Environmental Management stipulates that “any person, who causes, has caused or may cause significant pollution or degradation of the environment, must take reasonable measures to prevent such pollution or degradation from occurring”. The Environmental Conservative Act 73 of 1989, section 20(6) concentrates on the permit application of the waste facility and legislation for land use. There is a challenge with complying with all the governing waste management laws which tends to restrict the establishment of smaller waste processing facilities like clean material recovery facilities (Viljoen, 2010).

There are many timeous and effective management challenges presented by legislation. The legislation includes regulations for Environmental Impact Assessment (EIA) with a major focus on identification and assessment of projected impacts. The main legislation sources are: International Environmental Law, Constitution of RSA, National Statutes, Provincial Bylaws and Standards (Viljoen, 2010).

There are only three landfills sites remaining in Cape Town, namely Coastal Park, Bellville South and Vissershok (see Figure 3.9). They are filling very quickly as a result of increased waste generation. The waste volume per annum in Cape Town is 2.7 million tons, which excludes waste received by private waste sites. Urbanisation and population growth are the reasons for an increase in waste generation.

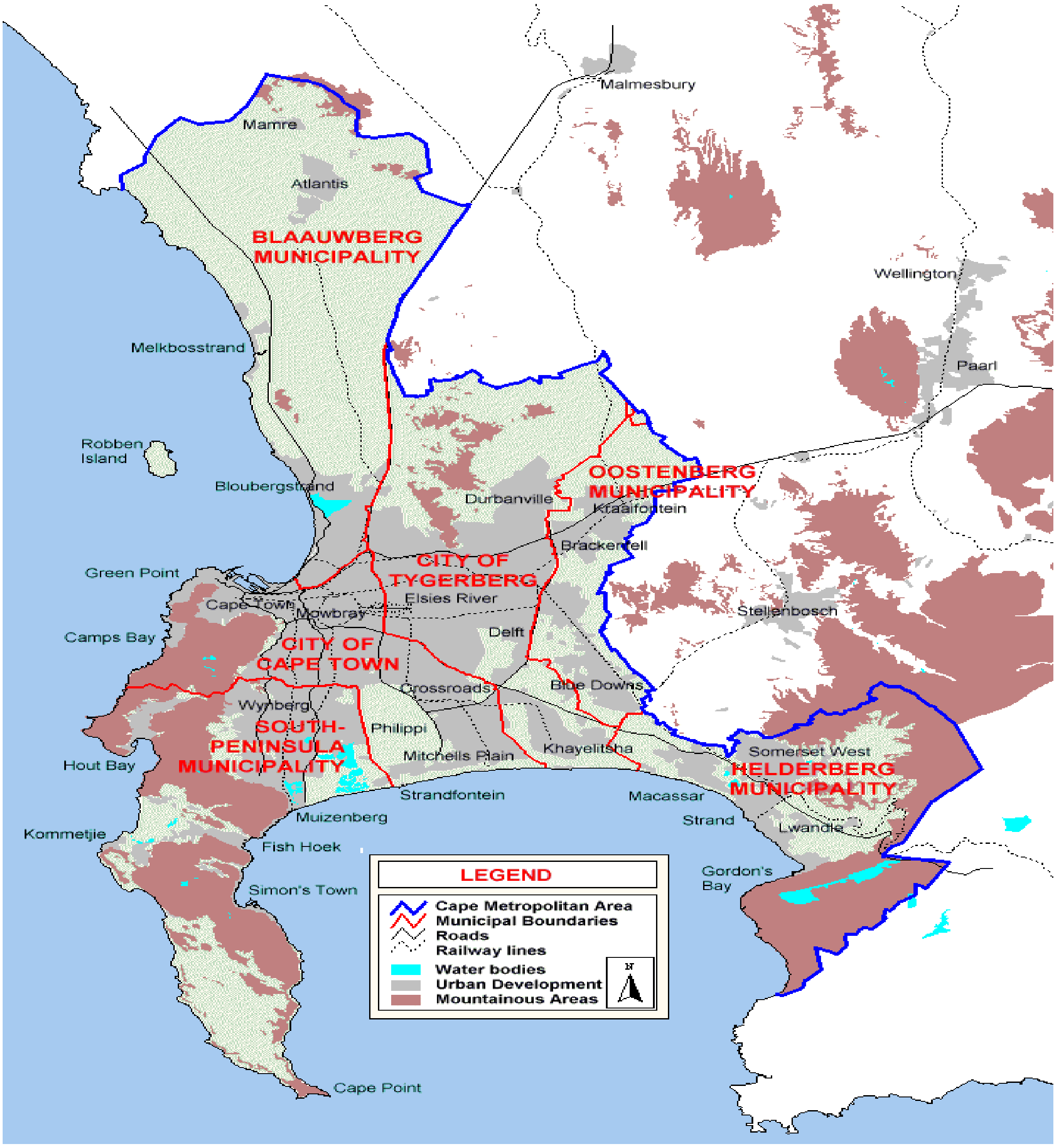


Figure 3.9: Landfill sites Western Cape (Viljoen, 2010)

There is also an additional challenge to the construction industry by the Municipal Finance Act and the Municipal Sysytems Act, which constrains waste management (Viljoen, 2010)

CHAPTER 4: Materials and Method

This chapter provides information with regards to properties of the material used and the manner of which the sample was obtained.

4.1 Materials

Recycled concrete aggregates were obtained from returned conventional concrete at a typical dry batch Ready-Mix Concrete (RMC) plant on the northern side of Bloemfontein in the Free State Province as indicated in Figure 4.1. The Plant produces mainly produces 25Mpa conventional concrete with 75mm slump with a density of 2600Kg/m^3. The RMC plant generates about 4115m^3 of returned concrete rubble per year which is transported to the Aggregates Quarry for dumping. The typical concrete mix design for conventional concrete is given in table 4.1 and raw material that were used are follows:

Design Strength@28 days		25Mpa
Product code		25Mpa Standard Mix
MATERIALS	UNITS	
Water	Lt	166
Cement	Kg	220
Fly Ash	Kg	55
20mm C/Stone	Kg	1176
7mm Crusher Sand	Kg	621
River Sand	Kg	305
Admixture	Lt	1.64
C/W	-	1.66
Design Slump	mm	75

Table 4.1: Typical mix design for 25Mpa conventional concrete

a) Powercrete plus Cem II 42.5R cement supplied by Lafarge from Litchtenburg in the North West Province. More technical information regarding the cement used to produce readymix concrete is given in Appendix B.

b) Fly ash from Lethabo power station supplied by Ash Resources from Metsimaholo in the Free State Province. More technical information regarding Fly Ash used to produce readymix concrete is given in Appendix C.

c) 19mm dolerite aggregates from Olive Hill Quarry in Bloemfontein in the Free State Province. More information regarding this material is given in Appendix D.

d) Minus 6.7mm dolerite washed crusher sand with from Olive Hill Quarry in Bloemfontein in the Free State Province.

e) Minus 4.75mm decomposed sandstone river sand in Wepener in the Free State Province., more technical information is given in Appendix E.

f) High range water reducing plasticiser, more technical information regarding the plasticiser is given in Appendix F.

g) Municipal tap water as supplied by Mangaung Municipality in Bloemfontein

The conventional ready-mix concrete rubble was transported to Olive Hill Quarry in Bloemfontein for processing. The material was produced by crushing it with a jaw crusher and screened through a top screen of 100mm and a bottom screen of 55mm. Three samples from the same stockpiles were taken for physical and chemical testing with the idea of establishing whether the properties of recycled concrete aggregates warrant it suitable for usage as base course material for pavements.

Figure 4.1 Returned readymix concrete rubble used in this study

4.2 Sub-base requirements

Committee of Land Transport Officials (1998) is used as a guideline for virgin road materials in South Africa. Committee of land transport officials (COLTO) guidelines have been developed to ensure that construction materials used in South African roads meet pavement design and durability performance expectations under South African conditions.

4.3 Physical and Mechanical Tests Method

4.3.1 Sieve Analysis

Sieve analysis was done to determine the particle size distribution of aggregates for road base material. The particle size distribution was used in conjunction with other tests for assessing the density, stability and compaction properties of recycled concrete aggregates. The test was done according to South African National Standards 3001 GR2+GR5: 2012 to determine the grading, dust content and grading modulus. Three samples were washed through the 0.075mm and dried for 24 hours before being sieved through a nest of sieves consist of 50mm, 37.5mm, 28mm, 20mm, 14mm, 5mm, 2mm, 0.425mm, 0.075mm. Material was oven-dried for 24 hours at a temperature not exceeding 110˚C. The material retained on different sieves was weighed to the nearest 1gram determine the particle distribution, dust content and grading modulus (GM) (SANS 3001, 2012). The grading modulus was determined by using the following formula:

$$GradingModulus = \frac{[300-(P2+P0.425+P0.075)]}{100}$$

Equation 3 (SANS 3001, 2012)

where P2.00 : The percentage passing 2.00mm sieve

where P0.425 : The percentage passing 0.425mm sieve

where P0.075 : The percentage passing 0.075mm sieve.

The results gave an indication of how the particles sizes of the material are distributed which is an important for classifying the material.

4.3.2 Loose and compacted bulk density

Compacted and loose bulk density was done to determine how aggregates could be densified, which is a function of particle shape, size distribution and relative density. The test was done according to South African National Standard 5845:2006. Aggregates were dried in ovens overnight at a temperature of 110˚C and removed from the oven the following day to allow it to cool. The Loose Bulk Density (CBD) was determined by filling appropriate bulk density cylinder with recycled concrete aggregates, the aggregates falling off the scoop at a height of not more than 50mm above the lip of the container. The material was rolled off with a tamping rod to level it and a hand was used to remove impeding material. The Compacted Bulk Density (CBD) was filling the container in three layers, each layer was tamped 30 times. The third layer was rolled off with a tamping rod similar to LBD, the mass of the container and sampled was determined to be used for calculating the CBD (SANS 5845, 2006). The mass of the sample and the container were determined to be used to calculate the LBD and CBD using the formula below.

$Bulkdensity(e) = \left[\frac{d}{a}\right] X1000$ Equation 4 (SANS 5845, 2006)

where:

Volume of cylinder is (a)

Mass of cylinder is (b)

Mass of aggregates & cylinder is (c)

Mass of aggregate is $(d) = c - b$ Equation 5 (SANS 5845, 2006)

$Voidcontent = \left[\frac{e}{fX10}\right] - 100$ Equation 6 (SANS 5845, 2006)

The LBD and CBD give an indication of how the particles of the material are packed which also gives an indication of the voids in the matrix of the material.

The apparent relative density was determined according to South African National Standards 5844: 2006. The material was put through a 4.75mm sieve and lumps were broken off by hand. About 500g of the sample was dried overnight at a temperature of 110˚C and removed to allow it to cool the following morning. The Pycnometer was tarred and a prepared sample of determined mass was placed inside the Pycnometer. Distilled water was poured into the Pycnometer to cover aggregates and wash down aggregates adhering to the walls. The entrapped air was removed with a vacuum below 13Kpa. The Pycnometer was filled with water to its brim once the contents stopped emitting air bubbles. The outside of the Pycnometer was cleaned and dried to determine the mass of the contents. The Pycnometer was cleaned and dried. The Pycnometer was filled with distilled water to the brim and the mass was determined, the mass of a Pycnometer was also determined. The mass of the sample, Pycnometer with contents, Pycnometer with distilled water, and an empty Pycnometer were used to determine the apparent relative density (SANS 5844, 2006).

$Apparent\ relative\ density = \left(\frac{a}{d}\right) Xdw$ Equation 7 (SANS 5844, 2006) where:

Mass of sample used is **(a)**

Mass of Pycnometer, glass plate, sample and water is **(b)**

Mass of Pycnometer, glass plate and water is **(c)**

$Mass\ of\ waterdisplaced(d) = (c + a) - b$ Equation 8 (SANS 5844, 2006)

d_w is density of water

The relative density gives an indication of the strength and permeability of the material and is also used for calculating yields.

4.3.3 Water absorption of aggregates

The water absorption was done to determine how much water is absorbed by the aggregates, which gives an indication of the likelihood of swelling as a result of moisture which may lead to deterioration of the pavement, the test was done according to South African National Standards 3001 AG21: 2014. The sample was riffled to get representative sample of 300g sample on -4.75mm and +0.075mm sieve. The 300g samples was dried in drying pans and covered under distilled water for 24h. The mass of a dry and clean Pycnometer with glass plate was recorded to the nearest 0.1g as **M1.** The mass of a Pycnometer filled with water and a glass plate was recorded as **M2.**

The soaked sample was spread on a flat surface to expose it to free moving air and stirred to ensure it is uniformly dry. Damp material was placed in a cone mould on a flat surface and tamped 25 times and the cone was removed vertically. This was repeated until the material slumped and the slumped material was taken to the dry Pycnometer and the mass recorded as **M3.** Distilled water was added to the Pycnometer until it was about ¾ full. Excessive air was removed with a vacuum, the Pycnometer was filled with distilled water and the mass was recorded as **M4.** The mass of the drying pan was recorded as **M5.** The wet material was transferred to the drying pan, dried at a temperature of 110˚C, the sample was allowed to cool and recorded as **M6** (South African National Standard 3001, 2014). The following formula was used to calculate the water absorption.

$Water\ Absorption = \frac{b-a}{a}$ X100 Equation 9 (SANS 3001, 2014)

where:

M1 = Mass of dry Pycnometer + glass plate Equation 10 (SANS 3001, 2014)

M2 = Mass of Pycnometer + water + glass plate Equation 11 (SANS 3001, 2014)

M3 = Mass of sample + Pycnometer + glass plate Equation 12 (SANS 3001, 2014)

M4 = Mass of sample + Pycnometer + water + glass plate Equation 13 (SANS 3001, 2014)

M5 = Mass of pan Equation 14 (SANS 3001, 2014)

M6 = Mass of dry sample + pan Equation 15 (SANS 3001, 2014)

SAMPLE MASS **(a = M3-M1)** Equation 16 (SANS 3001, 2014)

SAMPLE MASS **(b = M6- M5)** Equation 17 (SANS 3001, 2014)

The water absorption test gave an indication of how much water will be absorbed by the material which is important for compaction.

4.3.9 Cone liquid limit

The cone liquid limit test was done to classify the soil as clay or non-clay material. The classification of the soil is critical because material that contains clay is sensitive to moisture variations because it expands and shrinks with changes in moisture content which leads to pavement distress. The test was done according to British Standard 1377-2 (1990). About 300g of material was placed in a glass plate after being prepared. The paste was mixed for about 10 minutes using two palette knives. The portion of the mixed soil was put into a cup and struck off with a palette knife to get a smooth level surface. The penetration cone was locked in the raised position with the supporting assembly, with the tip of the cone touching the surface of the soil.

The stem of the dial gauge was lowered to touch the cone shaft and recorded to the nearest 0.1mm. The cone was allowed to drop for 5 seconds. The beginning and the end of the drop was recorded to the nearest 0.1mm and the difference between the beginning and the end was recorded. The cone was lifted and cleaned carefully. Water was added slightly and the penetration process was repeated three times with a difference range of more than 0.5mm and less than 1mm. A moisture content sample of 10g was taken in the area of penetration by the cone and the moisture content was determined.

The relationship between the cone penetration and the moisture content was plotted on linear scales and the best straight line fitting the plotted points was drawn. The moisture content corresponding to a cone penetration of 20mm was reported as the liquid limit of the soil sample. The cone liquid test gave an indication of whether the material was clay or non-clay.

4.3.10 Petrographic analysis and X-ray diffraction (XRD)

The petrography test was done to determine the minerals present in the aggregates and for geological classification as well. The samples was split and milled. The thin section was prepared from set in epoxy and the remaining specimen was split and milled for XRD. It should be noted that the quantities of minerals shown in the petrographic description were largely based on the amounts calculated from XRD analysis since this reflects a more representative composition.

The back loading preparation method was used to prepare the material. The analyses were done with PANalytical Aeris diffractometer with PIXcel detector and fixed slits of Fe filtered Co-Kα radiation. The X'PertHighscore plus software was used to identify phases. The Rietveld method was used to estimate the relative phase amounts (weight%).

The mineral names do not necessarily reflect the actual composition of minerals identified, they may instead reflect the mineral group. The results may not be as accurate as shown due to crystallite size and preferred orientation effects. The petrography test gave an indication of the geology of the material which is important for determining the performance of the material based on geological information.

4.3.11 Determination of the maximum dry density and optimum moisture content

The test was done to determine the moisture content required to achieve maximum dry density for compaction purpose. This test used to determine the compaction properties of recycled concrete aggregates. The test was done according to South African National Standards 3001-GR51(2013). About 7000g of the material was weighed and transferred to the mixing basin and small quantities of water were added and the material was stirred until the desired lump. The volume of water added was recorded and the material was covered with damp sack to prevent evaporation. Other basins were prepared with a moisture content higher and lower than the first basin respectively to determine optimum moisture content and the material was allowed to stand for half an hour in order for the moisture to be evenly distributed throughout.

The sample's moisture content was determined by weighing the clean mould and recording its mass. The moulds were assembled on the base plate and two filter papers were placed on the spacer plate to prevent the material from sticking to the plate and the collar of the mould was fitted. About 1100g of the material was weighed and transferred to the mould. The mould was put on the base plate and tamped 55 times with a 4.563kg tamper dropped at 457.2mm. The surface first layer after tamping was measured to 95 and 100mm and four more layers were tamped in a similar manner with the following depth limits:

- Second layer at 70 to 75mm, third layer at 40-45mm and fourth layer at 15 to 20mm.

The surface of the material was between 5 and 15mm above the top of the mould without the collar after compacting the fifth layer and the material was cut with the flat of the straight-edge until the material was level with the top of the mould (SANS 3001, 2013). The material cut was sieved through a 4.75mm sieve on top of the material in the mould and tapped lightly with the edge and cut-off and the compacted material was removed from the mould with sample extruder and the calculations were done as follows:

Moisture Content:

$d = \frac{a-b}{b-c} X100$ Equation 18 (SANS 3001, 2013)

where d is the moisture content in % of the dry soil

a is the mass of container and dry material (g)
b is the mass of container and dry material (g)
c is the mass of container (g)

Dry density:

$D = \left[\frac{W}{d+100}\right] XF$ Equation 19 (SANS 3001, 2013)

where
D is dry density
W is mass of wet material (g)
V is volume of mould (ml)
F is factor of the mould.

The moisture-density relationship was graphically determined by graphically plotting the respective densities against respective moisture contents. The peak of the curve was determined as optimum moisture content and maximum dry density of the material when compacted under this effort. The optimum moisture content and maximum dry density test gave an indication of how much moisture will be required to get the maximum dry density of the material.

4.3.12 California Bearing Ratio (CBR)

The test was done to determine the bearing capacity of pavement when soaked in water. The CBR test was used to assess the mechanical strength of recycled concrete aggregates as pavement base coarse material. The test was done according to Technical Methods for Highways - Method A8 (1986). The material was sieved on 19mm sieve and crushed lightly to pass the sieve. About 800g of the material was put in two containers and weighed immediately and dried at 110˚C overnight. The sample was allowed to cool and the moisture was calculated.

The optimum moisture content was determined as per South African National Standards 3001-GR51 (2015). Filter papers were placed on top of three perforated soaking plates and each mould was placed on the filter paper with the finished-off surface facing downwards. The moulds were screwed down tightly onto a soaking plate and 4 563kg surcharge weight was placed on top of the plate. Layers of chipped stone were placed in the bath and the whole assembly was transferred to the soaking bath and the tripod with a dial gauge was placed on the mould.

The stem of the perforated plate was adjusted so that the gauge read 1mm and the same position was used to take readings of the swell. The gauge was removed and the bath was filled with water to a depth of about 12mm above the top of the moulds. The moulds were soaked for four days and the readings were taken on daily basis. The moulds were removed from the bath after four days and the water was drained and allowed to dry for 15 minutes. The perforated plate was carefully removed with the stem and the soaking weights. The mould to be tested was placed centrally on the press with the surcharged weight on top of the sample and loose penetration piston inside the hole of the surcharge weight (TMH, 1986). The penetration was tested and recorded. Calculations were done as follows:

Amount of water admixed:

$$W = \frac{z(y-x)}{100} + X$$ Equation 20 (TMH, 1986)

where
W is amount of water to be admixed
X is hygroscopic moisture content
Y is required (optimum) moisture content
Z is mass of air – dried test sample

Swell (%):
$$S = [(k-L)127]X100$$ Equation 21 (TMH, 1986)
where
S is swell in % of the height of the moulded material before soaking
k is dial gauge reading after four days' soaking
L is dial gauge reading before soaking

California Bearing Ratio:
The stress-strain curve was drawn by plotting the load readings against the depth of penetration for each specimen. The CBR and density relationship was determined by plotting the CBR at 2.54mm penetration against the dry density for three compacted efforts. The CBR gave an indication of the load-bearing capacity of the material when soaked in water for given time frame.

4.3.13 Indirect Tensile Strength (ITS)

The test was done to determine the performance and durability of the pavement when stabilized. The test was done according to South African National Standards 3001-GR54 (2014). The curved side of the specimen was placed on the lower concave loading platen and the upper concave loading platen was placed on top of the specimen. The load transfer plate was centred on top of the loading platen and the assembly was placed centrally under the loading ram of the press machine. A force of 0.1KN was applied on the specimen to seat the loading platens and the assembly was inspected for symmetry and adjusted accordingly. The force was applied at a constant rate of 40KN per minute until failure (SANS 3001, 2014). The maximum applied force was recorded and the calculation was done as follows:

$$ITS = \frac{2G}{\pi X l X d}$$ Equation 22 (SANS 3001, 2014)

where

I_{TS} = the ITS, expressed in kilopascals (kPa);

G = the maximum applied force, expressed in Kilo Newtons (kN);

l = the length of the specimen, expressed in metres (m);

d = the diameter of the specimen, expressed in metres (m).

The indirect tensile strength test gave an indication of how durable and tensile resistance is the material when stabilised.

4.3.14 Unconfined compressive strength

The test was done to determine the bearing capacity of cement stabilised pavement. The test was done according to SANS 3001-GR53 (2010) and the sample was prepared and cured according to SANS 3001-GR50 (2013), SANS 3001-GR51 (2015), or SANS 3001-GR52 (2010). The specimen was removed from the container and merged in the water bath for four hours. The specimen was removed from the water and crushed to a total failure in the compressive machine at a rate of 150kN/minute and the maximum load was recorded to the nearest 1kN (SANS 3001, 2013).The unconfined compressive strength (UCS) was calculated using the following formula:

$$UCS = \frac{1000F}{\pi X r2}$$ Equation 23 (SANS 3001, 2013)

where
UCS = the unconfined compressive strength, in megapascals (MPa);
F = the force required to crush the specimen, in kilo Newtons (kN);
r = the radius of the specimen face, in millimetres (mm).

The unconfined compressive test gave an indication of the load bearing capacity of the material when stabilised.

4.3.15 Triaxial Test

The triaxial test was done to determine the shear strength of the material and it was done according to British Standard 1377 (1990) procedure as illustrated in figure 4.1. The test was carried out on a cylindrical specimen with a height to diameter ratio of 2:1 with the size of 100X50mm. The specimen was prepared and consolidated in the triaxial test device. The specimen was enclosed between capped end-caps with a sealed rubber membrane for sealing the cell water. The rubber O-rings were fitted over the membrane on the caps for sealing purpose. The specimen was subjected to an isotropic stress through filling the cell with water and increasing the pressure to a predetermined value. The drain was opened and the specimen was allowed to consolidate under the isotropic pressure until there was no more change in volume.

The cell pressure was kept constant while the drain was closed and the axial load was then increased until the sample shears and the ultimate stress was reached. The following readings were taken:

a) The change of the length of the specimen.

b) The axial load and the pore pressure of the specimen.

The tri-axial test gave an indication of the shear strength and load bearing performance of the material when subjected to tri-axial forces (BS 1377, 1990).

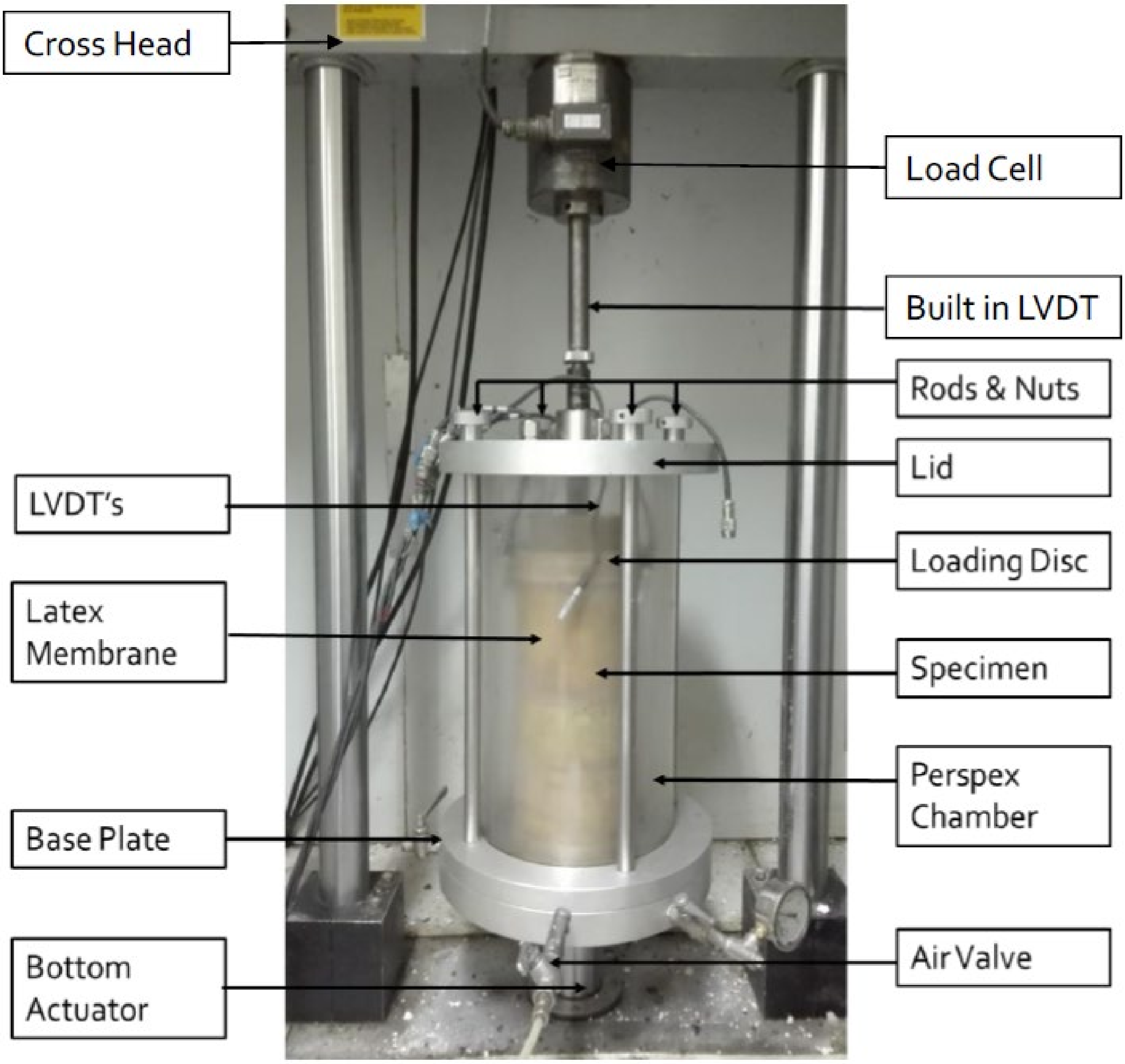


Figure 4.1: Tri-axial set-up (Bredenkamp, 2018)

4.4 Chemical Tests Methodology

4.4.1 Methylene blue

A methylene blue test was done to determine the presence of clay in aggregates which may result in deterioration of the pavement as a result of expansion and shrinking due to a change in moisture content. The test was done according to South African National Standards 6243 (2008). The sample was dried overnight at a temperature of 110˚C and about 1kg of was transferred onto 425µm sieve under which 75µm sieve and a pan were placed. The material passing 75µm sieve was placed in container. The methylene blue was transferred into a 100ml volumetric flask and dissolved with distilled water to make 100ml.

A sample weighing 5g from the material that passed 75µm sieve was mixed with 200ml of hydrogen peroxide into a 600ml with a 250ml measuring cylinder, the solution was boiled for 30minutes on a hot plate and allowed to cool at room temperature for 30min. The contents of the beaker were washed with distilled water and stirred with the magnetic stirrer. The beaker was allowed to stand undisturbed with its contents until the supernatant liquid was clear and there were no solid particles. The clear liquid was decanted until the sample until there was no solid material. The residue was dried overnight at 110˚C and cooled at room temperature.

About 1g of representative specimen was taken from the residue and placed in the Erlenmeyer flask, 30ml of distilled water was added and the specimen was shaken vigorously. A burette was filled with methylene blue indicator solution. Successions of 0.5ml of the indicator solutions were titrated to the dispersion in the Erlenmeyer flask by using the brunette. The contents of the flask were agitated for 1 minute after each addition of the indicator.

The drop of the dispersion was removed with a glass rod and dabbed carefully on a sheet of filter paper. The indicator was added until a definite blue halo was observed and the volume of the indicator solution that caused the blue halo to appear consistently on the filter paper was determined. The methylene blue test gave an indication of clay content which may result in expansion of the material due to changes in moisture content (SANS 6243, 2008).

4.4.2 Water soluble chlorides

Water soluble chlorides were assessed because their presence lead to damage of the overlaying bituminous layer. The test was done according to South African National Standards 202 (2006). A sample with a mass of 500g was dried at a temperature of 80˚C for 16 hours until after two successive four hours drying periods the decrease in mass did not exceed 0.1% of the total mass and the specimen was cooled to room temperature. 500g of test specimen was placed in the flask, mixed with 500ml of water and the contents were mixed by shaking them continuously for 1 hour. The flask was removed from the shaker and the insoluble material was allowed to settle for about 1 hour. A suitable quantity of the aqueous extract was decanted and filtered it through a double layer of glass fibre filter paper of fine texture with the aid of a vacuum. About 10ml of nitric acid was added to 100ml of a filtrate in a flask and the excess quantity of the silver nitrate solution. About 2mL of the nitrobenzene and 1mL of the indicator was added.

The flask was stoppered and the contents were shaken vigorously to coagulate the silver chloride precipitation which was covered with a film of nitrobenzene. The excess silver nitrate was titrated with the ammonium thiocyanate solution. The ammonium thiocyanate solution was added drop by drop towards the end of the titration. The contents of the flask were shaken vigorously to release silver nitrate absorbed by the precipitation before each drop was added (SANS 202, 2006). The chloride content of aggregates was calculated follows:

$$Cl = (B - A)NX0.0345$$ Equation 24 (SANS 202, 2006)

where

Cl is the chloride content of the aggregate which is expressed as a mass fraction percentage;
B is regarded as the ammonium thiocyanate solution, in millilitres which is used for the control titration;
A is regarded as the ammonium thiocyanate solution, in millilitres which is used for the titrating 100 mL of the filtrate;
N is regarded as the normality of the ammonium thiocyanate solution.

Water soluble chlorides test gave an indication of the likelihood of the deterioration of overlaying bituminous layer.

4.4.3 Determination of sulphates

Sulphates were determined to check the likelihood of the formation of swelling minerals such as ettringite and thaumasite in cement stabilised pavements. The test was done according to South African National Standards 5850-2 (2008). About 400g of the material that passed 425µm sieve was dried at a constant temperature of 80˚C and allowed to cool, sieved on 4750µm and 1700µm sieves. A specimen of 10g was weighed into a 400ml beaker and mixed with 200mL of 1:9 dilute hydrochloric acid. The contents were boiled and stirred for 15min and the beaker was placed in warm bath and allowed to stand undisturbed for 30 minutes. A dry 600mL beaker was placed in the Witt filter apparatus and a double layer of glass fibre filter paper was placed on the Buchner funnel and the paper was made wet with a few drops of aqueous extract.

The contents in the beaker were stirred until sediments in the beaker were in suspension. About 150mL of the suspended extract was filtered using a low vacuum and ensuring that the sediments in the beaker are not disturbed. The beaker was rinsed three times with 1:9 dilute hydrochloric acid and the washings were added to the Buchner funnel after each rinse.

About 0.5g of dry filter paper pulp was added to the filtrate and stirred until the paper has disintegrated and filtered through the same glass fibre filter paper again. The filter paper and the beaker were washed thoroughly with 1:99 dilute hydrochloric. The filtrate was boiled until its volume was reduced to about 50mL. The soluble sulphates test gave an indication of the likelihood of swelling and deterioration as a result of swelling substances such as sulphates in cement stabilised material (SANS 5850, 2008).

4.4.4 Determination of the potential hydrogen (pH) value

The pH was determined because too high pH has detrimental effects on aggregates and asphalt bond which leads to deterioration of the pavements and also has detrimental effects on environment next to the road. The sample was prepared and tested according to South African National Standards 5854 (2006). The electrodes and Automatic Temperature Compensation (ATC) probe were placed first in the first sample portion and stirred moderately using stirrer bar and magnet stirrer. The reading of the pH value was taken on the display. The sample was removed and electrode was rinsed with deionised water and dabbed with a soft paper towel to remove water drops. This process was repeated to determine the pH value for the second sample portion and the pH value was calculated as follows:

$$pHvalue(E) = \frac{C+D}{2}$$ Equation 25 (SANS 5850, 2008)

where:

pH value first reading (C)

pH value second reading (D)

pH first value is (C) and the second reading is (D).

4.4.5 Determination of organic impurities

Organic impurities were determined because organic matter such as vegetation has detrimental effects on road pavements especially when it decays, it leads to formation of voids which negatively affect the load bearing capacity of a pavement. The test was done according to South African National

Standards 5832 (2006). The test sample was put to the 125mL mark into the 250mL clear glass medicine bottle. About 3% of hydroxide solution was added to about 150mL, the bottle was stoppered and shaken vigorously to allow mixing. The bottle was washed on the sides with 3% sodium hydroxide solution up to 200mL mark and allowed to stand for 24 hours. The colour of the depth of the liquid layer was compared to that of the reference solution. The organic impurities test gave an indication of the loss of stability in the pavement due to formation of voids when the organic matter decays.

CHAPTER 5: Results and discussion

5.1 Physical and mechanical results

Natural and recycled concrete samples were obtained in the city of Bloemfontein in the Free State province of South Africa to test the physical properties. The physical tests that are discussed in this study are: sieve analysis, densities, Atterberg limits, maximum dry density and optimum moisture content, California bearing ratio, indirect tensile strength and unconfined compressive strength. The results are discussed for every physical test that was conducted and results are checked against existing standards where applicable.

5.1.1 Sieve analysis and densities

Sieve analysis was used for determining the maximum particle size, relative distribution of particle sizes and the amount of fine material present which affect the performance and density of the material. Recycled concrete aggregates and natural aggregates samples were tested as summarised in Table 5.1 and the results were plotted as shown in Figure 5.1 which gives a graphical representation of particle size distribution. Both recycled concrete aggregates and natural aggregates had a maximum particle size of 37.5mm. The coefficient of uniformity was greater than recommended value of 4 and the coefficient of curvature was in the recommended range of 1 and 3 for both natural and recycled concrete aggregates, which indicates a well-graded distribution.

The particle size ranged from 37.5mm to 0.75µm with a grading modulus of 2.48 and 2.56 for recycled and natural aggregates respectively which resulted in a dense material matrix. The loose and compacted bulk densities of recycled concrete aggregates were 1568kg/m^3 and 1758Kg/m^3 for an apparent relative density of 2.56, compared to loose bulk density of 1574kg/m^3 and compacted bulk density of 1761kg/m^3 with apparent relative density of 2.98 which is higher than recycled concrete aggregates due to good particle distribution when compared to recycled concrete aggregates.

The difference between loose and compacted bulk void ratio is less than 10% for both natural and recycled concrete aggregates which also indicates that material has a good particle distribution which resulted in dense material matrix. The grading modulus (GM) was 2.48 for recycled concrete aggregates and 2.56 for natural aggregates. The GM for recycled concrete aggregates which meet the COLTO G5 material requirements of a GM between 1.5 and 2.5, however natural aggregates have a slightly higher GM which is an indication of slightly coarse material with superior quality. The grading properties of recycled concrete aggregates fully comply with G5 requirements, which indicates that recycled concrete aggregates can replace natural aggregates and be used as G5 material.

5.1.2 Plasticity index

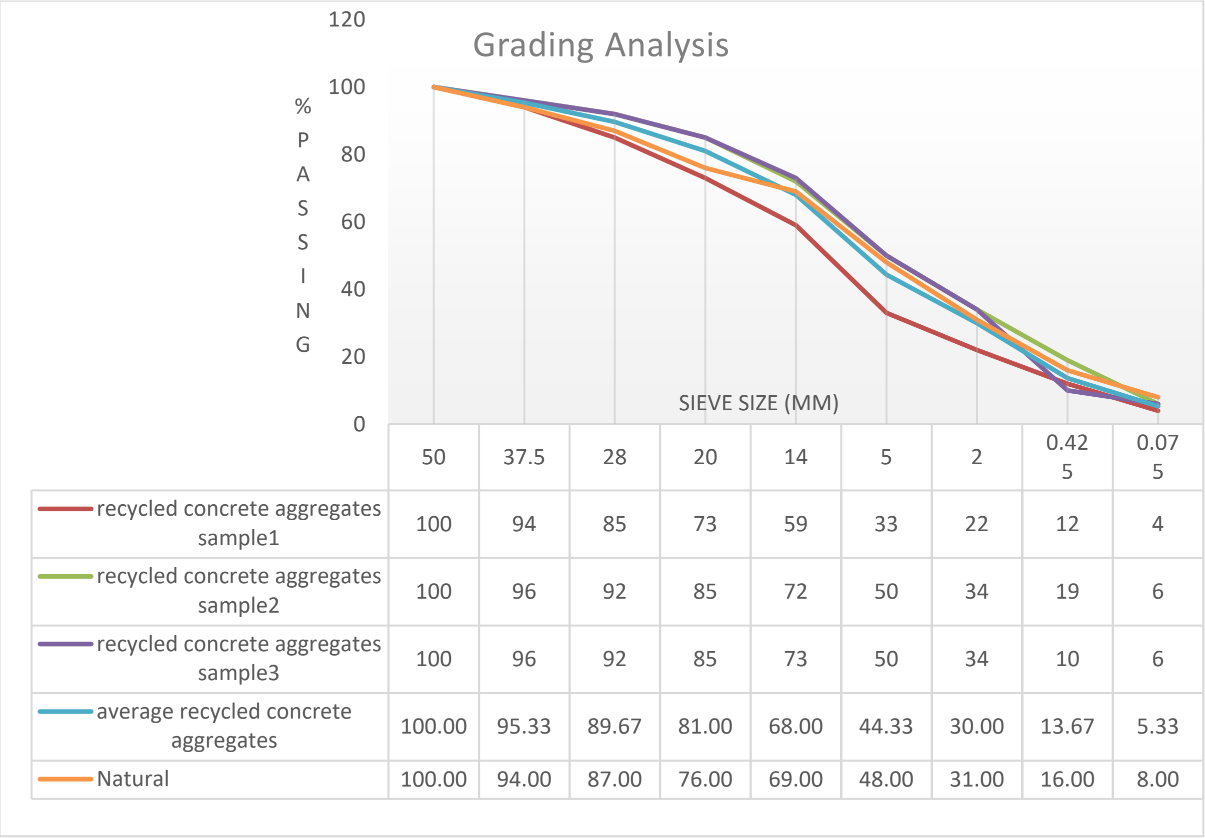
Atterberg limit tests were used for measuring the plasticity and classification of the material. Table 5.1 gives a summary of the Atterberg limits for liquid limit (LL) and plastic liquid (PL). The Atterberg Limits indicated that the recycled concrete was non plastic and natural aggregates have a PI of 8 which meets the requirements of G5 material. Recycled concrete aggregates were non-plastic at all due to cementitious material present in recycled concrete aggregates which improved the plastic properties of the material.

Both recycled concrete and natural aggregates gave a good indication for stability and deformation. The plasticity properties of recycled concrete aggregates were better than those of natural aggregates. Therefore recycled concrete aggregates won`t have significant volumetric changes when subjected to changes in moisture content as a result of expansion and shrinking that is associated with high plasticity index, which leads to pavement distress.

Table 5.1 Summary of recycled concrete aggregates and natural aggregates results

	Sieve Size in mm	**Recycled aggregates Sample1 (%)**	**Recycled aggregates Sample2 (%)**	**Recycled Aggregates Sample3 (%)**	**Recycled aggregates Average (%)**	**Natural aggregates (%)**	**COLTO G5 Requirements**
	50	100	100	100	100.00	100.00	Not applicable
	37.5	94	96	96	95.33	94.00	Not applicable
	28	85	92	92	89.67	87.00	Not applicable
	20	73	85	85	81.00	76.00	Not applicable
	14	59	72	73	68.00	69.00	Not applicable
	5	33	50	50	44.33	48.00	Not applicable
	2	22	34	34	30.00	31.00	20-70%
	0.425	12	19	10	13.67	16.00	Not applicable
	0.075	4	6	6	5.33	8.00	Not applicable
Soil Mortar Analysis	**Minus 0.425 Plus 2.0**	46	45	45	45.33	47	Not applicable
	Minus 0.425 Plus 0.25	17	17	16	16.67	10	Not applicable
	Minus 0.25 Plus 0.15	12	11	13	12.00	6	Not applicable
	Minus 0.15 Plus 0.075	9	8	10	9.00	10	Not applicable
	< 0.075	17	19	16	17.33	27	Not applicable
	GM	2.62	2.41	2.41	2.48	2.56	1.5 to 2.5
Atterberg	**LL**	Non plastic	Non plastic	Non plastic	Non plastic	26.00	≤30

Limits	**LS**	Non Plastic	Non plastic	Non plastic	Non plastic	4.50	≤6
	PI	Non plastic	Non plastic	Non plastic	Non plastic	8.00	≤15
Cone penetrometer liquid limit (%)							
Sample		40.4	46.2	47	44.53	19	Not applicable
Densities							
Compacted bulk density (CBD) in Kg/m3		1748	1749	1776	1758	1761	Not applicable
Loose bulk density (LBD) in (Kg/m3) in Kg/m3		1557	1556	1592	1568	1574	Not applicable
Void content (CBD) in (Kg/m3)		32	31.9	30.9	31.6	31.47	Not applicable
Void content (LBD) in (%)		38	39.5	38.1	38.53	38.77	Not applicable
Water absorption of fines in (%)		6.8	6.4	8.6	7.27	7.43	Not applicable
Coefficient of Uniformity		28.5	31	29	29.5	27	Not applicable
Coefficient of Curvature		1.59	1.58	1.55	1.57	1.44	Not applicable
Strength (CBR)		138	141	137	139	254	Not applicable



	50	37.5	28	20	14	5	2	0.425	0.075
recycled concrete aggregates sample1	100	94	85	73	59	33	22	12	4
recycled concrete aggregates sample2	100	96	92	85	72	50	34	19	6
recycled concrete aggregates sample3	100	96	92	85	73	50	34	10	6
average recycled concrete aggregates	100.00	95.33	89.67	81.00	68.00	44.33	30.00	13.67	5.33
Natural	100.00	94.00	87.00	76.00	69.00	48.00	31.00	16.00	8.00

Figure 5.1: Graphical representation of particle distribution

5.1.3 Compaction

The compaction test was done to determine the highest particle arrangement with less voids that can be achieved. The compaction test was done by determining Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). In road construction, pavement material is compacted at optimum moisture content to get to maximum dry density which is correlated to the performance of the pavement under loading from vehicles. The moisture required to give maximum moisture content is determined by a laboratory test.

Trials were conducted with recycled concrete aggregates and natural aggregates. The results are summarised in Table 5.2. Recycled concrete aggregates broke down into smaller pieces when compacted in relation to natural aggregates as a result of loss of aggregates stiffness due to second crushing and cementitious paste that coated aggregates.

The optimum moisture content of recycled concrete aggregates varied from 14.5 to 15.3% with an average 15.03% which is on the high side compared to 13.3% for natural aggregates. The optimum moisture for recycled concrete aggregates is high as a result of paste from concrete that is coating the particles of recycled material. The recycled concrete aggregates pavement matrix will be slightly more porous than natural aggregates due to slightly higher optimum moisture content, which results in more voids when water dries.

The maximum dry density for recycled concrete aggregates varied from 1887 to 1926 Kg/m3 with an average of 1906 Kg/m^3, which is on the lower side compared to natural aggregates which varied from 2048 to 2050 Kg/m^3 with an average of 2049 Kg/m^3. The maximum dry density for recycled concrete aggregates is on the lower side due to voids that are created by higher optimum moisture content and loss of aggregates stiffness since recycled concrete aggregates have been subjected to crushing twice. Recycled concrete aggregates varied more than natural aggregates due to different concrete strengths produced at the ready mix plant, cementitious paste coating aggregates, secondary crushing and insufficient blending during production.

Figure 5.2 indicates that recycled concrete aggregates were more susceptible to moisture changes before reaching the maximum dry density as a result of cementitious properties in recycled concrete aggregates which assist in strength gain when mixed with water.

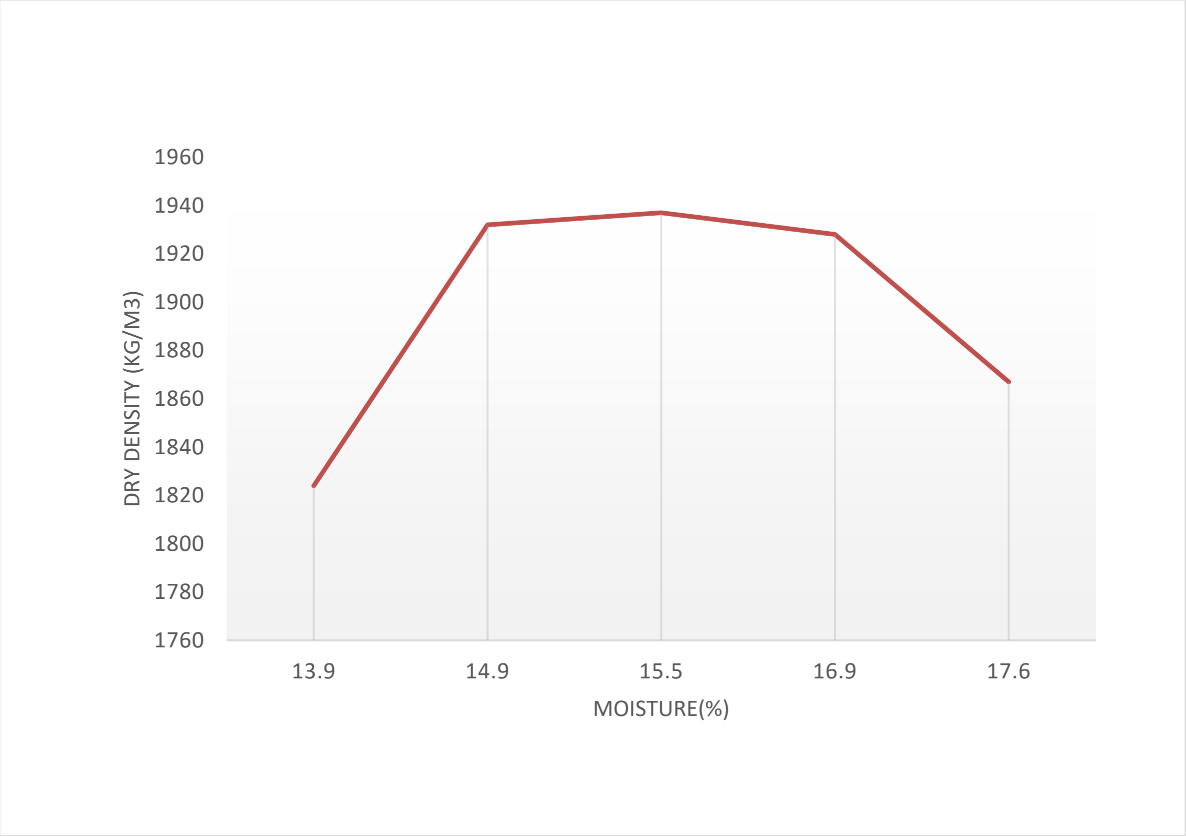


Figure 5.2: Dry density versus optimum moisture content for unstabilised recycled concrete aggregates

5.1.4 California Bearing Ratio (CBR)

The CBR was used to measure the indirect shear strength which is used to determine bearing capacity of the soil when used as base and sub-base material for pavement layers. The results of the CBR from 90 to 100% Mod AASHTO relative compaction are summarised in Table 5.2. The results indicate that the CBR of recycled concrete aggregates is lower than that of natural aggregates from 100 to 95% relative compaction.

The results indicate that on average the optimum moisture content of 15.03% gives a CBR value of 102.6 at 100% Mod ASSHTO for recycled concrete aggregates compared to an optimum moisture content of 13.3 with a CBR value of 245 at 100% Mod AASHTO for natural aggregates which is more than twice that of recycled concrete aggregates. The low CBR value and high moisture content for recycled concrete aggregates is due to cementitious paste coating aggregates and loss of aggregate stiffness as a result of being subjected to crushing twice. The CBR results for recycled concrete aggregates varied from 88.5 to 113.7 at 100% which is a difference of 16% compare to 5% variance for natural aggregates, which indicates that the material was very inconsistent as a result of different concrete strengths, cementitious paste coating and effects of secondary crushing. The swell for recycled concrete aggregates was 0.05% compared to 0.00% for natural aggregates. The plasticity properties indicates that recycled concrete aggregates are very stable and don`t expand much since they are nonplastic, as confirmed by the plasticity test. The swelling in recycled concrete aggregates can therefore be attributed to porousness as a result of higher optimum moisture content. The CBR for recycled concrete aggregates at 95% Mod ASSHTO was 76.03 which makes recycled concrete aggregates suitable to be used as G5 material since COLTO specifies CBR of not less than 45 at 95% for G5 material.

Table 5.2: Summary of density results at different CBR values for unstabilised recycled concrete and natural aggregates

Sample	**Recycled concrete aggregates**	**Natural aggregates**
Maximum dry density (Kg/m3)	1906.33	2049
Optimum moisture content (%)	15.03	13.3
Swell (%)	0.05	0.0
100 (%)	102.6	245
98 (%)	96.90	171
97 (%)	89.00	119.7
95 (%)	76.03	100
93 (%)	59.70	70
90 (%)	39.03	41

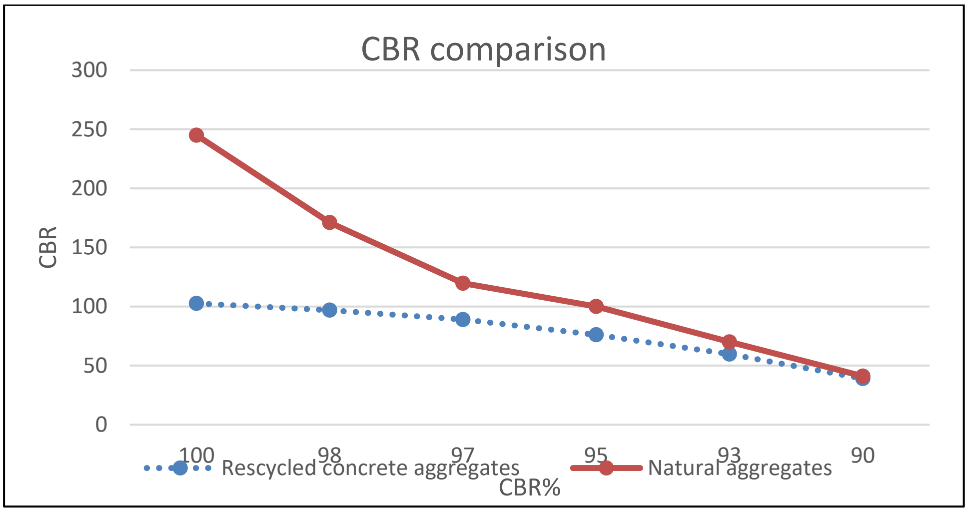


Figure 5.3: Recycled concrete and natural aggregates CBR comparison

5.1.5 Unconfined compressive strength (UCS) and Indirect Tensile Strength (ITS)

The UCS and ITS tests were done to assess the compressive and tensile strength parameters of stabilised recycled concrete and natural aggregates when subjected to loading. The stabilisation tests were done according to Technical Recommendations for High ways (TRH) 14 of 1985. Cem II/B-M (V-S) 32.5N which conforms to SANS 50197 (EN 197) specification was used for stabilisation of recycled concrete and natural aggregates respectively. The properties of the cement used for stabilisation are summarised in Appendix A. The unconfined compressive strength (UCS) test was done on different cement contents.

The cement content for UCS varied from 2 to 3% in increments of 0.5% respectively. The minimum and maximum UCS for recycled concrete aggregates were 1107 and 2023 KPa respectively which meet the material specification requirements for C4 and C3 as per COLTO, which specifies 750 to 1500 KPa and 1500 to 3000 KPa for C3 and C4 respectively at 100% Modified AASHTO compaction. The minimum and maximum UCS for natural aggregates were 4003 and 5071 KPa respectively. The UCS is influenced by the OMC and MDD, the low OMC and high MDD gives high UCS. The low UCS in recycled concrete aggregates can be attributed to low MDD as a result of high porosity associated with high OMC which affects the interlocking properties of recycled concrete aggregates.

The minimum and maximum indirect tensile strength (ITS) of 96 and 169 KPa for recycled concrete aggregates were achieved. The ITS for recycled concrete was also on the lower side with a minimum and maximum of 96 to 168.67KPa compared to 243 and 421 KPa for natural aggregates. The UCS and ITS increased for both recycled concrete and natural aggregates increased with the increase in cement quantity as expected, which indicates that even higher strengths can be achieved with further increase in cement content. It is usually easy to achieve any specified UCS than the ITS, care should be taken to avoid cracks with further increase in cement quantity to achieve high ITS. The ITS of recycled concrete aggregates was reduced by the residual fines from the original concrete. The coated surface of recycled aggregates affected the bond strength which resulted in low ITS.

The maximum dry density of stabilised material increased for both recycled and natural aggregates compared to that of unstabilised material, which indicates that stabilisation improves the particle arrangement which results less voids and an in improved performance and durability. The density of stabilised natural aggregates was higher than that of recycled concrete aggregates due to higher optimum moisture content of 13.13% on average for recycled concrete aggregates compared to an average of 5.27% for natural aggregates. The higher OMC for recycled concrete aggregates results in more voids when moisture is depleted, which drops the UCS and ITS performance.

Table 5.3: Summary of UCS and ITS for cement stabilised recycled concrete and natural aggregates

Recycled Concrete Aggregates						
Sample	**Recycled concrete aggregates sample**	**Recycled concrete aggregates sample**	**Recycled concrete aggregates sample**	**Natural aggregates**	**Natural aggregates**	**Natural aggregates**
UCS (Kpa)	**1107.00**	**1522.33**	**2022.67**	**4003**	**4945**	**5071**
ITS (Kpa)	**96.00**	**134.67**	**168.67**	**243**	**373**	**421**
Cement content (%)	**2.00**	**2.50**	**3.00**	**2.00**	**2.50**	**3.00**
Maximum dry density (Kg/m3)	**1955.67**	**1953.67**	**1953.67**	**2279**	**2279**	**2279**
Optimum moisture content (%)	**13.13**	**13.13**	**13.13**	**5.6**	**5.1**	**5.1**

5.1.6 Chemical results

The pH test was done to determine the levels of acidity, initial cement consumption and soluble salts which could be detrimental and result in a loss of bond between aggregates and bitumen. The initial pH of unstabilised recycled concrete aggregates was 13.01 which is higher than the pH value of 9.04 for unstabilised natural aggregates. The high pH value is because recycled concrete aggregates have cementitious properties due to cement that was initially used in the concrete mix design. The initial consumption of cement for recycled concrete aggregates was 2% compared to 3% for natural aggregates. The reduction in initial consumption of cement is due to the cement that was used in the concrete mix design. The initial consumption of cement should be met to ensure that stabilised material becomes more durable.

The sulfate and chloride contents were determined to assess the possibility of distress due to chlorides and the possibility of swelling and expansion which will have detrimental effects on the performance of the stabilised recycled concrete aggregates. The sulfate content for recycled concrete was 0.62% compared to 0.058% for natural aggregates which is extremely low. The sulfate content for both recycled and natural aggregates were less than the requirements of EN 197 which specifies a limit of 3.5 to 4.0 per cent for different strength classes. The sulphate content of recycled concrete aggregates was less than that of recycled concrete aggregates due to the presence of cementitious material in recycled concrete aggregates. The chloride content for recycled concrete aggregates was 0.002% compared to less than 0.001% for natural aggregates. The chloride content for both recycled concrete and natural aggregates were way lower than the maximum of 0.01 per cent as per SANS 1083 and therefore will not have detrimental effects even on reinforced concrete structure.

The chloride content of recycled concrete aggregates was less than that of natural aggregates due to a small percentage of chloride in the plasticiser used concrete production. There were also no organic impurities in both recycled concrete and natural aggregates which are likely to result in formation of voids when vegetation decomposes and form voids which lead to instability of pavement layers.

The methylene blue was 0.3 for recycled concrete aggregates compared to 0.45 for natural aggregates, which shows that the material did not have excessive clays which would be problematic due volumetric changes as a result of changes in moisture content, the threshold figure according to SANS 1083 is 0.7 and the obtained results were way below this figure. The methylene blue of recycled concrete aggregates was less than that of natural aggregates due to presence of cementitious material in recycled concrete aggregates which altered the plasticity properties.

Table 5.4: Potential Hydrogen (pH) and Initial Consumption of Cement (ICC)

Chemical Results						
pH and ICC TMH1:Method A 20, (SANRAL MANUAL M5 A17T)						
Sample No:		Sample1	Sample2	Sample3	Average	Average
Description:		Recycled concrete aggregates	Recycled concrete aggregates	Recycled concrete aggregates	Recycled concrete aggregates	Natural aggregates
%Lime	0	13.05	12.98	12.99	13.01	9.04
	0.5	13.2	13.07	13.07	13.11	11.59
	1	13.26	13.12	13.12	13.17	11.90
	1.5	13.31	13.15	13.16	13.21	12.05
	2	13.35	13.19	13.21	13.25	12.14
	2.5	13.37	13.22	13.24	13.28	12.16
	3	13.39	13.24	13.26	13.30	12.22
	3.5	13.4	13.25	13.27	13.31	12.23
	4	13.41	13.26	13.28	13.32	12.23
	4.5	13.42	13.27	13.29	13.33	12.26
	5	13.43	13.28	13.3	13.34	12.28
	5.5	13.44	13.29	13.31	13.35	12.30
ICC (%)		2	2	2	2	3
Methylene Blue		0.3	0.3	0.3	0.3	0.25
Water soluble chlorides		0.002	0.002	0.002	0.002	0.001
Sulfates		0.56	0.65	0.65	0.62	0.058
pH value		13.05	12.98	12.99	13.01	8.28
Organic impurities		Not Present	Not Present	Not Present	Not Present	Not present

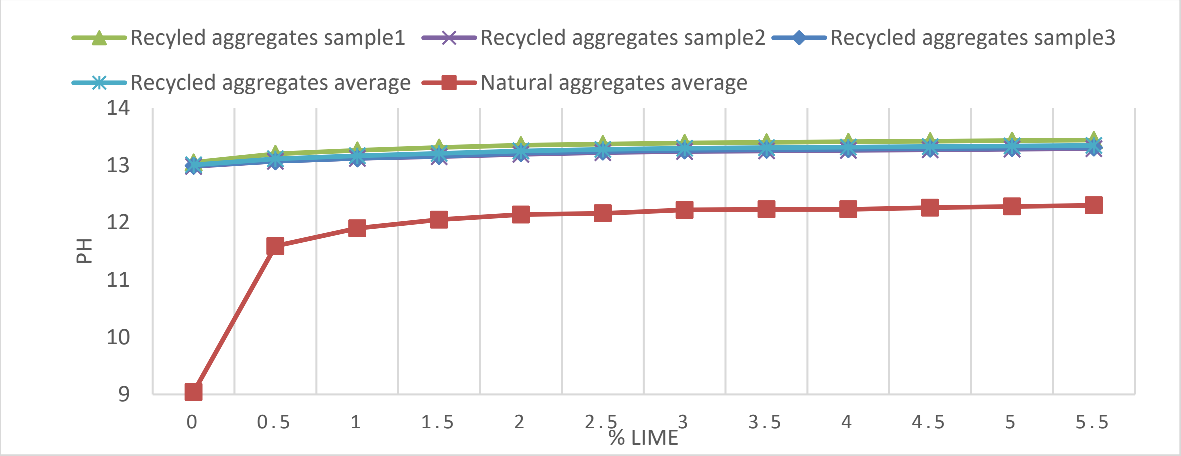


Figure 5.4: Graphical representation of pH and ICC

5.1.7 Geological Results

The X-ray diffraction (XRD) test was done on recycled and natural aggregates to determine the geology and to ascertain if there were any detrimental minerals. The results of the mineral quantities that were observed on both samples in thin sections are summarised in Table 5.5.

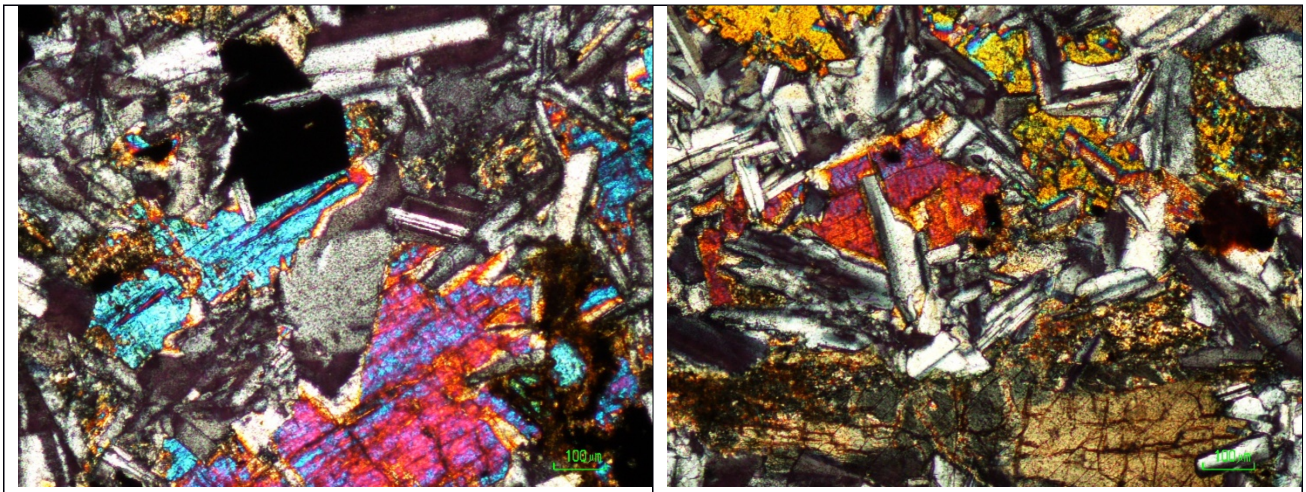
Table 5.5 Recycled concrete and natural aggregates XRD results

Recycled concrete aggregates XRD	
Anorthite (%)	46
Calcite (%)	7
Clinochlore (%)	1
Diopside (%)	17
Enstatite (%)	4
Muscovite (%)	3
Quartz (%)	16
Smectite (%)	5
Talc (%)	1
Natural aggregates XRD	
Augite (%)	25
Biotite (%)	1
Chlorite (%)	3
Enstatite (%)	5
Magnetite (%)	1
Microcline (%)	2
Muscovite (%)	2
Plagioclase (%)	53
Quartz (%)	3
Smectite (%)	3

The recycled concrete aggregates were petro-graphically described as dolerite composed of fragments of grey rock of small to medium grain size comprised of subhedral lath-shaped anorthite of

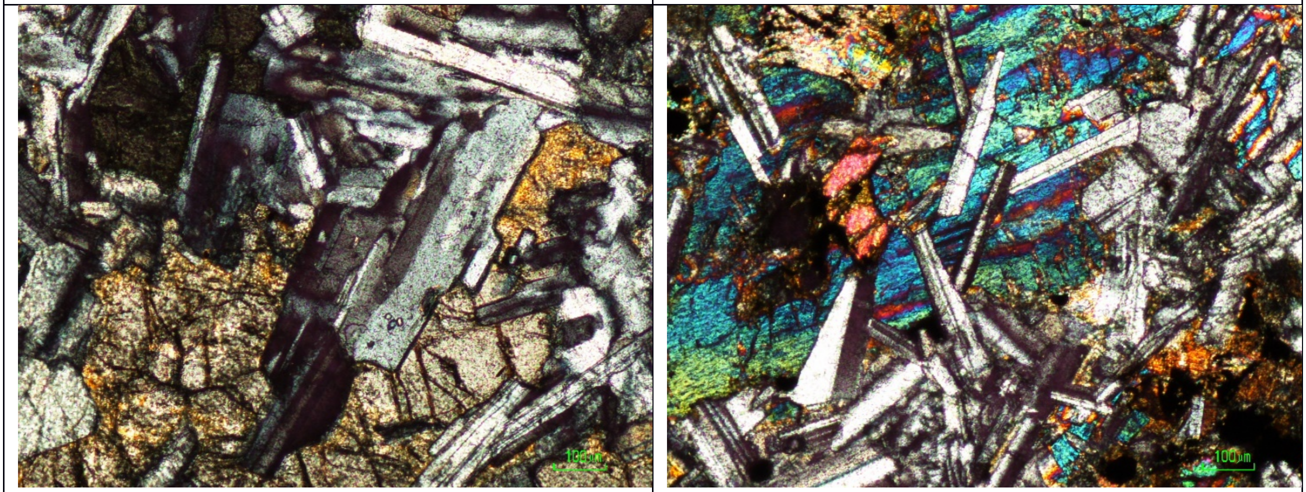
40 to 50%, and anhedral diopside of 15 to 25%, enstatite of about 4%, calcite of about 5 to 15%, quartz of about 10 to 20%, clinochlore of about 1%, muscovite of about 3%, talc of about 1% and smectite of about 5%. The rock largely represented dolerite with randomly orientated plagioclase (anorthite) and interstitial pyroxene (diopside and enstatite) with dispersed fine quartz, clinochlore, muscovite, calcite, talc and smectite that were only detected by XRD. Figure 5.5 gives the grain size data at 100-1000 micron. The rock types were based on the texture and mineralogy rather than the stratigraphic position. The sub-angular to sub rounded quartz were fairly cracked.

Natural aggregates were petro-graphically described as dolerite composed of plagioclase (50-60%), augite (20-30%), enstatite (5%), chlorite (3%), biotite (1%), muscovite (2%), smectite (3%), quartz (3%), microcline (2%) and magnetite (1%). Figure 5.6 gives the grain size data at 100-1000 micron.



Photomicrograph: Cross polarized light. 10x Magnification. Mainly plagioclase and pyroxene

Photomicrograph: Cross polarized light. 10x Magnification. Mainly plagioclase, pyroxene, forsterite

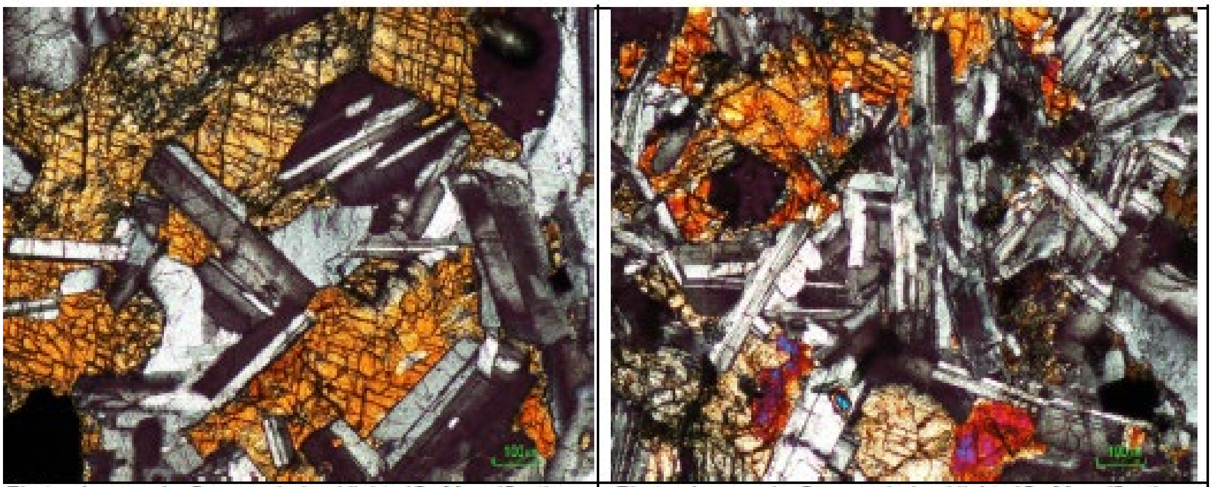


Photomicrograph: Cross polarized light. 10x Magnification. Mainly plagioclase and pyroxene

Photomicrograph: Cross polarized light. 10x Magnification. Mainly plagioclase and pyroxene

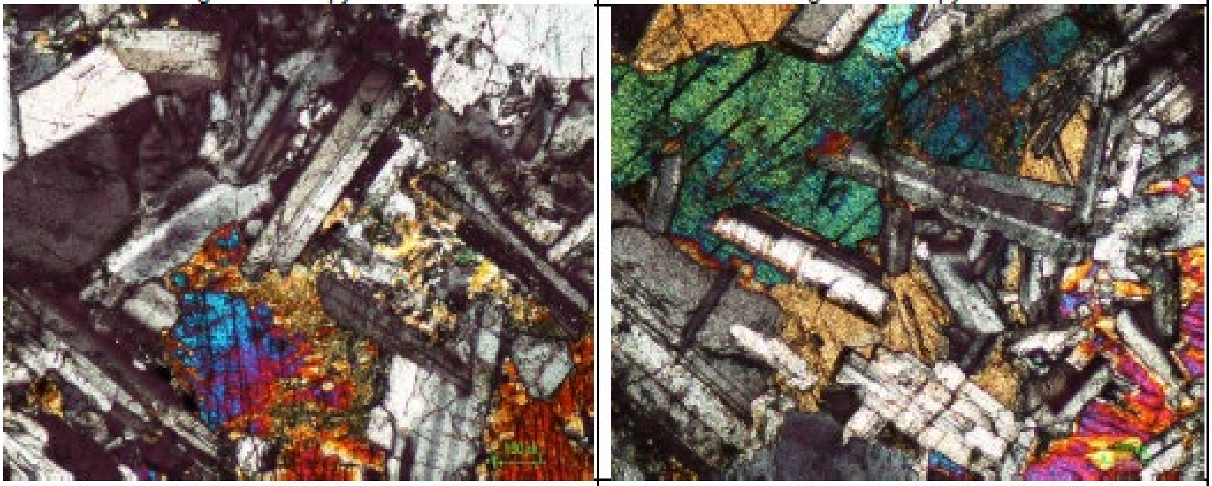
Figure 5.5: Grain size data of recycled concrete aggregates at 100-1000micron

Grain size data: 100-1000 micron



Photomicrograph: Cross polarized light. 10x Magnification.
Plagioclase and pyroxene

Photomicrograph: Cross polarized light. 10x Magnification.
Plagioclase and pyroxene



Photomicrograph: Cross polarized light. 10x Magnification.
Plagioclase and pyroxene

Photomicrograph: Cross polarized light. 10x Magnification.
Plagioclase and pyroxene

Figure 5.6: Grain size date of natural aggregates at 100-1000micron

The difference between the geology of recycled concrete and natural aggregates is due to -6.7mm sandstone river sand, 19mm dolerite coarse aggregates, -6.7mm dolerite washed crusher sand, cement and Fly Ash that were used to make concrete. Smectite in both recycled concrete and natural aggregates is minimal and therefore won`t pose any swelling challenges associated with smectite when exposed to moisture. There was high content of strained quartz of about 16% in recycled concrete aggregates, compared to about 3% in natural aggregates. The high content of strained quartz in recycled concrete aggregates may react with alkalis in cement which will require further testing to prove otherwise.

5.1.8 Tri-axial test

The triaxial test was used to assess the shear strength of aggregates. Recycled concrete and natural aggregates were subjected to compressive stresses on three orthogonal axes at confining pressures of 20, 100 and 150 KPa. The stress was applied in two stages, in the first stage the stress was applied until final consolidation was reached. In the second stage the axial load known as deviator stress was gradually increased while the cell pressure remained constant until the shear failure occurred which gave the peak deviator stress.

There`s currently no triaxial test specification for pavement layers in South Africa because the industry uses CBR for the bearing strength and the triaxial test is usually used by research institutions. Literature published by other researchers was used to interpret the results since there is no specification for tri-axial test in South Africa. Rudman and Jenkins (2015) and van Zyl (2015) conducted research in South Africa on recycled concrete aggregates as cited in Brendenkamp (2018). There was also research on recycled concrete aggregates as base or subbase material conducted in Australia by Cameron et al. (2013) and Aruljah et al. (2014) as cited in Brendenkamp (2018).

The gradings were kept consistent in most of the studies except for Aruljah (2014) to allow for good comparison between materials since the grading can have a significant effect on the results as cited by Brendenkamp (2018). There is an increase in cohesion strength if recycled concrete aggregates are cured for 28 days as summarised in Figure 5.9 by Rudmand and van Zyl (2015) as cited by Brendenkamp (2018). The increase in cohesion is due to presence of cementitious material from crushed concrete (Brendenkamp). Figure 5.8 and 5.9 gives a summary of the friction angle and cohesion strength of previous researchers as cited in Bredenkamp (2018).

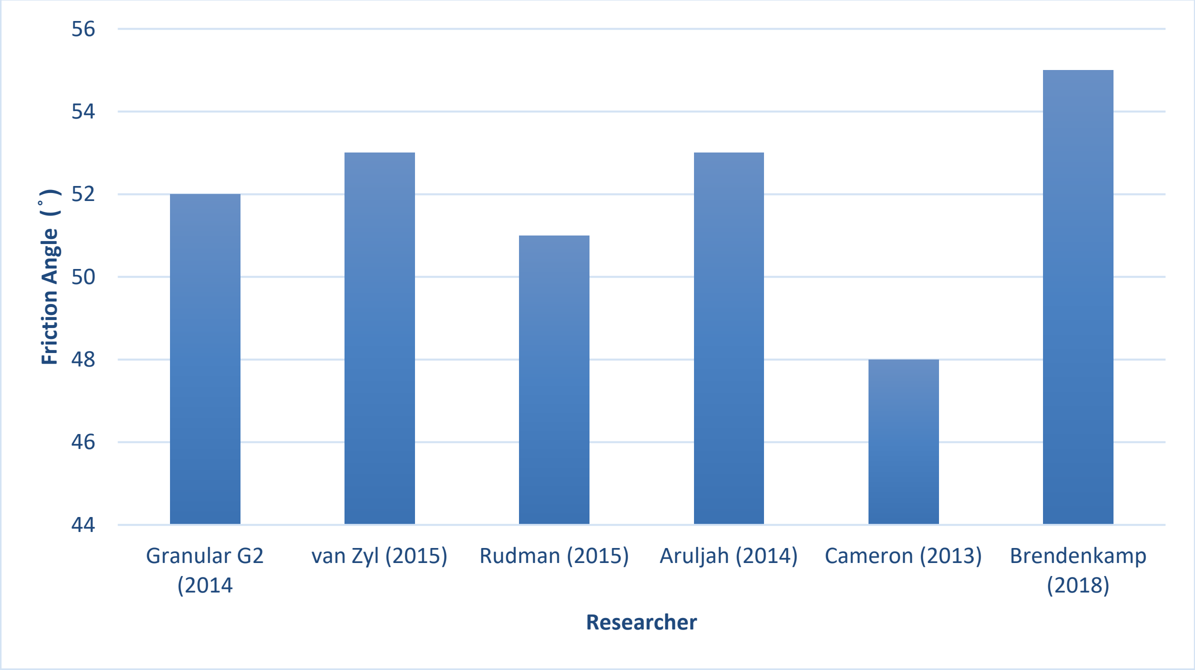


Figure 5.8: Friction angle of recycled concrete aggregates (Brendenkamp, 2018)

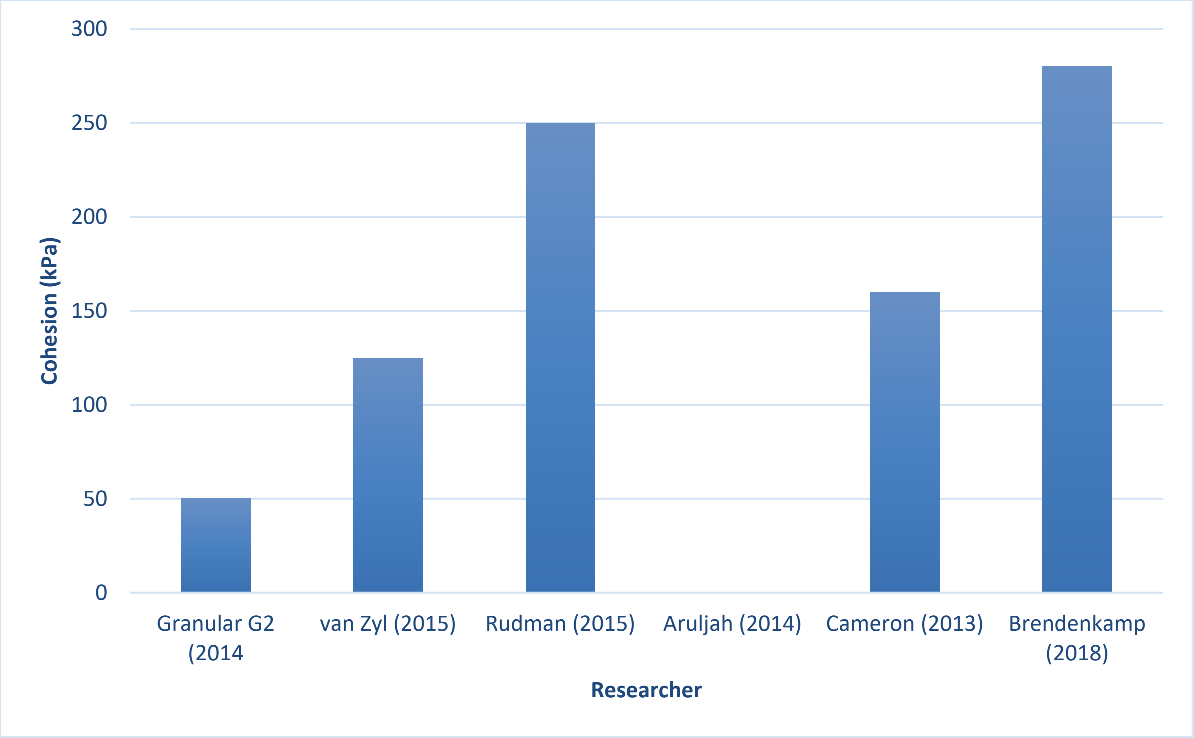


Figure 5.9: Cohesion strength of recycled concrete aggregates (Brendenkamp, 2018)

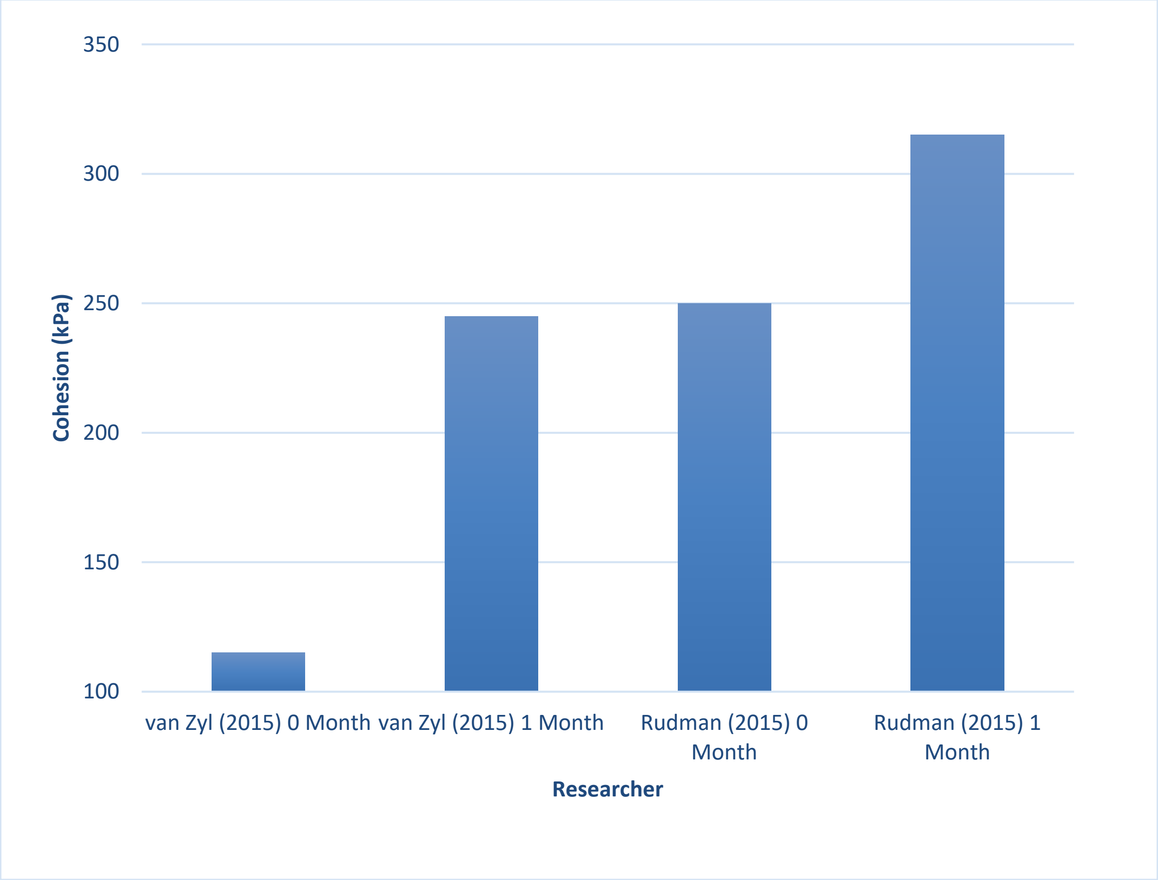


Figure 5.10: Cohesion strength summary for recycled concrete aggregates cured for 1 month (Brendenkamp, 2018)

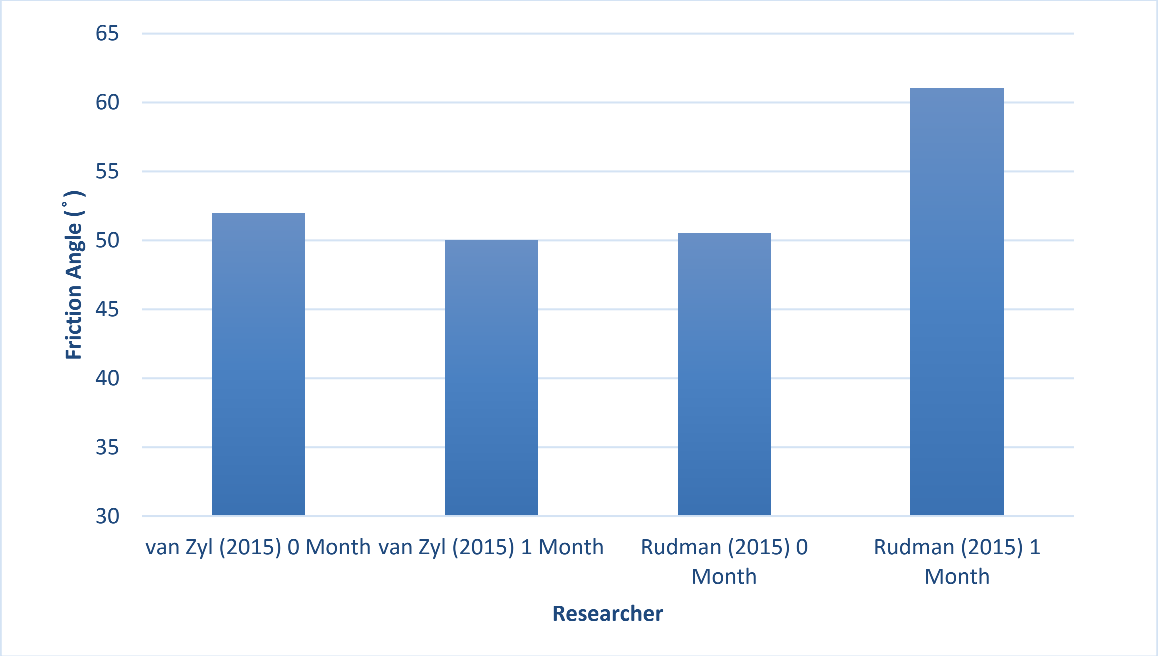


Figure 5.11: Friction angle for recycled concrete aggregates cured for 1 month (Brendenkamp, 2018)

Figure 5.12 is an illustration of displacement versus axial force for recycled concrete aggregates by Brendenkamp (2018).

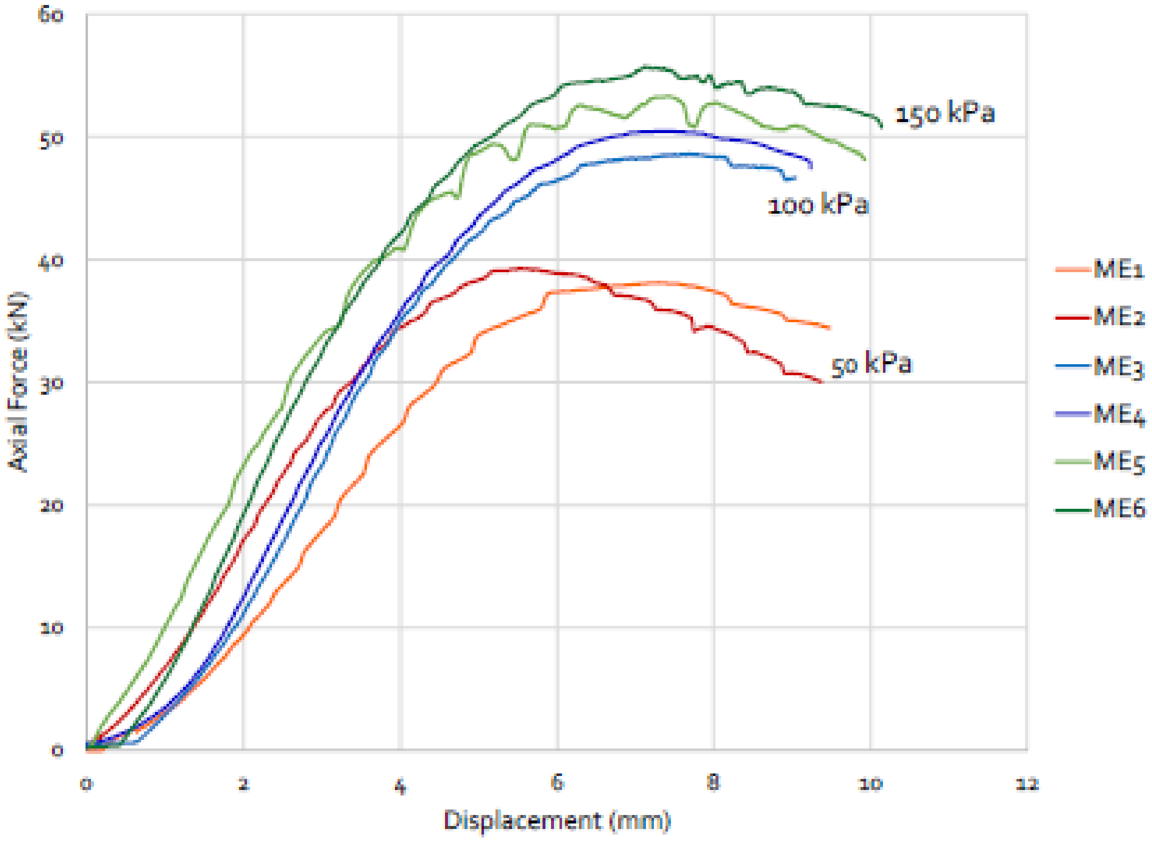


Figure 5.12: Recycled concrete aggregates displacement versus axial force (Brendenkamp, 2018)

The summary of the specimen compaction properties for the determination of shear strength testing, resilient modulus testing and permanent deformation resistance testing are shown in table 5.6, 5.7, 5.8 and 5.9 respectively.

Table 5.6: Specimen compaction properties for shear strength determination

Natural aggregates					
Sample	OMC (%)	MDD (Kg/m3)	Compacted Mass (Kg)	Target Mass (Kg)	Actual MC (%)
Natural aggregates sample1	5.7	2421	13.797	13.79	5.6

Natural aggregates sample2	5.7	2421	13.76	13.79	5.9
Natural aggregates sample3	5.7	2421	13.76	13.79	5.8
Natural aggregates sample4	5.7	2421	13.76	13.79	5.8
Natural aggregates sample5	5.7	2421	13.80	13.79	5.7
Natural aggregates sample6	5.7	2421	13.80	13.79	5.6
Natural aggregates sample7	5.7	2421	13.80	13.79	5.4
Recycled aggregates					
Recycled concrete aggregates sample1	13.8	1975.2	12.015	12.015	14.7
Recycled concrete aggregates sample2	13.8	1975.2	12.000	12.000	15.0
Recycled concrete aggregates sample3	13.8	1975.2	11.925	11.925	15.0
Recycled concrete aggregates sample4	13.8	1975.2	12.011	12.011	13.1
Recycled concrete aggregates sample5	13.8	1975.2	12.061	12.061	14.7
Recycled concrete aggregates sample6	13.8	1975.2	12.105	12.105	13.2
Recycled concrete aggregates sample7	13.8	1975.2	12.070	12.070	14.1

A summary of shear strength results is shown in table 5.7 below.

Table 5.7: Summary table of the shear strength results for recycled concrete and natural aggregates

Natural aggregates						
Sample	Actual OMC (%)	Sample height (mm)	Cell pressure (KPa)	Peak load (KPa)	Stress (KPa)	Total displacement (mm)
Sample1	5.6	303	50.35	14	792	8.60
Sample2	5.9	303	100.96	16	905	14.16
Sample3	5.8	303	150.2	18	1019	16.72
Recycled concrete aggregates						
Sample1	14.7	306	19.96	7	396	10.16
Sample2	15	306	100.06	18	1019	12.08
Sample3	15	306	151.78	26	1471	8.68

The summary of resilient modulus results is shown in table 5.8

Table 5.8: Summary table of the resilient modulus results for recycled concrete and natural aggregates

Natural aggregates								
Sample	Sample height (mm)	Confining pressure (KPa)	Failure Stress (KPa)	Sigma 1 (KPa)	p (KPa)	q (KPa)	Cohesion (KPa)	Friction angle (˚)
Sample 4	305	50	792	842	446	396	187	32
		101	905	1006	554	453		
		150	1019	1169	660	510		
Recycled concrete aggregates								
Sample 4	306	20	396	416	218	198	36.9	53.5
		100	1019	1119	610	510		
		151	1471	1622	887	736		

The summary of permanent deformation resistance results is shown in table 5.9.

Table 5.9: Summary table of the permanent deformation resistance results for recycled concrete and natural aggregates

Natural aggregates								
Sample	Sample height (mm)	Confining pressure (KPa)	Failure stress (KPa)	Sigma 1 (KPa)	p	q	Cohesion (KPa)	Friction angle (°)
Sample 5	306	50	792	842	446	396	189	32
		101	905	1006	554	453		
		150	1019	1169	660	510		
Sample 6	305	50	792	842	446	396	187	32
		101	905	1006	554	453		
		150	1019	1169	660	510		
Sample 7	306	50	792	842	446	396	187	32
		101	905	1006	554	453		
		150	1019	1169	660	510		
Recycled concrete aggregates								
Sample 5	306	20	396	416	218	198	36.9	53.5
		100	1019	1119	610	510		
		151	1471	1622	887	736		
Sample 6	306	20	396	416	218	198	37.0	54.0
		100	1019	1119	610	510		
		151	1471	1622	887	736		
Sample 7	306	20	396	416	218	198	36.9	53.5
		100	1019	1119	610	510		
		151	1471	1622	887	736		

Natural aggregates achieved cohesion strength of 187 KPa and a friction angle of 32° with OMC of 5.7% and MDD of 2421 Kg/m^3 , compared to cohesion strength of 36.9 KPa and cohesion angle of 53.5° with OMC of 13.8% and MDD of 1974.2 Kg/m^3 for recycled concrete aggregates. The cohesion strength is inversely proportional to OMC and directly proportional to MDD. The low cohesion strength of recycled concrete aggregates when subjected to axial loading is due to reduced stiffness as a result of coating of aggregates with fines from recycled concrete and water voids. The cohesion strength for recycled concrete aggregates was less than in previous researches.

The maximum failure stress for recycled concrete aggregates was 1471 KPa compared to 1019 KPa for natural aggregates. The high failure stress for recycled concrete aggregates is due to self-cementing properties of recycled concrete.

The axial load versus displacement was determined at confinement pressure of 19.96,10 and 151.70 KPa respectively as illustrated in Figure 5.14, 5.15 and 5.16 respectively. The total displacement for recycled concrete aggregates reduced from 10.16 to 8.68mm with an increase in stress from 396 to 1471 KPa. Natural aggregates displacement increased from 8.60 to 16.72mm with an increase in stress from 792 to 1019 KPa. The superior performance of recycled concrete aggregates can be attributed to self-cementing properties as a result of cementitious material from recycled concrete.

The recycled concrete aggregates results show that the axial load versus displacement pattern had a less degree of smoothness of the graph in comparison with natural aggregates. The inconsistency of recycled concrete aggregates is due to different cementitious contents from different classes of concrete that were blended together to obtain ready mix concrete rubble. The stress at peak loads for confinement pressure of 100 and 151.7 KPa for recycled concrete aggregates in this research were less than those of previous researches due to ready-mix concrete rubble that was used in this research compared to structural concrete in other researches. The shear properties of recycled concrete aggregates are graphically plotted Mohr-Coulomb strength envelope in figure

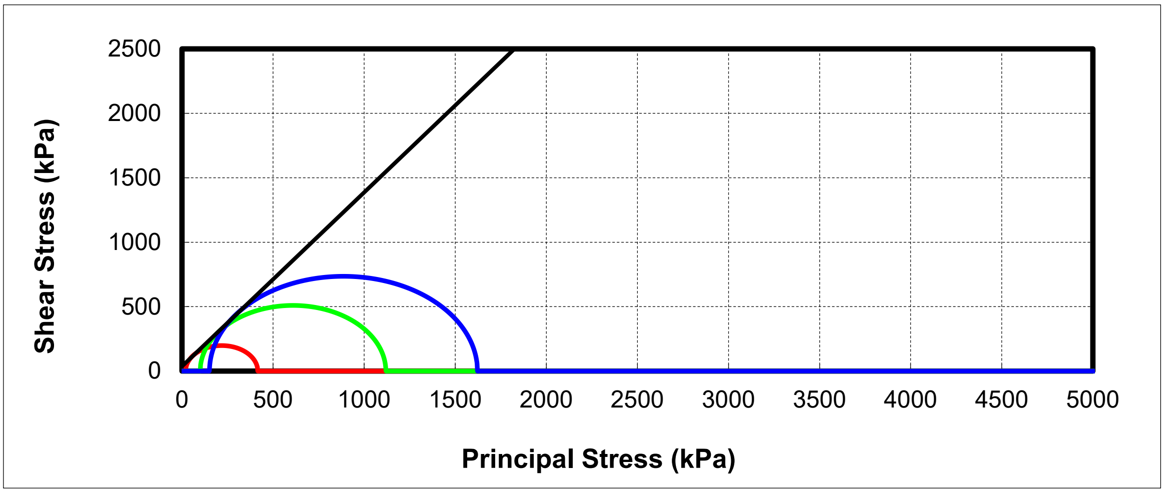


Figure 5.13: Recycled concrete aggregates Mohr-Coulomb strength envelope

Sample **S01**
Mass **11.956**
Moisture **14.7**

Shear Triaxial Test
Loading rate 2.4mm /

Cell **19.96**
Peak Load 7
% **0**

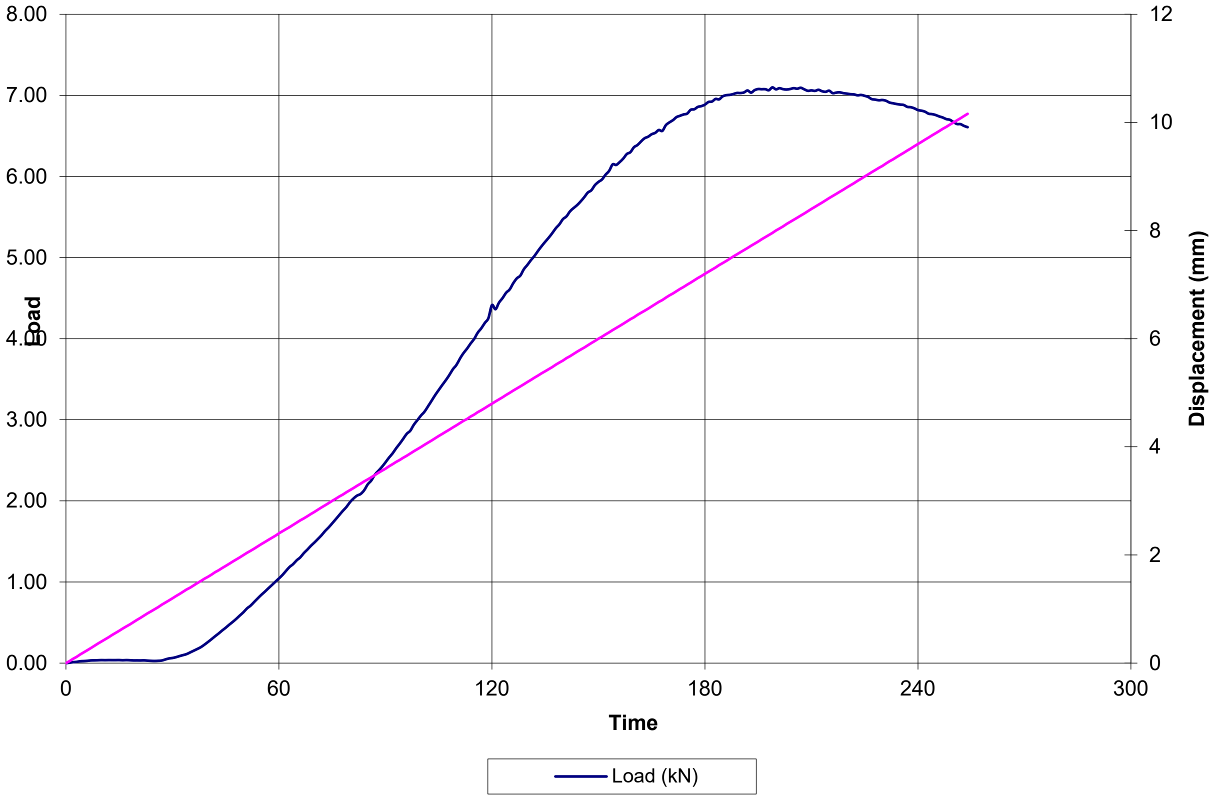


Figure 5.14: Recycled concrete aggregates sample 1 shear triaxial test

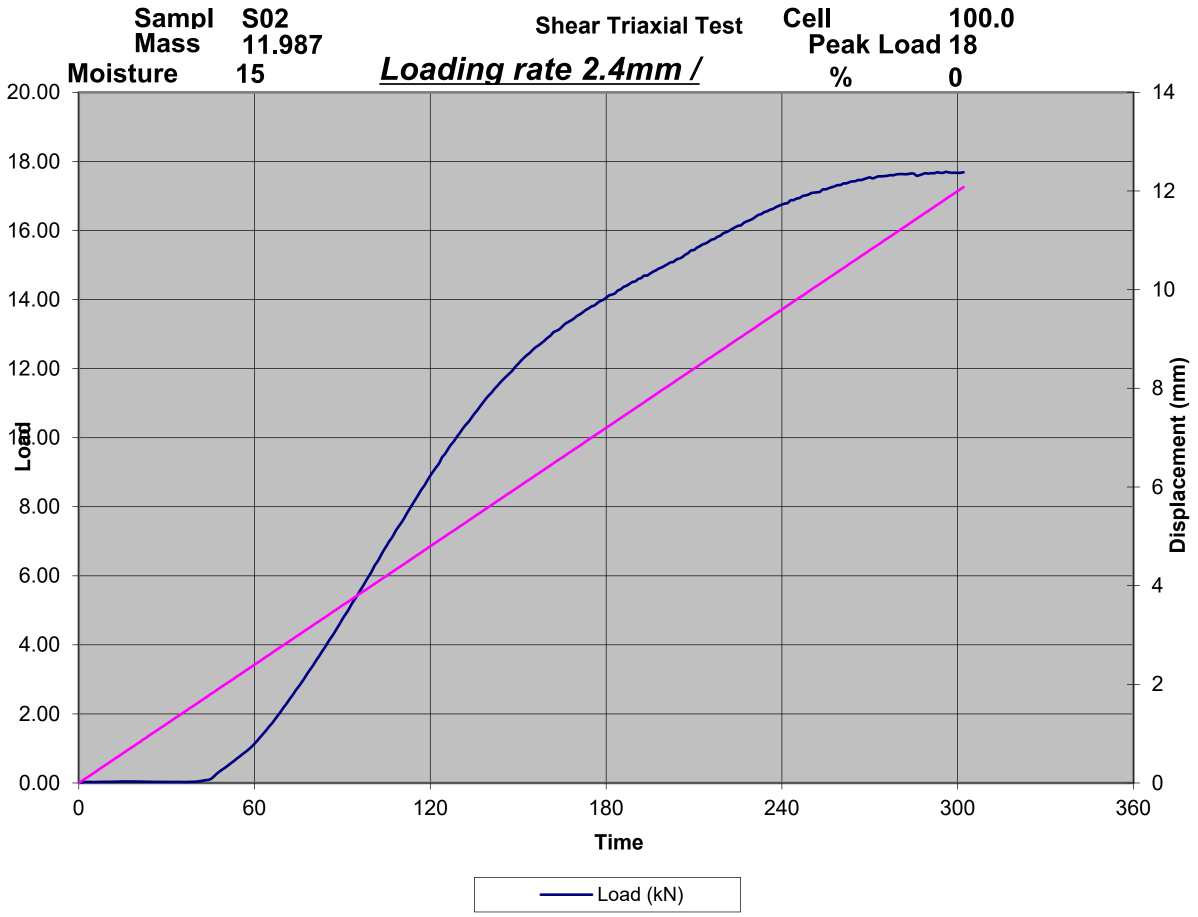


Figure 5.15: Recycled concrete aggregates sample 2 shear triaxial test

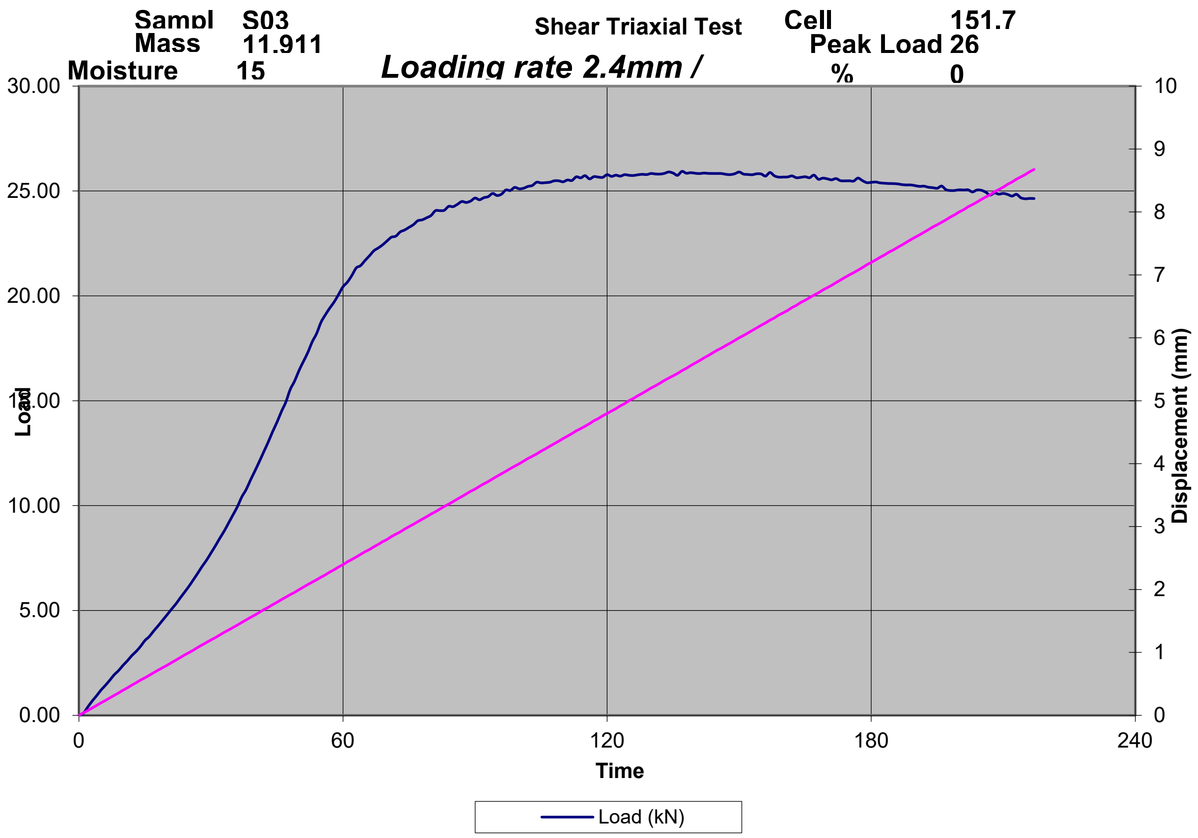


Figure 5.16: Recycled concrete aggregates sample 3 shear triaxial test

CHAPTER 6: CONCLUDING REMARKS

6.1 Conclusions

The objectives stated in Chapter 1.2 were achieved by different test procedures and analysis of C&DW as per experimental work in Chapter 4. The material for this study was obtained from returned concrete at a readymix plant in the city of Bloemfontein in South Africa.

The methodology for the laboratory experimental work was covered in Chapter 4. The physical and chemical results obtained in experimental work were also discussed in Chapter 4. Although a triaxial test is not used as a standard test in South Africa, it was added to the experimental work with the idea of getting more technical information on C&DW.

This chapter gives conclusions regarding literature review and discussion of results on this study, which may be summarised as follows:

- The annual generation of C&DW and life span reduction of landfills in South Africa warrants a necessity to recycle. There is a need to embark on a journey of using C&DW as pavement base course material. The use of C&DW as base course material should be viewed as an opportunity to extend the life span of landfills and reduce C&DW disposal costs. The reduction in the use of virgin aggregates will extend the life span of natural reserves and conserve the environment.

- Literature review indicates that European countries and Japan are at the forefront of recycling C&DW and have successfully managed to recycle C&DW. Japanese have a different philosophy to that of South Africa with regards to C&DW: they consider C&DW as a by-product instead of waste, which promotes recycling of C&DW.

- The biggest challenge in South Africa with regards to recycling C&DW is lack of local literature on the performance of C&DW as recycled material. Experimental work conducted in this study indicates that there is an opportunity to use C&DW as base course material. The physical and chemical test results obtained in this study met base course requirements for virgin aggregates as stipulated in local standards such as COLTO and SANS. The findings in experimental work correlated with literature review which indicated that C&DW could be successfully used as base course material.

It can be generally concluded that C&DW can be used as pavement base course material in South Africa. More research has to be conducted on the inconsistency challenge that comes with it, in order to come up with measures to be put in place to overcome it.

6.1 Recommendations

The results obtained in this study yielded positive results with regards to the performance of C&SW as pavement base coarse material in South Africa and following recommendations may be made:

- South Africa should invest in promotion of C&DW to conserve the environment and eradicate huge costs associated with disposal of C&DW. The promotion of use of C&DW should start with the philosophy regarding C&DW definition. C&DW should be perceived as a by-product instead of waste to be disposed of at landfills.

- Local authorities in South Africa should come up with regulations that will make it difficult to dispose of C&DW at landfills. This can be achieved by imposing penalties for disposing C&DW at landfills and there should also be incentives for recycling C&DW.

- There`s currently no standard for C&DW in South Africa, therefore there is a need to develop a local standard to promote the use of C&DW. The standard should be developed in line with ISO 9000 that was developed in 1996. This proposed standard will be a guideline for using C&DW and this will assist in the construction industry with information regarding C&DW.

- The material used in this research was a blend of different classes of concrete, which resulted in inconsistent results and this should be perceived as a challenge that future research should address to change the mindset of the industry. New research should look at addressing inconsistency by putting in place measures such as blending C&DW with virgin aggregates to produce a more consistent and robust product. More research has to done to check how recycled concrete aggregates would behave when prime coat applied, to establish if there would be any restrictions on the material type, emulsified or rapid curing.

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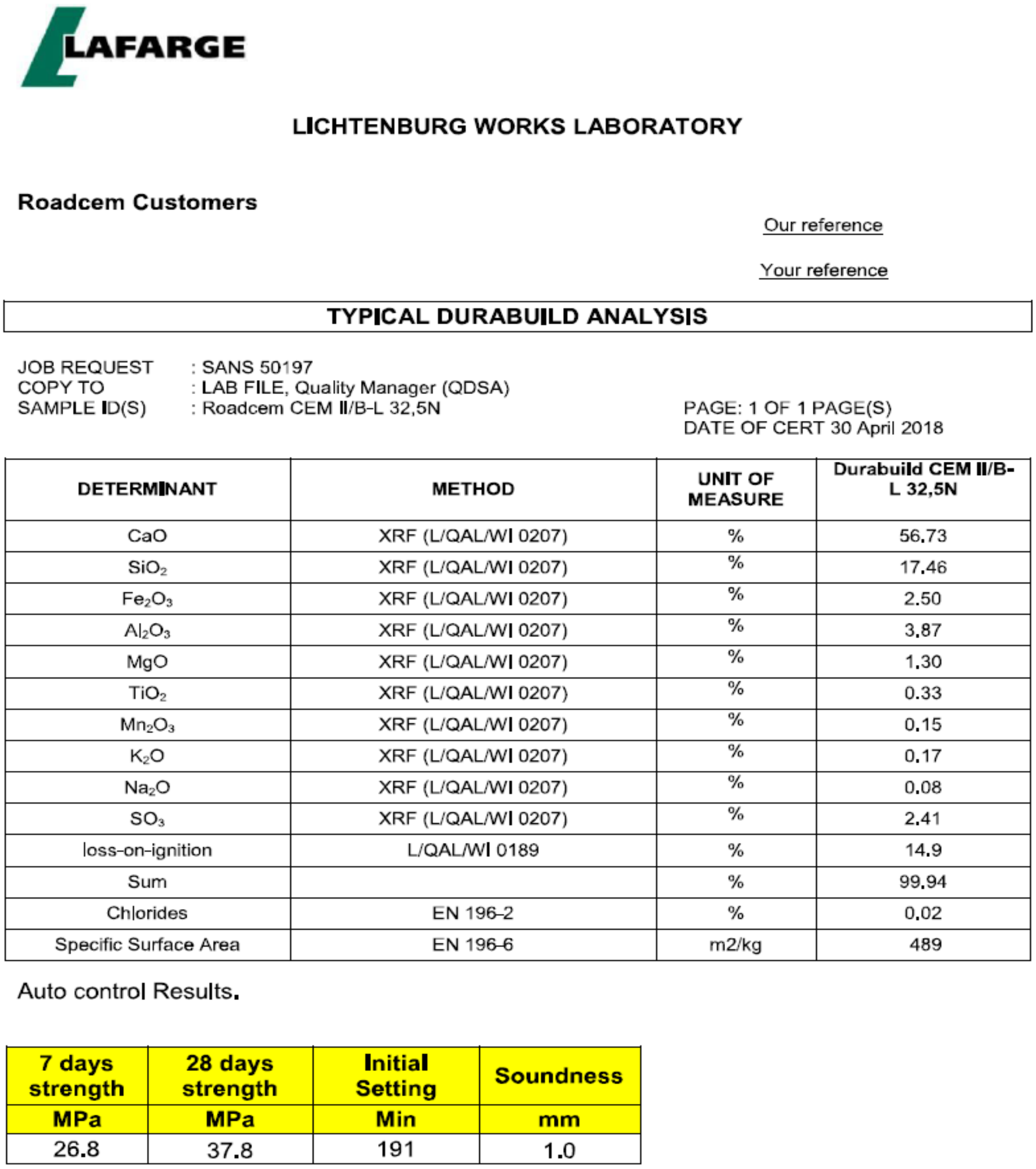
Appendices

Appendix A: Lafarge Roadcem properties



LAFARGE

LICHTENBURG WORKS LABORATORY

Roadcem Customers

Our reference

Your reference

TYPICAL DURABUILD ANALYSIS

JOB REQUEST : SANS 50197
COPY TO : LAB FILE, Quality Manager (QDSA)
SAMPLE ID(S) : Roadcem CEM II/B-L 32,5N

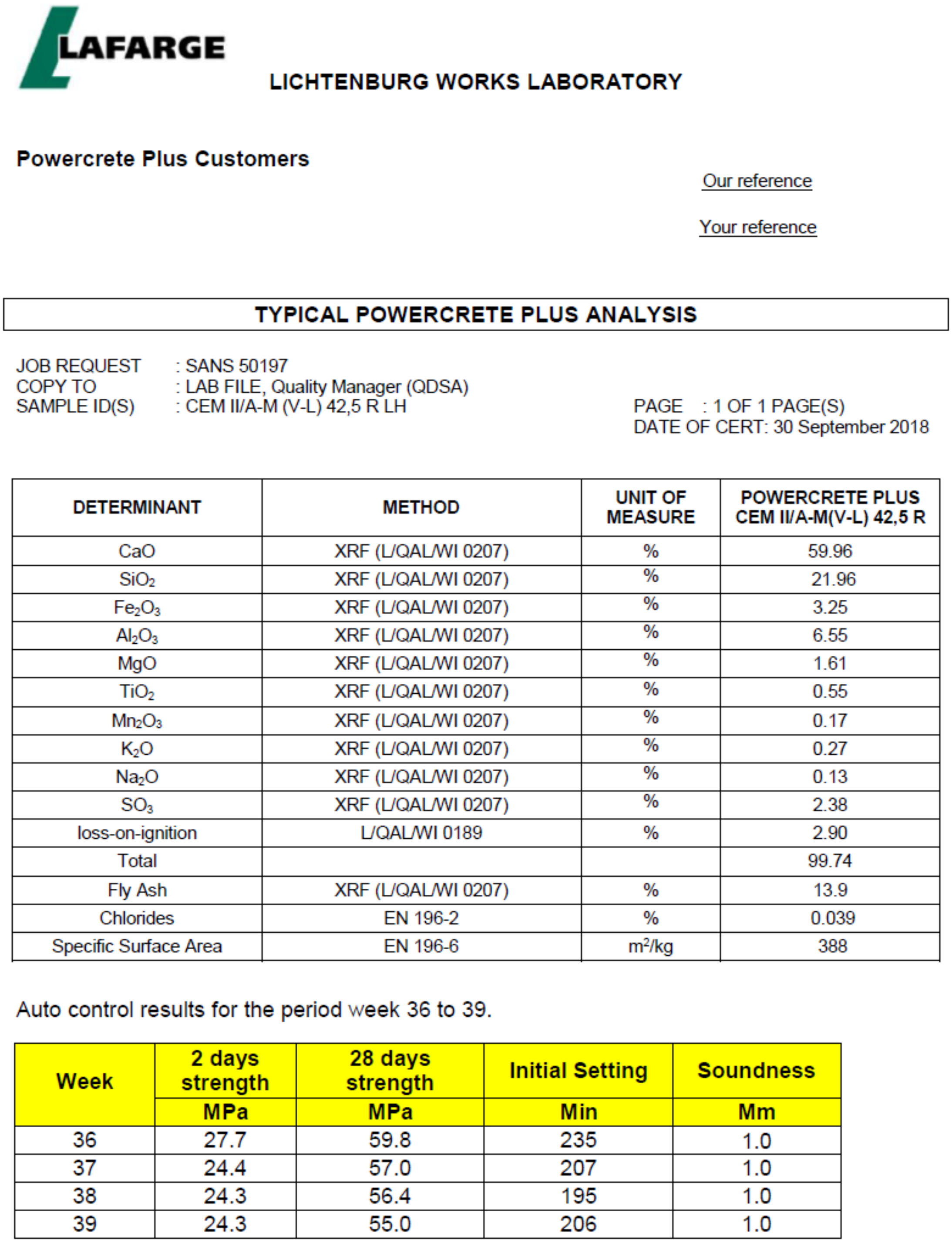
PAGE: 1 OF 1 PAGE(S)
DATE OF CERT 30 April 2018

DETERMINANT	METHOD	UNIT OF MEASURE	Durabuild CEM II/B-L 32,5N
CaO	XRF (L/QAL/WI 0207)	%	56.73
SiO_2	XRF (L/QAL/WI 0207)	%	17.46
Fe_2O_3	XRF (L/QAL/WI 0207)	%	2.50
Al_2O_3	XRF (L/QAL/WI 0207)	%	3.87
MgO	XRF (L/QAL/WI 0207)	%	1.30
TiO_2	XRF (L/QAL/WI 0207)	%	0.33
Mn_2O_3	XRF (L/QAL/WI 0207)	%	0.15
K_2O	XRF (L/QAL/WI 0207)	%	0.17
Na_2O	XRF (L/QAL/WI 0207)	%	0.08
SO_3	XRF (L/QAL/WI 0207)	%	2.41
loss-on-ignition	L/QAL/WI 0189	%	14.9
Sum		%	99.94
Chlorides	EN 196-2	%	0.02
Specific Surface Area	EN 196-6	m2/kg	489

Auto control Results.

7 days strength	28 days strength	Initial Setting	Soundness
MPa	**MPa**	**Min**	**mm**
26.8	37.8	191	1.0

Appendix B



LAFARGE

LICHTENBURG WORKS LABORATORY

Powercrete Plus Customers

Our reference

Your reference

TYPICAL POWERCRETE PLUS ANALYSIS

JOB REQUEST : SANS 50197
COPY TO : LAB FILE, Quality Manager (QDSA)
SAMPLE ID(S) : CEM II/A-M (V-L) 42,5 R LH

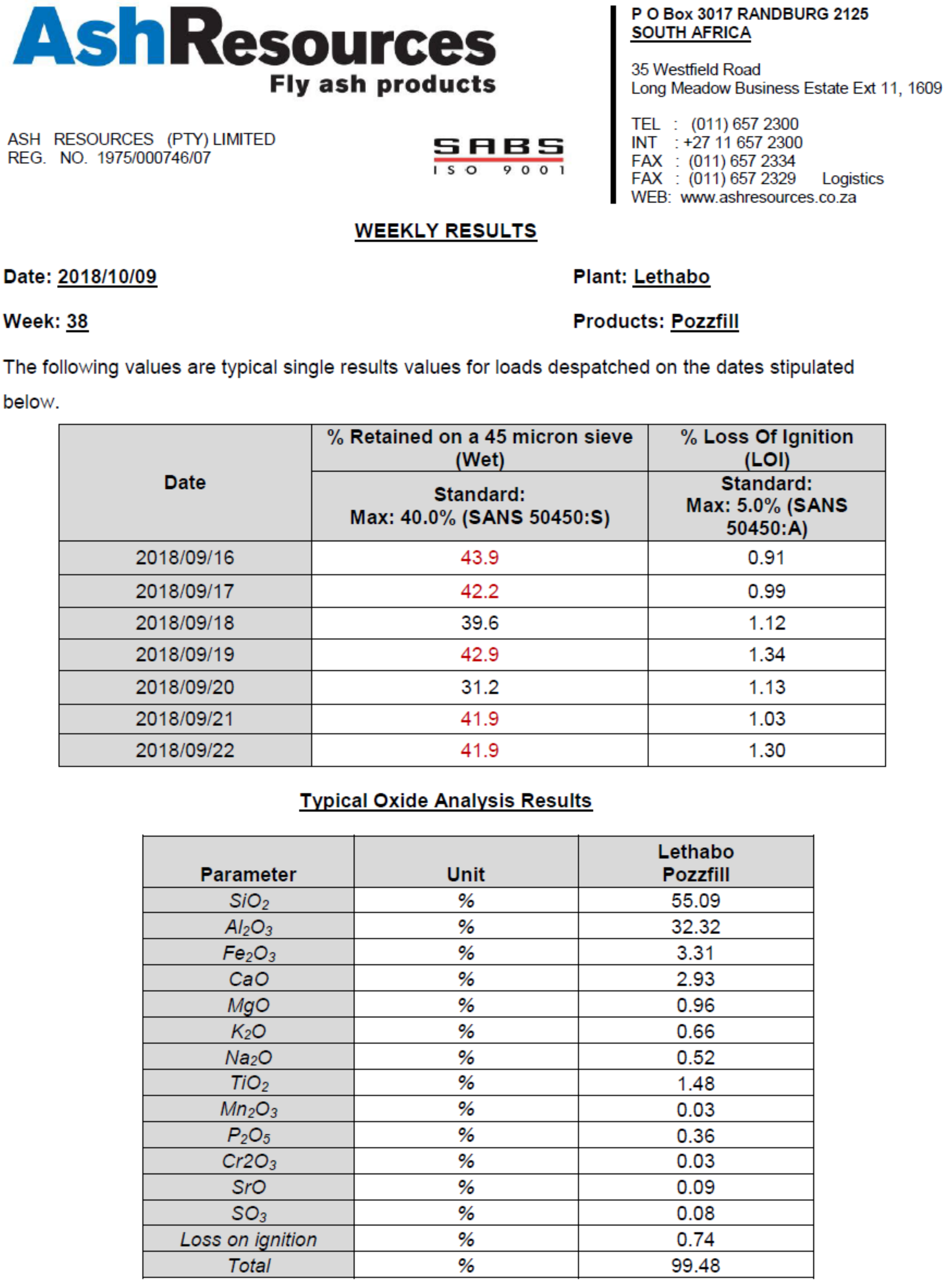
PAGE : 1 OF 1 PAGE(S)
DATE OF CERT: 30 September 2018

DETERMINANT	METHOD	UNIT OF MEASURE	POWERCRETE PLUS CEM II/A-M(V-L) 42,5 R
CaO	XRF (L/QAL/WI 0207)	%	59.96
SiO_2	XRF (L/QAL/WI 0207)	%	21.96
Fe_2O_3	XRF (L/QAL/WI 0207)	%	3.25
Al_2O_3	XRF (L/QAL/WI 0207)	%	6.55
MgO	XRF (L/QAL/WI 0207)	%	1.61
TiO_2	XRF (L/QAL/WI 0207)	%	0.55
Mn_2O_3	XRF (L/QAL/WI 0207)	%	0.17
K_2O	XRF (L/QAL/WI 0207)	%	0.27
Na_2O	XRF (L/QAL/WI 0207)	%	0.13
SO_3	XRF (L/QAL/WI 0207)	%	2.38
loss-on-ignition	L/QAL/WI 0189	%	2.90
Total			99.74
Fly Ash	XRF (L/QAL/WI 0207)	%	13.9
Chlorides	EN 196-2	%	0.039
Specific Surface Area	EN 196-6	m^2/kg	388

Auto control results for the period week 36 to 39.

Week	2 days strength	28 days strength	Initial Setting	Soundness
	MPa	MPa	Min	Mm
36	27.7	59.8	235	1.0
37	24.4	57.0	207	1.0
38	24.3	56.4	195	1.0
39	24.3	55.0	206	1.0

Appendix C



AshResources
Fly ash products

ASH RESOURCES (PTY) LIMITED
REG. NO. 1975/000746/07

SABS
ISO 9001

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WEEKLY RESULTS

Date: 2018/10/09 **Plant: Lethabo**

Week: 38 **Products: Pozzfill**

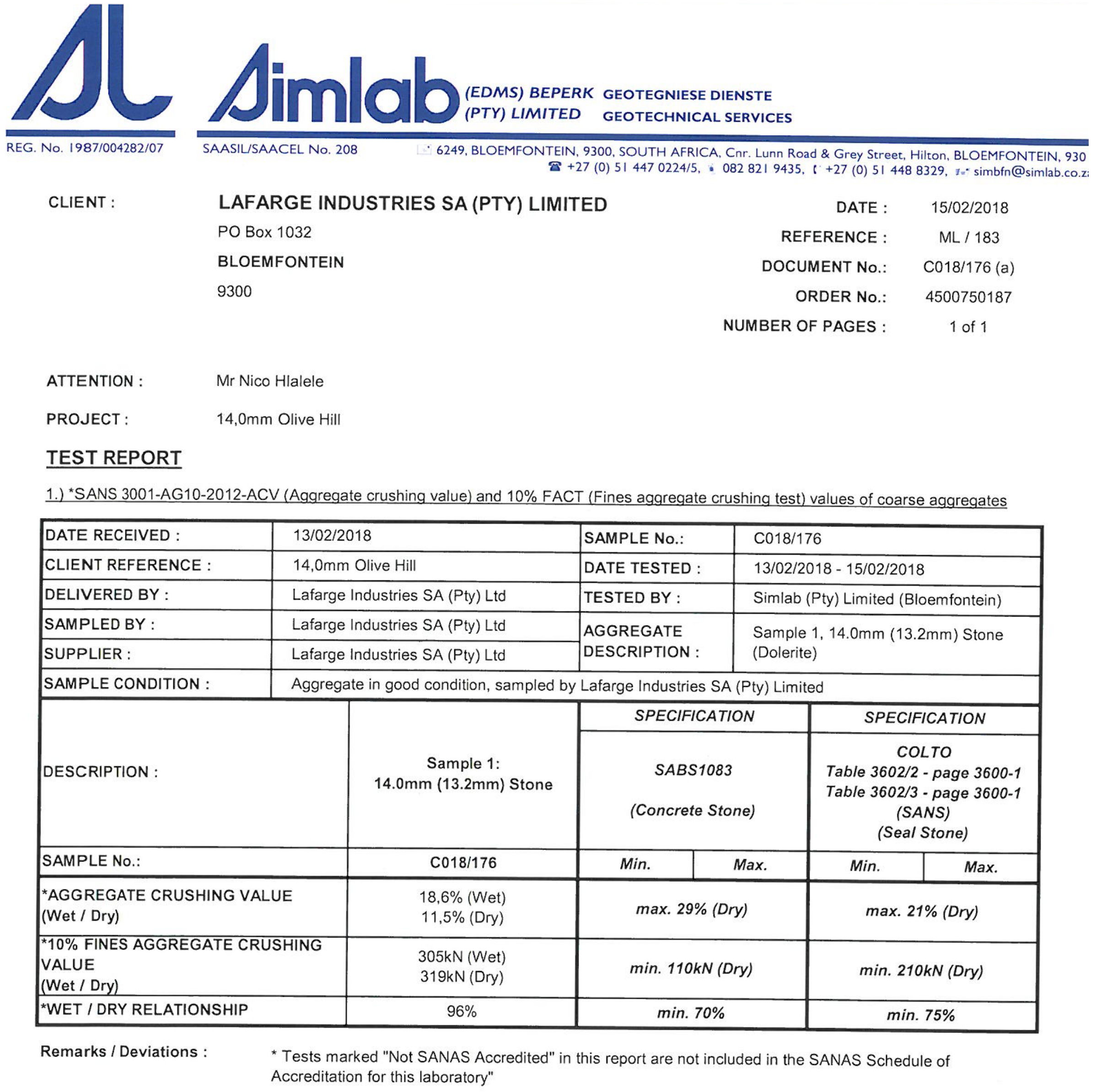
The following values are typical single results values for loads despatched on the dates stipulated below.

Date	**% Retained on a 45 micron sieve (Wet)**	**% Loss Of Ignition (LOI)**
	Standard: Max: 40.0% (SANS 50450:S)	**Standard: Max: 5.0% (SANS 50450:A)**
2018/09/16	43.9	0.91
2018/09/17	42.2	0.99
2018/09/18	39.6	1.12
2018/09/19	42.9	1.34
2018/09/20	31.2	1.13
2018/09/21	41.9	1.03
2018/09/22	41.9	1.30

Typical Oxide Analysis Results

Parameter	**Unit**	**Lethabo Pozzfill**
SiO_2	%	55.09
Al_2O_3	%	32.32
Fe_2O_3	%	3.31
CaO	%	2.93
MgO	%	0.96
K_2O	%	0.66
Na_2O	%	0.52
TiO_2	%	1.48
Mn_2O_3	%	0.03
P_2O_5	%	0.36
$Cr2O_3$	%	0.03
SrO	%	0.09
SO_3	%	0.08
Loss on ignition	%	0.74
Total	%	99.48

Appendix D



Simlab (EDMS) BEPERK GEOTEGNIESE DIENSTE
(PTY) LIMITED GEOTECHNICAL SERVICES

REG. No. 1987/004282/07
SAASIL/SAACEL No. 208
6249, BLOEMFONTEIN, 9300, SOUTH AFRICA, Cnr. Lunn Road & Grey Street, Hilton, BLOEMFONTEIN, 930
☎ +27 (0) 51 447 0224/5, 082 821 9435, +27 (0) 51 448 8329, simbfn@simlab.co.z

CLIENT : **LAFARGE INDUSTRIES SA (PTY) LIMITED**
PO Box 1032
BLOEMFONTEIN
9300

DATE : 15/02/2018
REFERENCE : ML / 183
DOCUMENT No.: C018/176 (a)
ORDER No.: 4500750187
NUMBER OF PAGES : 1 of 1

ATTENTION : Mr Nico Hlalele

PROJECT : 14,0mm Olive Hill

TEST REPORT

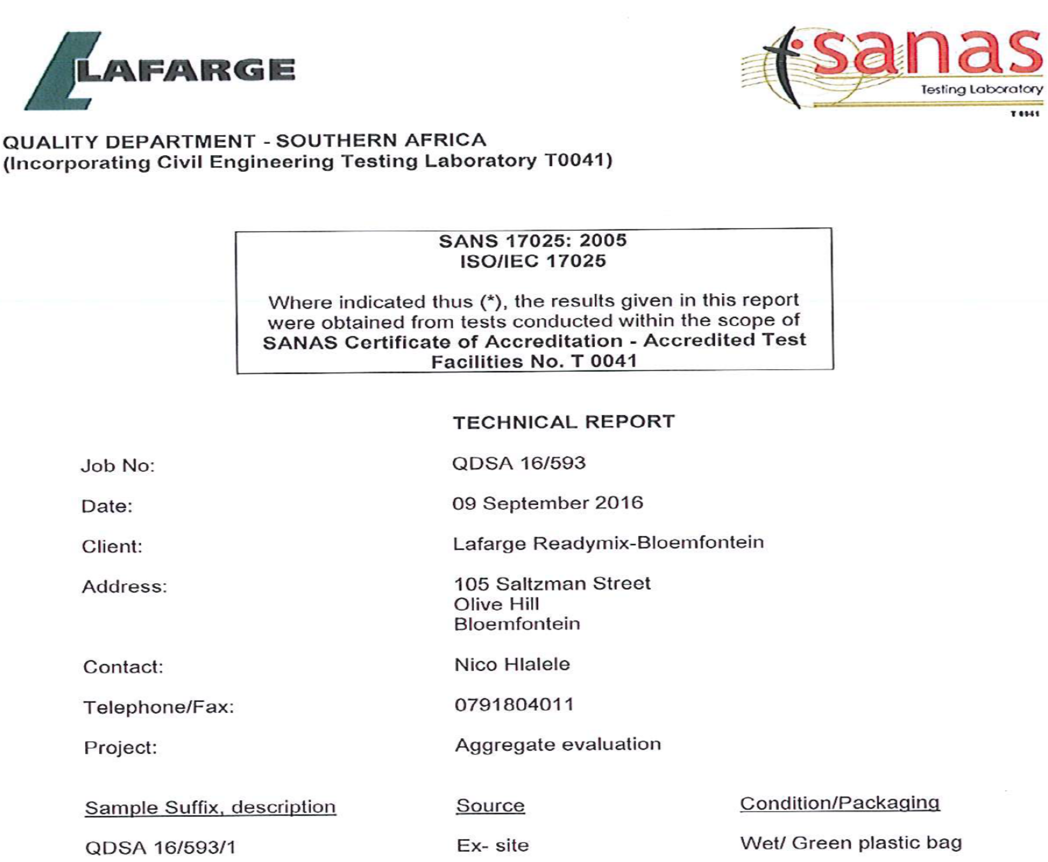
1.) *SANS 3001-AG10-2012-ACV (Aggregate crushing value) and 10% FACT (Fines aggregate crushing test) values of coarse aggregates

DATE RECEIVED :	13/02/2018	SAMPLE No.:	C018/176
CLIENT REFERENCE :	14,0mm Olive Hill	DATE TESTED :	13/02/2018 - 15/02/2018
DELIVERED BY :	Lafarge Industries SA (Pty) Ltd	TESTED BY :	Simlab (Pty) Limited (Bloemfontein)
SAMPLED BY :	Lafarge Industries SA (Pty) Ltd	AGGREGATE DESCRIPTION :	Sample 1, 14.0mm (13.2mm) Stone (Dolerite)
SUPPLIER :	Lafarge Industries SA (Pty) Ltd		
SAMPLE CONDITION :	Aggregate in good condition, sampled by Lafarge Industries SA (Pty) Limited		

DESCRIPTION :	Sample 1: 14.0mm (13.2mm) Stone	*SPECIFICATION*		*SPECIFICATION*	
		SABS1083 *(Concrete Stone)*		*COLTO* *Table 3602/2 - page 3600-1* *Table 3602/3 - page 3600-1* *(SANS)* *(Seal Stone)*	
SAMPLE No.:	C018/176	*Min.*	*Max.*	*Min.*	*Max.*
*AGGREGATE CRUSHING VALUE (Wet / Dry)	18,6% (Wet) 11,5% (Dry)	*max. 29% (Dry)*		*max. 21% (Dry)*	
*10% FINES AGGREGATE CRUSHING VALUE (Wet / Dry)	305kN (Wet) 319kN (Dry)	*min. 110kN (Dry)*		*min. 210kN (Dry)*	
*WET / DRY RELATIONSHIP	96%	*min. 70%*		*min. 75%*	

Remarks / Deviations : * Tests marked "Not SANAS Accredited" in this report are not included in the SANAS Schedule of Accreditation for this laboratory"

Appendix E



QUALITY DEPARTMENT - SOUTHERN AFRICA
(Incorporating Civil Engineering Testing Laboratory T0041)

SANS 17025: 2005
ISO/IEC 17025

Where indicated thus (*), the results given in this report were obtained from tests conducted within the scope of **SANS Certificate of Accreditation - Accredited Test Facilities No. T 0041**

TECHNICAL REPORT

Job No:	QDSA 16/593
Date:	09 September 2016
Client:	Lafarge Readymix-Bloemfontein
Address:	105 Saltzman Street Olive Hill Bloemfontein
Contact:	Nico Hlalele
Telephone/Fax:	0791804011
Project:	Aggregate evaluation

Sample Suffix, description	Source	Condition/Packaging
QDSA 16/593/1	Ex- site	Wet/ Green plastic bag

1. OBJECTIVE

To determine the filler sand submitted for the suitability of concrete mix according to the requirements of SANS 1083.

2. TESTS CONDUCTED

SANS Method 5833	Detection of sugar in fine aggregates (*)
SANS Method 197	Preparation of test samples of aggregate (*)
SANS Method 201	Fines content, dust content and sieve analysis of aggregate (*).
SANS 3001-AG20	Water absorption of coarse aggregate (*)
SANS 3001-AG21	Water absorption of fine aggregate (*)
SANS Method 5844	Particle and relative density of aggregates (*)
SANS Method 5845	Consolidated bulk density and voids content of aggregates (*)
SANS Method 5838	Sand equivalent value of fine aggregates
SANS Method 6243	Methylene blue test for aggregates.(*)
SANS Method 5832	Determination of organic Impurities in mortar and concrete sand (*)
SANS 202	Determination of chloride content

2.1 Deviations from Standard Test Methods

None.

3. RESULTS

3.1 Aggregate assessment:

Test		QDSA16/593/1 Filler Sand	Specification SANS 1083
Sand Equivalent	%	*62,51	≥ 85
Organic Impurities		Present	Not present
Sugar		Not present	Not present
Methylene Blue	%	0,3	≤ 0,7
Chlorides	%	*0,004	≤0,01 Precast concrete ≤0,03 Non reinforced concrete

*SANS 1083:1976
SANS 202:2005

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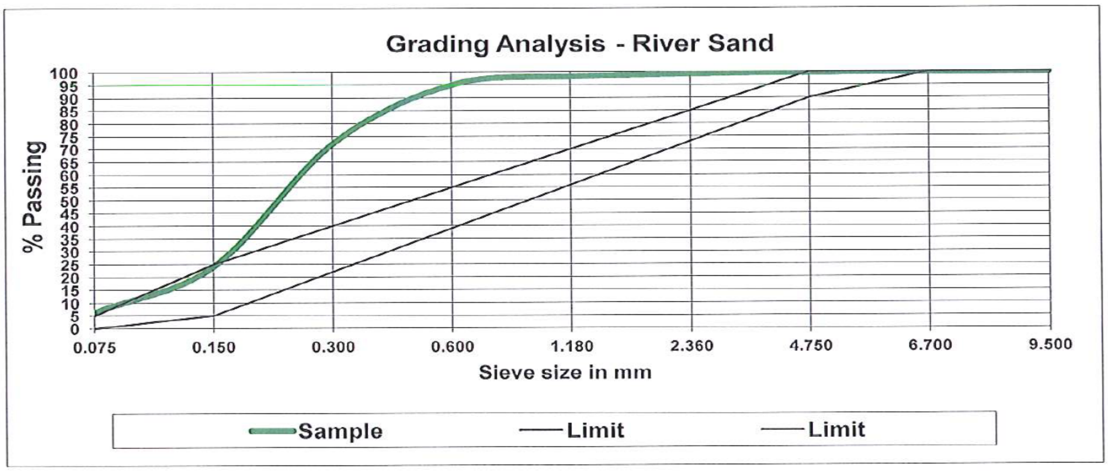
LAFARGE INDUSTRIES SOUTH AFRICA (PTY) LTD
QUALITY DEPARTMENT - SOUTHERN AFRICA
Grading Analysis of Fine Aggregates
SANS 201

Date:	23-Aug-16	Job no :	QDSA	16/593/1
Sample Description:	Filler Sand			

Sieve size mm	Mass Retained	% Retained	Cum. % Retained	% Passing	% Passing Specification
9.5	0.0	0.0	0.0	100.0	100
6.7	0.5	0.1	0.1	99.9	100
4.75	1.0	0.2	0.3	99.7	90-100
2.36	2.0	0.4	0.7	99.3	
1.18	5.0	1.0	1.8	98.2	
0.6	15.5	3.2	5.0	95.0	
0.3	111.0	23.0	28.0	72.0	
0.15	230.5	47.8	75.8	24.2	5 - 25
0.075	86.0	17.8		6.4	0 - 5
Pan	14.0				
Pan	17.0				
Dry Mass Washed	465.5				

W.A. = 3.13%

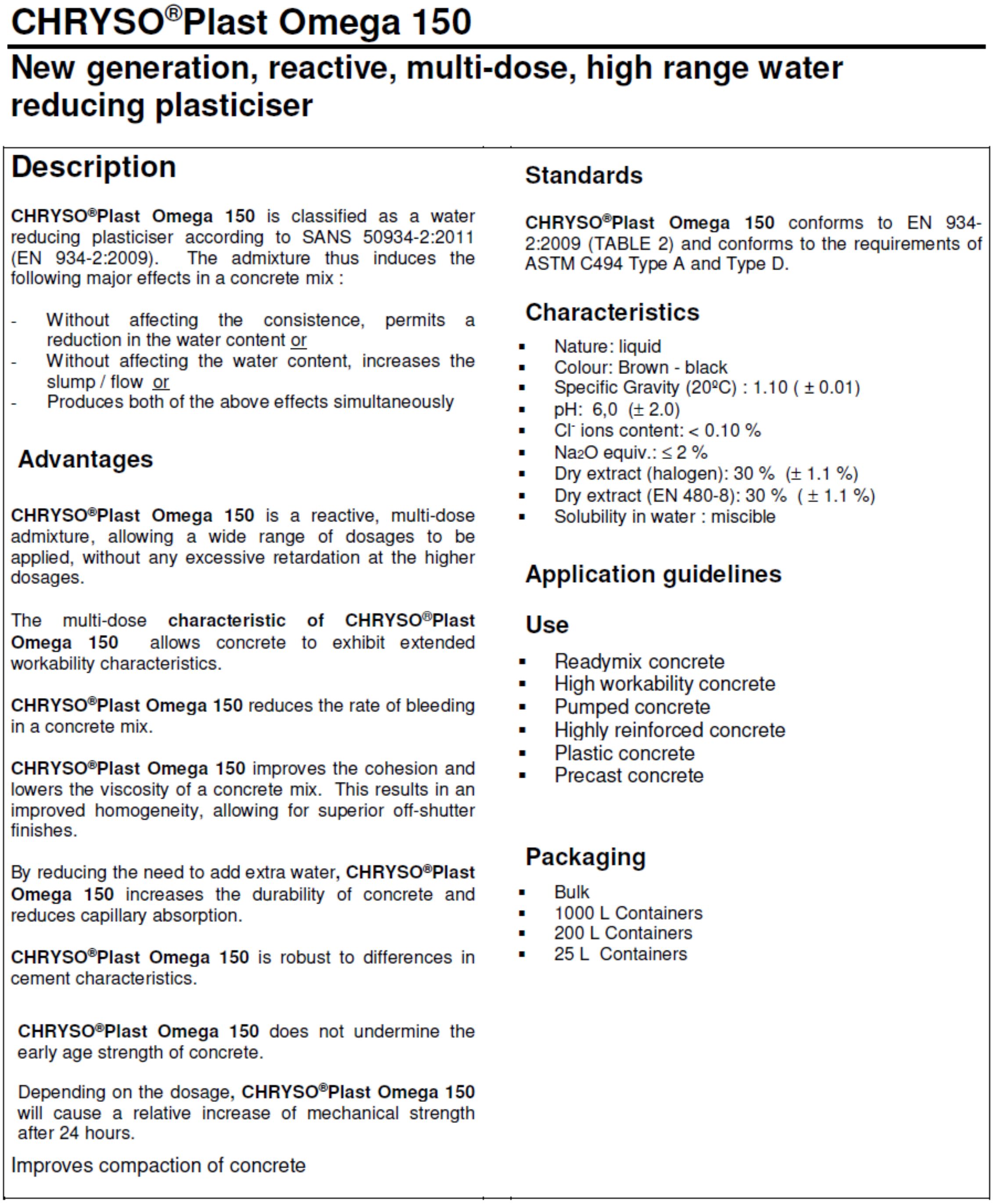
Wet Mass =	529.5
Dry Mass =	482.5
LBD (kg/m^3) =	1280
CBD (kg/m^3) =	1496
RD =	2.68
F.M. =	1.12
% Moisture =	9.74%
Dust Content=	6.4%



Results given above refer only to the sample submitted for testing

QDSA\SF\00273

Appendix F



CHRYSO®Plast Omega 150

New generation, reactive, multi-dose, high range water reducing plasticiser

Description

CHRYSO®Plast Omega 150 is classified as a water reducing plasticiser according to SANS 50934-2:2011 (EN 934-2:2009). The admixture thus induces the following major effects in a concrete mix :

- Without affecting the consistence, permits a reduction in the water content or
- Without affecting the water content, increases the slump / flow or
- Produces both of the above effects simultaneously

Advantages

CHRYSO®Plast Omega 150 is a reactive, multi-dose admixture, allowing a wide range of dosages to be applied, without any excessive retardation at the higher dosages.

The multi-dose **characteristic of CHRYSO®Plast Omega 150** allows concrete to exhibit extended workability characteristics.

CHRYSO®Plast Omega 150 reduces the rate of bleeding in a concrete mix.

CHRYSO®Plast Omega 150 improves the cohesion and lowers the viscosity of a concrete mix. This results in an improved homogeneity, allowing for superior off-shutter finishes.

By reducing the need to add extra water, **CHRYSO®Plast Omega 150** increases the durability of concrete and reduces capillary absorption.

CHRYSO®Plast Omega 150 is robust to differences in cement characteristics.

CHRYSO®Plast Omega 150 does not undermine the early age strength of concrete.

Depending on the dosage, **CHRYSO®Plast Omega 150** will cause a relative increase of mechanical strength after 24 hours.

Improves compaction of concrete

Standards

CHRYSO®Plast Omega 150 conforms to EN 934-2:2009 (TABLE 2) and conforms to the requirements of ASTM C494 Type A and Type D.

Characteristics

- Nature: liquid
- Colour: Brown - black
- Specific Gravity (20ºC) : 1.10 (± 0.01)
- pH: 6,0 (± 2.0)
- Cl^- ions content: < 0.10 %
- Na_2O equiv.: ≤ 2 %
- Dry extract (halogen): 30 % (± 1.1 %)
- Dry extract (EN 480-8): 30 % (± 1.1 %)
- Solubility in water : miscible

Application guidelines

Use

- Readymix concrete
- High workability concrete
- Pumped concrete
- Highly reinforced concrete
- Plastic concrete
- Precast concrete

Packaging

- Bulk
- 1000 L Containers
- 200 L Containers
- 25 L Containers