Non-conventional mix for ultrathin asphalt pavements in South Africa

By

Michiel Willem Heyns

Thesis submitted in fulfillment of the degree

DOCTOR of ENGINEERING in CIVIL ENGINEERING

In the FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

DEPARTMENT OF CIVIL ENGINEERING

at the

Central University of Technology, Free State

Supervisor: Prof. Mohamed MH Mostafa (UKZN)

Prof. D Das (UKZN)

Dr E Mukandila (Baobab (PTY) LTD)

Prof Y Woyessa (CUT)

2021

Declaration

I hereby declare that this dissertation, submitted for a Doctoral of Engineering in the Department of Civil Engineering, Central University of Technology, Bloemfontein, South Africa, is my own work and has not been submitted to any other institute of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a list of references

M.W. Heyns

Acknowledgements

This study was made possible by the co-operation of many individuals and institutions. I wish to record my sincere gratitude to the following:

1. CUT for encouragement and funding
2. Jodan Construction for support and funding
3. Roadlab for all testing and funding
4. Afrigrit for individual support and supply of all materials
5. Ulula Ash individual support and material supply
6. Prof. M. Mostafa for guidelines, leadership, assistance and moral support throughout this project
7. Special thanks to my wife Jackie for continuous support and love during this epic journey
8. Thanks to family and friends for encouragement

A paper is not complete without the words, which was given to me through the spiritual and grace received from the almighty God.

Abstract

Large quantities of natural materials are traditionally used in road construction, which leads to depletion of non-renewable natural resources. Concurrently, the world faces the problem of management of an increasing quantity of waste so that linking the two issues leads to a simple solution: growing and more diverse application of waste materials in road building and other areas of civil engineering alike.

Replacement of natural soils or minimisation of the use is desirable. An industrial by-product may be inferior to the traditional materials used in road pavement construction. However, the lower cost makes the by-products an attractive alternative if the required performance can be achieved. It is in the context of this study to produce results to further motivate the use of by-products, such as Fly Ash and Chrome Slag, in road construction.

Detailed asphalt mix design and investigations were completed to evaluate the use of Fly Ash and Chrome Slag as a suitable replacement in an asphalt mixture to reduce landfill sites and, in effect, become an environmental option for road construction in South Africa. The standards in the study were combined to form a basic step by step evaluation process that can be used by designers for in-depth evaluation of the use of Chrome Slag and Fly Ash in an asphalt mixture. The design applied to ultrathin asphalt thicknesses of 20mm and is aimed at urban and rural roads. The Fly Ash in the study was used to aid with the grading elements of the Chrome Slag and for the use as filler. The gradation was developed by using a combination of standards to get an optimum grading for the designs. The Chrome Slag and Fly Ash combination showed a better density packing characteristic than the Dolerite, Natural Aggregate.

Environment is a concern when using Fly Ash and Chrome Slag in construction projects. To evaluate the potential harmful effects to the environment, the Fly Ash samples, and Chrome Slag were subjected to leaching tests. The results were compared to drinking water maximum allowable elements also found in Fly Ash and Chrome Slag with possible health effects. The Fly Ash with no treatment shows that leached elements namely: Ba, Cr, Pb are of a concern once the elements have leached into the groundwater. The Chrome Slag aggregates showed that the leached elements of concern were namely: Ba, Se, and Cu. Chemical analysis on various (FeCr) Chrome Slag samples have detected traces of heavy metals such as chromium(IV) oxide, which is very toxic and leachable. The Leaching results on the asphalt mixtures, have shown that the Fly

Ash and Chrome Slag elements were "*entombed*" and the possibility of leachant releasing agents of a dangerous nature are to a minimal.

Volumetric design still remains the basis of this study. Marshall Stability and Flow, results was used to calculate the envisaged bearing capacity of the asphalt mixture which showed the % binders have psi that varies between 63psi and 108psi for the Chrome Slag on 50/70 binder and between 49psi and 126psi for the Natural Aggregate on the 50/70 binder. The AE-2 binder shows 87psi to 116psi for the Chrome Slag and between 104psi to 138psi for the Natural Aggregate. The VMA proved a confidence decision on the Natural Aggregate, but designers should be more aware of the Chrome Slag and Fly Ash mixtures as the VMA is on the low spectrum of the results and on the limits of the minimum required values. The Natural Aggregate conforms well above the requirements, while for the Chrome Slag and Fly Ash mixture on design voids the readings are low with 14.6 at 6% binder for AE-2 and 13.7 at 5.5% binder for the 50/70. The voids at the binder percentages for the Chrome Slag and Fly Ash mixtures are 3.4 and 3.6 respectively. The VFB has shown that the Chrome Slag and Fly Ash mixture, like the VMA, is very unpredictable. The results do conform to the minimum standard of between 70 and 80, but the voids are below 4% with 3.2% voids for the AE-2 mixture. The 50/70 binder proved more reliable at 4.3% voids. The Natural Aggregate conformed to the specifications at 5.5% AE-2 binder and at 5% 50/70 binder respectively.

Specialised testing was completed on the asphalt mixtures namely; MMLS, Gyratory, Modified Lottman, ITS and HWTT. The MMLS results have indicated ruts of between 3.26mm to 4.65mm for 50/70 binder and between 5.25mm and 5.35mm for AE-2 binder. The gyratory test has indicated voids after 300 gyratory of between 2,4% and 5.5% for the Natural Aggregate and 1.3% to 3.4% for the Chrome Slag and Fly Ash mixtures. The modified Lottman tests have shown that both Natural Aggregate and Chrome Slag have conformed to the test results with results above the minimum required in wet regions of 0.8. The results were all above 0.9. The ITS results were very favourable in showing cohesiveness. The results are indicative of toughness and durability and rutting resistance. On the 50/70 binder, the Chrome Slag shows a good ITS value at 6% binder, while the Natural Aggregate shows acceptable value at 5.5% binder. The AE-2 shows very good results with all results above 1100kPa range. The Hamburg test (HWTT) showed variable results for both Chrome Slag and Natural Aggregate mixtures. It can be that the thick compacted briquettes for the testing procedures are not suitable for the 10mm maximum size particles in the mixture. The increase in thickness for both MMLS and Hamburg have indicated that rutting is a concern with both products and binders thus the designer will have to apply

further investigation research to conclude design for the required thin asphalt. The study has indicated that the Chrome Slag and Fly Ash mixture does conform to most requirements and is a viable option as a suitable replacement for the Natural Aggregate for the application in rural/urban roads as an ultrathin asphalt mixture.

Keywords: Chrome Slag, Fly Ash, Chemical, Environment, Asphalt Design, Performance Indicators, Standards, Ultrathin asphalt mixture

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AASHTO - American Society of State Highway and Transportation Officials

Ag - Silver

Al - Aluminium

Al_2O_3 - Aluminium Oxide/Aluminia

As - Arsenic

ASTM - American Society for Testing and Materials

B - Boron

Ba - Barium

Be - Beryllium

Bi - Bismuth

Br - Bromine

BS - British Standards

C - Carbon

Ca - Calcium

CaO - Calcium Oxide/Lime

CCP - Coal Combustion Products

Cd - Cadmium

Ce - Cerium

Cl - Chloride

Co - Cobalt

COLTO - Committee of Land Transport Officials

Cr - Chromium

Cr_2O_3 - Chromium (III) Oxide

Cs - Caesium

CSA - Tri-calcium aluminate

Cu - Copper

EERC - Energy and Environmental Research Center

EN - European Norm

F - Fourine

FBC - Fluidised-bed Combustion

fCaO - free Lime

Fe - Iron

Fe_2O_3 - Feric Oxide

G5 - Gravel Soil Categories

Ga - Gallium

Ge - Germanium

H_2O - Water

Hf - Hafnium

Hg – Mercury

HMA – Hot Mix Asphalt

K - Potassium

K_2O - Potassium Oxide

kPa - Kilopascal

La - Lanthanum

LL - Liquid Limit

LOI - Loss Of Ignition

MC - Moisture Content

MDD - Maximum Dry Density

Mg - Magnesium

MgO - Magnesium Oxide

Mn - Manganese

Mn_2O_3 - Mangese (III) Oxide

Mo - Molybdenum

MPa - Megapascal

M_r - Resilient Modulus

MT - Million Tons

Na - Sodium

Na_2O - Sodium Oxide

Nb - Niobium

Nd - Neodymium

Ni - Nickel

NP - Non-Plastic

P - Phosphorus

P_2O_5 - Phosphorus Pentoxide

Pb - Lead

PC - Portland Cement

PI - Plastic Index

ppb - parts per billion

psi - pounds per square inch

Rb - Rubidium

RCaO - Reactive Lime

S - Sulphur

SANS - South Africa National Standards

Sb - Antimony

Sc - Scandium

Se - Selenium

Si - Silicon

SiO_2 - Silicon Dioxide/Silica

Sm – Samarium

SMA – Stone Mix Apshalt

SO_3 - Sulfur Trioxide

SP - Slightly Plastic

Sr - Stratium

SrO - Strantium Oxide

Ta - Tantalum

TCaO - Total Lime

Th - Tharium

TI - Thallium

Ti - Titanium

TiO_2 - Titanium Dioxide

TRR - Transport Research Board

U - Uranium

V - Vanadium

W - Tungsten

XRF - X-Ray Flourescence

Y - Yttrium

Yb - Ytterbium

Zn - Zinc

ZnO - Zinc Oxide

Zr - Zirconium

Chapter 1 Introduction

1.1 Introduction

This chapter deals with the introduction to the study, which entails the following: Background of the study, Problem Statement, Study Area, Research Design, Research Aims, Specific Objectives, Methodology and Outline of Subsequent Chapters.

1.2 Background

As the volume of waste and by-product materials generated in our society and the cost of disposal continues to increase, there is heightened pressure and incentive to recover and recycle these materials for use in a secondary application.

Chrome Slag is a waste material generated in purifying metals, their castings and alloying. In the course of this process, Chrome Slag is generated in two phases, namely:

1. The Ore is exposed to high temperatures to separate impurities.
2. The separated impurities are collected and removed, and this "waste" material is called Chrome Slag.

The type of generated Chrome Slag depends on the method of cooling, and the type of processed metal.

The first appearance of Chrome Slag was recorded as early as the year 700 B.C. It can also be concluded that the history of Chrome Slag is as old as the melting process in which it was generated. The first modern roads in the building of which Chrome Slag was utilised were built in England in 1813. After good experiences with the application of this material in road building were confirmed, Chrome Slag started to be used in railway construction as well in the mid-19th Century with the discovery of latent hydraulic properties of granulated blast furnace Chrome Slag. Since then, blocks obtained by casting of Chrome Slag have been massively applied in Europe/America for road pavements.

In South Africa, the submerged electrode arc-smelting process is mainly used to produce ferrochromium. During the smelting process, an Fe-Cr rich melt (the ferrochromium product) and a Chrome Slag (waste contain other residual materials) are produced. Several different processes are used to produce ferrochromium. During the submerged electrode arc-smelting process in South Africa, the chromite ore is blended with carbon-rich material (reductants) and fluxes (coke, char, and coal) to produce the feedstock. The feedstock is fed into an electric-arc furnace where it is melted (Hattingh, 2003). The smelting process uses electrical energy to melt the feedstock, raising the melt to a temperature at which the mixture will chemically react. The net result of the chemical reaction is that carbon (C) combines with oxygen (O) from the ore to form CO and CO_2 gases that evolve from the melted mixture, leaving a Fe-Cr rich melt (ferrochromium), as well as a Chrome Slag (waste product) containing other residual materials. Once enough ferrochromium has been produced, the furnace is opened, permitting the ferrochromium and Chrome Slag to flow out. Ferrochromium is extracted from the Cr ore to produce the final product. The metal and primary Chrome Slag are tapped through the furnace to the hole, into a ladle, and is then cast into silica sand/ferrochromium fines moulds. Primary Chrome Slag is a semi-solid waste still containing ferrochromium and 2% moisture, which is tapped into a Chrome Slag bell and processed through a metal-recovery processing plant where the Chrome Slag is crushed, screened, and separated from the residual metal through a hydro-jigging process. The metal and Chrome Slag are separated during this process because of their differences in density. The Chrome Slag is directly granulated during tapping where ferrochrome is tapped into ladles. The overflow from the ladles flows along the Chrome Slag launder to the granulation pond, where high-pressure water breaks Chrome Slag into small fractions and efficiently cools it down. The final Chrome Slag is then dumped on site (Niemela, 2007; Hattingh, 2003).

Using modern process control techniques and good quality charge materials, the optimal Chrome Slag composition can be attained. Some of the important factors relating to the above-mentioned process are good Chrome Slag composition, temperature, viscosity, and electrical conductivity.

The main components of the Chrome Slag are SiO_2, MgO, and Al_2O_3. The Chrome Slag also includes Cr and Fe oxides and calcium oxides. Common phases in the Chrome Slag are glass, spinels, and forsterite. The Chrome Slag chemistry is vital for the efficient ferrochrome production (Niemela, 2007). Typical ferrochrome Chrome Slag composition is 30% SiO_2, 26% Al_2O_3, 23% MgO, and 2% CaO.

Granulated Chrome Slag is a very homogenous product. A granule is partly crystalline and typically includes three (3) different phases, which are:

1. Amorphous glass phase
2. Metal drops
3. Crystalline and zonal Fe-Mg-Cr-Al-spinels

Chrome Slag can be compared to volcanic rock such as basalt and granite. Just like the natural materials, Chrome Slag does contain trace elements but are mostly bound up within the crystal lattice, and therefore almost impossible to leach. The Fraunhofer Institute showed that where debris of Chrome Slag used in road construction does not represent a danger to health due to Chrome Slag having a homogenous structure.

Large amounts of Chrome Slag is being produced daily in South Africa and historically this has been dumped without any pollution prevention, control, or remediation measures (Hattingh, 2003). Chrome Slag does contain certain trace elements that may pose a significant threat to human life and the environment, for example, hexavalent Cr, Fe, and Mn. It further has the potential to produce leachate and subsequent pollution of surface and groundwater resources. The presence of free calcium oxide (CaO), accounting for more than 1%, causes another adverse property of steel Chrome Slag, namely, the appearance of white powder in form of sediment. Free CaO from leachate is bound with water, creating calcium hydroxide, $Ca(OH_2)$, which, when exposed to atmospheric conditions, reacts with carbon dioxide (CO_2), creating calcium carbonate ($CaCO_3$). This causes obstruction in drainage systems and water retention (Ivana, 2010). It must be noted that the Chrome Slag in this study is ferrochrome Chrome Slag (FeCr). Therefore, all references of Chrome Slag is to ferrochrome.

Fly Ash is a waste thermal altered mineral by-product from burning of coal used to provide electricity. The following are the basic types of coal-fired boilers: Pulverised coal, Stoker-fired, fluidised-bed combustion boilers and cyclone. The common type used in South Africa is the pulverised coal boiler. The physical and chemical characteristics of the Fly Ash is determined by: Combustion method, source where coal is extracted and the particle shape (Fly Ash Facts for Highway Engineers, 2003). The common application on how Fly Ash is formed is from the boiler tubes that extract the heat generated and cool the flue gases which then causes the pulverised coal mineral matter to harden. The Fly Ash is found in the flue gas as suspended particles due to the lightness of the material. The Fly Ash is then removed from the flue gasses by means of electrostatic precipitators or in place filter bags. Boral noted that Fly Ash is much finer than Portland cement and lime (Boral, 2013). Fly Ash has various sizes from 0.5 micron to 100 micron all depending on the combustion process. The Fly Ash acts as an adequate mineral filler due to its physical characteristics of being spherical in shape and is an ideal mineral for various applications in the engineering field (FA FACTS, 2003). Mehta found that Fly Ash contains siliceous and aluminous materials which then, Fly Ash can be classified as a pozzolan material. In other words, when water is added to the material, it produces cementitious properties when it reacts with calcium hydroxide (Mehta, 1998). Fly Ash has two important chemical compounds namely, Silicon Dioxide and Calcium Oxide which makes Fly Ash an effective cementitious by-product of the coal combustion process.

Fly Ash varies in colour due to the various mineral and chemical properties (FA FACTS, 2003). Fly Ash with high lime content exhibit colours from tan to light grey. High iron contents are mostly indicated by a brownish colour while high unburned coal gives Fly Ash a dark grey to almost black in colour (Mehta, 1998).

South African Bureau of Standards (SABS) define Fly Ash as a powdery residue obtained from separation of the solids from the flue gasses during the combustion of pulverised coal. The residue known as Fly Ash represents up to 80% of the mineral released by combustion of coal.

Fly Ash has a very important main component and that is the presence of silicon dioxide and is found in 2 forms:

a. Rounded and smooth which is called amorphous
b. Sharp and pointed with hazardous aluminium oxide and iron oxide components in a crystalline form (Mehta, 1998; Ismail et al., 2007; FA FACTS, 2003)

Fly Ash consists of glassy materials with crystalline minerals such as quartz, mullite and various iron oxides thus classifying Fly Ash as a heterogeneous mineral (Ojo, 2010). As stated, Fly Ash has pozzolanic properties and this is directly related to the amount of free lime and not related to the amount of unburned carbon. There are traces of soluble oxides found in Fly Ash from power generated stations such as CaO and MgO. The chemical composition of Fly Ash is made up of major elements such as Si, Ca, Al, Mg, Fe, Na, K and with various trace elements such as Co, Cd, As, Se, Zn, Mo, Mn, Pb, B, Cu and Ni (Oppenshaw, 1992; Ojo, 2010). Studies have shown that Fly Ash have variables which is determined by the chemical and composition properties and has an impact on pH levels depending on the type of landfill sites (Oppenshaw, 1992; Gitari *et al*, 2009). The disposal and management of these Fly Ash dumps placed in dedicated landfill areas have become a major problem and has a negative effect on the environment due to vast number of volumes of Fly Ash being produced (National Inventory, 2001). Oppenshaw showed that the re-use of Fly Ash has had various positive results on the environmental impact but at the stage of the study, it was seen mostly as only trial studies (Oppenshaw, 1992). Hasset has indicated that the trace elements of Fly Ash used in soil stabilisation is not hazardous to the environment (Hassett *et al*, 2001). Hasset further indicated that by utilising the Fly Ash, it will minimise the disposal problem and the management of land can be dealt with in a more effective way. With the use of Fly Ash in soil stabilisation, the hazardous elements of concern that can have detrimental impact on the environment is bound within the chemical reactions taking place thus the chances of leaching elements are negligible (Hassett *et al*, 2001).

South Africa have 2 main provinces that generate large quantities of Fly Ash namely; Mpumalanga and the Free State (Hall, 2011). With the increase of the dumps on a daily basis worldwide, the need for a safer disposal option is critical.

The standard ASTM 618 was introduced worldwide to classify the Fly Ash (ASTM 618, 2011). The classification is divided into two classes namely: Class C and Class F. Class C contains more than 20% lime, therefore it also has a property of self-cementing agent. If water is added to Class C Fly Ash, it will cause a reaction like cement and harden over time. Class C Fly Ash is derived from the burning of the younger lignite or subbituminous coal. The chemical composition found in Class C Fly Ash has also become known as the high calcium Fly Ash worldwide. The opposite is noted for the Class F Fly Ash as it is derived from the burning of the old coal, such the harder anthracite and more bituminous coal. The chemical composition is different from the Class C and this class is referred to as the low calcium Fly Ash. The Class F Fly Ash contains less than 20% lime, therefore it does not react with water like the Class C. This Class F needs a reaction agent to start the process such as cement (FA FACTS, 2003). In South Africa, the standard developed for classification of Fly Ash was adapted from the American Society for Testing Materials (ASTM) for the local conditions, and the standard is a South African National Standard (SANS) 1491- 2 document which also references the ASTM standards (SANS 1491-2, 2005).

The use of Fly Ash in engineering fields is not new although the public is not overly convinced. Organisations have completed various studies to indicate that the use of Fly Ash in the field is acceptable and are encouraging the use with regards to strength properties and a more effective cost model (Oppenshaw, 1992).

1.3 Problem Statement

There is an urgent need for better fit-for-purpose asphalt mix definition, including credible product performance specifications and application guidelines. Asphalt surfacing and base layers constitute an estimate of 20% of new, reconstructed, and rehabilitated road costs, hence the importance of maximising product value by means of a credible fit-for-purpose performance specification system.

Numerous changes have taken place in the realms of material and construction techniques over the past 20 years. Despite the fact that traffic loads, traffic volumes, and tyre contact stresses have increased steadily, there have been relatively few changes in the asphalt mix design in South Africa over this period of time.

The overall performance of an asphalt mix is dependent on, amongst others, the properties of the constituent materials, which include aggregate, binder, and filler.

In road construction and quarries, large quantities of natural material is used. The use of non-renewable resources causes a depletion of natural resources and disrupts the eco balance of the environment in the areas of construction. The world is concurrently facing a problem of excessive waste increase on daily basis. The one way to look at the problem is to link the two issues to derive to a simple but effective solution. These inventive solutions can grow a more diverse application of waste materials in road building and overlays alike. Three (3) basic waste applications can be used in road construction, namely:

1. Reusable construction materials
2. Industry by-products
3. Natural construction materials of a lower usability value

The first group includes the materials from unbound base courses and materials from bitumen and hydraulically bound layers. Chrome Slag and Fly Ash belong to the group of industry by-products, whereas the group of natural construction materials with lower usability value is primarily represented by excavation materials and quarry waste (Ivana, 2010).

As Natural Aggregate sources are becoming depleted due to high demand in road construction, and the amount of disposed waste material keeps increasing, researchers are exploring the use of alternative materials which could preserve natural sources and save the environment. The utilisation of Chrome Slag will reduce landfill space, save natural resources, and improve the strength of pavement to sustain a higher volume of vehicles. This will shift the gear in sustainable pavement construction, which is most desirable in today's energy deficient world (Hainin, 2012).

Approximately 20 million tons have accumulated on Chrome Slag dumps in South Africa and a further 0.5 million tons are added every year (Groot, *et al*, 2013). The total amount of Chrome Slag dumps in the Witbank area alone, according to statics that is readily available, is 450 000 tons, and increases every month. Total elimination of the production of Chrome Slag is impossible at this stage. The environmentally acceptable method will be to minimise the Chrome Slag. At present, the only option available is that of re-use. Although some of the re-use options seem feasible, limited information is available about the environmental impact of these options (Hattingh, 2003).

Worldwide Fly Ash is produced on a daily basis and the increase of dump sites represents a major concern to the electricity industries.Accumulations of these Fly Ash landfill dumpsites have reached alarmingly high levels, requiring immediate attention for its disposal. Globally the demand for electricity as steadily increased over a span of 30 years but has recently increased rapidly due to influences of countries like India and China. It has been noted that coal has become the fastest fuel source than any other type of fuels in the recent years (Hall, 2011). Electricity demand from coal power sources have increased to 41% globally within urban populations worldwide the demand is expected to increase over time (Hall, 2011).

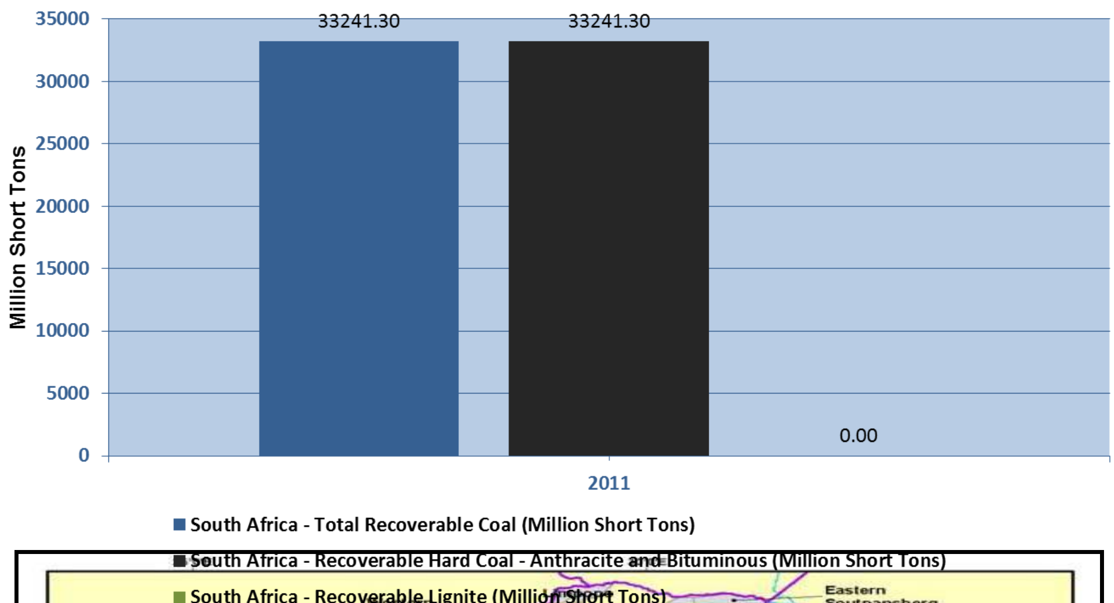
In South Africa, the coal industry provides up to 80% of the energy requirements and is the most crucial core of the country's economic development, up to 93% of the countries coal is utilized for producing electricity and the demand will increase significantly over the next decade (Hall, 2010). Table 1.1 currently shows the reserves of coal found in South Africa from a study done in 2015. South Africa currently produces millions of tons of Fly Ash per annum, of which only 6-10% is utilised for different purposes. In a survey undertook in 2001 by the energy branch of the Department of Minerals and Energy, it was found that coal remains South Africa's prime energy source, and 87.4 million tons are used by Eskom and 48.8 million tons are used by SASOL per annum. Discarded coal and slurry being produced annually is in excess of 53 million tons per annum. The majority of the larger discard dumps are situated in the Mpumalanga province, with the average age of these dumps being between 15 years and 50 years. Discard ash has a distribution figure of 40 to 50% of the surveyed dumps. (National Inventory, 2001). Figure 1 shows the extent of coal mines in South Africa, which is also an indicative value of the Fly Ash resources available.

The main supplier of electricity in South Africa is Eskom and currently, Eskom is planning a generation capacity expansion that will increase coal consumption to over 51million tons per year. Sasol, another entity, will also see the coal consumption increase to over 75 million tons per annum over the next upcoming years for synthetic fuel manufacturing (Mining Weekly, 2010).

In the recent years, the government have made changes in legislation and in the mining industry on how to start to use this valuable source. This changed the dispersant of the Fly Ash and now the dumps are compacted and rehabilitated to preserve the Fly Ash (National Inventory, 2001). Another factor that contributed to the increase in Fly Ash dumps was the change in environmental and health legislations. These legislations prevented the Fly Ash from being dispersed into the air and this has decreased the Fly Ash emissions to over 1% but has caused an increase in landfill sites (National Inventory, 2001).

The problem is now invested on the landfill sites the use of the by-products has become a critical focus point. The government has encouraged and put in place various programmes to study this issue and come up with viable approved solutions. The focus has mostly changed to the Dump Sites of Fly Ash and Chrome Slag. These are one of the areas that have increased tremendously over the years and it is the by-product of burning Coal and Iron.Fly Ash and Chrome Slag studies around the world have made major breakthroughs by using the product in various applications. The studies can be used as a platform on which South Africa can start utilising the by-product for its own use in its own unique environment.

Table 1.1: South African Coal reserves in 2015 (IES, 2015)



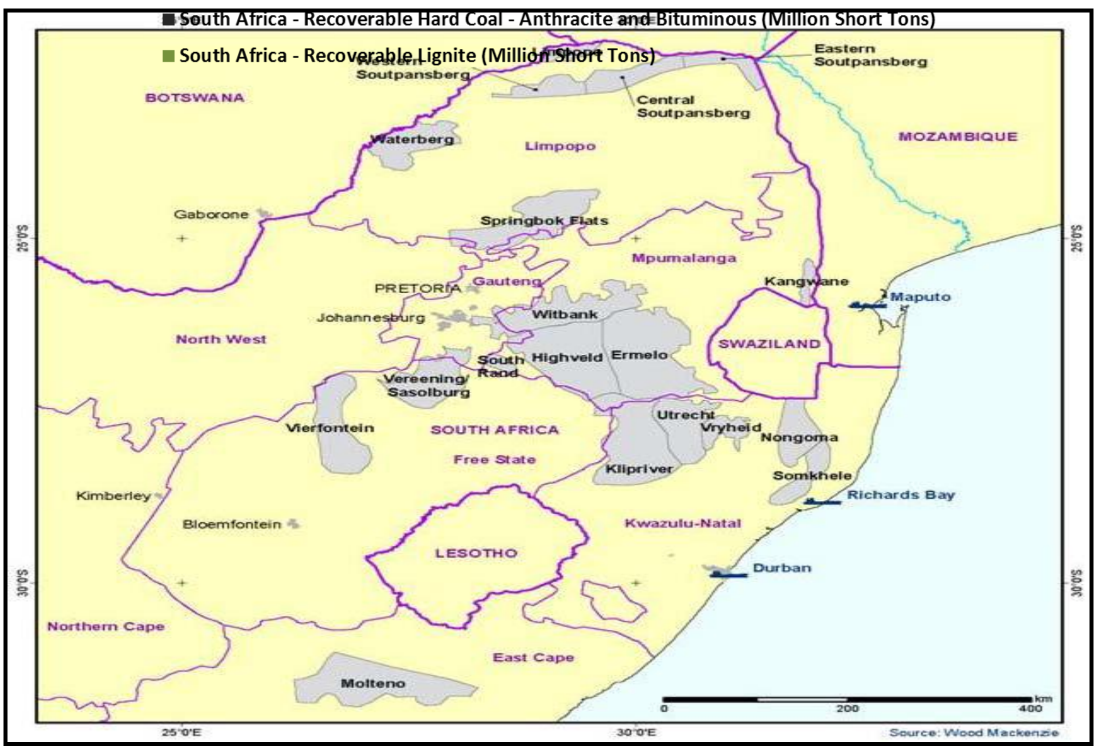


Figure 1: Coal Mines in South Africa (Hall, 2011)

1.4 Study Area

One coal-fired station was chosen and will be used in this study: Kriel. The Fly Ash will be supplied by Ulula Ash who currently supplies from Kriel. The Fly Ash dams are shown in Figure 2.

Figure 2 Kriel Ash Dump Dams (CER, 2015)

Chrome Slag will be supplied from AFRIGRIT in Witbank. Figure 1 shows that Witbank is situated in the area where the most coal mines are located, thus the availability of the two resources in the study are readily available. Figures 3 and 4 show Chrome Slag dumps of processed Chrome Slag and un-processed Chrome Slag, respectively.

Figure 3: Processed air cool Chrome Slag

Figure 4: Unprocessed Chrome Slag dump

1.5 Research Design

The research product will only incorporate detailed laboratory design specimens but, from the study, the results can only predict possible field performances of the products and performance.

Each method followed will be detailed and a standard can be compiled for future use. All implemented methods are currently followed by the standards set in South Africa.

1.6 Research aims

Only recycled waste will be utilised for this specific research project, namely: Fly and Chrome Slag.

A new factor or new formulae will also need to be evaluated, seeing as some specifications on standard asphalt mix designs cannot be used in this study. A theoretical calculated factor can be utilised to be more effective. The new factor will need to be in line with the current standards, which can then be used for all thin asphalt designs correlating to the design in this research project.

1.7 Specific objectives

Objective of this study:

1. Design possible ultra-thin asphalt for urban/rural roads using only waste products, namely: Fly Ash and Chrome Slag.
2. Study the properties and characteristics of the Fly Ash and Chrome Slag for their chemical and environmental effects.
3. Complete component testing for Fly Ash and Chrome Slag, including the reference sample versus the applicable testing standards found in South Africa.
4. Design an asphalt mix with the components of Chrome Slag and Fly Ash, and study the required performances as an Ultra-Thin Mix, and compare the outcome to the reference sample.
5. Analyse the application of the current traditional Marshall testing methods and possibly develop new formulae for applications in Ultra-Thin Mix Design.
6. Analyse the environmental impact of the samples in the design mixture.
7. Setup design criteria for ultra-thin asphalt using waste products.
8. Conclude that full or partial replacement can be achieved.

Using these by-products, Fly Ash and Chrome Slag, in any construction field can aid with the reduction of the landfill sites and have an impact on a decrease demand use of the natural resources.

With major landfill sites of Fly Ash and Chrome Slag that is readily available, it can be utilised immediately on construction sites, therefore increasing the percentage of reuse and sustainability. The use of Chrome Slag and Fly Ash will be justified due to the following:

1. Decrease in environmental degradation costs due to the use of precious topsoil and aggregates from borrow areas, quarry sources,
2. Decrease in loss of fertile agricultural land due to ash deposits than the actual savings achieved will be much higher and use of Fly Ash and Chrome Slag will be justified.

Disposal of Fly Ash and Chrome Slag is of major environmental concern because of the possible release of contaminants to ground and surface water after disposal. When used in asphalt work, chemical reactions take place which binds particles, therefore the chances of pollution in roadworks is negligible.

New studies are to be done to involve waste and by-product materials being produced by the mining industry and using them for road construction. Remodelling, remanufacturing, repair, and recycling will start new consumption patterns that will not only be dependent on virgin material. The waste material and by-product can be allocated to new landfill areas, for example: old quarries, which can then be delivered to various road construction sites. This will develop and open new economic opportunities, new job markets, and revenue streams, while addressing the problems relating to the construction industry and waste management.

1.8 Methodology

The materials employed will be subjected to extensive detailed testing. Each product/additive will be detailed according to classified standard tests to understand each product and recognise which combination of these will be the most effective in the design of the thin asphalt layer.

In order to achieve required results, a comparison will need to be completed between the new research product and a standards Ultra-Thin Asphalt mix using conventional aggregates and additives. The conventional aggregate to be used in this study is Dolerite.

The components of the mixes will be subjected to the following tests:

1. Physical Testing
    a. Grading analysis
    b. Physical strength component testing
    c. Durability testing
2. Chemical Testing

   a. XRD analysis of each component to understand further reactions that can contribute to strength and durability when compared to product using Natural Aggregates

The mixtures will be subjected to the following tests:

1. Mechanical Testing
   a. All testing relating to full Marshall / Specialised testing requirements
2. Durability Testing
   a. Actual performance testing
   b. Fatigue testing
   c. Age analysis

These tests involve the full testing of the products according to set standards, which will enable a mix design to be successfully produced and determine an evaluation thereafter to the performance of the products. Mechanical testing will also include over and above the normal testing procedures for example: MMLS, Gyratory testing, Modified Lottman and Hamburg wheel test.

1.8.1 General

A filler will be utilised in the research project. Fly Ash in South Africa is a Class F, which requires a cementing agent in order for reaction processes to start. The filler combination will be used as a reference sample to evaluate the performance of an asphalt sample without any cementing agent. A comparison between mix designs, which includes standard material resources, can be compared.

The bitumen used will also be subjected to the tests for the best optimisation in the product design stage.

Various bitumen compilations are found in South Africa. Numerous compilations will be studied, and decisive products will be selected on their performances. These performances will be dependent on weather conditions, elasticity, and the makeup of hard to soft compounds.

A full design will be completed on the most theoretical design mixture. Further testing over and above the norm will be completed to ensure the product will conform and endure the design life.

1.8.2 Environmental Effects

Mankind is becomingly increasingly concerned about the impact of his actions on the environment. Ferrochrome producers are no exception, particularly in the view of the effect of hexavalent chromium release into the atmosphere, water, and soil (Gericke W, 1995). Since Chrome Slag has the potential ability to be harmful, properly designed dumpsites had to be implemented at tremendous costs, which include the maintenance and transport costs. (Hattingh *et al*, 2003).

Fly Ash is recognised as an environmental pollutant. Fly Ash is alkaline and consists of heavy metals that are detrimental to human health and the environment. The storage and disposal of Coal Fly Ash can thus lead to the release of leached metals into soils, surface and ground waters (Ayanda *et al.*, 2012). Environmental changes due to various types of pollution, formed through energy production and use, affect soil structure and fertility. Soil pollution causes environmental disruption impacting on agricultural practices, thus threatening food security (Surridge *et al.*, 2009).

Chrome Slag, which is the largest FeCr waste by-product, has been overmanaged through legislation in South Africa. This has resulted in the build-up of Chrome Slag stockpiles instead of utilisation as is already achieved in several first world countries. Additional research is definitely required in this field (Beukes, JP *et al*, 2010).

Various studies have concluded that crucial main components of Chrome Slag have a high hazard potential to the environment. These elements do leach, and environment hazards cannot be excluded from this study. The same practices as per Fly Ash stated above is also found in Chrome Slag composition.
Overall studies have confirmed that both Fly Ash and Chrome Slag, if used and managed properly, is not hazardous to the environment. Techniques have been developed by using by-products in solidification/stabilisation that causes chemical reactions which binds the by-products and reduces the chances of pollution in roadworks.

1.8.3 Leaching Tests

Leaching is the process by which non-organic, organic contaminants, or radionuclides are released from the solid phase into the water phase under the influence of mineral dissolution, desorption, complexation processes as affected by pH, redox, dissolved organic matter, and micro-biological activity. Leaching process is universal, any material that is in contact with water will leach components depending on the porosity of the material being leached. The pH of the material must be regarded as the leaching behaviour is dependent on this factor. The pH value also contributes to better means of assessing the impact on the environment when leaching takes place (Hasset *et al.*, 2001).

The actual number of leach tests vary over the world and there is no actual identified method to estimate the environmental impact the by-product of waste, Fly Ash and Chrome Slag, has. (Kim, 2006).

Methods are basically classified according to the following:

1. Batch Leaching, in which a sample is placed in a given volume of leachant solution
2. Column or flow through systems
3. Bulk or flow around systems for monolithic samples

Physical characteristics of combustion residues include particle size, particle shape, hardness, and density (Kim, 2006).

Leach Testing will confirm any environmental concerns when the by-products are used for any road construction practices.

1.9 Outline of subsequent chapters

Chapter one is the introduction to this study. The overall thesis consists of 6 chapters and is detailed below.

Chapter 2 Literature Review

This chapter focuses on studies completed worldwide on the use of Fly Ash and Chrome Slag, chemical and physical composition, environmental impact, and construction techniques using the waste by-product.

Chapter 3 Materials

This chapter entails detail test analysis and description of materials used in this study. The tests are analysed to indicate the conformity to the South African set standards for construction evaluation of materials.

Chapter 4 Environmental effects on Fly Ash and Chrome Slag

This chapter focuses on the environmental impact the by-products, Fly Ash and Chrome Slag, has on the environment in its natural state and then the impact after it has been bound with applications to handling methods.

Chapter 5 Results and Discussion

This chapter deals with the evaluation of the test results following basic design steps according to set specifications. An additional testing criterion was also completed to evaluate if the results conform to a higher specification.

Chapter 6 Conclusions, recommendations, and future work

This chapter is to conclude the thesis and make viable recommendations for the road construction industry using Fly Ash and Chrome Slag

Chapter 2 Literature Review

2.1 Introduction

This chapter deals with review of literature on generation of Fly Ash and Chrome Slag, chemical and mineralogical compositions, utilisation, environmental impacts, and construction techniques.

2.2 Chrome Slag

Chrome Slag is waste material generated in purifying metals, their casting and alloying. Given the type of metal being processed, Chrome Slag is divided into two groups, namely: non-ferrous Chrome Slag which is from the production of aluminium, ferrochrome, and ferromanganese; ferrous Chrome Slag which is from the production and casting of iron and steel. In South Africa, the submerged electrode arc-smelting process is mainly used. During this process, the chromite ore is blended with carbon-rich material (reductants) and fluxes (coke, char, and coal) to produce the feedstock. The feedstock is fed into an electric-arc furnace where it is melted (Papp, 2000).

The smelting process uses electrical energy to melt the feedstock, raising the melt to a temperature at which the mixture will chemically react. The net result of the chemical reaction is that carbon (C) combines with oxygen (O) from the ore to form CO and CO_2 gases that evolve from the melted mixture, leaving a Fe-Cr rich melt (ferrochromium), as well as Chrome Slag (waste material) containing other residual materials. Once enough ferrochromium has been produced, the furnace is then opened, permitting the ferrochromium and Chrome Slag to flow out (Papp, 2000). Ferrochromium is extracted from the Cr ore to produce the final product. The metal and primary Chrome Slag is tapped from the furnaces. The primary Chrome Slag mainly consists of carbon monoxide and silicon, manganese, phosphorus, and some iron in the form of liquid oxides (Barisic, 2010). The primary Chrome Slag is tapped into a Chrome Slag bell and processed through a metal-recovery processing plant where the Chrome Slag is crushed, screened, and separated from the residual metal through a hydro-jigging process as the Chrome Slag still contains traces of ferrochromium. The metal and Chrome Slag are now separated during this process because of their differences in density, and the final Chrome Slag is dumped on site (Hattingh, 2003).

In summary, Chrome Slag is generated in two processes:

1. Ore is exposed to high temperatures in order to separate impurities.
2. The impurities are collected and removed, and this waste is called Chrome Slag.

The use of Chrome Slag has been recorded as early as 700 B.C. Chrome Slag was used for the first time in road construction as early as the Roman era, when Chrome Slag rubble from the processing of crude iron was utilised in building the roadbeds. The first modern roads constructed with Chrome Slag were built in England in 1813. The first actual record in road building with Chrome Slag was in 1830. A number of years after the use of Chrome Slag in road construction, with very good experiences, the railway started using Chrome Slag in construction of lines as well (Barisic, 2010).

The first experience of Chrome Slag in asphalt mixtures dated from 1969. The results obtained showed very good properties in terms of bearing capacity, resistance to external impacts, and durability (Emery, 1982).

Chrome Slag has become known as secondary aggregates which have similar physical properties to the conventional primary aggregate and can be processed, crushed, and screened into practical size for easy batching into both surfacing and base asphalt surfacing (Mikoc, 2010).

The most significant difference between steel Chrome Slag and most Natural Aggregates is its high particle density, which is the consequence of the presence of iron compounds.

Chrome Slag is also known as a pozzolanic material as it has a significant quantity of calcium oxide (CaO). The quantity of the CaO primarily indicates the existence of the possibility of the utilisation of Chrome Slag as a binder or a portion of binder (Barisic, 2010).

South Africa has an excess of Chrome Slag that covers hectares of ground. Some plants have been recording Chrome Slag dumps exceeding 5 million tons, which occupy approximately 5ha. Plants are planning to increase steel production thus increasing Chrome Slag dumps. An example of a plant is found in Machadodorp, which has a planned increase in Chrome Slag to over 8.5 million tons by the year 2025.

2.3 Fly Ash

The by-product of burning coal is Fly Ash, which is fine particles separated in flue gasses from the burning of coal. Fly Ash is collected in by electrostatic precipitators or filter bags. The Fly Ash ranges in size from 0.5 micron to 100 micron and is mostly spherical in shape (Rotaru *et al*, 2010).

SABS defines Fly Ash as powdery residue obtained from the burning of pulverised coal and is obtained by separation of the solids from the flue gasses (SABS, 2002). An estimated 80% of the solid coal burned is released as Fly Ash. The decrease of land by the slag dumps is of a concern by the South African government. The government is encouraging ways to use the Fly Ash in various fields through treatment, reuse, and beneficiation of Fly Ash (National Waste Management, 2010).

Various applications for the use of Fly Ash are in place, such as:

1. Acid mine drainage treatment
2. Commercial uses:
   a. Brickmaking
   b. Production of Cement
3. Soil stabilisation
4. Filler in an asphalt mixture

Eskom is continuously planning on expanding its coal powered generating capacity, therefore the quantities of Fly Ash waste will increase and at a tremendous pace. The mining industry and legislation has changed and is now at the stage that they realise how this Fly Ash is a valuable source (National Inventory, 2001).

The use of natural materials needs to be minimised, thus the use of an industrial by-product as replacement is becoming a more viable option. The by-products may not be as superior to the natural materials it is replacing but due to cost and attractive performances achieved, it has become an attractive option. Studies have shown that the use of by-products to enhance the properties of the traditional materials in road construction contributes to a well-controlled and superior product (Tuncer, 2006).

2.4 Fly Ash and Chrome Slag Characteristics

According to AST 618 (ASTM 618, 1994), Fly Ash has two classes:

1. Class C
2. Class F

The Fly Ash class is classified according to mineral contents of Alumina, Silica and Ferric Oxide. The described distinction between the classes is the sum of the mineral contents (SiO_2 + Al_2O_3 + Fe_2O_3). It is stated that if the sum of the mineral contents is greater than 70%, the Fly Ash is classified as a Class F, and if the sum of the mineral contents is between 50% and 70%, the Fly Ash is classified as a Class C. The basic classification of the Fly Ash in the study is seen in Table 2.1.

Class C Fly Ash is a by-product of the younger lignite or subbituminous coal combustion process. The Class C contains more than 20% lime, thus creating a mineral that has self-cementing properties. In other words, if water is added to the Class C Fly Ash, it will harden and become stronger over time (Boral, 2013).

Class F Fly Ash is a by-product of the older anthracite or bituminous coal combustion process. It does not have the self-cementing potential of Class C as it has less than 20% lime. It is still pozzolanic in nature, therefore it needs a cementing agent together with water to react and produce cementitious compounds (Boral, 2013).

Portland Cement (OPC), quick lime or hydrated lime, and the presence of water to react and produce cementitious compounds (Boral, 2013).

Chrome Slag is identified according to the type of metal being processed. Chrome Slag is basically divided into two groups:

1. Non-ferrous – Chrome Slag produced for the production of aluminium, ferrochrome, and ferromanganese.
2. Ferrous Chrome Slag – Chrome Slag produced from the production and casting of iron and steel.

Typical composition is 30% SiO_2, 26% Al_2O_3, 23% MgO, and 2% CaO. Ferrochrome Chrome Slag is available in a variety of forms, including small crystals, lumps, and granules, as well as in powder form. The Chrome Slag varies in colour from dark grey to light grey. Chrome Slag is odourless but can be dangerous when inhaled.

Table 2.1 Standard classification of Fly Ash (ASTM 618, 1994)

Component	**Class F**	**Class C**
$SiO_2 + Al_2O_3 + Fe_2O_3$, Min%	70	50
SO_3, Max%	5	5
Moisture Content, Max%	3	3
LOI, Max%	6	6
Available Alkalis, Max%	1.5	1.5

2.5 Physical Characteristics of Fly Ash and Chrome Slag

Fly Ash is spherical shape and is a fine material which ranges in size between 0.01µm and 100µm. Under the Unified Soil Classification System (USCS) (ASTM D2487, 2006), if eighty to ninety-nine percent of the Fly Ash by weight passes the required No. 200μm sieve, it is then classified as “fine grained” (Oppenshaw, 1992; Conn *et al.*, 1999; Mehta, 1998).

During the combustion process, high temperatures are reached and most of the minerals become fluid and then cools rapidly at the post-combustion zone, thus creating a glassy and transparent Fly Ash particle (Adriano *et al.*, 1980; Young, 1993). It was further found that the formation of spherical and amorphous Fly Ash particles is also created in the post-combustion zone (Rotaru *et al.*, 2010). Ojo noted that the fineness of the Fly Ash is dependable on the temperature of the coal combustion and the sizes of the pulverised coal that is introduced in the burners. Ojo further stated that the spherical shape of the Fly Ash is a result of the colling and solidifying process of the molten droplets of the coal residues during the post-combustion zone (Ojo, 2010). It was then further found that the Fly Ash, only in some cases, has a smooth hydrophilic surface and is prone to be highly porous (Bosch, 1990; Campbell, 1999; Iyer, 2002).

In evaluating the interaction between Fly Ash and an aqueous solution, all are dependent upon the particle size distribution and the surface area of the Fly Ash (Ojo, 2010). Mehta noted that this is an important characteristic to determine the reactivity of Fly Ash (Mehta, 1998).

Fly Ash is heterogeneous, consisting of glassy particles with various crystalline phases and a vitreous phase. Fly Ash that is self-cementing needs to have a high quantity of the vitreous phases and is thus an important characteristic (Rotaru *et al.*, 2010).

Fly Ash colour varies between tan and dark grey which is dependent on the chemicals and mineral constituents found in the Fly Ash after the coal combustion processes. The light colours is indicative of a high lime content while the dark grey colour is indicative of the amount of unburned coal content (FA FACTS, 2003; Mehta, 1998; Ayanda *et al.*, 2012).

Fly Ash has a large particle surface area when compared to its mass. The surface area of Fly Ash will increase as the particles sizes decreases. The smaller particles in Fly Ash are the particles that contain the potentially toxic elements (Oppenshaw, 1992).

Two important characteristics is identified for use of Fly Ash in concrete mixtures. One characteristic is the particle size. This is critical for cement and concrete industries as it determines the ability of the Fly Ash to fill voids and to determine an acceptable workability of a concrete mixture (Cooperative Research Centre for Coal in Sustainable Development (CCSD), 2007). The other characteristic is the fineness of the Fly Ash which contributes to the pozzolanic reaction (FA FACTS, 2003; Mehta, 1998; Rotura *et al.*, 2010).

The form on structure of a particle of Fly Ash is defined as the morphology (Oppenshaw, 1992). The morphology attributes to understand the physical properties as well as the leaching properties of the Fly Ash particles.

The raw material in the production of ferrochrome is chromite, which is chrome and iron oxides containing mineral. Chromite is used as lumpy ores or fine concentrates, which must be generally agglomerated to make them a usable charge for the furnace. The composition of ferrochrome Chrome Slag in the phase diagram is shown in Figure 5 ferrochrome Chrome Slag is acid.

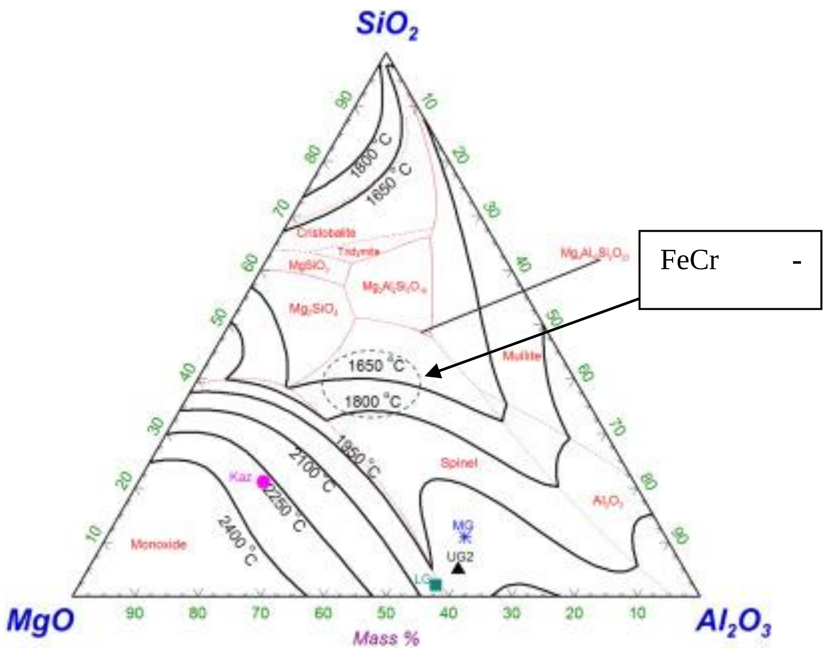


Figure 5: Phase Diagram MgO-Al_2O_3-SiO_2 (Niemela, 2007)

Chrome Slag products are granulated, from which crushed and screened Chrome Slag products are produced from air cooled lumpy Chrome Slag collected from various process phases (Niemela, 2007). Granulated Chrome Slag is a very homogenous product. The grain size is <6mm. A granule is tight and partly crystalline. Typically, the granulated Chrome Slag includes three different phases, namely:

1. Amorphous glass phase
2. Crystalline and zonal Fe-Mg-Cr-Al-spinels
3. Metal drops

A typical Chrome Slag process is shown in Figure 6.

The saleable products of Chrome Slag are the recovered alloy of 0 - 4 and 4 – 22mm. The crystallisation portion of lumpy Chrome Slag is higher due to slower air cooling than that of granulated Chrome Slag. The structure of the Chrome Slag is partly crystalline and partly glassy. Significant phases are namely:

1. Amorphous glass
2. Fe-Mg-Cr-Al-spinels
3. Forsterite
4. Mg-Al-silicate
5. Alloy.

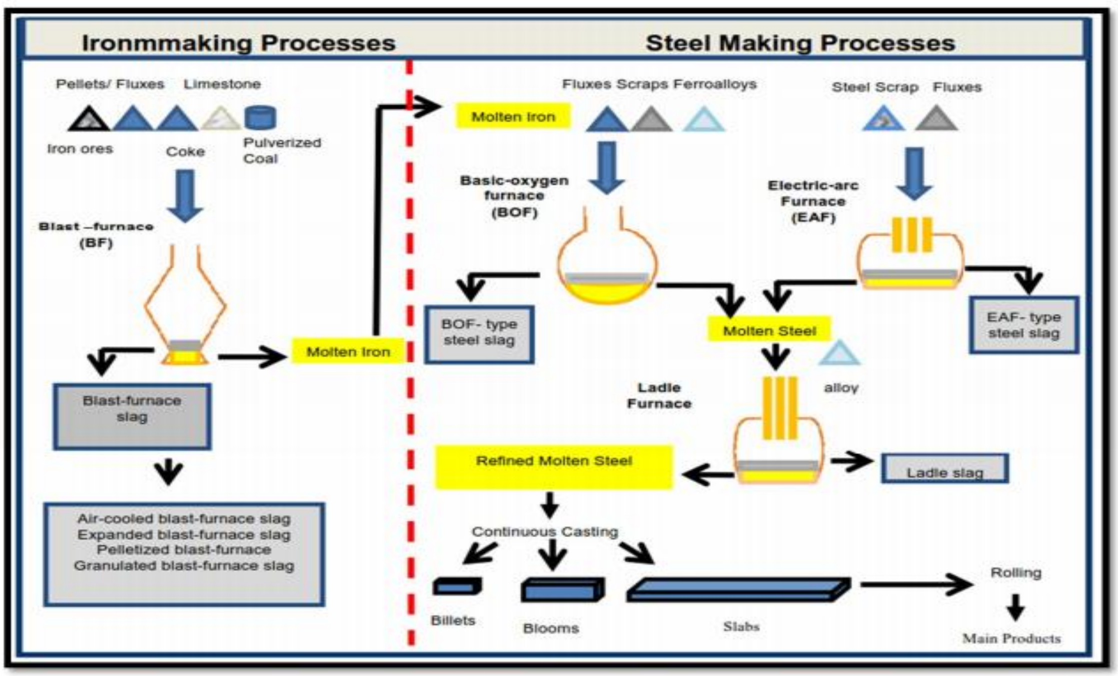


Figure 6: Typical Chrome Slag process

Ferrochrome Chrome Slag is available in a variety of forms, including small crystals, lumps, and granules, as well as in powder form. The Chrome Slag varies in colour from dark grey to light grey. Chrome Slag is odourless but can be dangerous when inhaled.

Chrome Slag aggregates are highly angular in shape and have a rough surface texture. Table 2.2 shows the typical physical properties of steel Chrome Slag.

Table 2.2: Typical physical properties of steel Chrome Slag

Property	Value
Specific Gravity >	3.2 - 3.6
Unit Weight, kg/m^3 (lb/ft^3)	1600 - 1920 (100 - 120)
Absorption	up to 3%

2.6 Chemical Composition of Fly Ash and Chrome Slag

The burning process or pre-treatment of the coal creates a variable chemical composition of the Fly Ash. Each Fly Ash discard area need to be individually characterised for each source that is to be used on a certain project (Oppenshaw, 1992). Fly Ash contains the following major elements: Silicon (Si), Aluminium (Al), Iron (Fe), Calcium (Ca), Carbon (C), Magnesium (Mg), Potassium (K), Sodium (Na), Sulphur (S), Titanium (Ti), Phosphorus (P), and Manganese (Mn). The elements named makes up the core of the Fly Ash and stays stable as it has not been volatised in the burning processes (Oppenshaw, 1992; Rotaru *et al.*, 2010; Reynold *et al.*, 2002). However, elements that do volatise during the combustion, attaches itself to the Fly Ash particles as the temperature cools in the flu gasses. These particles contribute to the increase in surface area concentrations and consists of possible toxic trace elements. Studies have indicated that major element composition is dependant of the Fly Ash particle size.

Volatile elements such as Cadmium (Cd), Zinc (Zn), Selenium (Se), Arsenic (As), Antimony (Sb), Molybdenum (Mo), Gallium (Ga), Lead (Pb), Vanadium (V) are explained by the vapour condensation mechanism, but element distribution within coal are important processes contributing to the inverse concentration dependence observed for higher boiling chemical species (Fischer *et al.*,1978).

Fly Ash is also enriched with S. The S content plays an important role in the pH value of Fly Ash, and ranges between 4.5 and 12.00. S is usually added to improve collective efficiency of the precipitators, which is the most popular additive used in South Africa (Ojo, 2010). pH appears to control the desorption of metals from the surface of Fly Ash surfaces. Desorption increases as pH decreases (Oppenshaw,1992; Gitari *et al.*, 2009; Reynolds *et al.*, 2002).

As stated in this study, Fly Ash is pozzolanic in nature as it contains siliceous and aluminous materials. In the natural state of Fly Ash, it is a stable mineral which has no capacity to lime or cement. Once water is added to the mineral, it reacts with hydroxide and forms cementitious properties (Conn *et al.*, 1999).

Pozzolans are then defined as a composite system formed of calcium (CaO), silica (SiO_2), and Aluminia (Al_2O_3) that constitute a solid liquid disperse system, interacting in certain conditions and transforming themselves into solid and strong materials (Molharta *et al.*, 1996).

The components of Fly Ash vary considerably due to the various process followed by the different entities in coal combustion, but Fly Ash still contain high amounts of silicon dioxide and calcium oxide (Rotaru *et al.*, 2010; Amar Ash Tech Enterprises (AATE), 2013). Oppenshaw noted that Fly Ash vary considerably from different sources, but generalisation can still be viewed according to size distribution, morphology, permeability, surface area, hydraulic conductivity, and density (Oppenshaw, 1992).

Chrome Slag is a waste material generated in purifying metals, their casting and alloying. It is in these processes that Chrome Slag does show various chemical compositions.

Jian-shiuh *et al, 2016*, Ivan *et al, 2002*, and Bouwmeester *et al, 2008*, stated that in the composition of Chrome Slag, there is a significant share of free calcium and magnesium oxides. Ivan *et al, 2002*, has further shown that the presence of free calcium oxide causes another adverse property of Chrome Slag, namely the appearance of a white powder in the form of sediment. Niemela *et al*, *2007*, identified that the main components of Chrome Slag are Fe, CaO, and SiO_2, which contributes between 75% and 85% of Chrome Slag. Further components of Chrome Slag are made up of FeCr, Al_2O_3, and MgO. Non-ferrous Chrome Slags also contain a certain number of toxic elements, such as; Pb, Zn, As, and Cd. Table 2.3 shows the typical Chrome Slag chemical composition.

Table 2.3: Typical steel Chrome Slag chemical composition

Constituent	**Composition (%)**
CaO	40 - 52
SiO_2	10 - 19
FeO	10 - 40 (70 - 80% FeO, 20 - 30% Fe2O3)
MnO	5 - 8
MgO	5 - 10
Al_2O_3	1 - 3
P_2O_5	0.5 - 1
S	< 0.1

Concerns of stability of Chrome Slag is the expansion of the material, which is attributed to the hydration of free lime in the form of CaO and MgO. Chrome Slag weathering in atmospheric conditions is considered one of the most appropriate methods of eliminating this adverse property. The purpose of aging was to allow potential hydration and its associated expansion to take place prior to use in asphalt mixes (Jian-shiuh *et al, 2016*, Ivana *et al, 2002*, Bouwmeester *et al, 2008*). However, Ivana *et al, 2002*, further identifying the sediment, concludes that the free CaO from leachate is bound with water creating Calcium Hydroxide $Ca(OH)_2$. This, when exposed to atmospheric conditions, reacts with carbon dioxide CO_2 and creates calcium carbonate $CaCO_3$. It settles down in the form of a white powder and cannot be prevented by Chrome Slag weathering. In freeze thaw conditions, Ivana *et al, 2002*, found that these reactions render large damage to pavement structures.

The CaO and MgO are not completely combined in Chrome Slags. Emery *et al, 1982*, noted that hydration of free lime and MgO in contact with moisture is largely responsible for the expansiveness of most Chrome Slags. The free lime hydrates rapidly and can cause volume changes in a few weeks. MgO hydrates more slowly and contributes to the long-term expansion that may take several years to develop in the field.

2.7 Ultra-thin asphalt mixes

2.7.1 Fly Ash as Filler

A number of studies have been made on the use of different types of fillers in various types of paving mixes. Although filler particles are small in size, fillers have a significant effect on the characteristics and performance of an asphalt mixture (Zulkati *et al*, 2011).

The inclusion of Fly Ash as a filler was found to increase the stiffness of the mastic (Sabolev *et al*; 2013). The increase in stiffness is theorised that, when the inter-particle distance is large compared with the mean particle size, the particle movements are so slow that its kinetic energy can be neglected and there is no slip relative to the particle surface. Therefore, Fly Ash as a particle filler hinders the matrix flow thereby increasing the stiffness.

Compared to cement as filler, the Fly Ash component as filler showed a significant effect on the characteristics and performance of asphalt mixture. Good packing of coarse aggregate, fine aggregate, and filler provides a strong backbone for the mixture. High filler concentrations resulted in a stronger pavement mixture, which attributed to a better asphalt cohesively and improved internal stability. However, it has been found that an excessive amount of filler concentration may weaken the mixture by increasing the volume of bitumen needed to coat the aggregate (Kandhal *et al*, 1998). This intern will affect the optimum bitumen content, Marshall stability, tensile strength, and the retaining stability of the mixes.

A study completed by Kar *et al*, 2014 was an attempt to explore the use of Fly Ash as a suitable filler, i.e.; material passing the 0,075mm sieve.

The study used three (3) types of fillers, namely:

1. Cement
2. Stone dust
3. Fly Ash

Each type of filler was dealt with separately and prepared with different bitumen contents as to obtain comparison sample results. The mixtures with cement and stone dust were considered to be control specimens. The mixtures were subdued to a full Marshall Test.

As with the study by Priyanka *et al, 2015* and Mistry *et al, 2016*, it was determined that the addition of 4% of Fly Ash in a full Marshall Test comparing various binders and contents, showed that all mixes satisfied the specific requirements. Both research studies found optimum bitumen content varied between 4% and 5%, although they concluded that 4% can be adopted as a standard with asphalt mix using Fly Ash as a filler (Priyanka *et al*, 2015; Mistry *et al*, 2016). The Marshall stability, Figure 7, showed an increase in all 3 specimens to about 5% and then decreased. The stability was always higher for the cement followed by the stone dust and Fly Ash. Table 2.4 shows the results of the study when compared to full Marshall testing requirements.

The Indirect Tensile Test (ITT) was completed at different temperatures. The test revealed that Fly Ash showed a lower tensile strength compared to other fillers.

Warden *et al, 2017*, determined that Fly Ash was a suitable filler material in terms of mixing, placing and compaction, stability, resistance to water damage and flexibility (Ali.ani, 2017). The same findings were observed by Topkin and Xie *et al, 2012*, where the addition of Fly Ash as a filler provided stability, improved asphalt hardening, moisture and freeze-thaw resistance, rutting resistance, fatigue life, density and tensile strength (Topkin, 2008; Xie *et al*, 2012). The studies were summarised by Sabolev *et al, 2013*, stating the Fly Ash in asphalt bitumen can be considered as a filler in a viscoelastic matrix, thus creating a dense mix referred to as a "mastic" (Sabolev *et al*, 2013).

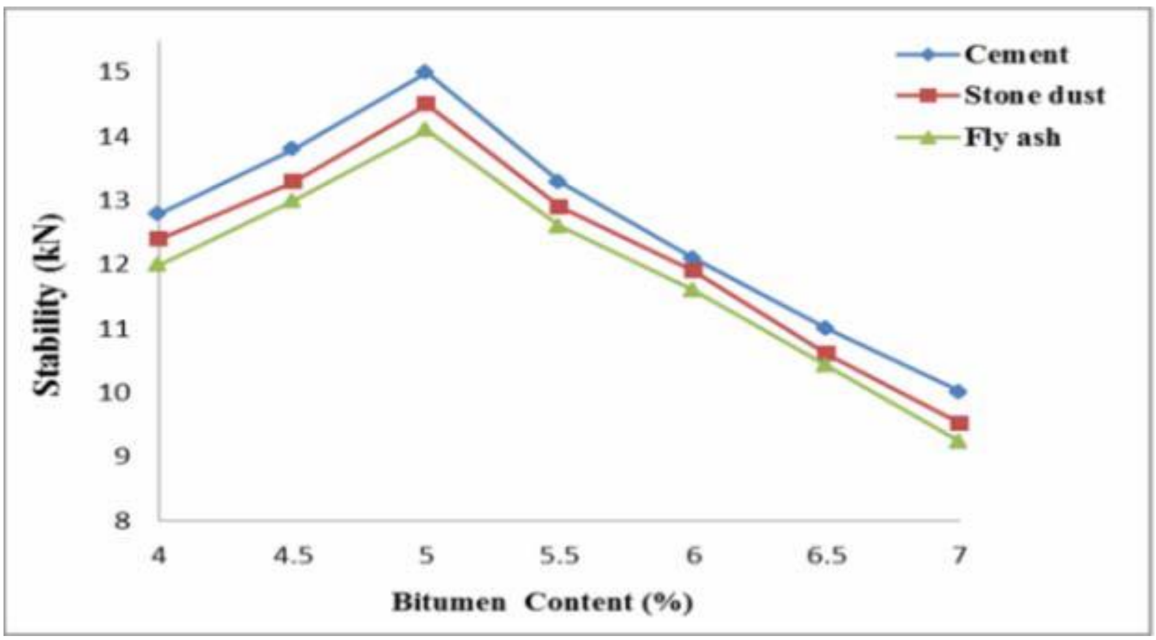


Figure 7: Variation of Marshall stability value with bitumen content for mixes with different fillers (Kar *et al*., 2014).

Table 2.4: Marshall Characteristics of bituminous mixes at optimum bitumen content (Kar *et al*., 2014).

Parameter \ Filler type	Cement	Stone dust	Fly ash
OBC (%)	5	5	5.2
Stability (kN)	15	14.5	14.1
Flow value (mm)	2.3	2.9	3.4
Air voids (%)	4.7	4.41	4.0
Unit weight (kN/m^3)	25.60	25.45	25.10
VMA (%)	17.20	16.83	16.20
VFB (%)	72	74	75

Very limited studies have been done on dense graded mixes with Fly Ash as filler, although research studies have showed that Fly Ash can effectively be used as filler in place of most commonly used fillers and showed good resistance to moisture-induced damages (Kar *et al*, 2014). Fly Ash will meet the mineral specification requirements for gradation, organic impurities, and plasticity. Fly Ash is hydrophobic, reducing the potential for asphalt stripping. The presences of lime will also aid the reduction of asphalt stripping.

Sobolev completed a study with the two classified Fly Ashes as a filler. The two types of Fly Ashes used, namely:

1. Class C
2. Class F

As per Kar *et al.*, 2014, Sobolev further introduced extended testing, namely:

1. Rheological study
2. Rolling thin film oven test (RTFO)
3. Bending Beam Rheometer (BBR)
4. Compaction of Hot Mix Asphalt (HMA)

A reference sample was also produced with non-Fly Ash for comparison. It was found that the addition of 5% of Fly Ash in Class C showed a lower result in the RTFO test than when compared to the reference samples as seen in Figure 8. This indicated that the binder could result in the aging protection effect of the Fly Ash. The BBR was used to quantify the change in stiffness and measure the relaxing coefficient of a binder/mastic at low temperatures corresponding to their performance grade.

The calculated values showed that Fly Ash reduces the low temperature stiffness. Class F showed the most reduction. The result indicated that low temperature stiffening effect, due to oxidation aging, is reduced by the addition of Fly Ash. This is evident in Figure 9.

Class F further showed the superiority to improve thermal relaxation of the mastics. As per previous studies, the maximum addition which displayed the optimum improvement was at 5% as indicated in Figure 10. The gyratory results revealed that Fly Ash can be successfully used in asphalt without compromising the air void structure, extending or reducing the binder used in asphalt as shown in Figure 11.

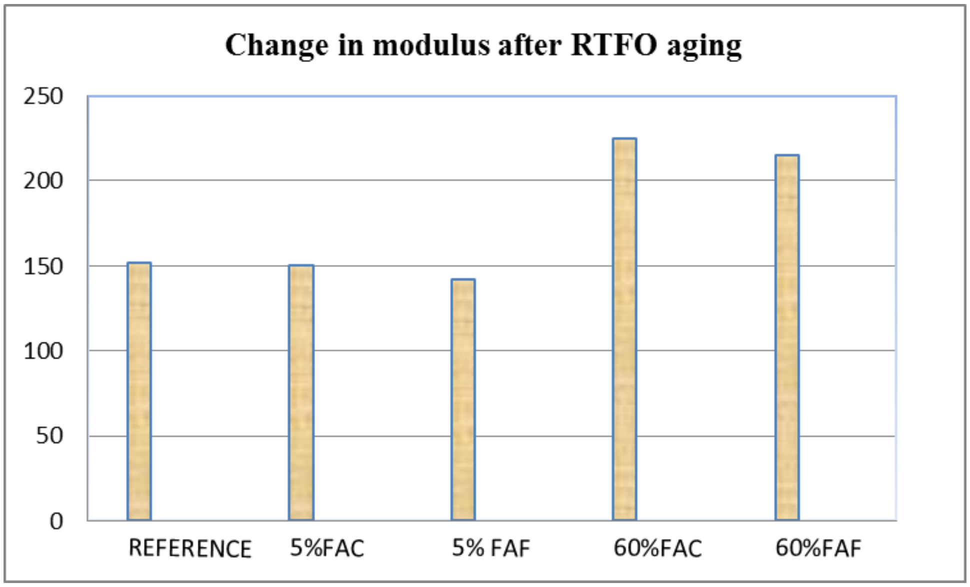


Figure 8: Change in modulus after laboratory aging for mastics with Fly Ash (Sobolev, 2013).

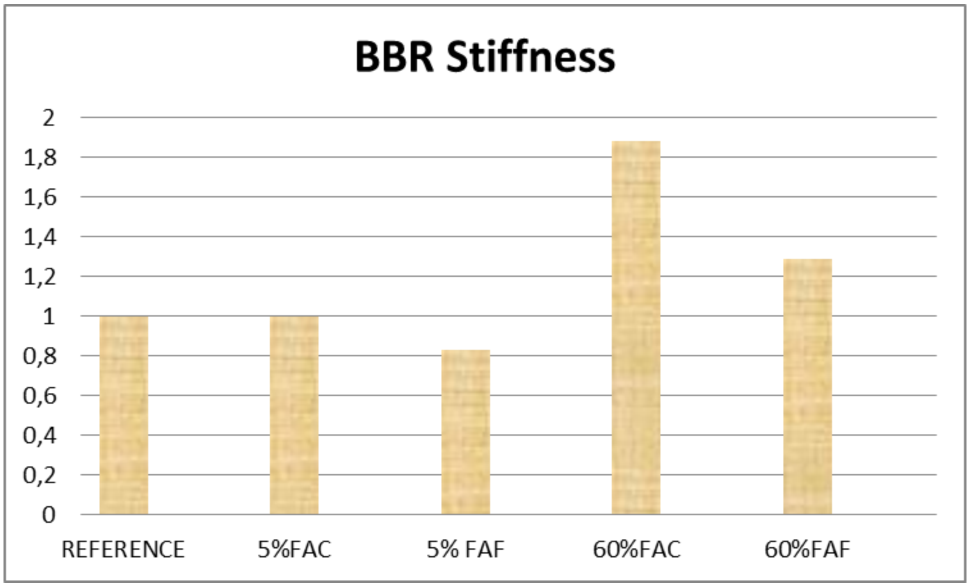


Figure 9: Relative low temperture stiffness of aged mastics with Fly Ash (Sobolev, 2013).

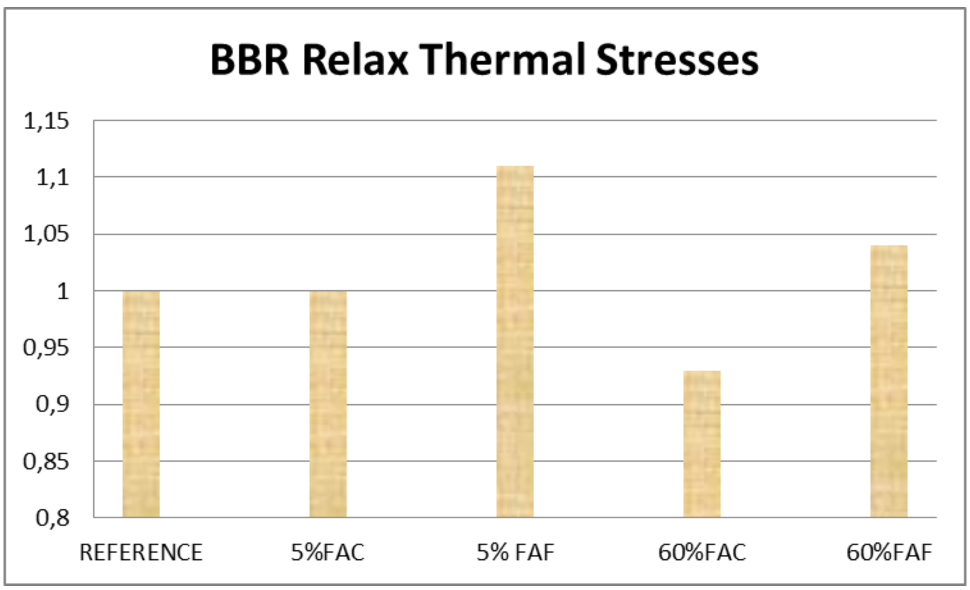


Figure 10: Relative values for relax thermal stresses for mastics with Fly Ash (Sobolev, 2013).

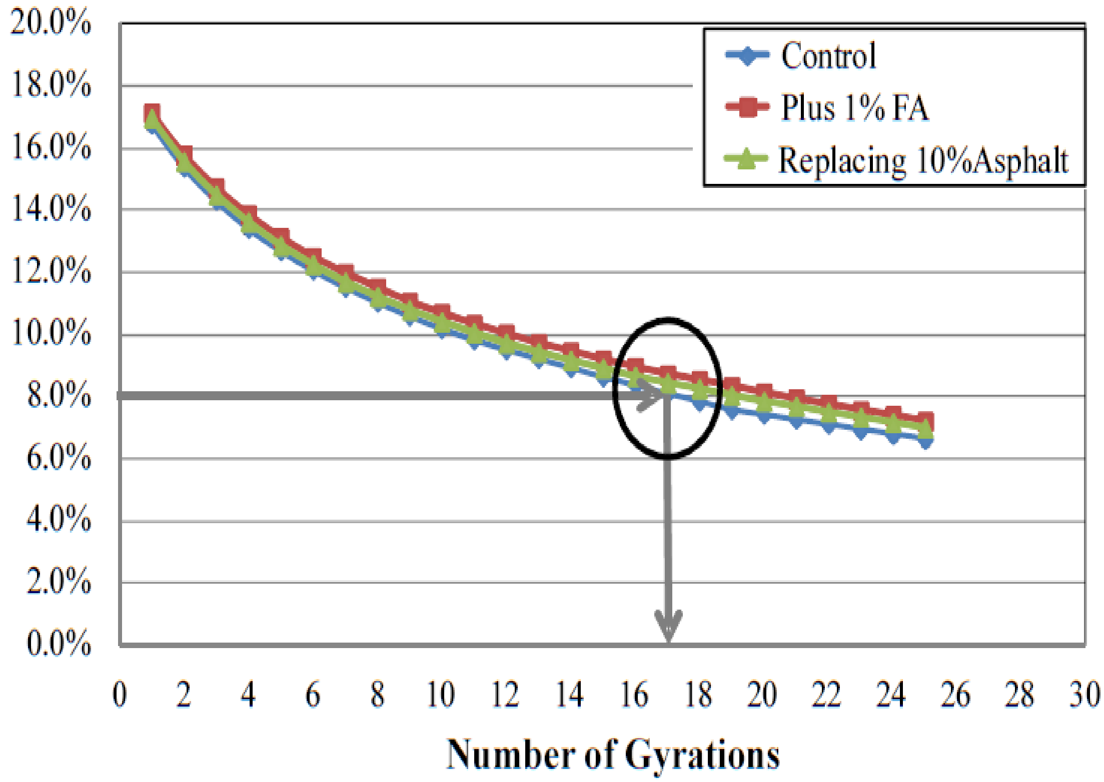


Figure 11: Gyratory results at compacted air voids (Sobolev, 2013).

2.7.2 Chrome Slag

The overall performance of an asphalt mix is dependent on, amongst other things, the properties of the constituent materials, which include aggregate, binder, and filler. The aggregate plays an important role in determining the overall performance of the asphalt mixes in pavements. Chrome Slag falls in a category aggregate named "manufactured aggregate" due to it being a by-product of an industrial process. The manufactured aggregate can also be crushed and serves the purpose in a civil engineering environment.

Chrome Slag has shown to be successfully utilised in asphalt mixes as a Natural Aggregate replacement. Concerns over expansion have been noted but eliminating this property was mostly due to natural weathering of the Chrome Slag in atmospheric conditions for a certain period of time. The purpose of aging was to allow potential hydration and its associated expansion to take place prior to use in asphalt mixes.

Emery *et al, 1982* stated that sufficient hydration needs to take place before it is used in pavement construction. However, it was found that weathering is not the critical criterion in the utilisation of Chrome Slag in asphalt layers if smaller fractions are used with a grain size of between 13 and

13.2mm. Bouwmeester *et al, 2008* indicated that minimum weathering time in South Africa is 3 months of a moisture content exceeding 6%. Afterwards, volumetric expansion should be tested. Emery stated it as being critical that steel Chrome Slags be checked for potential expansion, since even aging for long periods in large dumps does not guarantee the elimination of expansive behaviour.

Barisic *et al, 2010*, Jian-shiuh *et al, 2016* has shown that in the process of production of asphalt mixture, the aggregate undergoes washing and screening phases, as well as drying, ensuring instantaneous hydration and expansion of Chrome Slag. Pre-coating of the Chrome Slag aggregate in a binder film will limit the potential of Chrome Slag expansion.

Although negative properties of free lime have been discussed, it must be noted that free lime also has a positive impact in the application of Chrome Slag in asphalt mixes.

Shen *et al, 2009* stated that the presence of free lime increases the resistance to stripping, increases the adhesion between aggregate grains and binder, therefore, contributing to higher durability of road surface. Juin-shuih *et al, 2016* further demonstrated this with asphalt mix designs and subjected them to the Lottman Test. Using Natural Aggregate as reference, it was revealed that the conventional mixture showed the highest water damage, while Chrome Slag mixtures were the most robust as indicated in Figure 12. Bouwmeester *et al, 2008*, however, noted that water absorption of the Chrome Slag is relatively high, which leads to a higher binder content demand. However, there are no fissures in Chrome Slag as in some Natural Aggregates with high absorption, thus the selective absorption of the bitumen is not considered to be a problem.

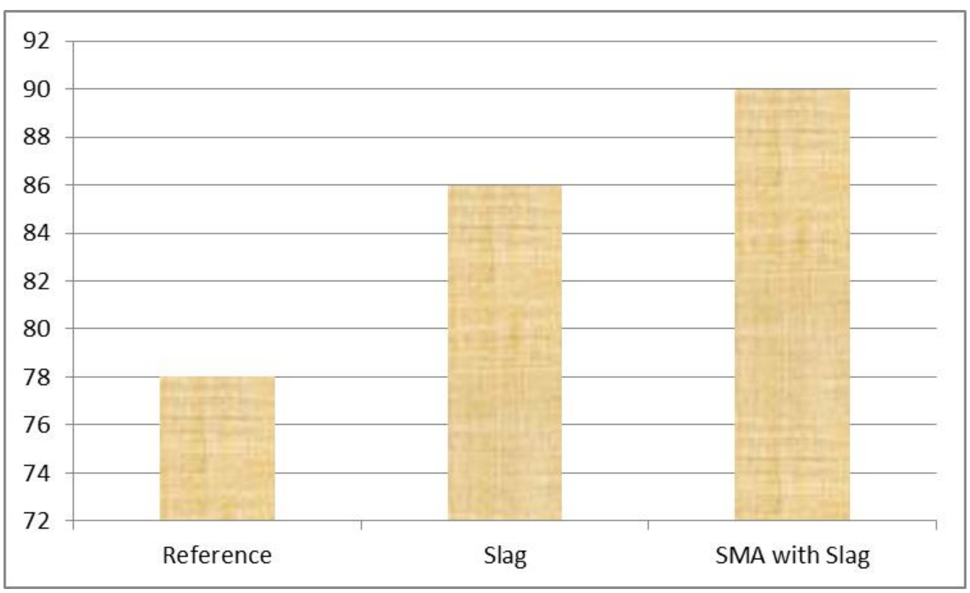


Figure 12: Moisture-induced damage results of Chrome Slag and control mixes (Shen, 2009).

Barisic *et al, 2010,* Bouwmeester *et al, 2008*, Juin-shuih *et al, 2016*, have shown that Chrome Slag has a better physical property than that of Natural Aggregates, namely:

1. Chrome Slag has sharp edges; the cubical shape is beneficial in providing micro texture and interlocking mechanism.
2. Chrome Slag retains heat longer than conventional aggregate, aiding in compaction.
3. Contributes to better adhesiveness of aggregate binder and grain.
4. Contributes to the increase in coefficient of internal friction of bituminous overlay more than any other Natural Aggregate.
5. Contributes to the increase of shear tightness and resistance to appearance of rut in the asphalt mixture.

Juin-shuih *et al, 2016,* further noted from the summary that Chrome Slag will have a higher resistance to rut due to its highly angular shape and rough surface texture, therefore creating a good stone-on-stone interlocking mechanism.

Bouwmeester *et al, 2008*, completed various standard tests for asphalt in South Africa, namely:

1. Marshall Stability and Flow, which showed the asphalt mix was stable and had some flexibility
2. The Indirect Tensile Strength (ITS) showed a significant increase when compared to South African standards.
3. The conclusion from the testing showed that the mixture was ideally suited for rut resistance.

Juin-shuih *et al, 2016*, also revealed a tremendous increase in ITS but similarly demonstrated that the mixtures showed an increase in resilient modulus, which indicated that the Chrome Slag had a good adhesion to bitumen as indicated in Figure 13. Bouwmeetser further explained that the implementation of gyratory testing on the samples exceeded the South African standard, showing that the mix will not easily compact under traffic conditions. Wheel tracking tests indicated the mix had a better deformation resistance when compared to some Natural Aggregates and in some instances SMA's.

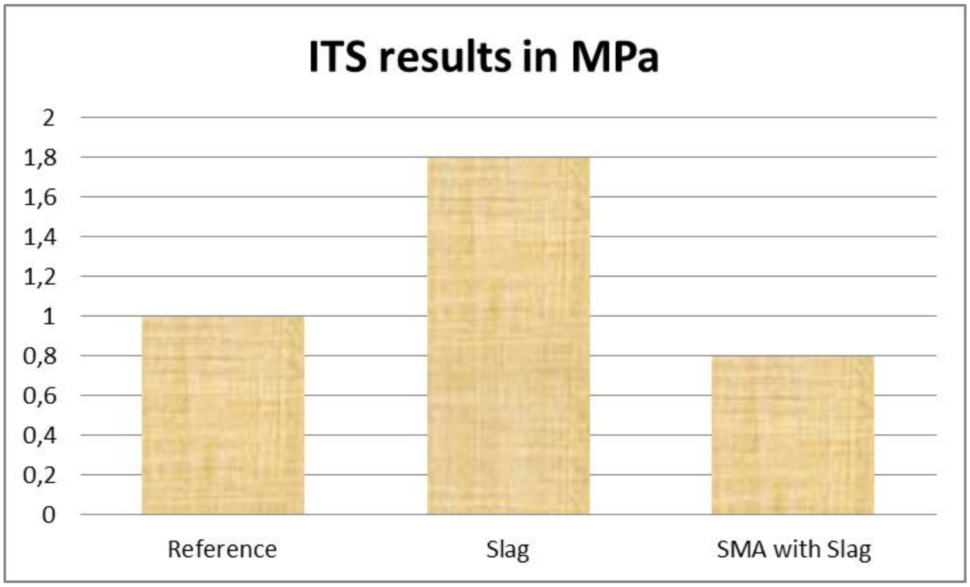


Figure 13: ITS results indicative of increased resilient modulus (Shen, 2009).

Studies have followed a similar procedure during asphalt mix designs using Chrome Slag and Fly Ash as a filler. Almost all studies have noted the anomaly of the expansion problems related to Chrome Slag and how it can be avoided by exposing the Chrome Slag for a period of time to atmospheric conditions.

Mikoc *et al, 2010,* completed a study on the influence of Chrome Slag, Fly Ash, and silica fume on the mechanical and physical properties of asphalt. Using the traditional testing method, a full Marshall testing procedure was followed.

The only difference in this particular study is that partial replacements of Natural Aggregate and filler was completed. Only in certain sieve sizes were the Natural Aggregate replaced by Chrome Slag. During the duration of the test, four (4) samples were prepared where the first (1) sample was the reference sample. The other three (3) were completed with a certain percentage (%) of Natural Aggregate removed and replaced by Chrome Slag. The same was done for the removal and addition of the filler to the samples. In this case the filler was:

1. Stone Flour
2. Fly Ash
3. Silica Fume

The bitumen used in the study was a standard 50/70 penetration grade.

The chemical composition in the study showed that the Fly Ash was classified as a Class F— as shown in the above literature review, the mixtures have an increased stability.

During the study, the following difference between Chrome Slag and Natural Aggregate was recorded:

1. Chrome Slag has a high particle density.
2. Chrome Slag will display greater stability.
3. Chrome Slag will display greater stiffness values.

Numerous studies during the mixing process of aggregate and bitumen do follow similar patterns to simulate the oxidation process at batch plants, otherwise known as short-term aging. Miroslav *et al, 2008,* and Paige-green *et al, 2007,* both pre-heated the aggregates but Miroslav left the heated aggregates in the chamber for 8hrs while Paige-Green followed the Superpave aging method after the mixture was completed as described by Von Quintus *et al.*, 1991.

Mikoc *et al, 2010,* mixed bitumen with the aggregate after the 8hr waiting period and heated the sample to a temperature of 150°C, then left the sample for 3 to 5hrs. Paige-green mixed in the bitumen after the aggregate was pre-heated and left the sample before compaction for 4 hours. Testing proceeded according to the required Marshall specifications. Both researchers tried to simulate short-term ageing with different methods.

The results were conclusive of the following:

1. The filler replacement with waste showed a higher stability than the control samples.
2. The addition of Chrome Slag increased the density of the asphalt including the stability of mixture.
3. The sample with the increased voids in aggregate was the sample with the Chrome Slag replacement. This is also in contrast with Bouwmeester *et al, 2008,* stating that Chrome Slag will absorb more bitumen, and this usually indicates that voids will decrease.
4. All gradings completed conform to the required specifications.
5. The replacement of aggregates and fillers from waste materials can be achieved through saving in the production of asphalt mixtures, which in turn contributes to environmental protection.

Paige-green *et al, 2007,* noted that aggregate plays an important role in determining the overall performance of asphalt mixes in pavements. As stated, Bouwmeester *et al, 2008,* noted that Chrome Slag properties are of a better quality than Natural Aggregates. Chrome Slag conforms to all the properties that are significant to the performance of a HMA.

Paige-green stated that aggregate properties must include:

1. Hardness/toughness
2. Durability
3. Shape and surface texture

4. Absorption and cleanliness

Niemela *et al, 2007*, completed a study comparing Chrome Slag to granite materials for road construction use. The comparison is summarised in Table 2.5. The study further indicated that Chrome Slag products are excellent materials for road construction, because the removal of the earth is less and the need of new material for roadwork is 30 – 50% smaller compared to natural rock.

Table 2.5: Properties of materials for the use in road construction (Niemela *et al*, 2007)

Character	**Chrome Slag**	**Granite (Crushed Stone)**
Apparent Density, Mg/m^3	1,40 - 1,70	1,5
Apparent Desnity of Structure, Mg/m^3	1,65 - 1,80	2,2
E-Modul, static, MN/m^2	100 - 150	280 - 350
Thermal Conductivity, m/s	0,5 - 0,7	2
Los Angeles value, %	18	

Niemela *et al, 2007*, further stated that Chrome Slag is hard and stable and is well suited for demanding structures. The study concluded that the Chrome Slag products can be used for road construction in the filtering and supporting layers, as well as aggregate in asphalt. The use of Chrome Slag products will also speed up the construction, thus making the Chrome Slag products more economical (Niemela *et a*l, 2007).

2.8 Environmental Impact

Mankind is becoming increasingly concerned about the impact of his actions on the environment. Ferrochrome producers are no exception, particularly in the view of the effect of hexavalent chromium release into the atmosphere, water, and soil (Gericke W.,1995).

Various organizations, as indicated in this study, have encourage the use of Fly Ash mostly in construction due to the strength and cost capabilities (Oppenshaw, 1992).

Environmental hazards are a major concern in relation to Fly Ash as the particles causes air, water, and soil pollution. One of the greatest concerns is the toxic element that can subsequently contaminate the groundwater. Leaching tests, is a method of showing what toxic elements will be a concern when using Fly Ash. Studies have indicated that Fly Ash used for soil stabilisation and concrete works have minimal leaching toxic elements (Oppenshaw, 1992).

South Africa disposes of Fly Ash in the form of slurries into settling ponds. This results in loss of huge areas of land that could be utilised for agricultural purposes (Ojo, 2010).

During rains, numerous salts and metallic content in the slurry can leach into the groundwater and contaminate it. There is a second method used in South Africa for dumping Fly Ash, called the dry method, which entails that Fly Ash is conditioned with wastewater and is conveyed to a disposal site where it is compacted and conditioned further with brine water (Gitari *et al.*, 2009).
Fly Ash undergoes dissolution on contact with aqueous solution, including highly saline effluents or brines. Release of certain species existing in Fly Ash may lead to cleaner effluents or to significant release of pollutants over time (Gitari *et al.*, 2009). It is thus important to understand the mobility and release patterns of the species of environmental concern once the Fly Ash is disposed.
Fly Ash that is used in construction activities have been proved to be advantageous environmental benefits:

1. Fly Ash concrete requires less energy and water to produce and has lower greenhouse gas emissions
2. Reduction in coal combustion products such as landfill sites
3. Conservation of other natural materials and resources
4. Environmental Protection Agency (EPA) (EPA, 1999) have indicated on numerous reports that the use of Fly Ash in construction is environmentally friendly and the EPA is encouraging the use of Fly Ash. A legislation by Resource Conservation and Recovery Act (RCRA) protects Fly Ash from being used as a hazardous waste. The use of Fly Ash as studied by American Road and Transportation Builders Association Transportation Development Foundation (ARTB-TDF) (ARTB-TDF, 2011) have indicated that Fly Ash has been used successfully in transportation projects in Europe. It was concluded that Fly Ash is as an important component for most high-performance designs in Europe (ARTB-TDF, 2011).

5. Fly Ash has proven itself as a sustainable alternative to non-renewable primary aggregates. Fly Ash has become a recognisable environmentally friendly benefit worldwide in the construction industry. Using Fly Ash, South Africa saves one ton of CO_2 emissions (National Inventory, 2001). The use of Fly Ash in South Africa has saved in excess of 6 million tons of greenhouse gas emissions (Ash Resources, 2012). South Africa produces millions of tons of Fly Ash per annum and only 6% is utilized (National

Inventory, 2001). This still raises a major concern on the leaching of the elements from the dumps not being utilized.

Hasset completed a study (Hasset *et al.*, 2001) to evaluate coal Fly Ash in typical soil stabilisation applications. The study involved 3 types of investigations:

1. Laboratory evaluations of Coal Fly Ash composition.
2. Evaluation of the runoff quality
3. Leaching of full-scale soil stabilisation projects

Also shown in the Oppenshaw (1992), studies, the following list of parameters were evaluated: antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadium (Cd), chromium (Cr), cobalt (Co), iron (Fe), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), thallium (Tl), vanadium (V), zinc (Zn), and sulphate. The reactions frequently take extended periods of time, therefore long-term laboratory leaching procedures do facilitate the potential field performances of the Fly Ashes. The studies revealed the following:

1. Fly Ash – soil leachants do not exceed limits of concern by regulatory communities for drinking water and groundwater.
2. Concentrations of the elements in long-term leachants have decreased.

One of the main environmental benefits by using Fly Ash to replace ordinary Portland Cement:

1. Benefit of recycling of Fly Ash.
2. Reduces emissions and energy to produce cement.
3. Reduces amount of water required in concrete mixing process.

The EPA stated in March 1999, "*No significant risks to human health and environment were identified or believed to exist for any beneficial uses of these wastes, with possible exception of minefill and agricultural use…*" (EPA, 1999).

Fly Ash landfill sites are carefully selected. Mostly the landfill sites are placed away from flood plains and groundwater to prevent water intrusion which could dissolve some trace elements of the Fly Ash dumpsites.

Electric Power Research Institute (EPRI) (EPRI, 1998) also studied the health and environmental effects of Fly Ash used in various applications over different regions in the USA. The results concluded that the health risks from ingesting Fly Ash were generally miniscule, therefore trace elements from Coal Fly Ash do not pose any public health risks (EPRI, 1998). Fly Ash consists chiefly of common compounds found in the earth. Effects from trace metal leaching and inhalation of Fly Ash are both localised and minimal (EPRI, 1998).

Questions have been raised regarding the use of steel Chrome Slag because of its elevated metal content and the associated potential for impact on human health and the environment. These concerns focus on exposures to humans, who may come into contact with Chrome Slag or are exposed to metals that may leach from Chrome Slag into drinking or surface water. In addition, concerns regarding ecological hazards resulting from pH fluctuations and metal leaching to surface water have been expressed (Proctor *et al*, 2000).

Various studies have been completed on the characteristics of Chrome Slag. Crucial main components have been identified that could have an impact on the environment. Niemela *et al, 2007,* Reuter *et al*, *2004,* and Hattingh *et al*, *2003,* have all found toxic elements, which are sources of environment contamination. Hattingh *et al, 2003,* has also noted that due to Chrome Slag has a high hazard potential, it can be environmentally acceptable if the Chrome Slag is to be re-used in certain applications.

Chrome Slag is regarded as harmless in terms of the International Agency for Research on Cancer (IARC) classifications, as the chromium is predominantly present in ferrochrome Chrome Slags s Cr (III). In south Africa, it can be consigned to a Class II landfill for non-hazardous substances with less onerous conditions than for a Class I landfill (Gericke WA, 1995).

Reuter *et al*, *2004,* has concluded that Chrome Slag contains the following impurities: As, Pb, Cd, Co, Cr, or Ni. These elements do leach from Chrome Slag, therefore environmental hazards could not be excluded. Proctor *et al, 2000,* further produced elements by completing acidic and neutral leach testing to determine mobility of metals from Chrome Slag under toxicity characteristic leaching procedure for acidic conditions and ASTM distilled water leach test for mobility of Chrome Slag in neutral conditions. The elements found are similar to Reuter *et al, 2004,* but Proctor *et al*, *2000,* further found that the primary constituents in each Chrome Slag type are aluminium, calcium, iron, magnesium, manganese, phosphate, silicon, and sulphur, while the elements found by Reuter *et al*, *2004,* has been classified as minor constituents by Proctor *et al*, *2000*.

Environmental studies developed during the last few decades inform us that utilisation of Chrome Slag has a long history. Many relationships were found between the application of Chrome Slag and its link to the smelting process. As Chrome Slags have more or less a similarity to natural stones, they can have the same applications in most of the fields, especially in civil engineering. Chrome Slags are chemically very stable and meet the main European Norm (EN) requirements. Column testing has showed that the Chrome Slag fulfils the dumping ground requirements in terms of both the most important components of Chrome Slag and other tested metals (Niemela *et al*, *2007*, Reuter *et al*,*2004*). This contrasts with the study completed by Hattingh *et al, 2003,* on South African dumps where the study concluded that potential elements are hazardous to the environment and proper detailed designed dumpsites need to be designed for Chrome Slag in which in this case has not happened. The study concluded that Chrome Slag found in South Africa has a rating of Class II, indicating high hazard (Hattingh *et al*, 2003).

This does show that the mineralogy of solid material is important when properties and environmental aspects of material are involved. Mineralogy and microstructure of Chrome Slag products do differ and this all boils down to production facilities.

Overall studies have confirmed that both Fly Ash and Chrome Slag, if used and managed properly, are not hazardous to the environment. Techniques have been developed by using by-products in solidification/stabilisation; therefore, the chance of pollution is negligible.

2.8.1 Leaching

Leaching is a process by which inorganic or organic contaminants are released from a solid phase into water phase under influence of mineral dissolution, desorption, and complexation processes affected by pH values.

Fly Ash in a leachant solution is highly variable and, in some cases, have been found in some instances to be higher than the United States Environmental Protection Agency (USEPA) drinking water levels (Oppenshaw, 1992). Comparable studies completed in South Africa have shown that several Fly Ash and Chrome Slag dumps are to the standard in quality of water which was fit for human consumption (Tau, 2005, Hattingh, 2003).

In many respects, leaching behaviour as reflected by the pH dependence leaching test and related characterisation leaching tests provides a better means of assessing environmental impact than analysis of total composition.

The leach sample comparison completed by Proctor *et al*, *2000,* was between soil and various types of Chrome Slag. The comparison with soil was deemed appropriate because naturally occurring levels of metals in soil are generally not considered to pose an environmental concern. From the various types of Chrome Slag, few specimens showed concentrations that are statistically more than background concentrations. See Table 2.6. The leach results indicated that none of the various types of Chrome Slags exceed the United States Environmental Protection Agency (USEPA) standards for determining whether the Chrome Slag is characteristically hazardous. See Table 2.7. Proctor *et al*, *2000,* found that the results indicated that the metals were very tightly bound and not released from the matrix, even under acidic conditions which generally render metals more mobile. The conclusion made was that Chrome Slag is less likely to impact groundwater above drinking water standards. This is in contrast with Hattingh *et al, 2003,* as the study showed that the Chrome Slag minerals exceeded the allowed acceptable risk level as implemented by Department of Water and Forestry (DWAF) in 1998 (Hattingh *et al*, 2003). This is shown in Table 2.8.

The studies have concluded that the potential for human and environmental risks should be evaluated separately by the Chrome Slag type produced.

Leach Testing will confirm any environmental concerns when the by-products are used for any road construction practices.

Table 2.6: Comparison of Steel Industry Chrome Slag Metal Concentrations to Metal Concentrations in U.S. Soils (Proctor *et al*, 2000)

Metal	U.S. Background		Slag Concentrations Arithmic mean (mg/kg)			Slag Concentrations SD (mg/kg)			Above background		
	Mean (mg/kg)	SD (mg/kg)	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF
Al	70995	80375	41245	23841	35009	5781	29845	11693	No	No	No
As	7,2	6,8	1,3	ND	1,9	3,5	ND	1,1	No	ND	No
Cr	54	57	132	1271	3046	226	391	1373	Yes	Yes	Yes
Pb	19	13	3,6	50	28	9,1	89	43	No	No	No
Mn	555	749	32853	39400	4833	4833	12321	7712	Yes	Yes	Yes
Hg	0,09	0,1	0,07	0,04	ND	ND	0,07	0,04	ND	No	No
Ni	19	19	1,4	4,9	30	0,9	2,5	47	No	No	Yes
Se	555	749	3,9	15	18	1,6	7,4	5,2	Yes	Yes	Yes
V	81	78	992	513	90	90	318	248	No	Yes	Yes
Zn	60	45	20	46	165	37	39	148	No	No	Yes

ND = Not Detected
BF = Blast Furnace Slag
BOF = Basic Oxygen Furnace Slag
EAF = Electric Arc Furnace Slag
Standard Deviation = SD

Table 2.7: Comparison of TCLP Chrome Slag Leachage Concentrations to TCLP Criteria (Proctor *et al*, 2000)

Metal	**TCLP Criterion (mg/L)**	**TCLP Leachage**			**Exeed Criterion**		
		BF	**BOF**	**EAF**	**BF**	**BOF**	**EAF**
As	5	0,0048	0,0054	0,011	No	No	No
Ba	100	1,2	0,88	1,67	No	No	No
Cd	1	0,0054	0,01	0,037	No	No	No
Cr	5	0,22	0,04	1	No	No	No
Pb	5	ND	0,015	0,063	No	No	No
Hg	0,2	ND	ND	0,0073	No	No	No
Se	1	ND	0,029	0,027	No	No	No

ND = Not Detected
BF = Blast Furnace Chrome Slag
BOF = Basic Oxygen Furnace Chrome Slag
EAF = Electric Arc Furnace Chrome Slag
TCLP = Toxicity Characteristic Leaching Procedure

Table 2.8: Leachate Elemental Analysis (Hattingh *et al*, 2003)

	Element						
Description	**Al**	**Cr**	**Fe**	**Mg**	**Mn**	**Ni**	**V**
ARL	0,39	4,7	9		0,3		1,3
Chrome Slag Sample	4,3	0,09	9,1	6,03	0,45	0,14	0,04

Units in parts per million (ppm)
ARL = Acceptable Risk Level (DWAF, 1998)

2.9 Summary

Fly Ash has been studied and investigated worldwide with the aim to expedite its disposal and to minimise the impact the elements have on the environment due to the chemical composition the particles have when leaching takes place before it is successfully used on a project.

Fly Ash varies in colour, which is mostly effected by the amount of iron-riched fractions and the amount of unburned carbon. Fly Ash with low amounts of unburned carbon have a light colour.

The use of Fly Ash is still an environmental disquietude. The studies shown have indicated that if Fly Ash is used properly, it will not have influence on the environment as indicated. It is still a factor that the handling of Fly Ash in the industry must be properly evaluated for health and safety disquietude.

Without the environmental concerns and changes to legislation, the Fly Ash was consigned within the flu gasses and scattered into the atmosphere. Once the legislations were introduced, the Fly Ash emissions have dropped to 1% of ash produced but it impacted negatively to the land as an increase in landfill sites were introduced.

Studies using Fly Ash as a filler have shown, that:

1. Addition of Fly Ash improves the rheological properties of the asphalt mixtures.
2. Fly Ash improves the aging properties, and therefore increases the longevity of the pavement infrastructure
3. It improves the thermal relaxation, thus increases resistance to cracking.
4. The conventional mix design procedures and pavement construction technologies are applicable for asphalt with Fly Ash.
5. It can aid in reducing mixing and placing temperatures and extend the workability of mixtures for effective placement in the field.

Chrome Slag is a waste by-product generated in purifying metals, their casting, and alloying. Chrome Slag is divided into two basic groups, namely:

1. Non-ferrous Chrome Slag
2. Ferrous Chrome Slag

Chrome Slag has a significant share of free lime (CaO) and magnesium oxide (MgO). These elements are concerning as it is related to volume expansion. The CaO causes rapid expansion, while the MgO causes expansion over time. Chrome Slag colour various from grey to dark grey.

Although free lime is a concern, it also has a positive impact in the application of Chrome Slag in asphalt mixtures. The amount of free lime increases the resistance in stripping and binds the mixture, which contributes to higher durability of a road surface.

Overall studies have shown that Chrome Slag in an asphalt mixture:

1. Would have a better increase interlocking mechanism.
2. ITS showed superior moisture resistance and rut resistance.
3. Field tests have shown better performance than when compared to Natural Aggregates.
4. Fatigue life exceeds the expectations of a natural asphalt mixture.

As Chrome Slag weathers in the environment over time, it is expected to break down to smaller size particles, increasing its potential for suspension to ambient air. However, with time, many applications of Chrome Slag will be ultimately covered or encapsulated, reducing the availability of Chrome Slag for suspension.

The primary components of Chrome Slag are Cao and SiO_2. Other components include alumina (Al) and MgO, as well as small amounts of sulphur (S) and iron oxide (FeO). However, because the refining time is short and the amount of limestone contained is large, a portion of the limestone auxiliary material may remain undissolved as free CaO.

These components exist in the natural world in places such as the Earth's crust, natural rock, and minerals. The chemical composition is very similar to that of Portland Cement. The shape and physical characteristics of Chrome Slag are similar to ordinary crushed stone and sand, however, due to differences such as the chemical components and cooling processes, it is possible to provide different types of Chrome Slag with a wide variety of unique properties.

Many applications utilising the physical and chemical characteristics of Chrome Slag have been developed and are being used in a broad range of fields.

Both Chrome Slag and Fly Ash in the literature review do show concerns of environmental hazards. It has been shown that Fly Ash can be entombed to reduce the concerns to an acceptable environmental standard. Chrome Slag has various mixed studies. It seems that in the first world countries, Chrome Slag processes are better controlled with technologies that contributes to less harmful elements left in the Chrome Slag, thus making it environmentally friendly. In South Africa, the opposite is found as Chrome Slag is classified as hazardous. In other words, Chrome Slag needs to be properly understood in South Africa and carefully selected for the purpose of use.

Based on the studies in the literature review, it can be concluded that:

1. Aggregate and filler in asphalt mixture can be replaced with waste materials such as Fly Ash and Chrome Slag.

2. Chrome Slag as an aggregate in asphalt mixture increases the density and stability of the mixture.
3. The replacement of aggregates and fillers form waste materials, which can be achieved through saving in the production of asphalt mixtures and contribute to environmental protection.
4. A longer service life could now be feasible due to increased resistance to mechanical and environmental loading.
5. The Fly Ash component as filler showed a significant effect on the characteristics and performance of asphalt mixture.
6. High filler concentrations resulted in a stronger pavement mixture, which attributed to a better asphalt cohesively and better internal stability.
7. Fly Ash as a particle filler hinders the matrix flow, thereby increasing the stiffness.
8. With the components of the Chrome Slag, good packing of coarse aggregate, fine aggregate and filler provides a strong backbone for the mixture.

The studies have also recognised that there is an urgent need for a better fit-for-purpose asphalt mix definition, including credible product performance specifications and application guidelines. This is to ensure that the asphalt mixes are optimally designed for specific target areas with the necessary performance specifications. The studies have also revealed that with a standard available test that specifications for a conventional mix can be met and even bettered with the introduction of the waste materials, in this case: Chrome Slag and Fly Ash.

It has been noted that there are limited applications in which Fly Ash has been used in asphalt pavements. This is also found with very limited information on the combination of both Chrome Slag and Fly Ash in an asphalt mix design. Information is limited considering the performance of such mixture in the field.

The literature review has confirmed that the utilisation of Chrome Slag and Fly Ash in South Africa will reduce landfill and save our natural resources. The studies have also shown that natural resources are becoming depleted due to high demand in road construction and the amount of waste material continually increasing, thus researchers have started to explore the use of alternative materials which could preserve natural sources and save the environment. This will shift the gear in sustainable pavement construction, which is most desirable in today's energy deficient world. With the limited information available on the use of both Chrome Slag and Fly Ash in an asphalt mixture, the study has opened a new door of development by using only recycled materials in a mixture that could reduce cost and be used mostly in rural developments.

Chapter 3 Materials

3.1 Introduction

This chapter deals with the background and definitions of asphalt overlay. It also gives details, descriptions, and tests related to specifications and properties of the materials used in this study.

3.2 Thin Asphalt layers

Pavement designs are based on the premise that minimum specified structural quality will be achieved for each layer of material in a pavement system (Guyer, 2011). Each layer in the design must be resistant to shearing, and excessive deflections that will cause fatigue cracking within the layer or in the overlying layers and prevent permanent deformation through densification (Guyer, 2011). The overall performance of an asphalt mix is dependent on, amongst others, the properties of the constituent materials, which include aggregate, binder, and filler.

In the selection of a suitable asphalt mixture, the following factors need to be considered:

1. Aggregate properties
2. Purpose for which the layer will be utilised
3. Type of filler and binder to be utilised
4. Required deformation resistance and durability performances of the asphalt overlay
5. Cost and environmental conditions
6. Traffic considerations
7. Pavement considerations
8. Climate considerations

General guidelines on the selection of a suitable asphalt mixture are well published in South Africa. The common books is the TRH8; Design and use of hot-mix asphalt in pavements (1987), TRH14; Guidelines for road construction materials (1985), COLTO; Committee of Land Transport Officials (1998), HMA; Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa (2001); TMH1, Standard methods for testing road construction materials (1986); TG1, Technical Guideline: The use of Modified Bituminous Binders in Road Construction (2001); SABITA Manual 2, Bituminous Binders for road construction and maintenance (2007); SANS, South Africa National Standards; South African Pavement Engineering Manual (SAPEM), 2013; SABITA Manual 24, User Guide for the Design of Asphalt Mixes (2019) and SABITA Manual

35, Design and use of Asphalt in Road Pavements (2020) . Type of guidelines is published tables and formulae for quick reference and decisions during a pavement design stage.

A criterion for selection of an appropriate mix is closely linked to the above-mentioned documents. Proper consideration of all these documents allows designers to evaluate the different design objectives, namely: stability, fatigue resistance, environmental durability, and permeability. This available information can be used to select the most appropriate mix type, as well as the level of performance testing needed for a specific project. In general, the pavement structure provides support for the asphalt layer, and as such comprises an important element to be considered in mix design (IGDHMA, 2001).

3.3 Fly Ash

Researchers have extensively investigated the use of by-products such as Fly Ash in the construction industry to improve material properties (Sobolev and Naik, 2005). Fly Ash has been extensively used in concrete production but has limited applications in asphalt pavements (Ali *et al*, 1996; Churchill *et al*, 1999; Asi *et al*. 2005; Faheem and Bahia, 2010). In all the studies, Fly Ash has been viewed as filler with the expectation of performance similar to mineral fillers. Sobolev reported that the incorporation of Fly Ash into asphalt mixtures improves the performance of the asphalt. This effect is attributed to the unique spherical shape, beneficial size distribution, and chemical properties of the Fly Ash.

Class F Fly Ash has been successfully studied and has been identified as a pozzolanic material, which entails that it reacts with lime/cement to form cementitious compounds (Guyer, 2011; Mehta, 1998). The Fly Ash goes through a process of *"pozzolanic reaction"* with calcium hydroxide ($Ca(OH)_2$) from the hydration process from the mixture of water and cement. Each individual Fly Ash dump site contain various particle sizes, density, chemical compositions and morphology, thus it can be said that Fly Ash is not a homogenous product and must be dealt with as such (Kruger, 2013). The abundance of Fly Ash available in South Africa is processed for commercial uses, mostly exclusively to concrete and cement admixtures.

For the purpose of this study, a single source of Fly Ash has been used from Kriel Power station situated in the province of Mpumalanga. The Fly Ash is air classified and Figure 14 shows the air classification process of the Fly Ash. Fly Ash is air classified due to its capability of providing product quality by controlling the fineness and reducing the loss of ignition (LOI) (Ash Resources, 2012). The Fly Ash selected is namely:

1. ULULA Ash – Air classified Fly Ash from Kriel power station

The choice of these Fly Ashes provides a variation in composition and particle size. ULULA Ash is classified into two categories, namely:

1. Class N Fly Ash – Fly Ash is emanated from the power station and analysed and diverted to ULULA Ash plant. This selected unclassified Fly Ash is stored and dispatched from the weighbridge into bulk tankers.
2. Class S Fly Ash – Fly Ash is emanated from the power station and analysed and diverted to the ULULA Ash plant. The Fly Ash is then fed into a classifier which further selects/splits the Fly Ash.

3.4 Fly Ash Standards

The current issue with Fly Ash in South Africa is that there is no actual standard available for the use of Fly Ash as an active filler. The standards that are extensively utilised are those for the determination of the properties of the Fly Ash as an extender in cement production (C&CI, 1998). This study also uses these standards to determine the properties and suitability of Fly Ash for use as filler (COLTO, 1998; TMH1, 1986). The current South African National Standards (SANS) methods developed for Fly Ash analysing will be used, which also correlates with British Standards (BS) that are still followed. Compliance with various requirements assures the user that unsuitable Fly Ash is not utilised.

To evaluate the components of Fly Ash such as the physical and chemical properties, the following standards are reverted to for the supplied Fly Ash in this study:

1. SANS 50450-1 (2011)
2. SANS 50197-1 (2000)
3. European Standard EN450-1 (2001)

In order to understand the characteristics of the Fly Ash, it is compared to the standards as noted in this study. Chemical and the mineralogical composition of Fly Ash is what determines the performance of the mineral, and we also have to take note of the morphology and granulometry. To assess the filler potential, only specific characteristics were selected and measured.

1. Composition of the Fly Ash by XRF analysis.
2. Estimation of cementing potential by calculation of the CaO/SiO_2 ratio.
3. Determination of Sulphur content (SO_3) for possible changes in bitumen structure.
4. Determination of the amount of free lime (fCaO)
5. Determining the effect of fineness on performance.

3.4.1 ULULA Ash

ULULA Ash is a recognised high quality Fly Ash. ULULA Ash is mostly used in concrete mixes, where it contributes to a reduced carbon dioxide (CO_2) footprint. The Ash particle is spherical in shape, has a fine particle size, and is pozzolanically reactive (ULULA Ash, 2017). Table 3.1 shows the results for compliance to SANS 50197-1(2000), SANS 50450 (2011) and EN450-1 (2001) for Class N and the Class S Fly Ash.

Table 3.2 shows the XRF analysis for Class S Fly Ash, and Table 3.3 shows the XRF analysis for Class N Fly Ash. All the parameters of the test results confirm that Kriel ULULA Ash complies with SANS 50450 (2011), SANS 50197-1 (2000) and EN450-1 (2001). The compliance with SANS 50197-1 (2000) also shows that it can be used as a constituent in cement.

Table 3.1 ULULA Fly Ash test results according to specifications

Method	Description	Specification	Class N	Class S
SANS50450 (Category A)	LOI	<5.0	1,5	0,8
SANS50450 - 1:2011	LOI	<5.0	4	1,6
SANS50450 - 1:2011	Sulphur content	<2.5	0,9	1
EN451-1	FCaO	<2,5	2,5	1,9
SANS50450 (Category N)	Fineness	<40	25	N/A
SANS50450 (Category S)	Fineness	<12.0	N/A	11
SANS50450 - 1:2011	Activity Index	Min 75% @ 28 days	78	83
SANS50450 - 1:2011	Activity Index	Min 85% @ 90 days	90	99
SANS50450 - 1:2011	Soundness, expansion	<10mm	1	<0,1
SANS50450 - 1:2011	Particle Density		2240Kg/m³	2250Kg/m³

Table 3.2 XRF Analysis for ULULA Class S Fly Ash

Parameter	Unit	Result
SiO_2	(%)	58.24
Al_2O_3	(%)	19.35
Fe_2O_3	(%)	6.15
CaO	(%)	9.31
MgO	(%)	1.36
K_2O	(%)	0.81
Na_2O	(%)	0.8
TiO_2	(%)	1.26
P_2O_5	(%)	0.18
Cr_2O_3	(%)	0.04
SO_3	(%)	0.81
LOI	(%)	1.14
CaO/SiO_2	ratio	0.16
$SiO_2 + Al_2O_3+Fe_2O_3$		83.74

Table 3.3 XRF Analysis for ULULA Class N Fly Ash

Parameter	Unit	Result
SiO_2	(%)	53.84
Al_2O_3	(%)	20.24
Fe_2O_3	(%)	10.64
CaO	(%)	7.01
MgO	(%)	1.2
K_2O	(%)	0.8
Na_2O	(%)	0.87
TiO_2	(%)	1.51
P_2O_5	(%)	0.16
Cr_2O_3	(%)	0.08
SO_3	(%)	0.15
LOI	(%)	2.97
CaO/SiO_2	ratio	0.13
$SiO_2 + Al_2O_3+Fe_2O_3$		84.72

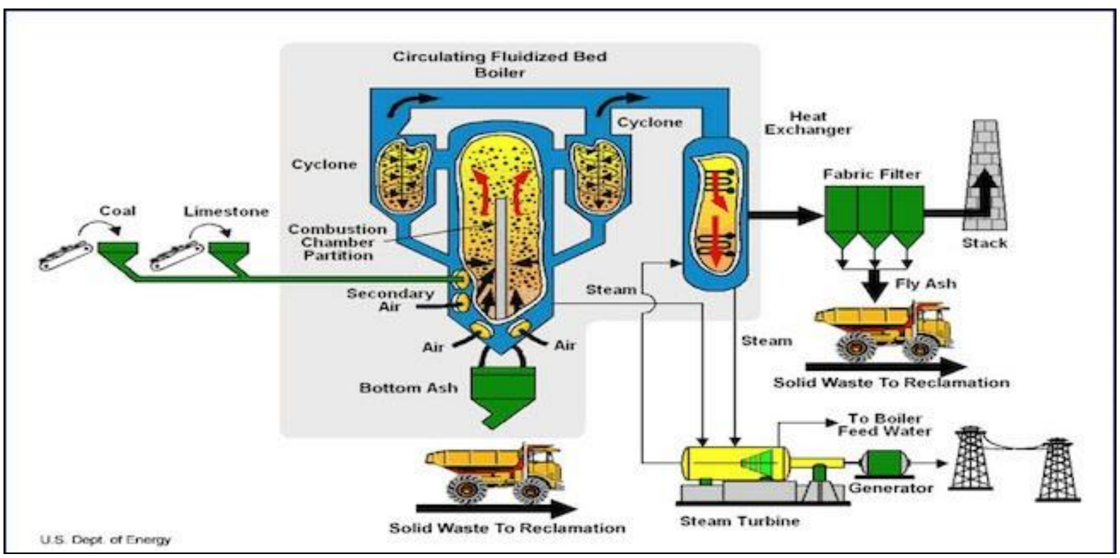


Figure 14: Typical air classification process of South Africa Fly Ash

3.5 Chrome Slag

As previously stated in this study, electric arc furnace Chrome Slag is a by-product of steel in an electric arc furnace. In the electric arc furnaces, the charge materials—which is scrap iron and steel—are loaded into the furnace and directly exposed to electric terminals. The current passing through the terminal creates an electric arc that melts the charge materials. Chrome Slag formers are added to the furnace to:

1. Act as a destination for oxidised materials
2. Act as a thermal blanket to prevent excessive heat loss
3. Reduce erosion of the refractory lining.

The Chrome Slag formers in this regard are CaO and MgO. The Chrome Slag is very angular and porous with a rough surface texture. This can be seen in Figure 12 of the samples collected. The aggregates formed from Chrome Slag is mostly comprised of CaO, SiO_2, Fe_2O_3, MgO, MnO, Al_2O_3, and SO_3. Typical chemistry is shown in Table 4.1 and Table 4.3 of this study.

The physical properties of the Chrome Slag used in this study are discussed in Item 3.6.7 Aggregates of this study. As also stated in literature review, it has been found that asphalt mixes with Chrome Slag had higher resilient modulus values, less deformation, higher tensile strengths, and were less susceptible to moisture damage than the mixes with Natural Aggregate, although the Chrome Slag mixes required more binder than the Natural Aggregate mix (Washington State DOT, 2015).

Figure 15: Typical Chrome Slag samples.

Chrome Slag samples are dark grey in colour with particles sizes ranging between 0.5mm to required sizes. The Chrome Slag has a slight dusty odour with a pH of 7.9. The Chrome Slag has a density of about 3470 Kg/m^3 with the following chemical properties:

Conductivity - 68µS/cm

Sulphate – 4.9mg/l

Nitrate – 0.3mg/l

Chloride – 19mg/l

Silica – 0.43mg/l

The Chrome Slag used in this study has been listed in the Hazardous Chemical Substances Regulations for the Occupational Exposure Limit (Afrigrit, 2014).

The basicity of Chrome Slag is calculated using the following formulae stated by Niemela *et al*, *2007*:

$$B_3 = \frac{0{,}0178 \text{ x } \%CaO + 0{,}0248 \text{ x } \%MgO}{0{,}0166 \text{ x } \%SiO_2 + 0{,}0098 \text{ x } \%Al_2O_3}$$

Using Table 4.1 with the values of the 9.5mm aggregate, the following answers can be calculated:

$$B_3 = \frac{0{,}0178 \text{ x } 4.17 + 0{,}0248 \text{ x } 17.15}{0{,}0166 \text{ x } 36.96 + 0{,}0098 \text{ x } 25.86}$$

B_3 = 0.6 – Acidic Chrome Slag.

The petrographic descriptions of the Chrome Slag under microscope showed that the sample is composed of fragments of grey rock of very small grain size. Under the microscopic description, the samples represent a Chrome Slag mainly made up of spinel, chromite and an amorphous phase with random prismatic crystals of clinopyroxene and olivine. The spinel and chromite spinel appear as black round minerals under cross polarised light. The amorphous phase appears as dark purple blobs. Table 3.4 shows the XRD results of the Chrome Slag. Figure 16 to 19 show the minerals as seen under the microscopic description.

Table 3.4 XRD Minerals found in Chrome Slag

Mineral	%
Chromite	11,78
Spinel	21,79
Quartz	1,22
Olivine	6,38
Clinopyroxene	4,31
Amorphous	54,52

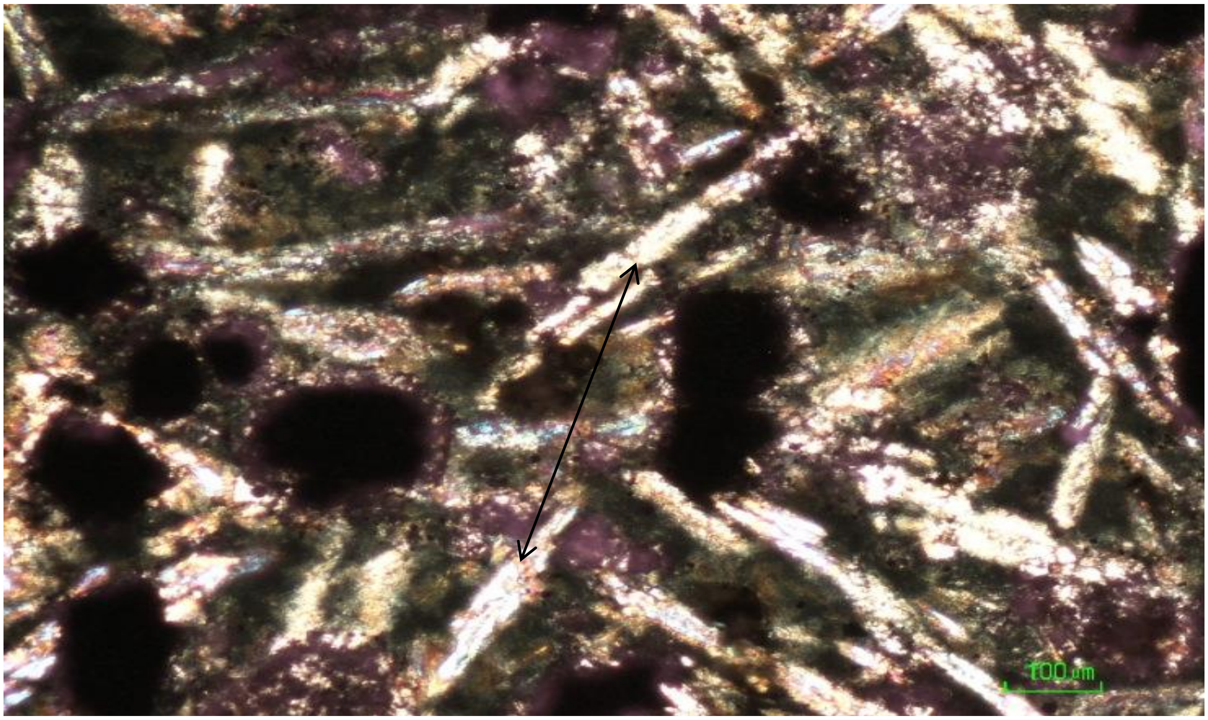


Figure 16 Prismatic crystals of clinopyroxene and olivine

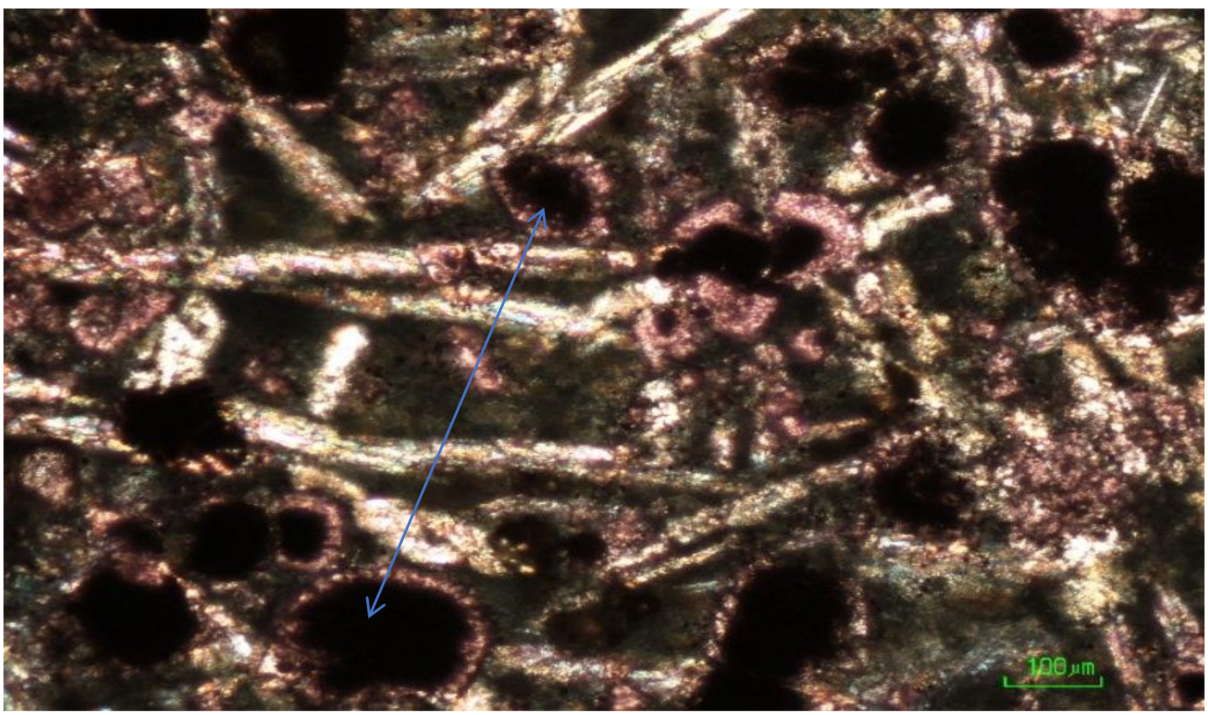


Figure 17: Spinel and Chromite Spinel as black round minerals

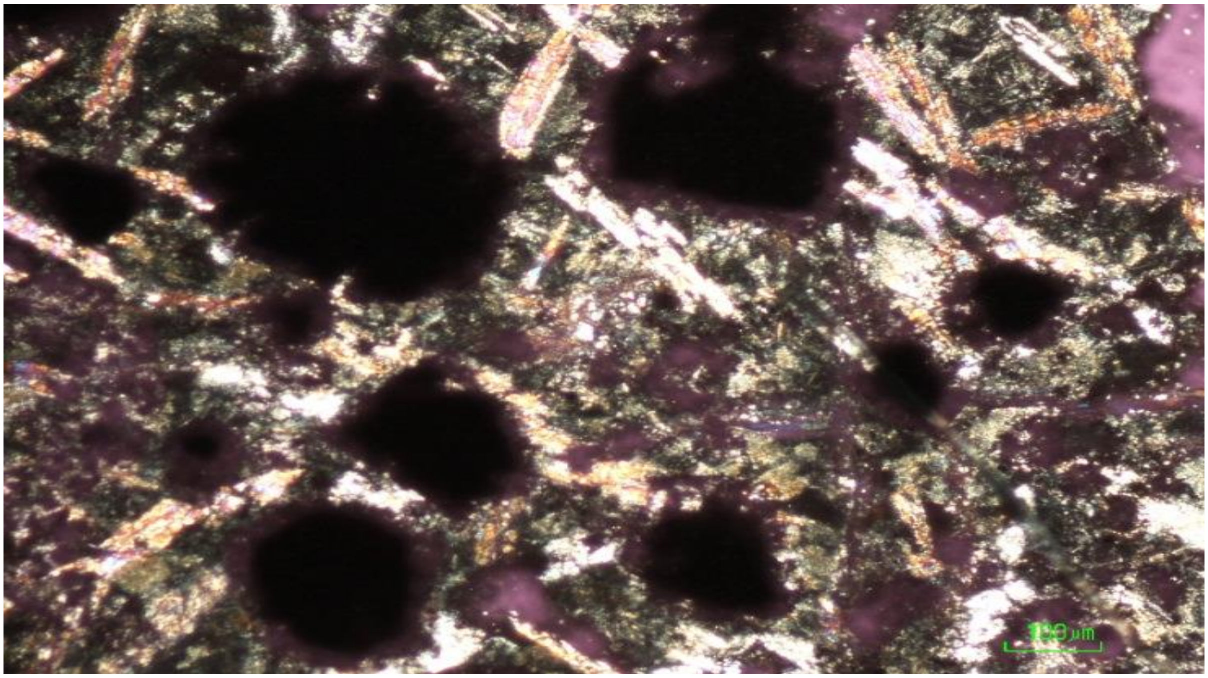


Figure 18: Spinel and Chromite Spinel

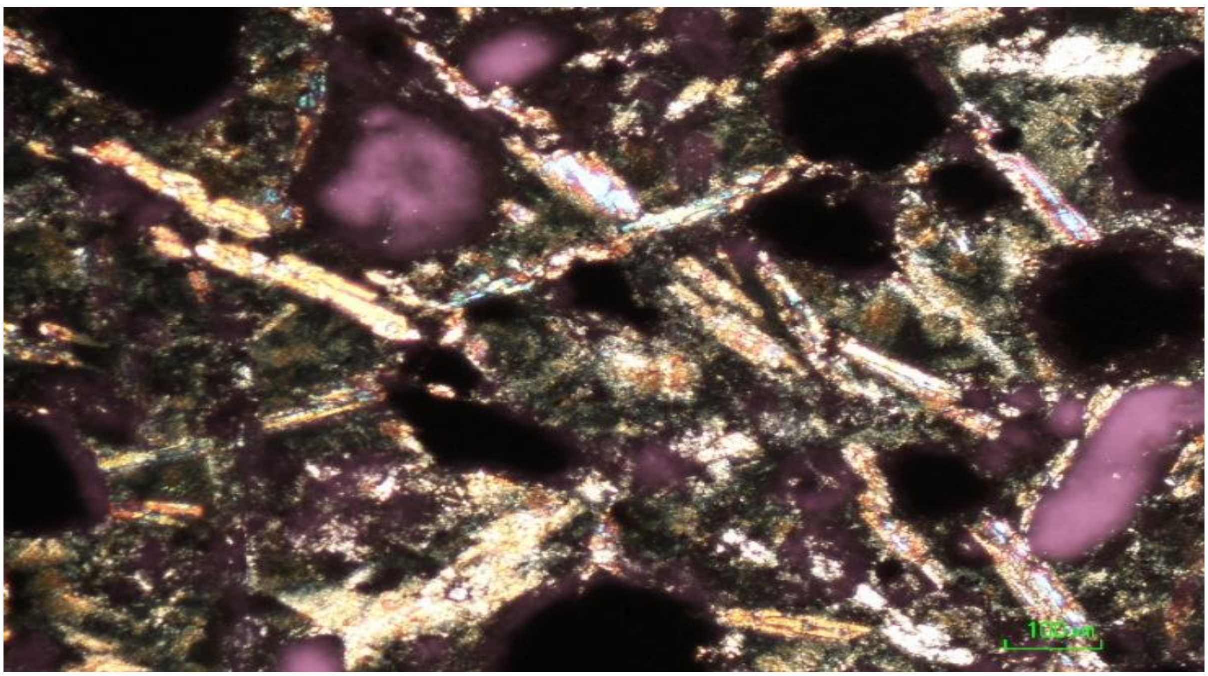


Figure 19: Amorphous phase as purple blobs

3.6 Bitumen

3.6.1 Modified Binders

Bitumen modification is used quite commonly in many countries over the world, for over 50 years. In Europe, the development of modified binders was specifically stimulated in countries where the clients, typically road authorities, required the contractor to give performance guarantees for several years (SAPEM, 2013).

There is an increasing tendency in South Africa to use modified binders in asphalt surfacing to cope with higher intensity loading, arising from increasing traffic volumes, axle loads, and tyre pressures. The requirements imposed on asphalt layers and surface treatments in terms of resistance to rutting, fatigue, or adhesion, are reaching the limits of what can be achieved with conventional binders, therefore modified binders are required (SAPEM, 2013).

Generic classes of modified binders have been coded according to the applications in which they are intended to perform. These are coded by means of letter codes and are defined as follows:

S – Surfacing seal application (hot applied)

SC – Surfacing seal application (cold applied)

A – Hot-mix asphalt

C – Crack seal application (hot applied)

CC – Crack seal application (cold applied)

E – Polymer of the elastomer type (e.g. SBE and SBS)

P – Polymer of plastomer type (e.g. EVA)

R – Crumbed rubber

Numerical codes have also been assigned to the products. The numerical code has no bearing on the concentration of the modifier contained within the product but identifies the product according to specific product properties/requirements as shown in Table 3.5. The code allows for additional binders to be added to a specific binder class in the future. The classification of hot-mix asphalt applicable to the study is AE-2 as shown in Table 3.6.

The increased interest in bitumen modification, especially in AE-2, is attributed to the following factors:

1. Increased demand on asphalt pavements in terms of traffic volumes and wheel loads.
2. Normal binders have difficulty in meeting the requirements in regions with extreme climatic conditions.
3. In many cases, regular maintenance has not been done and there is a need to provide an economically viable solution to poor road conditions.

4. Availability of high-performance binders.
5. Porous asphalt and stone mastic asphalt perform well with modified binders.

Modified binders have the ability to improve the performance over conventional binders. AE-2 is the modified binder chosen for this study. The benefits of this binder over conventional binder include the following:

1. Improved consistency
2. Reduced temperature susceptibility for flushing and bleeding
3. Improved stiffness and cohesion
4. Improved flexibility, resilience, and toughness by permitting higher binder film thickness for increased mix durability.
5. Improved binder-aggregate adhesion
6. Improved resistance to in-service ageing related to fatigue, ageing or oxidation.
7. Improved fuel resistance.

Table 3.5: Properties of polymer modified binders for hot mix asphalt (TG1, 2007; TG1, 2001)

Property	Unit	Min/Max	Test Method	Binder Class	
				A-E1	A-E2
Softening Point	°C	Min	MB-17	55-65	65-85
Dynamic Viscosity @ 165°C	Pa.s	Max	MB-18	0,6	0,6
Dynamic Viscosity @ 150°C	Pa.s	-	MB-18	Report	Report
Dynamic Viscosity @ 135°C	Pa.s	-	MB-18	Report	Report
Ductility @ 15°C	cm	Min	MB-19	75	50
Force Ductility		N		Report	Report
Elastic Recovery @ 15°C	%	Min	MB-4	>50	>60
Torsional Recovery @ 25°C	%	-	MB-5	Report	Report
Flash point	°C	Min	ASTM: D93-97	≥230	≥230
Complex shear moduluis G*/sin δ @ 10 rads/s	°C	-	AASHTO: TP5	Report	Report
Creep Stiffness	Mpa	-	AASHTO: TP1	Report	Report
Properties after ageing (RTFOT)			MB-3		
Diff. in softening point	°C	-	MB-17	-2 to +8	-2 to +8
Elastic Recovery @ 15°C	%	Min	MB-4	>40	>50
Mass change	%	Max	MB-3	1	1
Torsional Recovery @ 25°C	%	-	MB-5	Report	Report

Notes: It has been noted that there is a possibility that the current “Report” test properties could in future form part of the specifications. It is recommended that these tests are carried out at the commencement of the project.

Table 3.6; Classification of Modified Binders of Hot Mix Asphalt (TG1, 2001)

Modified Binder Class (A)	**Application**
A-E1	Hot mix asphalt - Fatigue
A-E2	Hot mix asphalt - Fatigue/Deformation

Even though modified binder has improved characteristics, the fundamental rules of mix design for hot mix asphalt should not be ignored. Modified binders are more expensive but require appropriate design of the final product to maximise the benefits appropriate to the specific need. Very often, performance requirements for routine situations can be met with the use of appropriate conventional binders. This is the reason why this study will in affect also incorporate a conventional binder (50/70 penetration grade) for a comparison and can be more cost effective at the end.

Typical conditions where such binders should be considered for hot mix asphalt are as follows:

1. On relatively high flexible pavements
2. In areas of high stress such as heavy traffic, steep inclines, intersections, and sharp curves
3. In areas experiencing large daily/seasonal temperature fluctuations
4. In open graded mixes requiring a high film thickness
5. In remote areas where thin layer overlays are required

3.6.2 Penetration Grade Bitumen

Penetration grade bitumen is manufactured either by straight-run distillation of crude oil or by blending two base components, i.e.: one hard binder such as 35/50 penetration, and a soft binder such as 150/200 penetration. Penetration grade bitumen is used either as a primary binder or base bitumen for the manufacture of cutback bitumen, modified binders, or bitumen emulsions (SAPEM, 2013). There are currently six (6) grades available from the South African refineries, namely: 10/20, 15/25, 35/50, 50/70, 70/100, 150/200. Specifications for the penetration grade bitumen are shown in Table 3.7. The required performance of the bitumen after being subjected to rolling thin oven test is shown in Table 3.8.

Table 3.7: Penetration Grade Bitumen specification (SANS 4001 – BT1, 2014)

Property	Penetration Grade				Test Method
	35/50	50/70	70/100	150/200	
	Road Grade				
	B24	B12	B8	B4	
Penetration at 25°C/100g/5s,0,1mm	35 - 50	50 - 70	70 - 100	150 - 200	ASTM D5
Softening point °C	49-59	46-56	42-51	36-43	ASTM D36
Viscosity at 135°C, Pa.s., min	270 - 700	220 - 500	150 - 400	120 - 300	ASTM D4402
Flash Point °C, min	240	230	230	220	ASTM D92

Penetration grade bitumen is a residual product that is obtained from the vacuum distillation of crude oil in petroleum refineries. Penetration grade bitumen is used as a binder in the construction of chip seals and for the manufacture of hot mix asphalt.

The bituminous binder should be selected with due consideration of the aggregate packing of the mix, and in conjunction with traffic and environment. Bituminous binders and modifiers in general use in wearing coarse asphalt is set out in Table 3.9. Bitumen may also contain additives, which improve the properties for specific applications, whilst not forming an integral part of the binder. Additives in general use are given in Table 3.10.

Table 3.8: Performance specifications after the thin rolling thin film oven test (SANS 4001 – BT1, 2014).

Property	Penetration Grade				Test Method
	35/50	50/70	70/100	150/200	
	Road Grade				
	B24	B12	B8	B4	
Mass change (% by mass fraction), max.	0,3	0,3	0,3	0,3	ASTM D2872
Viscosity at 60°C (% of original), max	300	300	300	300	ASTM D4402
Softening point °C, min	52	48	44	37	ASTM D36
Increase in softening point °C, max	7	7	7	7	ASTM D36
Retained penetration % of original, min	60	55	50	50	EN 1426
Spot Test (% xylene), max	30	30	30	30	AASHTO T102

Table 3.9: Bituminous Binders for Asphalt Surfacing (SAPEM, 2013)

Class	Category	Grade/type	Applications
Conventional Binders (complying with SANS 4001-BT1)	Penetration grade road bitumen	35/50 pen	High traffic situations where high stiffness is required.
			Generally, not appropriate for situations of yielding support layers and low temperatures
		50/70 pen	Gap, semi-gap, continuous and open-graded asphalt for typical applications in most climatic zones.
		70/100 pen	For improved flexibility of asphalt on more flexible pavements
			Especially appropriate for very thin layers on residential streets, where extending the compaction window under conditions of rapid cooling may be critical consideration
Modified Binders (complying with TG1)	Elastomer	Styrene-butadiene-rubber (SBR) latex	Improved flexibility and resistance to fracture. Increased stiffness at elevated temperatures. Lower stiffness at low service temperatures
		Styrene-butadiene styrene (SBS)	
		Bitumen-rubber	
	Plastomer	Ethyl-vinyl-acetate (EVA)	Improved resistance to permanent deformation
	Natural hydrocarbons	Gilsonite	Stiffening of the bitumen, hence the stiffness modulus of the asphalt layer
		Durasphalt	
	Aliphatic synthetic wax	FT Wax	Primarily for lowering the mixing and laying temperatures
			Also as a beneficial effect on the resistance to permanent deformation
			More resistant to fuel spillage than conventional binders

Table 3.10: Bitumen Additives (SAPEM, 2013)

Additive	Type	General Purpose
Natural or synthetic fibres	Natural Rock wool	Reduced risk of drain-down of binder, especially in open-graded asphalt and SMA. Improved tensile strength and cohesion of the asphalt
	Polypropylene	
	Polyester	
	Fibreglass	
	Mineral cellulose	
Anti-stripping agents	Amines	Minimises stripping of binder from aggregate
	Lime	

AE-2 bitumen to be used in this study is shown in Table 3.11. The AE-2 conforms to the standard requirements when the base bitumen is tested. An example of the reports can be seen in the appendices. The penetration grade bitumen 50/70 test results, which is also to be used in this study, is shown in Table 3.12. The results also conform to the requirements as set out in this document. Although some results have not been reported, it is noted that it is only an evaluation of a report and that crucial testing has only been done for the purpose of the basic design checks.

Table 3.11: AE-2 test results

Property	Test Method	Unit	Min/Max	Test Results		Average
				AE-2	AE-2	
Before Rolling Thin Film Oven Test (RTFO)						
Ring and Ball Softening Point	ASTM D36	°C	65-85	67,3	86,3	76,8
Flash Point	ASTM D93	°C	>230	278	278	278
Dynamic Viscosity @ 165°C	ASTM4402	°C	<0,6	0,27	0,33	0,3
Elastic Recovery @ 15°C	TG1 MB-4	%	>60	78	82,5	80,25
After RTFO						
Mass Change	ASTM D2872	%	≤0,3	0	0	0
Ring and Ball Softening Point	ASTM D36	°C	Min 63	68,5	83,75	76,125
Elastic Recovery @ 15°C	TG1 MB-4	%	>50	67,5	73	70,25

Table 3.12: 50/70 Penetration Grade Test results

Property	Test Method	Unit	Min/Max	Test Results			Average
				50/70	50/70	50/70	
Before Rolling Thin Film Oven Test (RTFO)							
Spot Test (Xylene)	ASHTO T102	%	Max 30	NA	NA	20	20
Needle Penetration @25°C	ASTM D5	1/10mm	50-70	53	69	65,2	62,4
Ring and Ball Softening Point	ASTM D36	°C	46-56	48,3	46,8	48,3	47,8
Brookfield Viscosity @ 135°C	TG1 MB-13	Pa.s	0,220 - 0,500	0,415	0,314	0,304	0,344
Flash Point	ASTM D93	°C	>230	351,7	NA	315,8	333,8
After RTFO							
Mass Change	ASTM D2872	%	0,3	0,057	0,036	0,091	0,061
Ring and Ball Softening Point	ASTM D36	°C	Min 48	52,9	53,5	51,5	52,6
Difference in Softening Point	ASTM D36	°C	Max 7	5,4	6,7	3,2	5,1
Viscosity @ 60°C of original	TG1 MB-13	%	Max 300	191,82	247	199,9	212,9
Needle Penetration @25°C	ASTM D5	1/10mm		36,3	47,3	40,3	41,3
Retained Penetration	ASTM D5	%	Min 55	68,49	69,6	61,8	66,63

3.6.3 Aggregates

Soil is defined as the uncemented aggregate of mineral grains and decayed organic matter, along with liquid and gas that occupy the empty spaces between the solid particles. In civil engineering road construction design phase, this is a study of the properties of soil, such as origin, grain size distribution, ability to drain water, compressibility, shear strength, load bearing capacity, etc. With the growth of science and technology, need for better and more economical structured design and construction becomes more critical (Principles of Geotech, 2010).

Most aggregate sources form a commercial or project quarry, which are seldomly totally uniform in quality. The existence of distinct geological formations can significantly affect the quality of aggregate (SAPEM, 2013).

Aggregate is one of the main components of an asphalt mix design, seeing as it constitutes the larger portion of material used in the manufacture of hot mix asphalt. The physical properties of aggregate are generally regarded as the most important aspect of aggregate selection. The physical properties of aggregates are affected by the mineralogy of the parent rock, the extent to which the parent rock has been altered by leaching and oxidation, as well as by the processes required to produce graded and blended aggregate.

Natural Aggregate for production in asphalt mixes is usually sourced from a quarry. Aggregate properties produced by one source, however, vary over time as different seams in the quarry are operated (Komba, *et al*, 2014).

Aggregates properties commonly used to produce asphalt depend on many factors, namely:

1. Mineralogy of the parent rock
2. The extent to which the parent rock has been altered, mostly by means of leaching and oxidation
3. The process required to produce the required aggregate particle sizes.

Aggregate properties that are significant to the performance of hot mix asphalt include:

1. Hardness/toughness
2. Durability
3. Shape
4. Surface Texture
5. Absorption
6. Cleanliness

Hard and rough textured aggregate results in stable and rut-resistant hot mix asphalt mixes (Komba J, 2014). Durability is another key aspect that should be possessed by aggregates used in the production of asphalt. The aggregate should be able to resist breaking down and disintegrating under environmental conditions.

Equal dimensional aggregate is preferred over flat and elongated aggregates in terms of shape. Flat and elongated aggregate particles tend to lock up and resist orientation, which results in difficulty during the compaction process (Button *et al*, 1990; Arasan *et al*, 2011). Angular aggregate particles are preferred over round-shaped aggregates as they improve mechanical interlock, provide better resistance to permanent deformation and improve resilient response of hot mix asphalt mixes (Pan *et al*, 2005). Standard tests to evaluate the properties of the aggregate include:

1. For evaluation of hardness:
    a. Aggregate Crushing Value (ACV)
    b. Ten Percent Fines Aggregate Crushing Value (10% FACT)
2. For evaluation of durability:
    a. Methylene Blue Absorption
    b. Ethylene Glycol Testing, including on both ACV and 10% FACT.
3. For evaluation of shape properties:
    a. Flakiness Index (FI)
    b. Average Least Dimension (ALD)
    c. Polishing Stone Value (PSV)
4. For evaluation of absorption:
    a. Water absorption
5. For evaluation of density:
    a. Apparent Relative Density (ARD)
    b. Bulk Relative Density (BRD)

One of the most common natural materials found in South Africa and used frequently in road construction projects is Dolerite. Dolerite is associated with the basic crystalline group thus giving high quality material for the use on any type of project that requires earthworks. Dolerite compromises of two essential and other minor minerals. The essential minerals are plagioclase feldspar and pyroxene. Other minerals are quartz, hornblende and mica. Quartz normally comprises of between 20% to 40% of the dolerite rock. Quartz is one of the main key elements due to its hardness and lack of chemical activity make it one of the most desirable properties that is required in an earthwork's construction project. Dolerite is found in batholiths or large magma plumes that rose into the continental rocks and can also be seen in other intrusive features like numbers of dykes and sills, an example of these intrusions can be viewed in Figure 20. As with all natural materials, they are subjected to weathering and with dolerite, the feldspar is one of the main components that weather and is replaced by clay minerals like illite and kaolinite (Fultons, 2009).

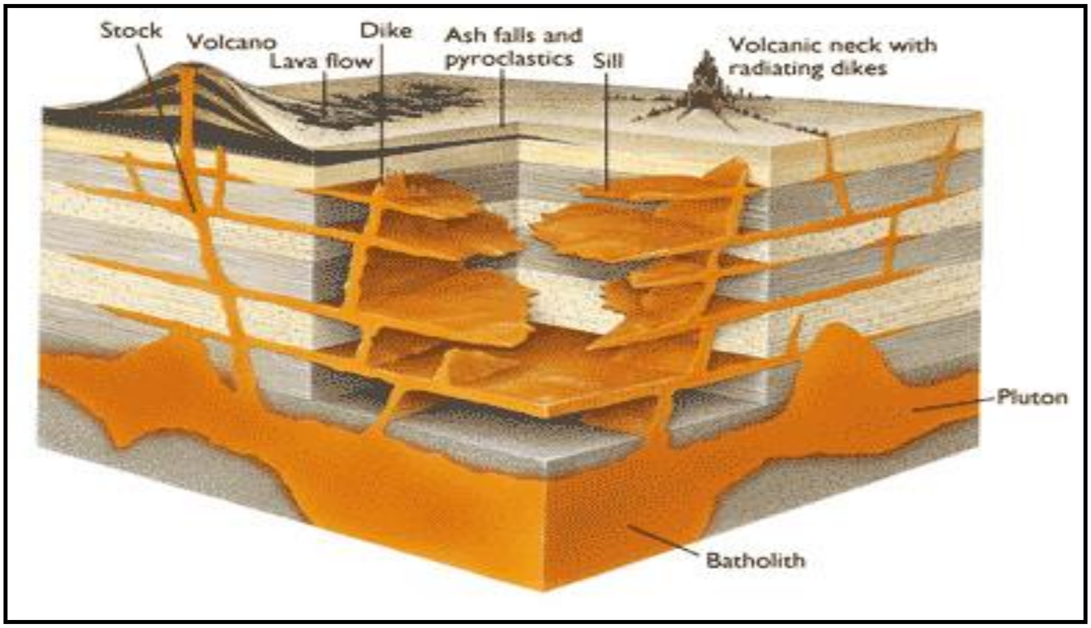


Figure 20: Example of Dykes and Sill

Chrome Slag can be compared to volcanic rock such as basalt and granite. Just like the natural materials, Chrome Slag does contain trace elements, that can be harmful, but these trace elements are mostly bound up within the crystal lattice, and therefore almost impossible to leach.

Chrome Slag is a waste material generated in purifying metals, their castings and alloying. During this process, Chrome Slag is generated in two phases, namely:

3. The ore is exposed to high temperatures to separate impurities.
4. The separated impurities are collected and removed, and this “waste” material is called Chrome Slag.

The type of generated Chrome Slag depends on the method of cooling, and the type of processed metal.

The Chrome Slag is directly granulated during tapping where ferrochrome is tapped into ladles. The overflow from the ladles flows along the Chrome Slag launder to the granulation pond, where high-pressure water breaks Chrome Slag into small fractions and efficiently cools it down. The final Chrome Slag is then dumped on site (Niemela, 2007; Hattingh, 2003).

As previously stated, the aggregate needs to be durable and testing requirements has been established to ensure the durability of the required materials. The table used for comparisons can be found in the Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa, Table 3.1. The tests were completed on both natural (Dolerite) and Chrome Slag aggregates. The specifications are summarised below in Table 3.13.

Table 3.13: Tests used to Evaluate the Physical Properties of Aggregates

Property	Test	Designation	Criteria
Hardness/Toughness	Fines Aggregate Crushing Test (10% FACT) (-10,0mm + 7,1mm fraction) & (-7,1mm +5mm Fraction)	SANS 3001 – AG10 & AG15	Minimum: 160kN
	Aggregate Crushing Value (ACV)	SANS 3001 – AG10	Max: 25%
Durability/Soundness	Methylene Blue Adsorption	SANS1243	No standards Specified. Indicators: <5: High quality filler >5: Additional Testing Required
	Ethylene Glycol	SANS 3001 – AG14	Visual evaluation
Particle Shape and Texture	Flakiness Index Test	SANS 3001 – AG4	Max: 9,5mm Aggregate – 30 6,7mm Aggregate – 30
	Polished Stone Value (PSV)	SANS 3001 – AG11	Min: 50
Absorption	Water Absorption	SANS 3001 – AG20 & AG21	Max: 1% by mass
Cleanliness	Sand Equivalent Test	SANS 3001 – AG5	Min: 50 on Total Fines Fraction
Abrasion	Los Angeles (L.A.) Abrasion Test		

3.6.3.1 Hardness/Toughness

Aggregates are subjective to abrasive wear during various stages of crushing, screening, manufacturing, and placement of HMA (Hot Mix Asphalt), then finally trafficking. To ensure that all aggregates are stable and physically rut-resistant, it is essential that the aggregates keep their harsh angular texture throughout these processes. Hardness and toughness are thus an imperative component for aggregates for providing rut-resistant and good micro texture in an asphalt mixture. The tests evaluated are discussed below. Although these tests are only for evaluation on material retained on the 4.75mm sieve, the finer aggregate must be taken note of as these can reduce the stability of the mixture.

3.6.3.1.1 ACV and 10% Fines Aggregate Crushing Values (FACT)

A conventional dry and wet aggregate crushing test should be carried out using either ACV or 10% FACT. The test assesses the strength properties of the aggregate. The difference between ACV and 10% FACT is that ACV determines the percentage fines produced under a load of 40kN/min up to 400kN over 10 minutes while the 10% FACT determines the load required to produce 10% fines. ACV is less reliable for indication of weaker materials therefore the 10% FACT is the preferred method. The durability of aggregates, the wet 10% FACT is carried out as part of the normal 10% FACT test. Aggregates are prepared as for the standard test requirements but are soaked in water for 24hrs. The test is carried out for both dry and soaked aggregate and the results are reported in percentage. A wet/dry ratio of greater than 75% indicates a satisfactory durability. Table 3.14 shows the results of the comparison materials. In addition to the testing, aggregate soaked in Ethylene Glycol for 4 (four) days must also be subjected to the ACV and 10% FACT test procedures. The results of the Ethylene Glycol test procedures must conform to the requirements as specified in the documents to ensure durability. (SANS 3001 – AG10; SANS 3001 – AG14; SANS 3001 – AG15; SAPEM, 2011; COLTO, 1998; IGDHMSA, 2001).

Table 3.14: Hardness results of the aggregates

Description	Test Method	UOM	Material Description			
			Chrome Slag		Aggregate	
			9,5mm	6,7mm	9,5mm	6,7mm
ACV Dry	SANS 3001 - AG10	%	8,2	18,8	6,1	7,6
ACV Wet	SANS 3001 - AG10	%	9,7	13,3	8,8	9,9
ACV (EG)	SANS 3001 - AG10	%	9,1	20,2	8,8	8
10 % FACT Wet/Dry Ratio	SANS 3001 - AG9	%	97	93	84	72
10% FACT	SANS 3001 - AG9	kN	488	219	656	526
10% FACT Dry	SANS 3001 - AG9	kN	381	325	421	417
10% FACT wet	SANS 3001 - AG9	kN	370	301	355	301
10% FACT (EG)	SANS 3001 - AG9	kN	440	198	455	500

3.6.3.2 Durability/Soundness

Durability and soundness is the ability of the aggregate to resist breakdown and disintegration under the action of the environment. The tests included in this section are namely: Ethylene Glycol Durability Index and the Methylene Blue test.

3.6.3.2.1 Ethylene Glycol Durability Index (EGDI)

Durability of any materials of the acid/basic crystalline rock groups and including slag, is of critical importance to ensure life span of a design is achieved. The test method used for durability is the ethylene glycol test method.The test is a good indicator of the potential breakdown of the aggregates in medium to long term after exposure to atmosphere. Rapid weathering does occur when rocks contain smectite clay minerals and dolerites, which are known for the primary minerals in rock to be altered to active clay smectite (Paige-Green, 2007; SANS 3001 – AG14). The test consists of soaking rock fragments in ethylene glycol and observing deterioration on a daily basis. The durability index is obtained by adding the disintegration classification, this indicates the severity of the disintegration to the time classification over a number of days taken for the most severe disintegration to take place. A modified technique, suggested by Paige-Green, uses 40 (forty) pieces of aggregate placed in a fixed position. This technique is to assess each aggregate and its behaviour with time recorded. The inspection should take place after 5 (five), 10 (ten), and 20 (twenty) days. The individual pieces are recorded with the following 3 (three) assessments:

1. Shed of small fragments from edges
2. Fractured into not more than 3 (three) pieces
3. Disintegrated, samples split into more than 3 (three) pieces

The results of the test will indicate possible problematic aggregates that will affect long term durability. As the effect of the ethylene glycol depends on the accessibility of the liquid to the deleterious clays within the aggregate pieces, the test was carried out for 20 (twenty) days to determine whether there could be a longer-term durability problem. Should the EGDI after 20 (twenty) days be greater than 1.5 times the EGDI after 5 (five) days, the material should be regarded as having suspect durability.

The results of the EGDI tests are then related to the expected performance of material as road construction aggregate according to the following criteria:

Subbase – mEGDI < 20

Base Course – mEGDI < 10

mEGDI after 20 (twenty) days < 1,5 x mEGDI after 5 (five) days

Results of the samples tested are seen in Table 3.15 for 9.5mm Chrome Slag; Table 3.16 for 6.7mm Chrome Slag; Table 3.17 for 9.5mm aggregate and Table 3.18 for 6.7mm aggregate. Figure 21 and 22 shows the condition of the aggregate Chrome Slag and the natural dolerite soaked in ethylene glycol after 20 (twenty) days.

Figure 21: Chrome Slag soaked in Ethylene Glycol

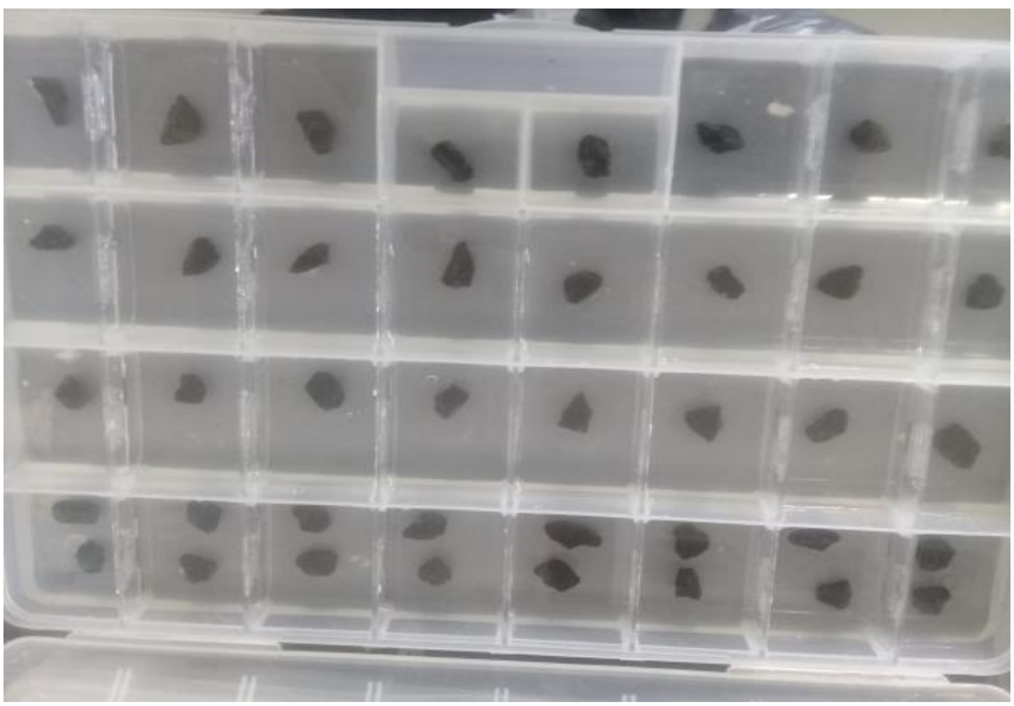


Figure 22: Dolerite Aggregate soaked in Ethylene Glycol

Table 3.15: EGDI results for 9,5mm Chrome Slag.

Day	Spalled [a]	Ds	Fractured [b]	Df	Disintegrated [C]	Dd	Durability Index
1	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0

a	Weighting Factor	0,5
b	Weighting Factor	1
c	Weighting Factor	2,5

Type of deterioration	Definition
Spalled (Ds)	Shedding of small fragments from aggregate edges
fractured (Df)	Splitting into two or three pieces
Disintegrated (Dd)	Splitting into more than three pieces

5 day mEGDI	20 day mEGDI	1,5 x 5 day mEGDI
0	0	0

Table 3.16: EGDI results for 6.7mm Chrome Slag

Day	Spalled [a]	Ds	Fractured [b]	Df	Disintegrated [C]	Dd	Durability Index
1	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0

a	Weighting Factor	0,5
b	Weighting Factor	1
c	Weighting Factor	2,5

Type of deterioration	Definition
Spalled (Ds)	Shedding of small fragments from aggregate edges
fractured (Df)	Splitting into two or three pieces
Disintegrated (Dd)	Splitting into more than three pieces

5 day mEGDI	20 day mEGDI	1,5 x 5 day mEGDI
0	0	0

Table 3.17: EGDI results for 9.5mm Aggregate

Day	Spalled [a]	Ds	Fractured [b]	Df	Disintegrated [C]	Dd	Durability Index
1	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0

a	Weighting Factor	0,5
b	Weighting Factor	1
c	Weighting Factor	2,5

Type of deterioration	Definition
Spalled (Ds)	Shedding of small fragments from aggregate edges
fractured (Df)	Splitting into two or three pieces
Disintegrated (Dd)	Splitting into more than three pieces

5 day mEGDI	20 day mEGDI	1,5 x 5 day mEGDI
0	0	0

Table 3.18: EGDI results for 6.7mm Aggregate

Day	Spalled [a]	Ds	Fractured [b]	Df	Disintegrated [C]	Dd	Durability Index
1	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0

a	Weighting Factor	0,5
b	Weighting Factor	1
c	Weighting Factor	2,5

Type of deterioration	Definition
Spalled (Ds)	Shedding of small fragments from aggregate edges
fractured (Df)	Splitting into two or three pieces
Disintegrated (Dd)	Splitting into more than three pieces

5 day mEGDI	20 day mEGDI	1,5 x 5 day mEGDI
0	0	0

3.6.3.2.2 Methylene Blue Test

Methylene Blue Test is a rapid qualitative test to determine whether the clay content of the fines of an aggregate contains deleterious swelling clay minerals, which could adversely affect the quality of the asphalt mixture (SAPEM,2011). The deleterious swelling clay materials usually results of the weathering of rock. Experience shows that the methylene blue values of 5 (five) or less are indicative of high-quality filler. Fillers with methylene blue values above 5 (five) should further be evaluated by means of hydrometer analysis and Atterberg analysis (IGDHSA, 2001).
The test is completed by weighing out by dispersing 1g of sample of material passing 0.075mm sieve in water. The sample is then titrated with an indicator dissolved solution of methylene blue. Quantity of the solution is added in increments of 0.5ml until a fine halo appears. The quantity of the solution is then calculated to achieve the effect (SANS 1243, 2012).

Table 3.19 below shows the comparison result of both the Chrome Slag and aggregate.

Table 3.19: Methylene Blue test results

Reference sample	Test Method	Requirement	Result
Dolerite	SANS 1243	<5: High quality filler >5: Additonal Testing Required	0,1
Chrome Slag	SANS 1243	<5: High quality filler >5: Additonal Testing Required	0,15

3.6.3.3 Particle Shape and Texture

The workability and stability of an asphalt mixture is affected by the shape of the aggregate particles. Angular aggregates promote stability while rounder aggregates tolerate the workability. It is recommended that during the design and evaluation of the aggregates, 95% of the aggregates have at least 3 (three) fractured faces. Flat, elongated, and thin aggregates should be avoided as these types of shapes will cause problems during paving and compaction of the asphalt layer (SAPEM, 2011; IDGHSA, 2001). The tests discussed and evaluated are namely: Flakiness Index and Polish Stone Value.

3.6.3.3.1 Flakiness Index

The flakiness index of a coarse aggregate is the mass of particles in that aggregate, expressed as a percentage of the total mass of that aggregate, which will pass the slot or slots of specified width for the appropriate size fraction. The width of the slots is half that of the sieve openings through which each of the fractions passes (SAPEM, 2011; COLTO, 1998; IGDHSA, 2001; SANS 3001 – AG4, 2012).

The test is carried out by determining the percentage of the total mass of the aggregate that passes through slots of a specified width in a metal plate. The standard specifications require that the test should be carried out on two fractions of the aggregate. COLTO specifies that the flakiness should conform to the standards as shown in Table 4302/10 of the COLTO (COLTO, 1998). The result of the testing is shown in Table 3.20. The flakiness index is a rough guide to describe the shape of the aggregate.

Table 3.20: Flakiness results according to specification (COLTO, 1998)

Nominal size of the aggregate	Maximum flakiness index	Chrome Slag	Natural Aggregate (Dolerite)
9,5mm	30	13,4	14.1
6,7mm	30	12,5	12,6

3.6.3.3.2 Polish Stone Value (PSV)

The PSV gives a measure of the resistance of roadstone to the polishing action of the vehicle tyres under conditions similar to those occurring on the surface of a road (SANS 5848, 2008).

The PSV test is applicable to aggregates as it plays a major role in macro surface texture. The aggregates are subjected to accelerated polishing machine using emery abrasive powders and water. The PSV values relate to general conditions of traffic flow. For high and heavy traffic values, it is recommended that the PSV values are at a minimum value of 55 (fifty-five) were for low traffic volumes, the minimum value of 47 (forty-seven) can be adopted. According to the SAPEM manual and COLTO, the required minimum specification should be at least 50 (fifty) (SAPEM, 2011; COLTO, 1998; IGDHSA, 2001; SANS 3001 – AG11, 2012). Test results are shown in Table 3.21.

The test is in two parts, namely;

1. Samples of stone subjected to a polishing action in a polishing machine
2. State of polish reached is measured by means of a friction test and is expressed as the laboratory determined PSV.

Table 3.21: PSV values of Natural Aggregate and Chrome Slag

Ref	Test Method	Requirement	Result
Dolerite	SABS 848	Min: 50	53
Chrome Slag	SABS 848	Min: 50	52

3.6.3.4 Absorption

The test assesses the quality of the aggregates. Aggregate with high water absorption indicates poor qualities. Two (2) tests are completed to finalise the concluded results. The tests are completed with aggregates retained on the 5mm sieve and then on material passing the 5mm sieve fractions. The water absorption test samples are soaked in water for 24hrs before being brought to a saturated surface dry condition and the weighed. The samples are then oven-dried and weighed. The results are expressed as a percentage (%) defined as the loss of mass between saturated surface dry of the oven-dried aggregates. Table 3.22 shows the result comparison between the Chrome Slag and the dolerite samples.

Table 3.22: Water absorption results.

Test Method	Requirement	Dolerite				Slag			
		9,5mm	6,7mm	4,7mm	0-2,75mm	9,5mm	6,7mm	4,7mm	0-2,75mm
SANS 3001 – AG20 & AG21	Max: 1% by mass	0,6	0,4	0,7	0,4	0,8	0,7	0,9	0,4

3.6.3.5 Sand Equivalent

Sand equivalent test indicates the relative proportion of clay-like materials to sand particles in the granular material. The higher the sand equivalent value is, indicates that there is less clay-like material in the samples. There is less clay-like materials in the samples if there is a higher sand equivalent value. Clay-like materials have a direct effect on the performance of hot mix asphalt and the amount should be controlled. A large amount of clay-like particles can coat the aggregate surfaces and prevent the binder from completely coating and adhering to the aggregate.

The test consists of fine aggregate passing through the 5mm sieve. The sample is then oven-dried and transferred into a transparent measuring cylinder. A solution of calcium chloride, glycerine, and formaldehyde diluted in water is added to the sample. The transparent cylinder is thoroughly shaken after which a metal irrigator is used to flush fines upwards. The cylinder is then left to stand undisturbed. A weighted foot is inserted into the cylinder after 20 (twenty) minutes at the top of the fines reading, it is then further lowered onto the sand readings. The sand equivalent is then calculated by expressing the fines reading as a percentage of the sand reading. High sand equivalent values indicate better quality fine aggregate compared to those with low sand equivalent values (SAPEM, 2014; SANS 3001 – AG5). Table 3.23 shows the sand equivalent results of both the Chrome Slag and the dolerite samples.

Table 3.23: Sand Equivalent results

Reference sample	Test Method	Requirement	Result
Dolerite	SANS 3001 - AG6	Min: 50 on Total Fines Fraction	86,4
Chrome Slag	SANS 3001 - AG7	Min: 50 on Total Fines Fraction	79,2

3.6.3.6 Los Angeles (L.A.) Abrasion Test

The Los Angeles test is a measure of degradation of mineral aggregates of standard grading resulting from a combination of actions, including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres. The Los Angeles (L.A.) abrasion test is a common test method used to indicate aggregate toughness and abrasion characteristics. Aggregate abrasion characteristics are important because the constituent aggregate in HMA must resist crushing, degradation, and disintegration in order to produce a high quality HMA.

The principle of the test is to produce the abrasive action by use of standard steel balls which when mixed with the aggregate and rotated in a drum for specific number of revolution cause impact on aggregate. The percentage (%) wear due to rubbing with steel balls is determined and is known as abrasion value. The sample is prepared by the portion of an aggregate sample retained on the 1.70mm sieve and place in a large rotating drum that contains a shelf plate attached to the outer wall. The prepared sample is placed in the abrasion-testing machine. A specified number of steel spheres are then placed in the machine and the drum is rotated for 400 revolutions at a speed of 30 - 33 revolutions per minute (RPM). The material is then separated into material passing the 1.70mm sieve and material retained on the 1.70mm sieve. The sample is then dried in an oven. The % loss is then calculated by calculating the difference between the retained material (larger particles) compared to the original sample weight. The difference in weight is reported as a percent of the original weight and called the "percent loss". The results are shown in Table 3.24.

Table 3.24: Los Angeles Abrasion Test Results

Refs	400
Aggregate	12.5
Chrome Slag	16,4

3.7 Discussion

Two key discussion points are identified for Fly Ash and Chrome Slag, namely: physical and chemical properties.

Chemical Properties

Fly Ash has high silica (SiO_2) content and this reacts with the calcium hydroxide ($Ca(OH_2)$) with the addition of water to form stable cementitious compounds. This type of reaction is the pozzolanic reaction and will continue while moisture is available for periods of time. The high percentage of SiO_2 shown in Tables 3.2, 3.3 confirms that the Fly Ash samples for this study will continue with the reaction process if used with a reaction agent like cement or lime. The lime/silica (CaO/SiO_2) ratio, which is indicative of cementing potential, varies between 0.16 for the ULULA Class S Fly Ash in Table 3.2, and 0.13 for the ULULA Class N Fly Ash shown in Table 3.3. The Fly Ash specimens show a low cementing potential therefore a cementing agent will be required during any project such as for example: stabilisation. Fly Ashes are classified by American Society for Testing and Materials (ASTM), a distinction between Class C and Class F. Fly Ash is made according to their aggregate alumina, silica and ferric oxide contents. Distinction is made on the sum of the total aggregate alumina (Al_2O_3), silica (SiO_2), and ferric oxide (Fe_2O_3) and is presented in the following formulae:

$SiO_2 + Al_2O_3 + Fe_2O_3$

If the sum is greater than 70%, then the Fly Ash is classified as Class F, and if the sum is between 50% - 70%, it is classified as a Class C. In Tables 3.2, 3.3, it shows that all the Fly Ashes fall in the range of Class F Fly Ash (ASTM C618, 1993).

Fly Ash needs to have a test completed to indicate the amount of unburned coal remaining in the ash samples and LOI is thus completed. This will give an idea of possible air entrapment problems in fresh concrete which can lead to durability problems in concrete. LOI is low on the Fly Ash results as shown in Tables 3.1, 3.2, and 3.3 varied from 1.14 to 1.6 for ULULA Class S Fly Ash and 0.13 to 4 for the ULULU Class N Fly Ash. These Fly Ashes are well below the required standard of not greater than 5%. (SANS 1491-2, 2005). LOI will not affect any part of the asphalt mixture design as the Fly Ash only acts as a filler and aids in some instances with the gradation. Some of the applications using Fly Ash are not affected by LOI namely:

1. Fly Ash is used as a filler in asphalt
2. Fly Ash is used as a flowable fill
3. Fly Ash is used in structural fills
4. Stabilisation of pavement materials.

Chrome Slag is made up mostly of SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, and Cr_2O_3 as shown in Tables 4.1 and 4.3 respectively. The main concern of using Chrome Slag is the amount of MgO and CaO that is found within the Chrome Slag fragments. These components have results of 17.15ppm and 4.17ppm respectively according to results in Table 3.1. The hydration of CaO and MgO in contact with moisture is largely responsible for the expansiveness of most Chrome Slags. The free lime hydrates rapidly and can cause volume changes in a few weeks. MgO hydrates more slowly and contributes to the long-term expansion that may take several years to develop in the field. This can be controlled when the Chrome Slag is bound within an asphalt mixture. Free CaO from leachate is bound with water forming $Ca(OH)_2$. When exposed to atmospheric conditions, like with the free CaO of the Fly Ash, it forms CO_2, and creates calcium carbonate ($CaCO_3$). It settles down in the form of a white powder.

It has been noted that ferrochrome Chrome Slag is an acid (Niemela et al, 2007). The basicity of the Chrome Slag can be calculated using the following formulae:

$$B_3 = \frac{0{,}0178 \text{ x } \%CaO + 0{,}0248 \text{ x } \%MgO}{0{,}0166 \text{ x } \%SiO_2 + 0{,}0098 \text{ x } \%Al_2O_3}$$

$B_3 = 0.6$ – Acidic Chrome Slag.

If the results calculated indicates a value greater than 1, it means that the Chrome Slag is basic but if the value is less than 1, it indicates that the Chrome Slag is acidic.

The higher the value of basicity, the higher the process of carburisation, but this only occurs within the Chrome Slag as Chrome Slag is not capable of releasing any carbon.

Acidic Chrome Slag losses silicon elements due to oxidation as silicon forms part of the acid reaction.

Acidic materials need a coating as the binder will not always bind to the aggregate therefore the Fly Ash aids the binding to the Chrome Slag. The degree of basicity in an acidic cupola furnace Chrome Slag is between 0.5 and 0.7, that of a basic Chrome Slag is between 1.5 and 2, neutral Chrome Slags have a basicity degree between 0.7 and 1.5.

The total chemical composition of Chrome Slag defines the order of crystallisation during the cooling process. The crystallisation phase for Chrome Slag as shown in the XRD Table 4.5 is divided into three (3) phases, namely:

1. Amorphous glass phase
2. Crystalline and zonal Fe-Mg-Cr-Al-spinels
3. Metal drops.

The XRD results showed a high amount of amorphous material of between 50-60% and less than 2% of quartz.

Physical Properties

The fineness for of the Fly Ashes is within specified limits of less than 12% as shown in Tables 3.1 for Class S and less than 40% for Class N. The gradation of Fly Ash is an important factor as a coarse gradation could lead to less reactive ash and could contain higher carbon contents (FA FACTS, 2003; Conn *et al*, 1999). The Fly Ash particles range from 0.300mm to 0,002mm for both Class N and Class S ULULA Flay Ashes. It has been noted in a recent study that at least 40% of the sample should pass the 10 micron sieve (1000 microns = 1mm) as these are the particles that contribute to the strength regardless of the type of the Fly Ash (Mehta, 1998). Samples above the 0,300mm sieve are considered inert as they do not participate in pozzolanic reactions. Particles between the 0.010mm sieve and the 0,300mm sieve are the ones that slowly react. The Fly Ash have mostly particle sizes between 0,020mm sieve and 0,300mm sieve, therefore these will react slowly over time. These will react slowly, as previously stated above, but the material above the 0,300mm sieve will be inert material and will basically behave like sand, which only contributes to the granular modulus of the material. As stated, particles passing the 10 micron sieve (0.010mm) are very critical as these are the more reactive particles. Figure 23 gives a visual idea of Fly Ash reactivity according to gradation. The Fly Ash material passes the 0.020mm sieve of 54 %. It was also stated that at least 40 % should pass the 10 micron sieve for more reactive material but this is not the case with the Fly Ash as seen in Figure 24. It is also one of the reasons why Class F Fly Ash requires a cementing agent to form pozzolanic reactions for early strength gain. After the initial strength gain, the Fly Ash in this study has enough pozzolanic material to continue with the slow reactions which will occur continuously over time. The Fly Ash is fine silty Fly Ash, which is common of Fly Ash and can be used to improve gradings of coarse granular materials. It is critical that the fineness of Fly Ash be within limits stated by ASTM. Although SANS 1491-2 (2005) states that the Fly Ash % retained on the 0.045mm sieve must not exceed 12.5%, it is however specified in AASHTO M295 (ASTM C618) that maximum to be retained on the 44µm sieve is not to exceed 34%. It can then be stated that with SANS 1491-2 the Fly Ash can be utilised if the required specification is enforced but with AASHTO M295. Table 4.1, shows the sampling of Fly Ash over a 7 (seven) day period where gradation was conducted on each sample. It is typical values taken at various loads dispatched. To use and design with Fly Ash, it is imperative that the supply of Fly Ash be uniform in order to supply a consistent product. The Fly Ash is consistent with gradation and LOI requirements, due to that the Fly Ash is already processed. The colour of the Fly Ash specimen is pale grey. The colour depends on its chemical and mineral constituents. Fly Ash is very consistent for each power plant and coal resources. Fly Ash is composed of various elements as shown in Table 3.1, X-ray spectrometry of the Fly Ash.

Under the XRD fraction, Chrome Slag is composed of fragments of grey rock of very small grain size but is mostly made up of spinel, chromite, and an amorphous phase. Chrome Slag is dark grey in colour with a density of about 3470kg/m^3. Chrome Slag is a coarse material with little dust as compared to natural construction materials. The material is acidic, and the pH values vary between 7 and 10.

GRADING ANALYSIS

SIEVE	ULULA		
3,350			
2,360			
1,180			
0,600			
0,425			
0,300	100		
0,150	99		
0,075	96		
0,060	77		
0,050	73		
0,020	54		
0,005	2		
0,002	1		

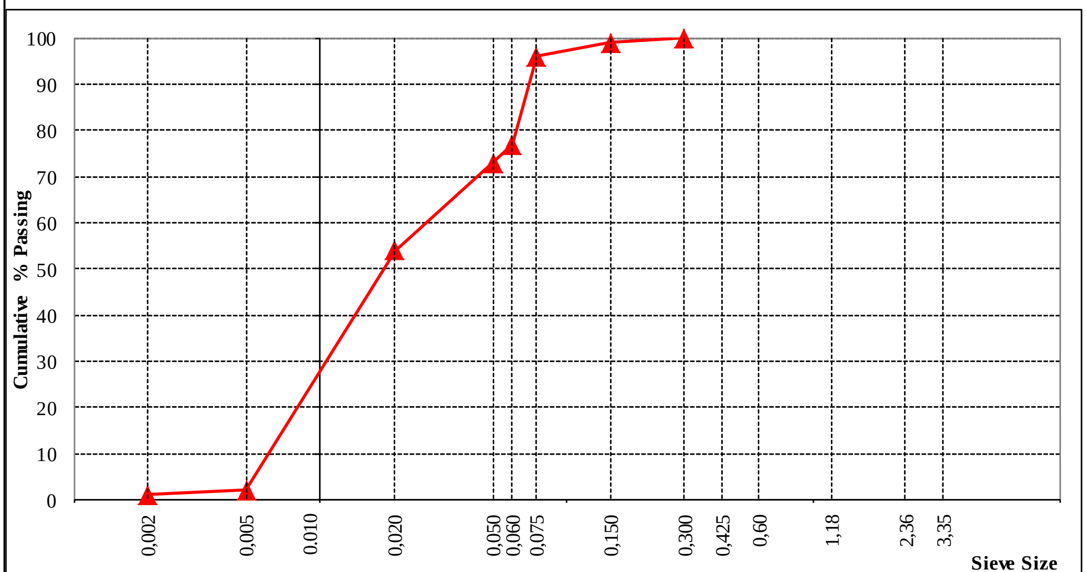


Figure 23: Size distribution curves of Fly Ash

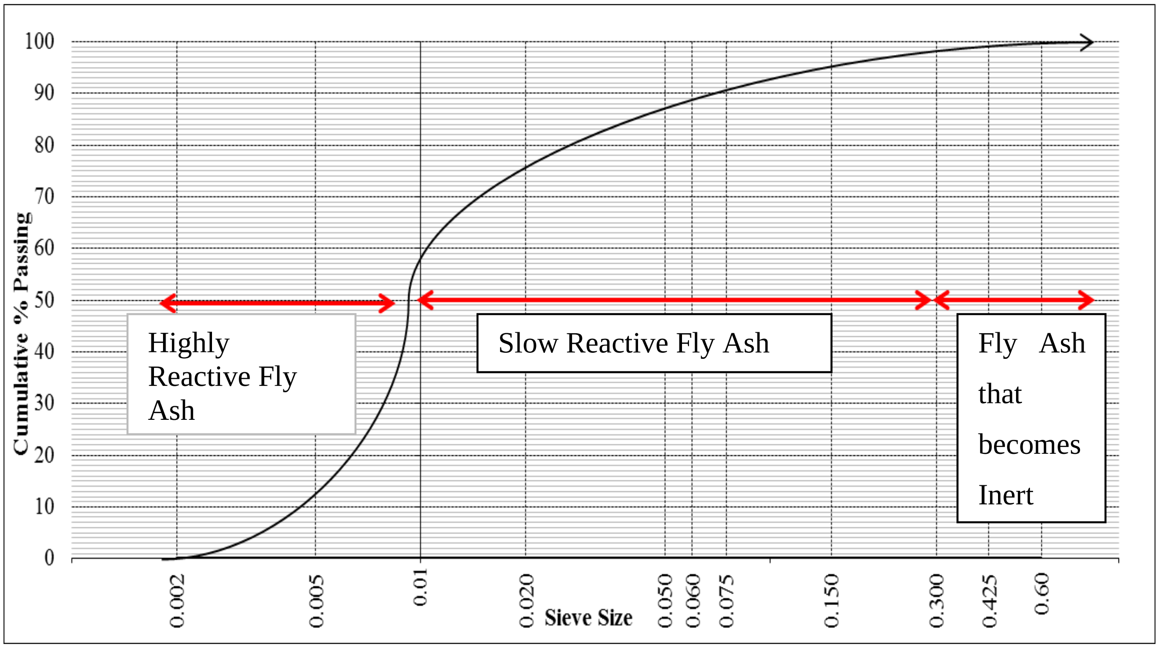


Figure 24: Reactivity of Fly Ash according to Grading

The grading packing of the Chrome Slag is discussed in Chapter 5 of this study.

Aggregates

The aggregates in this study needs to confirm to the required standards as set out in Table 3.1. Chrome Slag conforms to all the requirements set out. The Chrome Slag showed that it is “softer” when compared to the Natural Aggregate when it came to the hardness and toughness test but it was still within the requirements which included the ethylene glycol test which also had to confirm to the hardness test. On average, the difference between the Natural Aggregate and Chrome Slag on the ACV test was 13% which the Natural Aggregate test harder. On the 10% FACT, the aggregate showed a higher kN crushing rate than the Chrome Slag. The evaluation is only done on the 9.5mm Chrome Slag as this is the main stone in the asphalt mix which will take most of the loads.

Durability of both materials were subjected to Methylene Blue test and EGDI test with results showed in Table 3.19 and Table 3.15-3.18 respectively. The EGDI results came out to the values of 0 (zero), which indicated that both the Natural Aggregate and Chrome Slag is durable and will perform to the required life span for what it is intended for. The Methylene Blue test results for the aggregate and Chrome Slag were 0.1 and 0.15 respectively. Both the materials have showed that there are no deleterious materials that will adversely affect the mixture when bound in an asphalt mixture.

Particle shape and texture was tested by means of Flakiness Index test and the Polish Stone Value test. With results in Tables 3.20 and 3.21 respectively, both materials conformed to the specifications. The Chrome Slag did, however, show a better flakiness index than the Natural Aggregate with results of 13.5 and 14.1. This indicates that the material is quite angular with little flakiness material that will contribute to the strength and workability of the asphalt mixture. The Polish Stone values test showed that both materials are durable and are above the minimum requirements as stated in Table 3.21 of 50 with Chrome Slag's value of 52 and Natural Aggregate of 53.

Absorption is a test indicates the quality of the aggregates. The Chrome Slag material as shown in Table 3.22 displays a higher absorption than the Natural Aggregate but it is due to the porous nature of the material. The results still show that the material conforms to the specifications and can be used as is, but this could influence the binder absorption which is evaluated in Chapter 5 of this study.

Sand equivalent test indicates the relative proportion of clay-like materials to sand particles in the granular material. The higher the value is indicative of there being less clay-like material in the samples. In Table 3.23, the results for the Natural Aggregate were 86.4 while the Chrome Slag was 79.2. Both the materials are well above the minimum requirement of 50. The bitumen will bind well with the materials in this study.

The L.A. Abrasion test is a test for materials durability/hardness and results are indicated in Table 3.24. The Chrome Slag showed a percentage loss of the original grading after 400 revolutions to 16.4 respectively. The materials show that degradation and crushing will not happen during the life span for what the material will be sued for. The Natural Aggregate does show a more durable result of 12.5 after 400 revolutions. The Natural Aggregate indicates a much stronger and durable material.

Bitumen

Bitumen is used in penetration grade bitumen and modified bitumen. The penetration grade bitumen used for the study is 50/70 and the modified will be AE-2. These bitumens are the norm used by most of the design engineers in South Africa. As per Tables 3.11 and 3.12, all the standard requirements are met for the approval of the binder to be used in an asphalt mixture.

3.8 Summary

The overall performance of an asphalt mix is dependent on, amongst others, the properties of the constituent materials, which include aggregate, binder, and filler.

In the selection of a suitable asphalt mixture, the following factors need to be considered:

1. Aggregate properties
2. Purpose for which the layer will be utilised
3. Type of filler and binder to be utilised
4. Required deformation resistance and durability performances of the asphalt overlay
5. Cost and environmental conditions
6. Traffic considerations
7. Pavement considerations
8. Climate considerations

General guidelines on the selection of a suitable asphalt mixture are well published as noted in this study. The common books used in this study:

- TRH8; Design and use of hot-mix asphalt in pavements (1987),
- TRH14; Guidelines for road construction materials (1985),
- COLTO; Committee of Land Transport Officials (1998),
- HMA; Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa (2001);
- TMH1, Standard methods for testing road construction materials (1986);
- TG1, Technical Guideline: The use of Modified Bituminous Binders in Road Construction (2001);
- SABITA Manual 2, Bituminous Binders for road construction and maintenance (2007);
- SANS, South Africa National Standards;
- South African Pavement Engineering Manual (SAPEM), 2013 and
- SABITA Manual 24, User Guide for the Design of Asphalt Mixes (2019).

With use of Fly Ash as a suitable filler, is fairly new to South Africa but not new worldwide. In this study, ULULA Fly Ash was chosen and was classified as Class N and Class S. To utilise the Fly Ash, the Fly Ash needs to be evaluated for physical and chemical properties to see if the Fly Ash will be able to be used as a filler in the asphalt mixture. To date, no actual standards exist in South Africa for the use of Fly Ash, therefore current standards that are being used for cement production needs to be sued and adopted to suit the needs for asphalt mix design.

Fly Ash can be chemically evaluated and classified according to the following steps:

1. Application of the XRF analysis, one can determine the classification of the Fly Ash.
2. Determine the Loss of Ignition (LOI) for strength evaluation
3. Determine the amount of free lime (fCaO) for activation of possible anti-stripping agent

Compiling a gradation graph, one can physically study the following aspects of the Fly Ash:

1. Fineness must be less than 45% retained on the 0.045mm sieve due to that any coarse material will lead to possible less reactive Fly Ash.
2. The gradation is divided into 3 distinctive areas, namely: percentage above 0.300mm sieve, percentage between 0.300mm sieve and 0.010mm sieve and percentage below the 0.010mm sieve
3. The division of the grading can be evaluated as follows:
    a. The gradation above the 0.300mm indicates a non-reactive mineral and thus can only be used to adapt the gradation of the full sample for a certain criterion.
    b. The gradation between 0.300mm sieve and the 0.010mm sieve is a typical indication of Class F Fly Ash and shows that it will be able to react once suitable compounds are added to a certain mixture.

All the Fly Ashes gradation fall between the 0,300mm sieve and the 0,010mm sieve which is indicative that that the Fly Ash will contribute as a gradation component to the asphalt mixture and as a filler, as seen in Figure 24.

The Fly Ash in this study have colours of pale grey, which is indicative of its chemical and mineral constituents and association with unburned carbon content. The Fly Ash as a filler will contribute to an anti-stripping agent due to the amount of free CaO available

As stated in the study, Aggregates properties commonly used for the production of asphalt depend on many factors, namely:

1. Mineralogy of the parent rock
2. The extent to which the parent rock has altered mostly by means of leaching and oxidation
3. The process required to produce the required aggregate particle sizes.

Aggregate properties that are significant to the performance of hot mix asphalt, include:

4. Hardness/toughness
5. Durability
6. Shape
7. Surface Texture

8. Absorption
9. Cleanliness

Hard and rough textured aggregate results in stable and rut-resistant hot mix asphalt mixes (Komba, 2014). Durability is another key aspect that should be possessed by aggregates used in the production of asphalt. The aggregate should be able to resist breaking down and disintegration under environmental conditions.

Aggregates need to have angular rough surface texture for resistance to permanent deformation (rutting). This is important for heavy traffic applications accompanied by high ambient temperatures. Smooth aggregates may only be considered for low traffic, where workability is generally more important than stability. It must then be considered that for an effective asphalt layer, aggregates must display more rough angular material than smooth material. The designer must evaluate the results in order to determine the effectiveness the aggregates will have on the required for the optimum design mixture. The surface texture of the aggregates has an effect on the skid resistance of the layer. A harsh texture provides skid resistance at low speeds. Durability of the aggregates play an important role for life span of the aggregate, therefore it is critical that polish stone values are adhered to in the design process.

Ethylene Glycol Testing has been completed to ensure durability of the aggregates which includes both comparison natural dolerite aggregates and the Chrome Slag samples. Ethylene Glycol testing have further been evaluated to ensure durability by means of ACV and 10% FACT testing requirements. These requirements are written in contract documents. The requirements for the study were evaluated according to the COLTO tables 3602/2 and 3602/3.

The L.A. Abrasion test is an empirical test; it is not directly related to field performance of aggregates. Field observations generally do not show a good relationship between L.A. abrasion values and field performance. L.A. abrasion loss is unable to predict field performance. Specifically, the test may not be satisfactory for some types of aggregates. Some aggregates, such as Chrome Slag and some limestones, tend to have high L.A. Abrasion loss but perform adequately in the field. L.A. abrasion loss seems to be reasonable well correlated with dust formation during handling and HMA production in those aggregates with higher LA. abrasion loss values typically generate more dust. L.A. Abrasion can be summarised as follows:

1. For an aggregate to perform satisfactory in pavement, it must be sufficiently hard to resist the abrasive effect of traffic over a long period of time. The soft aggregates will be quickly ground to dust, whilst the hard aggregates are quite resistant to crushing effect.
2. The test also determines the quality of the aggregate.

3. The L.A. Abrasion test is widely used as an indicator of the relative quality or competence of mineral aggregates.

Both Chrome Slag and Dolerite in this study conformed well above the norm standard as discussed in this study. Even though Chrome Slag was “softer”, Chrome Slag is angular and porous, has a high specific gravity, is more resistant to abrasion and weathering, is highly stable due to high angles of internal friction, and has hardness that approaches quartz. Chrome Slag, shown in this study, has similar physical properties to the conventional, primary aggregate and can be processed, crushed, and screened into practical size for easy batching into both surfacing and base asphalt surfacing. The most significant difference between steel Chrome Slag and most Natural Aggregates is its high particle density, which is the consequence of the presence of iron compounds.

The use of Chrome Slag as a replacement of Natural Aggregate can be utilised in an asphalt mixture as the Chrome Slag conforms to the requirements as set out in design procedures developed for South African conditions.

The Bitumen used in the study is pen grade 50/70 and AE-2. Both the bitumen is used currently throughout South Africa and is the preferred bitumen to be used in asphalt mixtures. The choice of the two was due to them conforming to the following:

1. Both can be used in most climatic zones
2. Readily available
3. Both can be used for asphalt mixtures of thickness from 20mm and above.

As stated, there is more interest in using AE-2 which is attributed to the following factors:

1. Increased demand on asphalt pavements in terms of traffic volumes and wheel loads.
2. Normal binders have difficulty in meeting the requirements in regions with extreme climatic conditions.
3. In many cases, regular maintenance has not been done and there is a need to provide an economically viable solution to poor road conditions.
4. Availability of high-performance binders.
5. Porous asphalt and stone mastic asphalt perform well with modified binders.

The benefits of this binder over conventional binder include the following:

1. Improved consistency
2. Reduced temperature susceptibility for flushing and bleeding
3. Improved stiffness and cohesion

4. Improved flexibility, resilience, and toughness by permitting higher binder film thickness for increased mix durability.
5. Improved binder-aggregate adhesion
6. Improved resistance to in-service ageing related to fatigue, ageing, or oxidation.
7. Improved fuel resistance.

Modified binders are more expensive but require appropriate design of the final product to maximise the benefits appropriate to the specific need. This study is to use recycled materials for construction of urban/rural roads by placing a non-conventional thin layer asphalt.
This is the reason why this study will, in effect, also incorporate a conventional binder (50/70 penetration grade) for a comparison and can be more cost effective at the end.

Chapter 4 Environmental Effects of Fly Ash and Chrome Slag

4.1 Introduction

This chapter presents studies related to the effects of Fly Ash and Chrome Slag on the environment, focusing mainly on Leaching properties of both Fly Ash and Chrome Slag.

4.2 Environmental Effect from Leaching

Leaching is water that collects contaminants as it permeates through and over material and this has a key probable hydrological effect. Typically, leaching is an aesthetic issue and not harmful to the environment. If leaching does occur, remediation can be accomplished by dilution, containment of the leachate, and removal by vacuuming, or natural oxidation, all of which can be effective.

4.2.1 Fly Ash

Leachant testing is administered to scrutinize the solubility of the Fly Ash samples (Oppenshaw, 1992; Solc *et al.*, 1995). The process of coal combustion and type of plant processes initiates Fly Ash samples that are extremely fluctuated (Roy *et al.*, 1981). Studies have also found that some elements tend to decrease in leaching as the material ages. As the materials ages, the pH levels also fluctuate and these encourage the leaching of trace metals and it was found that arsenic has been favoured to leach at high pH levels (Sloc *et al.*, 1995; Gitari *et al.*, 2009; Moolman, 2011).

Roy *et al* (1981) also reported relative concentrations of elements leached in comparison, with amount available from ash sluice water of various pH levels, namely:

- Alkaline: Se>B>Cr>Ni>Cu>Ba>As>Zn>Al
- Neutral: B>Cd>As>Se>Zn>Ni>Mn>Cu>Ba
- Acidic: B>Zn>Ca>F>Na>Mg,Co>Ni,Sr>Be>Cu,Pb,Al>Si,Fe,K

Some metals found in Fly Ash are calamitous but have been found to be within RCRA limits. Arsenic is one lethal element that is found all levels of pH, but it is in a non-toxic form (Oppenshaw, 1992; Solc *et al.*, 1995; Moolman, 2011).

Numerous studies have analysed the leaching of Fly Ash elements and what the impact is on the environment. Mostly, the studies have revealed that when Fly Ash is used in concrete, the Fly Ash is entombed and the risk of leaching of toxic elements is minimal. Heyns concluded that Fly Ash used in road stabilisation has proven to leach minimal amounts of trace elements that is not detrimental to the environment (Heyns, 2016). Coal Fly Ash has been successfully used as a proven yield from agricultural land, soil cleansing agent including for sludge and effluvium treatment and hazardous waste treatment (Moolman, 2011). The soils for agricultural has seen change in pH levels, the fertility of the soil structure and microbial communities due to the environmental pollution formed through energy creation. Micro-organisms become microbial to soil pollution and can degenerate the pollutants in the soil that leads to a recovery of pollutant soils (Surridge *et al.*, 2009). As shown in this study, Fly Ash's physical appearance is fine with powdery particles that are spherical in shape and is mostly without a clearly defined form (amorphous). Bituminous coal Fly Ash mostly contains trace elements of silica, iron oxide, calcium, and alumina with copious amount of unburnt and burnt carbon. The pH value of fresh Fly Ash is about 12 when newly processed and once placed in landfills sites, the Fly Ash ages and the pH stabilises at about 8.5, thus further classifying Fly Ash as an alkaline material (Surridge *et al.*, 2009). With the pH stabilising, it is a probable contributor to agricultural land rehabilitation as a liming agent. The basic elements found in Fly Ash such as silicates, oxides, sulphates and alumina silicates cannot be broken in the environment, but they are susceptible to change (Ayanda *et al.*, 2012). The heavy metals found in Fly Ash can infiltrate that aquatic environment and create a steady level in the aquatic environment (Ayanda *et al.*, 2012). In South Africa, the elements in Fly Ash have been analysed for concentration of the toxicity. Some of the Fly Ashes in South Africa have been analysed for detectable concentration of all toxic and potentially toxic elements. The elements included: Cobalt (Co), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Vanadium (V), Titanium (Ti), Selenium (Se), Stratium (Sr), Zinc (Z), which are essential to health, while other elements, also known as heavy metals, such as Arsenic (As), Antimony (Sb), Cadmium (Cd), Chromium (Cr), and Lead (Pb) are harmful to health in excessive amounts (Ayanda *et al.*, 2012). Table 4.1 show the elements found in common South African Class F Fly Ash conducted under an X-Ray spectrometry test.

Fly Ash is used for various environmental applications that include:

1. Phosphorous retention
2. Heavy metal immobilisation
3. Acid mine drainage

Further research was completed on the application of Fly Ash to soil which influences the bioavailability of the required nutrients and metals. The bioavailability promotes the amount of chemicals available for organisms either in a positive or negative way. It is an important factor as this can alleviate chemicals once they come into direct contact with soil (Seshadri *et al.*, 2010). Seshadri *et al*, 2010, identified 2 major elements if Fly Ash to contribute to nutrition in plants namely, S and Ca. Vascular plants rely on the Boron element found in Fly Ash. These elements make Fly Ash a suitable fertiliser to increase the efficiency of the crop. Reynolds *et al*, 2002, produced artificial soil by combining Fly Ash, lime and sewage sludge. The Fly Ash and sludge formed insoluble metal hydroxides and thus creating and improved soil type texture and increased the fertility for better crop efficiency. Ciccu *et al*, 2001, used Fly Ash to reduce the heavy metals in the soil from contamination of mining in Italy. The study revealed that Fly Ash can be successfully used to disable the heavy metals ions.

Germany is a front runner with Fly Ash power plant producing no water pollution as this proved with mixture of Fly ash and water to a ratio of 1:1 and these tests indicated no unpropitious effects on fish, aquatic plants and organisms (Moolman, 2011).

Britain has conducted a study of the Fly Ash dumps discharge into the surface water. The results revealed that the water from the dumps needed not to be diluted at all to influence fresh water in the area. The deposits had no adverse or potentially harmful elements even though the dump sites have been operation for a number of years (Moolman, 2011).

Laboratory leach tests compiled have indicated that Fly Ash components showed restricted movement. The study made Fly Ash as a viable option for use in the construction industry (Heebink *et al.*, 2011). Usem (1988) investigated the leaching properties of Fly Ash after stabilisation of soil using it with admixtures like lime, cement, and bentonite. The toxicity elements found in the Fly Ash was reduced to acceptable standards.

4.2.2 Chrome Slag

Iron and steel Chrome Slags are formed through the addition of fluxing agents such as, but is not limited to, limestone or dolomite to blast furnaces and steel furnaces to strip impurities from iron ore, steel, and other ferrous feeds. Fluxing agents normally used are namely:

1. Limestone
2. Dolomite
3. Lime

These calcium compounds couple with aluminium, silica, phosphorous and other impurities in the iron to form Chrome Slag. The Chrome Slag floats to the top of the melt and is poured off into piles for disposal (Simmons *et al*, 2001).

Since Chrome Slag is formed in such high temperature, most compounds with lower boiling points have been driven off. Any residuals of these compounds such as sulphur, selenium, carbon, cadmium, lead, copper, and mercury, are typically encased within Chrome Slag's glassy matrix (Ziemkiewicz & Skouser, 1998). Chemical bases of Chrome Slag consist mostly of lime, magnesia, and other basic compounds, and leaching of this material results in the liberation of high concentrations of alkalinity to the dissolving fluid. This can drive the pH of the fluid to 10 or 11. The test results have shown that Chrome Slag pH is 9.87 respectively. However, it has been noted that the lime in Chrome Slag is unlike ordinary agricultural lime—the Chrome Slag lime is in loose chemical combination with silica, iron, and manganese. Chrome Slag does not "burn" like agricultural lime nor revert to carbonates. As a results of this, Chrome Slag remains in a stable form where it will produce alkalinity over long periods of time until exhausted (Simmons *et al*, 2001).

Most steel Chrome Slags contain heavy metals, therefore, there has been some concern with the potential of these metals to leach under acidic conditions. Before utilising Chrome Slag in the field, it is important to determine the leachability of these metals in a controlled laboratory test. Typical Chrome Slag chemistry is shown in Table 4.1.

Table 4.1: Typical air-cooled Chrome Slag chemistry

Parameter	Unit	AG 4.75	AG 9.5	AP P/SAND
SiO2	% g/g	28,92	36,96	23,65
TiO2	% g/g	0,9	0,77	0,9
Al2O3	% g/g	23,61	25,86	23,88
Fe2O3	% g/g	8,92	5,16	7,32
MnO	% g/g	0,33	0,31	0,45
MgO	% g/g	18,74	17,15	21,78
CaO	% g/g	4,88	4,17	4,74
Na2O	% g/g	<0.01	<0.01	<0.01
K2O	% g/g	0,14	0,13	0,13
P2O5	% g/g	<0.01	0,01	<0.01
Cr2O3	% g/g	13,85	10,44	18,09
SO3	% g/g	0,16	0,16	0,17

Note: % g/g = ppm

The rate of leaching diminishes rapidly with time and the chemical nature of the sulphur products changes from sulphide to sulphate by aging (oxidation). Although no exact timetable for this process has been established, most leachate events are of short duration and are a onetime occurrence. Typically, leaching is an aesthetic issue and not harmful to the environment (NSA, 2003).

The Federal Register, vol 45, No. 98, May 19, 1980, lists the substances ruled hazardous by EPA. On page 33124, four steel-industry substances were listed. These were identified to EPA by a consulting firm requested to examine all steel-industry products, including Chrome Slag, to determine which were hazardous under EPA criteria. The only furnace-related by-product of the steel industry listed as hazardous is the electric-furnace emission control dust or sludge, based on possible high concentrations of hexavalent chromium, lead, and cadmium. Individual sources can be tested from these materials and cleared from the hazardous classification on an individual plant basis. EPA’s own research studies performed over 10 years have listed Chrome Slag as non-hazardous (Federal Register, 1980).

Simmons *et al*, 2001, studied steel Chrome Slags with varying neutralisation potentials that were leached with acid mine drainage of a known quality, using an established laboratory procedure. Leachates were analysed for pH, alkalinity/acidity, Fe, Al, Mn, Ca, Mg, Ag, As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Se, TI, V, Zn. The results showed that very little of the metals in the leachates originated from Chrome Slag leaching, even under acidic conditions. The results further indicate that many metals present in Chrome Slag may be bound in insoluble forms that remains stable under a variety of pH ranges (Simmons *et al*, 2001).

Laboratory studies by Bowden *et al*., 2009, have shown that basic oxygen furnace Chrome Slag can be utilised to remove phosphorous from an onsite water disposal system. The researchers postulated that the Chrome Slag could be used in single pass, self-contained treatment modules in alternative treatment systems. Their studies showed that the Chrome Slag removed greater than 99% of PO_4 from a 10mg/L PO_4-P solution within 1hr of contact. Long-term attenuation capacities of the mixtures were assessed by continually loading bench scale columns with a 3.3mg/L PO_4-P solution at representative groundwater flow rates.

The Australasian (iron & steel) Chrome Slag Association (ASA) investigated six different types of iron and Chrome Slag to determine their effectiveness in removing contaminants from artificially polluted stormwater runoff. The contaminants included 17 heavy metals listed as follows: Al, As, Sb, B, Ba, Be, Cd, Cr, Cu, Pb, Mg, Hg, Mo, Ni, Se, Sn, and Zn. The study was concluded showing that all Chrome Slags had the potential to be utilised as stormwater filter media as they reduced the concentrations of As, Cd, Cu, Pb, Ni, Zn, phosphorus, and nitrogen in the artificial stormwater. However, it was noted that different type of Chrome Slags will act in different ways, so it is recommended that field trials are necessary to determine the optimal treatment based on Chrome Slag type and runoff characterisation (ASA, 2006).

4.3 Comparison

To understand what the impact of these elements are on the environment, a comparison needs to be completed. The elements need to be able to be compared for maximum allowable absorption which is fit for human and environment survival. Water will be a perfect comparison as this is the source of life and set standards have been published worldwide for the maximum allowable elements (Bicki *et al.*, 1993; Oram B, 2019). Table 4.3 show the comparisons of required maximum allowable elements also found in Fly Ash and Chrome Slag with possible effects on health. The results must be in Table 4.3 is for the samples found in the readily available dump sites without any treatment. The Chrome Slag, however, has been crushed to various sized aggregates. It is thus critical that leach tests be conducted so that potential hazards can be red flagged for the use of Fly Ash and Chrome Slag in any destined project. The Fly Ash with no treatment shows that leached elements namely: Ba, Cr, Pb are of a concern once the elements have leached into the groundwater. Arsenic, however, is low and does not create a concern if leached into the groundwater. The Chrome Slag aggregates indicated that the leached elements of concern were namely: Ba, Se, and Cu. Arsenic in the Chrome Slag results are shown to be lower than Fly Ash. The Chrome Slag results shown in Table 4.3 are of a concern, due to the heavy metals that are present which does indicate a potential hazard.

Fly Ash left to weathering suffers from long term disintegration thus the neutralization of Fly Ash is extended. This creates an opportunity of liming potential that has an increased life span and is nondramatic like agricultural lime (Surridge *et al.*, 2009). The slow liming potential by the decrease of pH values allows for the environment to adapt and change the microbial organisms and plants within the Fly Ash soils (Surridge *et al.*, 2009).

For any type of construction project, due to the variables found in Fly Ash and Chrome Slag, it is of the utmost importance that leach tests be conducted to evaluate any potential harmful elements and to reduce any possible pollution of the environment. To show that the use of the Fly Ash and Chrome Slag noted in this study will not have any harmful effects, leach tests were completed on the Fly Ash and Chrome Slag in an asphalt mix design briquette.

The chosen mixtures for this study were subjected to leach testing, and comparison tables could be drawn up to compare to Tables 4.1, 4.2, and 4.3.

Table 4.2 shows the leach elements of the Fly Ash and Chrome Slag when compared to maximum allowable inorganics in accepted drinking water. High levels of Ba and Cr are found in the results. Therefore, it can be said that Fly Ash left in dumps can be harmful once elements are leached and once the elements find their way into the groundwater system. However, the Chrome Slag is quite the opposite, showing minimal harmful elements being leached, but caution still needs to be taken. Table 4.3 shows the leach elements of the Chrome Slag when compared to maximum allowable inorganics in accepted drinking water.

An environmental study was concluded by Lind *et al*, 2001, on FeCr Chrome Slag in road construction. The results from the insitu leachate tests revealed that there was a low migration of particles from the Chrome Slag to the underlying soil, and that the leaching into the groundwater was also low for all the elements analysed.

Table 4.2 X-Ray spectrometry tests on typical Class F Fly Ash

Parameter	Range (ppm
As	16
Cu	57
Ga	66
Mo	9
Nb	38
Ni	67
Pb	84
Rb	64
Sr	1643
Th	54
U	22
W*	18
Y	78
Zn	81
Zr	457
Cl*	8
Co	22
Cr	232
F*	964
S*	2270
Sc	29
V	160
Cs	13
Ba	1704
La	109
Ce	285

Table 4.3: Maximum allowable inorganics accepted in drinking water (Bicki *et al.*, 1993; Oram B, 2019)

Material	**Fly Ash Results (ppm)**	**Chrome Slag Results (ppm)**			**Maximum Acceptable Level (ppm)**	**Possible Effects of Higher Levels**
		4,75mm	**9,75mm**	**Sand**		
As	16	6.54	5.74	5.37	0.05	Lung Cancer, kidney damage
Ba	1502	70.1	82.9	56.6	2	Heart damage
Cr	232	13.85	10.44	18.09	0.1	Liver, kidney damage, circulatory disorders
Pb	84	2.03	2.03	2.03	0.015	Brain damage, kidneys, nervous system
Se	2,8	0.36	0.75	0.36	0.01	Growth inhibition, liver damage
Cu	57	4.19	4.19	4.19	1.3	Metallic taste, blue-green stains on fixtures, gastrointestinal irritation

Table 4.4: X-Ray spectrometry tests on the Chrome Slag

Parameter	Parts per million (ppm)		
	AG 4.75mm	**AG 9.5mm**	**AP P/SAND**
As	6,54	5,74	5,37
Ba	70,1	82,9	56,6
Bi	3,68	5,43	4,13
Cd	21	53,5	69,5
Ce	<3.08	6,69	27,5
Cl	<2.59	<2.59	<2.59
Co	<0.56	<0.56	<0.56
Cs	0,9	0,92	0,88
Cu	<4.19	<4.19	<4.19
Ga	<3.21	<3.21	<3.21
Ge	<0.50	<0.50	<0.50
Hf	4,07	4,05	4,08
Hg	<1.00	<1.00	<1.00
La	42,3	38,9	39,5
Lu	1,91	2,41	2,17
Mo	0,86	<0.51	<0.51
Nb	<2.15	<2.15	<2.15
Nd	449	590	472
Ni	56,8	84,1	67,7
Pb	<2.03	<2.03	<2.03
Rb	6,32	7,13	6,51
Sb	<1.48	2,05	<1.48
Sc	24,4	29,4	27
Se	<0.36	0,75	<0.36
Sm	<1.62	<1.62	1,73
Sn	4,07	3,92	4,34
Sr	51,2	56,7	53
Ta	0,64	0,75	1,01
Te	<0.16	<0.16	<0.16
Th	<0.88	<0.88	<0.88
Tl	2,34	2,71	2,65
U	<0.74	<0.74	<0.74
V	298	449	323

W	1,12	1,54	1,43
Y	10,5	11,8	10,1
Yb	4,05	6,38	6,77
Zn	<5.49	<5.49	<5.49
Zr	66,6	71,9	72,9

As previously stated, once the samples are mixed with bitumen and compacted, the leach elements are "entombed", therefore the possibility of leach elements contaminating the groundwater tables is minimal. The samples were compacted using the "by-product" materials, and also the reference samples using Natural Aggregates. All the samples were then subdued to leach testing. Table 4.5 shows the Chrome Slag leach results while Table 4.6 shows the Natural Aggregate results.

Table 4.5: Chrome Slag Leach results

Analyte Name	Units	Slag 5% AE-2	Slag 6% AE-2	Slag 5.5% 50/70	Slag 6% 50/70
Silver	mg/l	<0.002	<0.002	<0.002	<0.002
Aluminium	mg/l	0,12	0,04	0,08	0,03
Arsenic	mg/l	<0.01	<0.01	<0.01	<0.01
Boron	mg/l	0,027	0,019	0,018	0,014
Barium	mg/l	0,003	<0.002	<0.002	<0.002
Beryllium	mg/l	<0.0001	<0.0001	<0.0001	<0.0001
Bismuth	mg/l	<0.03	<0.03	<0.03	<0.03
Calcium	mg/l	4,5	3,6	3,4	2
Cadmium	mg/l	<0.001	<0.001	<0.001	<0.001
Cobalt	mg/l	<0.005	<0.005	<0.005	<0.005
Chromium	mg/l	0,003	0,003	0,005	0,003
Copper	mg/l	<0.02	<0.02	<0.02	<0.02
Iron	mg/l	<0.05	0,08	<0.05	<0.05
Potassium	mg/l	0,4	0,3	<0.2	<0.2
Lithium	mg/l	<0.005	<0.005	<0.005	<0.005
Magnesium	mg/l	0,21	0,24	0,18	0,13
Manganese	mg/l	0,03	0,02	0,01	0,01
Molybdenum	mg/l	<0.005	<0.005	<0.005	<0.005
Sodium	mg/l	0,6	0,5	<0.5	<0.5
Nickel	mg/l	0,11	0,092	0,042	0,051
Lead	mg/l	<0.01	<0.01	<0.01	<0.01
Selenium	mg/l	<0.01	<0.01	<0.01	<0.01
Strontium	mg/l	0,02	0,008	0,01	0,006
Tellurium	mg/l	<0.17	<0.17	<0.17	<0.17
Thallium	mg/l	<0.01	<0.01	<0.01	<0.01
Uranium	mg/l	<0.01	<0.01	<0.01	<0.01
Vanadium	mg/l	<0.001	<0.001	<0.001	<0.001
Zinc	mg/l	0,04	0,01	0,03	0,02
Final pH	-	9	7,4	7,5	7,1
Rubidium	mg/l	<0.004	<0.004	<0.004	<0.004
Gallium	mg/l	<0.050	<0.050	<0.050	<0.050

Table 4.6: Natural Aggregate Leach results

Analyte Name	Units	Nat 5% AE-2	Nat 5.5% AE-2	Nat 5% 50/70	Nat 5,5% 50/70
Silver	mg/l	<0.002	<0.002	<0.002	<0.002
Aluminium	mg/l	<0.02	<0.02	0,02	<0.02
Arsenic	mg/l	<0.01	<0.01	<0.01	<0.01
Boron	mg/l	0,01	0,009	0,016	0,01
Barium	mg/l	<0.002	<0.002	<0.002	<0.002
Beryllium	mg/l	<0.0001	<0.0001	<0.0001	<0.0001
Bismuth	mg/l	<0.03	<0.03	<0.03	<0.03
Calcium	mg/l	<0.5	0,7	0,9	0,6
Cadmium	mg/l	<0.001	<0.001	<0.001	<0.001
Cobalt	mg/l	<0.005	<0.005	<0.005	<0.005
Chromium	mg/l	0,004	0,003	<0.002	0,002
Copper	mg/l	<0.02	<0.02	<0.02	<0.02
Iron	mg/l	<0.05	<0.05	<0.05	<0.05
Potassium	mg/l	<0.2	0,2	<0.2	0,2
Lithium	mg/l	<0.005	<0.005	<0.005	<0.005
Magnesium	mg/l	0,04	0,08	0,07	0,06
Manganese	mg/l	<0.01	<0.01	<0.01	<0.01
Molybdenum	mg/l	<0.005	<0.005	<0.005	<0.005
Sodium	mg/l	1,6	1,4	3,2	1,4
Nickel	mg/l	0,012	0,023	0,005	0,006
Lead	mg/l	<0.01	<0.01	<0.01	<0.01
Selenium	mg/l	<0.01	<0.01	<0.01	<0.01
Strontium	mg/l	<0.001	0,002	0,002	0,001
Tellurium	mg/l	<0.17	<0.17	<0.17	<0.17
Thallium	mg/l	<0.01	<0.01	<0.01	<0.01
Uranium	mg/l	<0.01	<0.01	<0.01	<0.01
Vanadium	mg/l	<0.001	<0.001	<0.001	<0.001
Zinc	mg/l	0,02	0,02	0,02	0,02
Final pH	-	6,8	6,6	7,2	6,9
Rubidium	mg/l	<0.004	<0.004	<0.004	<0.004
Gallium	mg/l	<0.050	<0.050	<0.050	<0.050

Taking into consideration Table 4.2 limits, the elements from Table 4.4 & 4.5 can thus be added to see what the bounding of materials has produced in reducing the leaching elements. These results are now seen in Table 4.6 for Chrome Slag Asphalt mixture and Table 4.7 for Natural Aggregate mixture.

Table 4.7: Chrome Slag Asphalt Mixture Leach elements versus drinking water allowable (Bicki *et al*., 1993; Oram B, 2019)

Material	Slag				Maximum Acceptable Level (ppm)	Possible Effects of Higher Levels
	5%AE-2	6% AE-2	5,5% 50/70	6% 50/70		
As	<0,01	<0,01	<0,01	<0,01	0.05	Lung Cancer, kidney damage
Ba	0,003	<0,002	<0,002	<0,002	2	Heart damage
Cr	0,003	0,003	0,005	0,003	0.1	Liver, kidney damage, circulatory disorders
Pb	<0,01	<0,01	<0,01	<0,01	0.015	Brain damage, kidneys, nervous system
Se	<0,01	<0,01	<0,01	<0,01	0.01	Growth inhibition, liver damage
Cu	<0,002	<0,002	<0,002	<0,002	1.3	Metallic taste, blue-green stains on fixtures, gastrointestinal irritation

Table 4.8: Natural Aggregate Asphalt Mixture Leach versus drinking water allowable (Bicki *et al*., 1993; Oram B, 2019)

Material	Natural Aggregate				Maximum Acceptable Level (ppm)	Possible Effects of Higher Levels
	5%AE-2	5,5% AE-2	5,0% 50/70	5,5% 50/70		
As	<0,01	<0,01	<0,01	<0,01	0.05	Lung Cancer, kidney damage
Ba	<0,002	<0,002	<0,002	<0,002	2	Heart damage
Cr	0,004	0,003	<0,002	0,002	0.1	Liver, kidney damage, circulatory disorders
Pb	<0,01	<0,01	<0,01	<0,01	0.015	Brain damage, kidneys, nervous system
Se	<0,01	<0,01	<0,01	<0,01	0.01	Growth inhibition, liver damage
Cu	<0,002	<0,002	<0,002	<0,002	1.3	Metallic taste, blue-green stains on fixtures, gastrointestinal irritation

The % binder indicated on the tables is the chosen % binder as per mix design discussed in Chapter 5of this study.

4.4 Handling of Fly Ash and Chrome Slag

4.4.1 Fly Ash

The structure of Fly Ash, which consists mostly of fine powder and glassy particles, will not cause imminent danger to short-term exposure (Ash Resources, 2012; Oppenshaw, 1992; Mehta, 1998; FA FACTS, 2012). It must be noted that safety steps still need to be followed as the Fly Ash is an alkaline material and when in contact with water can cause the following problems:

1. Cause delayed or immediate irritation and flu arch when in contact with eyes.
2. Cause dry and irritated skin.
3. Cause of irritation of throat and lungs when dust is breathed in.

The industry has placed emphasis on the handling procedure of Fly Ash and have adapted the method on how cement is handled (MSDS, 2012; Amar, 2013). Fly Ash is normally stored in silos, where it is kept dry pending utilisation or further procession. When stored, the relative density of the Fly Ash plays an important role. Fly Ash is relative lighter than cement. The relative density (RD) is on average 2.23 for the Fly Ashes. The RD for cement is 3.15. It is mostly for practical reasons the RD plays an important role, which is why the Fly Ash is only supplied in 40kg bulk bags, and if transported by rail, the rail cars can normally accommodate 52 tons of cement, while for Fly Ash it can only accommodate 40 tons.

When Fly Ash is supplied in bulk bags, the following must be taken into consideration:

1. Fly Ash is moisture sensitive, and, like cement, it must be stored on pallets in a cool, dry environment.
2. Opened bags must be utilised immediately as the moisture will hamper the free-flowing characteristics and the material may become agglomerated.

Fly Ash is a non-hazardous and non-toxic material, but it is important to follow in-depth rules and regulations as set out in most Material Safety Data Sheets (MSDS) (MSDS, 2012).

4.4.2 Chrome Slag

Chrome Slag aggregates have been listed with no hazard identification. Chrome Slag dust on aggregate does pose little hazard during short-term exposure and is treated as any other foreign object or dust. Chrome Slag has the following non-hazards: Flammability, Chemical, Biological, and Reproductive hazards.

The following toxicological hazards are identified with Chrome Slag:

1. Dust may cause irritation to nose, throat, and lungs.
2. Redness and soreness of the skin and tearing of eye tissue.
3. Ulceration of central nasal septum of the nose, chronic dermatitis over a prolonged period.

No ecological hazards have been identified with chrome Chrome Slag. The density of Chrome Slag varies but the average is about 3470kg/m^3. Particle sizes range between 0.5mm and 37mm with a slight dust odour. It is delivered loose and not in bags.

Stockpiling of the material must be in an approved area, which must not be according to the following conditions:

1. Highly acidic conditions

2. Stockpiled where leaching may occur
3. Needs to be protected from acid rain
4. Must not be stockpiled where material will be in contact with organic material over a long period of time.

Further precautions must be acknowledged and followed as per Material Safety Data Sheets (MSDS) (MSDS, 2014).

4.5 Summary

The exploitation of the vast mineral resources in South Africa places great responsibility on the miners and smelters in terms of awareness and management of the environment.
Substantial information is found worldwide for protection of the environment when using Fly Ash and Chrome Slag and is mostly publicized by agencies like RCRA and EPA. Both Fly Ash and Chrome Slag is constantly evaluated and studied to produce reports, namely:

1. Coal Fly Ash and Chrome Slag composition
2. Leaching to facilitate field performances
3. Determine concentrations of Fly Ash and Chrome Slag elements in long term leachants
4. Advantages of using recycled Fly Ash and Chrome Slag
5. Report on emissions and energy produced, including the reduction of landfill sites

The publicised reports are constantly updated with new research data. Fly Ash is still of an environmental concern in South Africa. In-depth research has taken place on the landfill sites to collect data on age and to monitor and evaluate the possible contamination of water around the dumps including the surface run-off. Conclusive research data is based on the use of Fly Ash in cement manufacturing, therefore, all MSDS and environment control is based around cement manufacturing.

Environmentally, Fly Ash is utilised for:

1. Making positive contributions to agricultural and land reclamation
2. Supplying of elements for better plant nutrition
3. Production of artificial soil
4. Immobilisation of heavy metal ions from contaminated soils

Taking into consideration of the Fly Ash elements that are highly variable, the Class F Fly Ash processed in South Africa do indicate possible hazardous elements when compared to the maximum permissible inorganics in water. The comparison of possible hazardous leaching must only take place after the Fly Ash has been used for the intended purpose to evaluate the toxic levels.

The pH values of the asphalt designs varied between 10.29 and 10.82, which shows that the material is alkaline with zero (0) acidity found. This will ensure that the leachability of certain elements will be decreased over a period. The pH values are also not high, which reduces the leaching of arsenic over time.

Chemical analysis on various FeCr Chrome Slag samples have detected traces of heavy metals such as chromium(IV) oxide, which is very toxic and leachable. This leaching characteristic may classify the Chrome Slag as hazardous waste and restricts its use and disposal. However, it is only when Chrome Slag is fresh and is in the early phases of oxidation. In all studies, the leaching of other heavy elements, except for the Cr(IV) is negligible in terms of environmental impact. The results from the insitu leachate test revealed that there was a low migration of particles from the Chrome Slag to possible groundwater and soil conditions for all elements analysed. Chrome Slag is formed at such high temperatures that most compounds with lower boiling points have been driven off. Residual compounds such as Se, C, Cd, Pb, Cu, and Hg are encased within the Chrome Slag's glassy matrix. The lime in Chrome Slag, unlike ordinary agricultural lime, is in loose chemical combination with Si, Fe, and manganese. Chrome Slag does not "burn" like agricultural lime nor revert to carbonates. Therefore, Chrome Slag remains in a stable form where it will produce alkalinity over long periods of time until exhausted (US Steel, 1964). The results from the tests in this study have shown that minimal leaching will occur from the natural Chrome Slag, which indicates that most leaching elements will only occur during the early phases of the material reaching the dumps. The metals in Chrome Slags are fused together and tightly bound, therefore are not readily liberated from the Chrome Slag particles, or easily leached into the environment.

The results of the Fly Ash and Chrome Slag mixtures have indicated that most of the harmful elements are *"entombed"*, and the risk of environmental pollution is minimal. The elements of hazardous nature that are leached are of a minor concern if the elements enter the water tables and will not be harmful to life. The leach tests in this study have shown that the Fly Ash and Chrome Slag combination in an asphalt mixture is environmentally friendly. It also shows that the Fly Ash and Chrome Slag particles that are normally released are bound within the asphalt mixture and will continue to be bound.

Application on the type of Leaching method depends on what is to be evaluated and what the information will contribute to the required outcome.

The environmental impact assessment in this study has shown that Fly Ash and FeCr Chrome Slag is non-hazardous material and environmentally friendly, and to be used as a green construction material in lieu of Natural Aggregates and replacement filler.

The most important aspect of this chapter is that all safety and regulations currently in place for handling of Fly Ash and Chrome Slag should be followed to minimise any health risks that could be obtained from prolonged exposure to the Fly Ash and Chrome Slag.

Strictly speaking, the utilisation of Chrome Slag and Fly Ash in any application can be viewed as an environmental application, since the reuse or recovery of this material provides environmentally related benefits.

5. Results and Discussion

5.1 Introduction

This chapter deals with the evaluation of the test results following basic design steps according to set specifications. An additional testing criterion was also completed to evaluate if the results conform to a higher specification as well. The main focus is to evaluate the asphalt design for achieving the requirements using only Chrome Slag and Fly Ash.

5.2 South Africa Test Protocols

Testing protocols are developed and continuously updated worldwide. South Africa continuously evaluates the updated testing methods and adapts the protocols to the South Africa environment. Majority of the roads in South Africa are constructed to set standards. These standards have recently gone through major updates with the following factors taken into consideration:

a. Advances in pavement design.

b. More sophisticated testing to evaluate engineering properties more accurately.

c. Introduction in new design technologies.

The main consideration of pavement is the quality of materials. The materials in the top end of the pavement is of the highest achievable quality and this produces the most economical flexible pavement structure. New studies/research data is completed and evaluated numerously to adapt, change, and encourage the use of recycled materials without compromising the required quality of the pavement structure for more cost effectiveness. These updated designs and protocols using the research data can create optimization construction techniques and designs for an envisaged greener future.

Over the past few years, several changes have taken place in the road building industry, which have exposed deficiencies in the scope and depth of the methodology contained in the TRH8:1987. These changes include:

a. More aggressive design situations caused by increases in legal axle weight limits and heavy traffic volumes.

b. Influx of overseas information and of new methods, which may lead to a fragmentation of methods used in South Africa.

c. New test methods.

d. The introduction and development of modified binders.

e. The need to design mixes for high volume roads compared to lower volume roads.

f. The fact that field measurements do not always match the design intentions or laboratory findings.

The TRH8 review has been replaced by additional information and testing procedures for designs by: HMA; Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa (2001); TMH1, Standard methods for testing road construction materials (1986); TG1, Technical Guideline: The use of Modified Bituminous Binders in Road Construction (2001); SABITA Manual 2, Bituminous Binders for road construction and maintenance (2007); SANS, South Africa National Standards; South African Pavement Engineering Manual (SAPEM), 2013, and SABITA Manual 24, User Guide for the Design of Asphalt Mixes (2019)

5.3 Methodology

A general concern exists regarding the ability of the South African Hot Mix Asphalt design (HMA) method to accurately predict the performance of HMA designs through laboratory evaluation. The TRH8:1987 is, in some aspects, the document still used today, but with influxes of new design methods. Practitioners, through committees, have acknowledged that improvements in the design of hot mix asphalt have become a necessity in order to ensure that the technology is geared to address current deficiencies and needs. The following documents will be used to compile a design to acknowledge and cover most of the testing requirements for a design using the materials discussed in this study;

a. Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa (IGHMA,2001)

b. User Guide for Design of Hot Mix Asphalt, Manual 35 (SABITA, 2019)

c. South African Pavement Engineering Manual (SAPEM, 2013)

d. SABITA Manual 24, 2019

The study will concentrate on applying all the above documents, including previous research data to be able to compile guideline document to enhance confidence in asphalt design using waste material as per this current study. The design will be based on cost effectiveness as well, thus a reduction in layer thickness is one aspect of the design. The design will apply the material to thicknesses of 20mm asphalt and will only be aimed at urban/rural roads. With the current costs of placement of standard medium 40mm asphalt, by applying a thinner application with recycled materials can provide more roads being paved due to being more cost effective. These types of thicknesses have been successfully used in Europe and exclusively used to obtain the desired functional properties namely;

a. Riding quality

b. Noise reduction

c. Skid resistance

The principles of asphalt mix design work that will be carried out in the laboratory to optimise aggregate gradings and binder content, as well as the testing undertaken to evaluate the performance of the asphalt mix. Following the determination of the design objectives, preliminary selection of mix type, and evaluation of the various components, the actual volumetric design process can begin.

5.4 Overview of Design Guidelines

The documents that are available, as stated in the study, are in actual fact what it is—just guidelines. Although the TRH8 does not stipulate the guideline notation. But, at the end of the day, the design is based on basic engineering principles and the application required for a certain project. These documents are used to ensure parameters are met and the product is placed and conforms to the requirements of a basic asphalt mixture. This study will combine the documents to evaluate the comparisons between the waste material versus the natural material and develop a fit for purpose product that can be used effectively in South Africa.

The designer must take into consideration the following Engineering properties for a design:

1. Durability
2. Resistance to cracking
3. Resistance to permanent deformation
4. Resistance to rutting
5. Flexibility
6. Skid Resistance

7. Permeability

8. Stiffness

9. Workability

The above steps are used to determine a checklist for the design of an asphalt mixture. The details are all described in detail in the documents related to this study and will be discussed in this chapter. Once again, it must be noted that it is a guideline.

The design process document and flow charts are made available for referencing. Figure 26 and Figure 27 show a typical design flow chart as found in SABITA Manual 24 (SABITA Manual 24, 2019).

The designer should not design asphalt in isolation but must have a clear understanding of the conditions at the site where the asphalt mixture will be placed. The current methodology of an asphalt design in South Africa is based on the conventional Marshall Mix Design combined with a few performance-simulated design criteria; namely but not limited to:

1. ITS

2. Gyratory compaction

3. MMLS

4. Modified Lottman

The Marshall design is an adopted volumetric design procedure which aims to balance the aggregate grading and the ration of aggregate and binder in such a way as to ensure both adequate film thickness and adequate voids-in-mix to prevent close up of the mix. The Superpave design method did not take to South Africa due to a complicated design methodology, but the Gyratory Compactor proved as a handy source of information to be used for the volumetric criteria.

A process of testing has been set out in Table 5.1 indicating the tests that will be carried out with the processes and statements made in this study to compile a volumetric design suitable for using waste material such as Chrome Slag.

Volumetric properties are defined in accordance with the schematic representation of the volume of compacted asphalt mix shown in Figure 25.

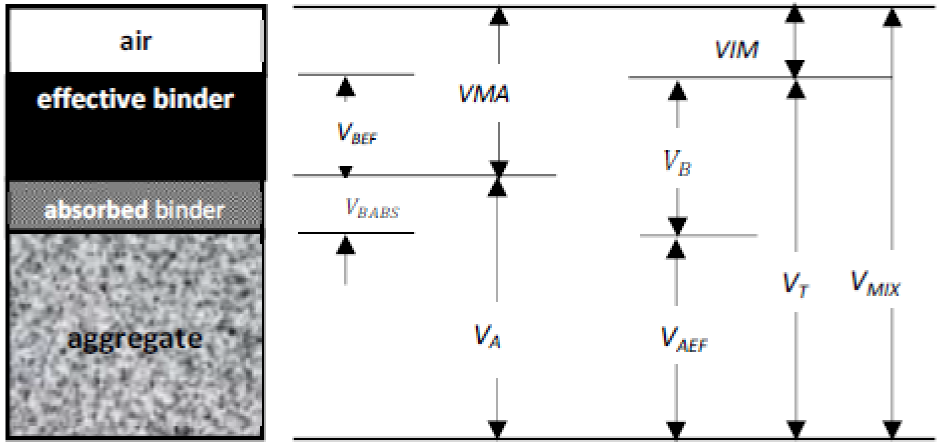


Figure 25: Volumetric parameters of compacted asphalt specimen (SABITA Manual 35, 2019)

VIM = Volume of voids, represents the volume of the pores in the mix and interstices.

VMA = Volume of voids in mineral aggregate.

VB = Total volume of binder within the asphalt mix.

VBABS = Volume of absorbed binder that penetrates into the aggregate pores.

VBEF = Effective volume of binder i.e. that which does not penetrate into aggregate pores.

VA = Bulk volume of aggregate, including all permeable surface pores.

VAEF = Effective volume of aggregate excluding surface pores filled with binder.

VT = Total volume of binder and aggregate in the mix.

VMIX = Total (apparent) volume of compacted asphalt specimen.

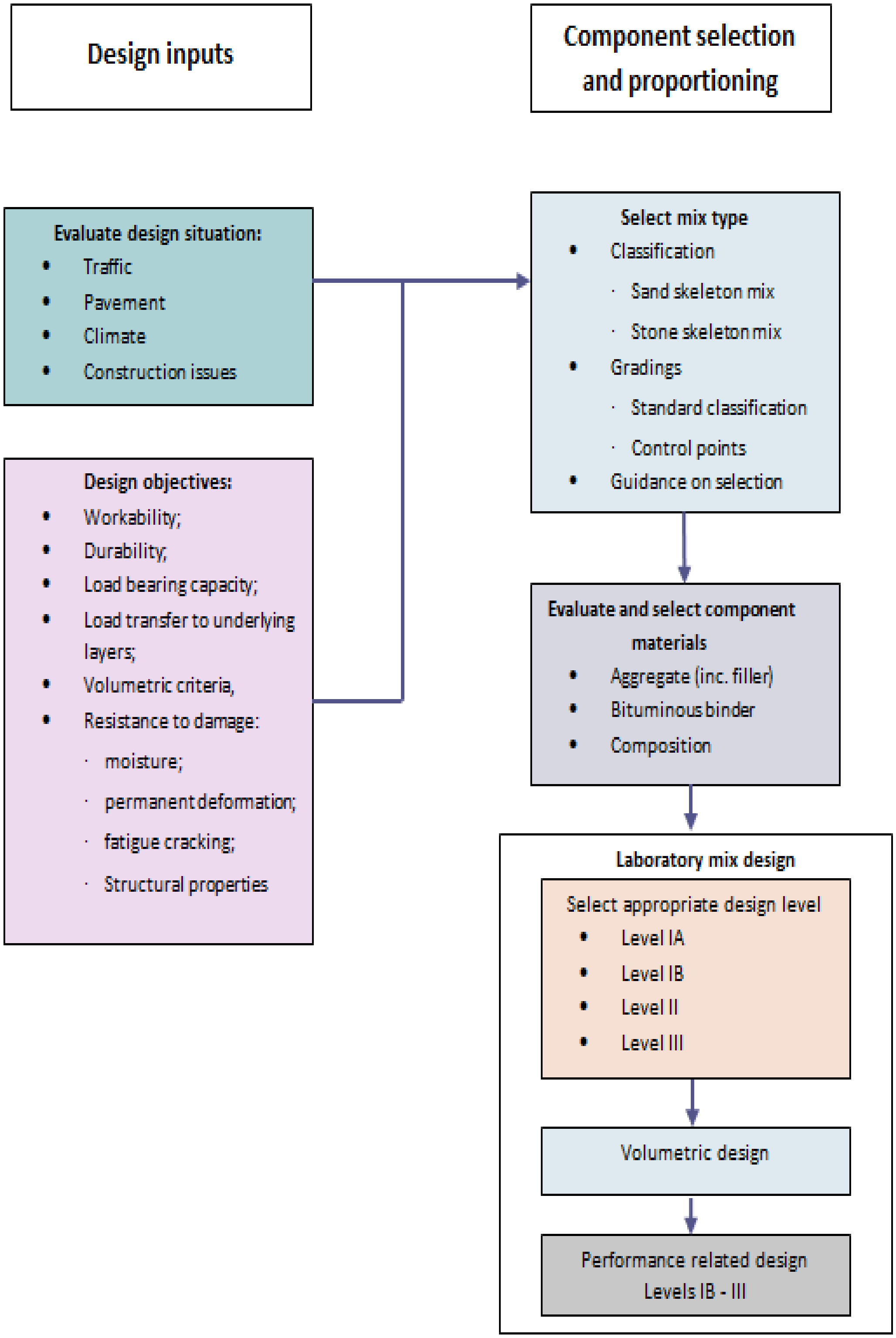


Figure 26: Laboratory Design Process

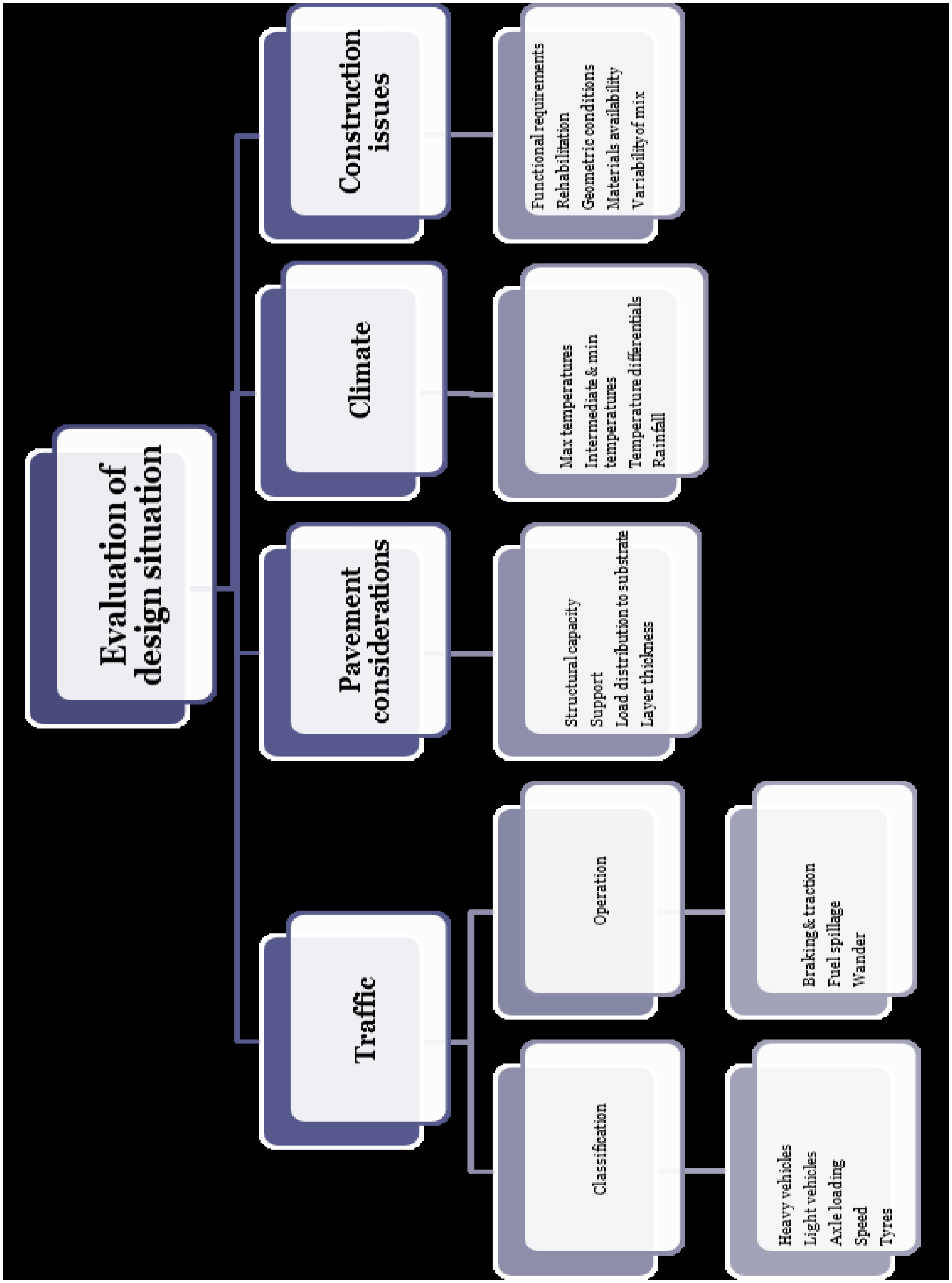


Figure 27: Engineering Design Considerations

Table 5.1: Mix design Tests

Test	Test Method
Grading	SANS 3001-AG1
Marshall Briquettes	SANS 3001 - AS1
Marshall Stability and Flow	SANS 3001 - AS2
Bulk Density	SANS 3001 - AS10
Void content of compacted asphalt	SANS 3001 - AS10
Maximum voidless theoretical relative density of mix (RICE)	SANS 3001 - AS11
Quantity of binder absorbed by Aggregate	SANS 3001 - AS11
Effective Binder Content	Shell Bitumen Handbook 6th Edition
Soluble binder content and particle size	SANS 3001 - AS20
Immersion Index	TMH1 C5
Moisture content of asphalt	SANS 3001 - AS23
Voids in the Mineral Aggregate (VMA)	
Voids Filled with Binder (VFB)	
Moisture sensitivity Test (Modified Lottman)	ASTM D4867
Indirect Tensile Strength	ASTM D6931 - 07
Gyratory Compaction	ASTM D6925 - 09
Hamburg Wheel-Tracking Device	Tex - 24 - F
MMLS	SANS 3001 - PD1

5.4.1 Filler

The filler of an asphalt mixture is the material that substantially passes the 0.075mm sieve and are essential components for producing asphalt mixes which are dense, cohesive, durable, and resistant to damaging effects of moisture (SABITA Manual 24, 2019). The main purpose of the filler is to (SAPEM, 2013):

1. Act as a binder extender to stiffen the mastic.
2. Act as a void filling material.
3. Improve the bond between the binder and the aggregate.

According to the SAPEM document, fillers should meet the following criteria (SAPEM, 2013):

1. Percentage mass passing the 0.075mm sieve: minimum of 70%
2. Voids in the compacted filler: 0.5%
3. Methylene blue test: <5; >5 further testing needs to be applied by means of hydrometer and determination of Atterburg limits.

The methylene blue test procedure has been discussed in Chapter 4 of this study. Fly Ash in an asphalt mixture as a filler contributes to the following:

1. Improves mix compatibility.
2. Low Bulk Density.
3. Fly Ash is hydrophobic, reducing the potential for asphalt stripping.
4. Presences of lime (CaO) will also aid the reduction of asphalt stripping.
5. It is placed as an active filler (SABITA Manual 35, 2019).

Care should be taken when adding excessive quantities of active fillers, which may cause the increase of viscosity of the mastic. This has major implications on workability during mixing and paving. As a rule, it is recommended that the filler-binder ratio should not exceed 1:2. For thin asphalt layers <30mm thick, a maximum ratio of 1:1.5 is the norm (SAPEM, 2013, SABITA Manual 35, 2019; SABITA Manual 24, 2019). Table 5.1A shows the results of the filler ratio of the Fly Ash samples.

The filler is essentially the volumetric measurement of filler-binder ratios that will affect the stiffness/workability of the mix. It is thus proposed that a normalisation of the mass-based proportions of the filler be carried out. The filler-binder ratio is based on the following formula (SABITA Manual 35, 2019; SABITA Manual 24, 2019):

$$\frac{2,65}{D_f} \times \frac{\text{\% mass of filler passing the 0.075mm sieve}}{\text{Mass of binder}}$$

D_f = Bulk Relative Density of the filler material.

Table 5.1A: Binder ratio of the Fly Ash as a Filler

	AE-2		50/70	
Binder %	5	6	5,5	6
Fly Ash (FA) (g)	68,4	67,7	68	67,7
Particle Density of FA (kg/m³)	2240	2240	2240	2240
Binder (g)	60	72	66	72
Ratio	1,3	1,1	1,2	1,1

5.4.2 Grading

Studies have shown that important performance parameters have resistance against permanent deformation and fatigue resistance, as well as mix permeability and compactability, which are strongly related to the grading characteristics of the coarse aggregate (Verhaeghe et al, 2007). It has been customary to categorise mixes in terms of a set of grading parameters, but circumstances in today's world have further looked in the requirements of volumetric, spatial concepts.

This has led to further understanding the development of:

1. How the components of the mix pack together.
2. How the packing influences performance.

To select the design structure, the designer trial blends by mathematically combining the gradations of the individual materials into a single gradation. The gradings of most asphalt mixes are generally classified into 5 classes; namely, and shown as a representative graph in Figure 28:

1. Continuously graded
2. Gap-graded
3. Semi-gap graded
4. Open-graded
5. Semi-open graded

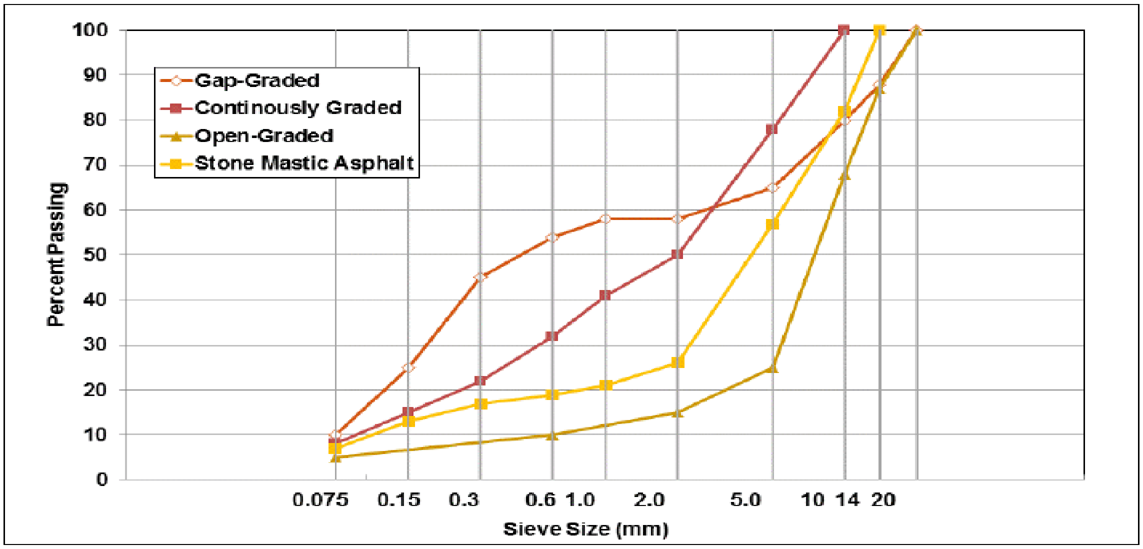


Figure 28: Representative Continuous, Gap and Open Graded Mixes (SABITA Manual 24, 2019)

In determining the grading of an aggregate, a sample of the material is sieved through a nest of sieves and the percentage by mass of material passing each sieve is determined. The main aim of the study is following the continuously graded mix design, which is mostly used for lighter traffic loading demands.

The following steps and guidelines to obtain the design grading are as follows:

1. The materials are sampled from stockpiles, which contains a given size of an aggregate fraction.
2. Aggregates must be clean and free from deleterious materials.
3. The samples are then oven dried for 16 hours at 105°C.
4. The samples are then riffled to obtain a homogeneity sample.
5. A wet sieve analysis is then conducted as per required SANS test method (SANS 3001-AG1).
6. The aggregates sieve sizes are plotted, then the combination of the individual aggregate fractions is compiled into a trial blend.

In South Africa, the designs are plotted on a design standard form, called the D3 form. The actual designs of the mixes for the study are placed on these forms and are attached in the appendices. The aggregate blend or mixture is developed by using the Bailey Method or as stated in the

TRH8, the Fuller Curve. Both methods incorporate the sieves and are plotted to the 0.45 power chart. These plots are seen on Figure 29. Although these methods can be followed, the laboratories blends can be obtained by trial and error using excel solver or any commercially available software that completes the proposed grading mixture and is placed on a D3 form.

A chart that also incorporates certain key control points is shown in Table 5.2, which provides grading control points for four nominal maximum particle sizes of aggregates used for production of sand skeleton/continuously graded mixes (SABITA Manual 24, 2019). The concentration will be on the nominal particle size of 10mm in this study. The control points are included in Figure 29. Specifications of the gradings, in general, are found in the various documents as stated in the study. The general specification for a continue medium is shown in Table 5.2 and is used to plot the gradings as shown the figure 29.

Table 5.2: Gradings for Asphalt Surfacing with Conventional Binders

Sieve sizes (mm)	Continoulsy Graded		
	Coarse	Medium	Fine
28	100		
20	88-100		
14	73-86	100	
10	64-77	85-100	100
5	44-62	56-77	66-89
2	27-45	33-48	42-59
1	21-35	25-40	31-51
0,6	16-28	18-32	24-40
0,3	12-20	11-23	16-28
0,15	8-15	7-16	10-20
0,075	4-10	4-10	4-12

Table 5.3: Aggregate Control Points (SABITA Manual 24, 2019)

Sieve sizes (mm)	Percent passing nominal maximum particle size (NMPS)							
	NMPS = 28mm		NMPS = 20mm		NMPS = 14mm		NMPS = 10mm	
	Min	Max	Min	Max	Min	Max	Min	Max
37,5	100							
28	85	100	100					
20		85	85	100	100			
14				85	85	100	100	
10						85	85	100
7,1								85
5								
2	19	45	23	49	28	58	32	67
1								
0,6								
0,3								
0,15								
0,075	4	7	4	8	4	10	4	10

The control points in Table 5.3 are to guide the designer in the aggregate blend. The designer uses the points to try and get the grading to lie within control points. The programmes developed on the D3 forms show the required percentages for each blend. Tables 5.5 to 5.6 show the blends for each of the required designs with the comparison samples. The final blends are plotted according to Figure 29, which is for NMPS of 10mm and are shown on figures 30 and 31. The same grading for Chrome Slag and aggregate will be used for both 50/70 penetration grade bitumen and AE-2 for the modified bitumen.

A Primary Control Sieve (PCS) is the first principle of The Baily Method to divide aggregate between coarse and fine of a specific mix. The size is the standard sieve closest to the following formulae:

0.22 x the NPMS for which the design is aimed at.

The study is using 10mm therefore: 0.22 x 10 = 2.2 ≈ 2mm Sieve will be the control sieve. The PCS for various NMPS are found on Table 5.4 which includes the % passing as per SABITA Manual 24 (SABITA Manual 24, 2019). The PCS classifies the graphs into the following criteria:

1. Coarse graded: >50% of the aggregate blend is retained PCS sieve.
2. Fine graded: ≤50% of the aggregate is retained on the PCS sieve.

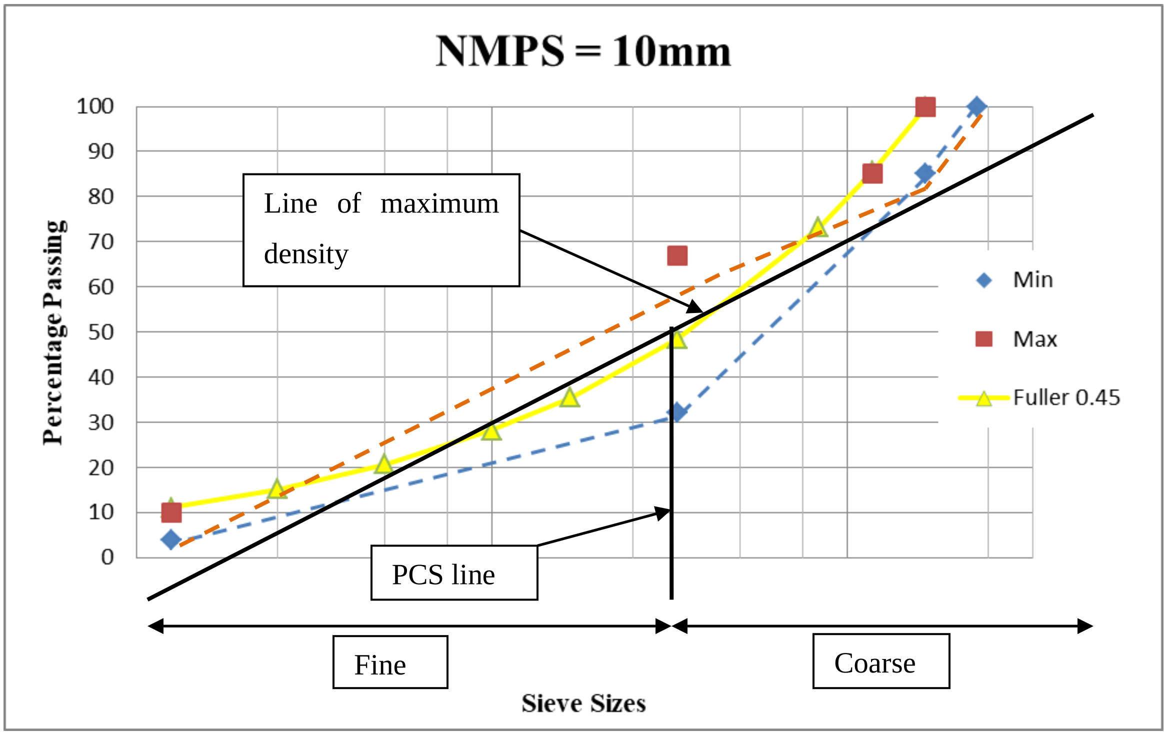


Figure 29: Primary control points with Fuller Curve

Table 5.4 : PCS for NMPS and percentage passing PCS control Sieve

NMPS	PCS sieve	PCS control point (% passing)
25mm	5mm	40%
20mm	5mm	47%
14mm	2mm	39%
10mm	2mm	47%

Table 5.5: New grading combination for Natural Aggregate

Legend - Sample No.	
1	10mm
2	7mm
3	Super Sand
4	Crusher Dust

	Sample No.	1	2	3	4	New Combined Grading
	% in Mix	15	8	26	51	100
Sieve Size (mm)	28	100	100	100	100	100
	20	100	100	100	100	100
	14	100	100	100	100	100
	10	87	100	100	100	98
	7	6	79	100	99	84
	5	0,4	10	98	86	70
	2	0,2	0,3	64	56	45
	1	0,2	0	38	34	27
	0,6	0,2	0	24	20	16
	0,3	0,2	0	15	14	11
	0,15	0,2	0	9	11	8
	0,075	0,1	0,1	3,5	8,9	5,5

Table 5.6: New grading combination for Chrome Slag

Legend - Sample No.	
1	10mm
2	7mm
3	5mm
4	2mm
5	Fly Ash

	Sample No.	1	2	3	4	5	New Combined Grading
	% in Mix	17	15	10	52	6	100
Sieve Size (mm)	28	100	100	100	100	100	100
	20	100	100	100	100	100	100
	14	100	100	100	100	100	100
	10	95	100	100	100	100	99
	7	15	70	100	100	100	81
	5	4	9	72	99	100	67
	2	2	2	7	66	100	42
	1	2	1	6	39	100	27
	0,6	2	1	5	23	100	19
	0,3	2	1	5	12	100	13
	0,15	1	0	3	6	97	9
	0,075	0,6	0,2	1,6	2,4	80,7	6,4

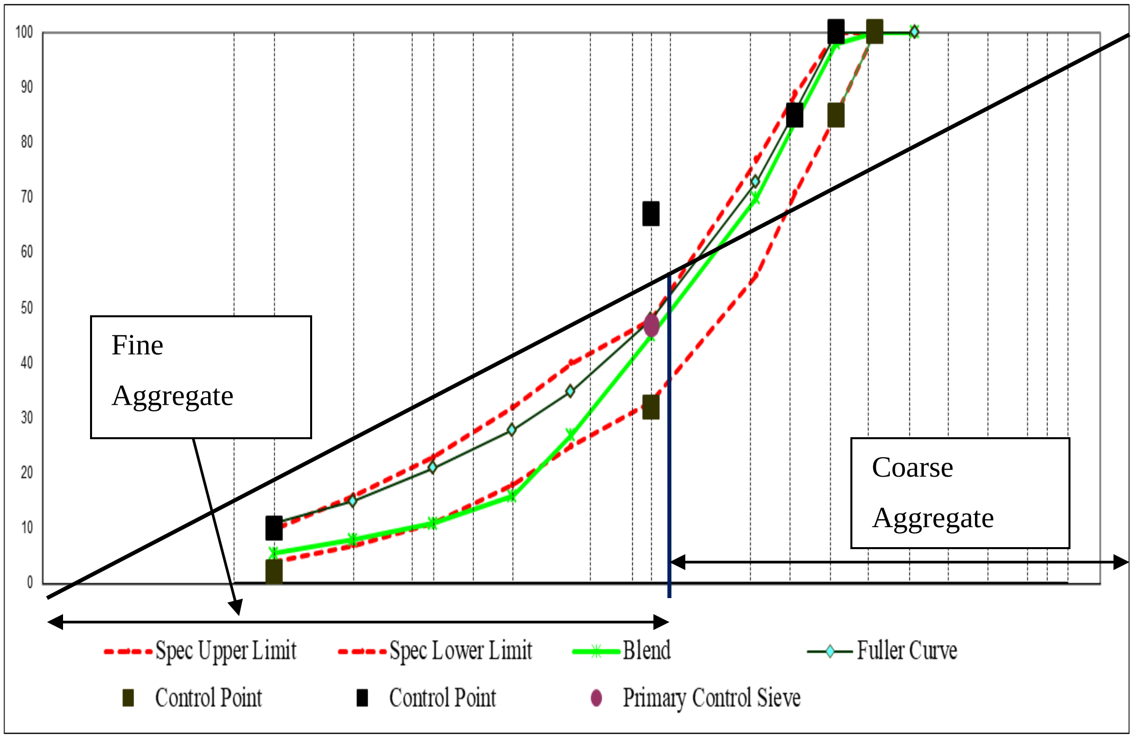


Figure 30: Natural Aggregate Blend 50/70 Penetration Grade Bitumen and AE-2

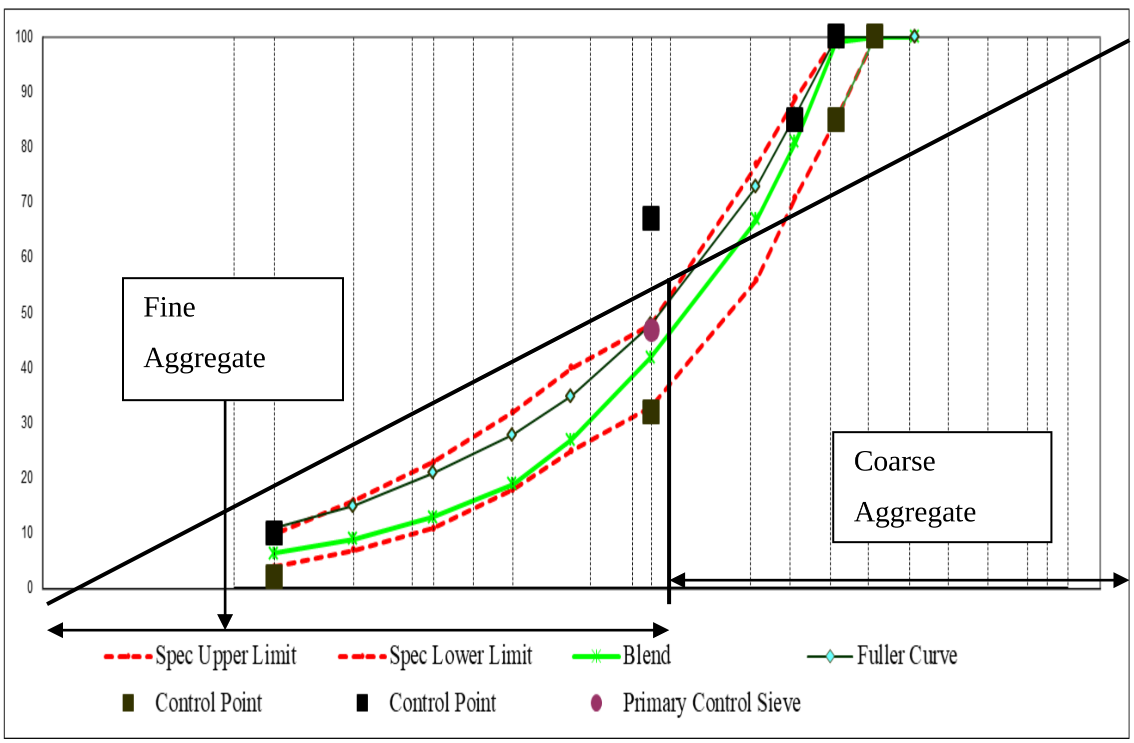


Figure 31: Chrome Slag Blend 50/70 Penetration Grade Bitumen and AE-2

5.4.3 Surface area of aggregate

The surface area of the mix blends is used to calculate the % binder content for the required asphalt mixture (SABITA, 2014). The finer the grading blend, the larger the total surface area of the aggregate, therefore the greater amount of binder required to uniformly coat the aggregate particles in the asphalt blend. The surface area (SA) is calculated by using the following formula:

$SA = (2 + 0.02\,a + 0.04\,b + 0.08\,c + 0.1\,d + 0.30\,e + 0.60\,f + 1.6g)´0.20482$

a = percentage passing 5 mm sieve;

b = percentage passing 2 mm sieve;

c = percentage passing 1 mm sieve;

d = percentage passing 0.60 mm sieve;

e = percentage passing 0.30 mm sieve;

f = percentage passing 0.15 mm sieve, and

g = percentage passing 0.075 mm sieve.

The results are shown in Table 5.8A for Natural Aggregate and Chrome Slag.

Table5.8A: Surface area for aggregates

Natural Aggregate	5,297
Chrome Slag	5,862

5.4.4 Marshall Briquettes (Compaction)

Marshall Compaction is the conventional static impact method applicable to all mix types. Briquettes are compacted from the mixtures prepared in the laboratory. The mixtures are placed in a mould and compacted by means of a standard mechanical compaction hammer. The height of the hammer is fixed and the number of blows on each face of the material in the mould is predetermined, which will determine the optimum binder content. The Marshall Compaction does not simulate field compaction accurately, but it would appear that 75 Marshall blows only on one side of the laboratory specimen provides a rough estimate of typical construction compactive effort for most densely graded mixes. There is caution that needs to be considered during the compaction process, namely;

a. Specimens compacted with this device should not be used to determine any performance properties, particularly in densely graded mixes, due to the aggregate packing produced by the device which is not representative of field packing.

b. The number of blows required to compact the asphalt briquettes to refusal density may differ for different mixes due to composition of the mix and workability. Compaction may lead to crushing of aggregates. However, according to the test methods, 35, 50, and 75 blows per side should be carried out to assess the differences in density at different blow counts and this should only be used for design purposes. (SABITA,2005; IGHMA,2001; SAPEM, 2013).

c. The device may underestimate the density of mixes that are difficult to compact, and alternatively needs to be checked using the gyratory shear compaction.

In South Africa, the standard method is 75 blows per side and the void content results are showed on the D3 form versus the binder content. The results for the designs on the materials is shown on Table 5.7.

In South Africa, an introduction was made to the Marshall Compaction, which allows the designer to better assess the mix behaviour during compaction and traffic densification. This method is known as the Modified Marshall Compaction Method.

The Modified Marshall Compaction is used to introduce control points for initial and final void contents for four design traffic classes, namely;

1. Light Traffic
2. Medium Traffic
3. Heavy Traffic
4. Very Heavy Traffic

The control points are shown in Table 5.8.

In the past, the specified maximum void content for dense graded mixes after construction was set at 97% of Maximum Theoretical Relative Density (MTRD) minus the design voids which was determined in the Marshall Design Procedure. This meant that the design void content was set at 4%, hence the specified maximum construction void content was set at 7%. This type of design worked well on heavily trafficked roads, but resulted in porous mixes on lightly traffic roads which did not compact further due to light traffic, and ultimately resulted in a mix that oxidised rapidly over time (IGDHMSA, 2001).

A consideration is taken on a range of initial as well as ultimate void content criteria on the proposed design depending on the expected traffic volume. In the derivation of these criteria, variability must also be considered to ensure the absolute minimum limits for void content are met at possible isolated points where the actual void content may differ from the design void content.

Table 5.8 shows the criteria for the selection of an optimum binder content for dense graded mixes. These criteria ensure that permeability and density requirements after construction are met, and at the same time ensure that stability requirements based on minimum void content are met after trafficking.

Table 5.8: Guidelines on Voids Criteria to select an Optimum Binder Content

Traffic Level	Allowable Void Content Range after 75 Marshall Blows (to simulate field compaction)		Allowable Void Content Range after additional compaction to simulate trafficking		
				Void Content	
	Minimum	Maximum	Total No. of Blows	Minimum	Maximum
Light	3,5%	5,5%	75+15	3,0%	4,5%
Medium	4,5%	6,5%	75+45	3,0%	5,0%
Heavy	5,5%	7,5%	75+75	4,0%	5,0%
	Min. voids content of 1,5% after 300 gyrations with Gyratory compactor, according to SHRP testing protocol Permeability of the mix within acceptable norms				
Very Heavy	6,0%	8,0%	75+75	4,5%	5,5%
	Min. voids content of 2,5% after 300 gyrations with Gyratory compactor, according to SHRP testing protocol Permeability of the mix within acceptable norms				

The design on the D3 form does not cater for the Modified Marshall Compaction but only for the normal 75 blows per side. Gyratory compaction was developed in the United States Strategic Highways Research Programme Superpave mix design method. It is similar to the Modified Marshall Compaction Test where the samples are also compacted to monitor the increase in sample density with increasing compaction efforts. Gyratory is used to determine a mix optimisation procedure which is based on the volumetric principles (Verhaeghe *et al*,2007).

The gyratory compaction process identifies more discrete distinctions between the different proportions of coarse aggregate fracture (Carlberg *et al*, 2003). The gyratory compactor is adapted to give more realistically compacted specimen densities that occurs under construction and loading conditions. The gyratory is a method using basic asphaltic materials properties and give more reliable results in predicting a better rut performance mixture (Verhaeghe *et al*, 2007). In the Superpave Method, the density is evaluated at three (3) points along the densification curve on the expected traffic, while in the IGHMA method, a maximum of 300 gyrations is applied to sand skeletons.

With this in mind, the Modified Marshall Compaction will not be evaluated in this due to factors that come into play, namely;

1. Over compaction.
2. Risk of crushing of materials that are not visually seen.
3. Under compaction.
4. No definite studies that produced recommendations on appropriate levels of additional compaction.

5.4.5 Marshall Stability and Flow

Marshall Stability and Flow results are used for the laboratory mix design and for the evaluation of the bituminous mixtures. It gives an indication of the resistance of the mix to permanent deformation. Marshall briquettes are preconditioned at 60° C for 30 minutes. The sample is then placed in a pre-heated breaking head assembly and loaded in a direction perpendicular to the cylindrical axis at a predetermined rate. The load on the specimen and deformation (flow) is then recorded. (SANS 3001 – AS2).

In addition, Marshall Stability and Flow may also be used to make relative assessments of effects of conditioning such as with water. The ratio of stability to the flow is termed the "quotient" (SAPEM, 2013). The specifications of the criteria are limited to the TRH8 as this test has become under scrutiny lately and is shown in Table 5.9.
Table 5.10 and 5.11 show the results for both Natural Aggregate and Chrome Slag with Binders AE-2 and 50/70 respectively.
Marshall Stability and Flow design represents that the load-carrying ability of an asphaltic mix and is defined as a function of the flow value as well as the stability, and reveal the inadequacy of

the usual specifications which call for only a minimum stability and maximum flow value (Metcalf, 1969) Marshall Stability alone, however, is not an absolute measure of strength. The results are shown in Table 5.12 for AE-2 binder and Table 5.13 for the 50/70 binder respectively. The Bearing Capacity is shown in a simple formula:

$$\text{Bearing Capacity (psi)} = \frac{\text{Stability}}{\text{Flow}} \times \frac{(120\text{-Flow})}{{}^{*}100}$$

* The unit load figures are roughly equivalent to tyre pressures of vehicles using the pavement. The *100 is a curve representing the maximum present intensity of highway loading. Placed in common terms, it means that a load of 100psi is considered to be equal to most severe loading imposed by truck tyres.

Table 5.9: Specifications for Marshall and Stability (TRH8, 1987)

Traffic Class	**E4**		**E3**		**≤E2**		**Test Method**
Property	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	SANS 3001 - AS2
Marshall Stability kN	8	18	7	15	4	10	
Marshall Flow mm	2	4	2	4	2	5	
Stability/Flow kN/mm	2,5	N/A	2	N/A	2	N/A	

Traffic Class	**Cumulative Equivalent Traffic (E80s/Lane)**
E4	$12\text{-}50\text{x}10^6$
E3	$3\text{-}12\text{x}10^6$
E2	$0{,}8\text{-}3\text{x}10^6$
E1	$0{,}2\text{-}0{,}8\text{x}10^6$

Table 5.10: Results for Chrome Slag and Natural Aggregate with AE-2 Binder

Traffic Class	AE-2							
Property	Chrome Slag				Natural Aggregate			
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6
Marshall Stability kN	6.9	7.1	9.4	10.6	8	8,7	8	10,9
Marshall Flow mm	4.6	4.2	5.2	5.2	4,5	4,8	4,3	4,6
Stability/Flow kN/mm	1.5	1.7	1.8	2.0	1,8	1,8	1,9	2,4

Table 5.11: Results for Chrome Slag and Natural Aggregate with 50/70 Binder

Traffic Class	50/70							
Property	Chrome Slag				Natural Aggregate			
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6

Marshall Stability kN	5	5	6.3	6.6	7,3	7,5	7,5	4,4
Marshall Flow mm	4.6	4,2	4.3	3.8	3,9	3,6	4	5,1
Stability/Flow kN/mm	1.1	1.2	1.5	1.7	1,9	2,1	1,9	0,9

Table 5.12: Bearing Capacity for Chrome Slag and Natural Aggregate with AE-2 Binder

Traffic Class	AE-2							
Property	Chrome Slag				Natural Aggregate			
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6
Bearing Capacity (psi)	87.2	99.8	102.7	115.8	103,8	104,6	109,5	137,9
Marshall Stability lb	1551	1596	2113	2383	1798	1956	1798	2450
Marshall Flow 0,01in	18	17	20	20	18	19	17	18

Table 5.13: Bearing Capacity for Chrome Slag and Natural Aggregate with 50/70 Binder

Traffic Class	50/70							
Property	Chrome Slag				Natural Aggregate			
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6
Bearing Capacity (psi)	104,2	68.4	88.6	104.2	111,8	125,9	111,6	49,2
Marshall Stability lb	1124	1124	1416	1484	1641	1686	1686	989,2
Marshall Flow 0,01in	18	17	17	15	15	14	16	20

5.4.6 Bulk Density

The bulk density (BD) is the density of sample particles expressed as the mass of the sample particles divided by the volume of the sample particles, including the impermeable (internal) and permeable (surface) voids, but excluding the inter-particle voids (SAPEM, 2014). The results obtained are used to determine the unit weight of compacted asphalt briquettes and to obtain the percentage of air voids in the samples. The values are also used to calculate the degree of field compaction and the volumetric properties required for design (SANS 3001 – AS10). Results for each percentage binder is found in Table 5.13A for AE-2 and Table 5.14 for 50/70 respectively.

Table 5.13A: Bulk Density for AE-2 Binder

Bulk Density	% Binder			
	4,5	5	5,5	6
Chrome Slag kg/m³	2,557	2,552	2,596	2,64
Natural Aggregate kg/m³	2,506	2,51	2,513	2,567

Table 5.14: Bulk Density for 50/70 Binder

Bulk Density	% Binder			
	4,5	5	5,5	6
Chrome Slag kg/m³	2,610	2,622	2,653	2,677
Natural Aggregate kg/m³	2,528	2,568	2,539	2,540

5.4.7 Void Content of Compacted Asphalt

Air voids are small airspaces or pockets of air that occur between the coated aggregate particles in the final compacted mix. A certain percentage of air voids is crucial in all dense graded mixes to allow additional pavement compaction under traffic and to provide spaces into which small amounts of asphalt can flow. The durability is a function of the air-void content. The lower the air voids, the less permeable the mixture becomes. Too high air voids provide passageways through the mix for the entrance of damaging air and water (CAPA,2007). It is important to understand how the voids in the aggregate and related binder content are determined, to ensure that the binder will not fill all the available voids and result in the aggregate "floating" in the binder. This can lead to bleeding of the asphalt surface and reduced resistance to permanent deformation (SABITA, 2005). Three (3) procedures are described for the determination of the volume of test specimens, depending on the estimated surface voids expressed as the water absorption and the accessibility of the voids in the specimen:

a. For closed surface with water absorption of less than 0.85%, saturated surface dry procedure is used.

b. For open or coarse surface, where water absorption is between 0.85% and 15%, the specimens are sealed with an elastic film covering.

c. For regular surface and geometric shape, water absorption is greater than 15%, direct measurement is used.

The bulk density, voids in mix, and voids in mineral aggregate of the asphalt are determined calculations (SANS 3001 – AS10). Voids-in-Mix (VIM) in numerous research papers have indicated that in case of heavy-duty asphalt surfacing, which needs to be highly deformation resistant, there needs to be in excess of 5%. However, mixes that will receive low traffic volumes or those expected to receive high fatigue strain loading will show much better durability at VIM values of between 3% and 4% (Pretorius *et al*, 2004). In new design methods, final void content criteria are proposed depending on the expected traffic volume (Jooste *et al*, 2000). VIM is calculated using the following formula:

$$VIM = 100 \times \frac{(MVD - BD_{mix})}{MVD}$$

BD_{mix} = Bulk Density of mix

MVD = Maximum voidless density of the mix (Rice method)

Table 5.15 and 5.16 show the results for the VIM for AE-2 and 50/70 binder respectively with the specifications shown in Table 5.17.

Table 5.15: VIM for AE-2 binder

VIM	% Binder			
	4,5	5	5,5	6
Chrome Slag %	9,1	8,6	6,0	3,2
Natural Aggregate %	6,2	5,3	4,3	1,5

Table 5.16: VIM for 50/70 binder

VIM	% Binder			
	4,5	5	5,5	6
Chrome Slag %	7,0	6,0	3,6	2,1
Natural Aggregate %	6,3	4,3	3,4	2,3

Table 5.17: Specification voids for low E80's

VIM	<0,3 million E80's	
	Minimum	Maximum
Specification	3,0	5,0

5.4.8 Maximum Voidless Theoretical Density (RICE) and Quantity of Binder Absorbed by the Aggregate

This method of testing is referred to as the RICE method. This test is performed on the laboratory prepared samples and is to calculate air voids in the compacted asphalt, the amount of bitumen absorbed by aggregate, and to provide target values for the compaction of asphalt layers. Binder absorption is defined as the mass of binder, expressed as a percentage of the mass aggregate that is absorbed by the aggregate without altering the aggregates bulk density, and which does not contribute towards inter-particle adhesion. This test will also assess the suitability of the aggregate used in this study for the use in asphalt. Results are shown in Table 5.18 and 5.19 for AE-2 and 50/70 binder respectively.

Table 5.18: RICE results with % absorbed binder for AE-2 binder

Bulk Density	% Binder			
	4,5	5	5,5	6
Chrome Slag kg/m³	2,812	2,792	2,763	2,728
Chrome Slag Absorbed Binder %	1,82	1,89	1,84	1,69
Natural Aggregate kg/m³	2,671	2,65	2,625	2,605
Natural Aggregate Absorbed Binder %	0,11	0,13	0,08	0,11

Table 5.19: RICE results with % absorbed binder for 50/70 binder

Bulk Density	% Binder			
	4,5	5	5,5	6
Chrome Slag kg/m³	2,806	2,788	2,753	2,735
Chrome Slag absorbed Binder %	1,74	1,84	1,70	1,79
Natural Aggregate kg/m³	2,699	2,683	2,628	2,601
Natural Aggregate Absorbed Binder %	0,53	0,63	0,13	0,04

5.4.9 Soluble Binder Content and Particle Size

This method is to evaluate the mix properties of the asphalt by quantitatively determining the binder content and the particle size analysis. The binder is extracted from the mix with an organic solvent. The binder content is calculated as the difference of the mass of the original asphalt and that of the extracted aggregate, moisture content, and mineral matter. The bitumen is expressed as a percentage by mass of the moisture-free mix (SANS 3001 – AS20). This test is normally done after the construction of the asphalt has taken place. It is to evaluate statistically the binder content of the lot, including the grading of the average of the lot. This is not part of the design but for information purposes.

5.4.10 Immersion Index

The test is completed to measure the moisture sensitivity of the asphalt mix. The compacted Marshall briquettes are soaked for 24hrs at 60°C the Marshall stabilities obtained are reported as a percentage of the original mix's stability. Low immersion index values indicate that the asphalt mix is sensitive to moisture. The results are expressed as a percentage of the original Marshall stability (TMH1 C5, 1986). The results and specifications is viewed in Tables 5.20 to 5.22. Although, this test is still being applied in today's standard, the Modified Lottman Test is the preferred test.

Table 5.20: Immersion Index Specification.

Traffic Class	**E4**		**E3**		**≤E2**		**Test Method**
Property	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	TMH1, C5
Immersion Index %	75	N/A	75	N/A	75	N/A	

Traffic Class	**Cumulative Equivalent Traffic (E80s/Lane)**
E4	$12\text{-}50x10^6$
E3	$3\text{-}12x10^6$
E2	$0{,}8\text{-}3x10^6$
E1	$0{,}2\text{-}0{,}8x10^6$

Table 5.21: Immersion Index results for AE-2 binder mixture

Immersion Index	% Binder			
	4,5	5	5,5	6
Chrome Slag %	86,3	87,4	84,7	88,3
Natural Aggregate %	81,3	83,6	87,8	89,3

Table 5.22: Immersion Index results for 50/70 binder mixture

Immersion Index	% Binder			
	4,5	5	5,5	6
Chrome Slag %	84,7	82,9	85,6	87,8
Natural Aggregate %	87,2	80,4	81,5	84,3

5.4.11 Voids in Mineral Aggregate (VMA)

The VMA serves as a cornerstone of volumetric design. VMA is defined as "*the volume of voids between coated particles plus the volume of effective binder*" (IGHMA, 2001). The volumes that are involved in a packing of binder-coated aggregates are, namely;

a. Volume of solid aggregate

b. Volume of cavities in the aggregate which cannot be penetrated by binder

c. Volume of binder absorbed into cavities in the aggregate (Absorbed Binder)

d. Volume of binder not absorbed (Effective Binder)

e. Volume of voids between coated particles (Air voids)

The VMA is another important volumetric quantity which requires the aggregate relative density in its calculations. Adequate VMA is needed to ensure that adequate amount of asphalt could be added to the mixture without over filling the voids and resulting in asphalt bleeding. The VMA is calculated by subtracting the following from the total sample volume:

a. The volume of the aggregate plus,

b. The volume of the voids filled and,

c. Not filled with binder

Schematic illustration of an aggregate coated with a film of binder is shown in Figure 32.

Thus, the VMA calculations are based on the bulk relative density of the aggregate as shown in Figure 33 (IGHMA, 2001; SABITA Manual 35, 2019, SABITA Manual 24, 2019). When VMA is not adequate, two (2) possible problems may arise (CAPA, 2007):

a. When enough binder to coat the aggregate is added, low air voids and bleeding will result.

b. When not enough is added, low durability will result.

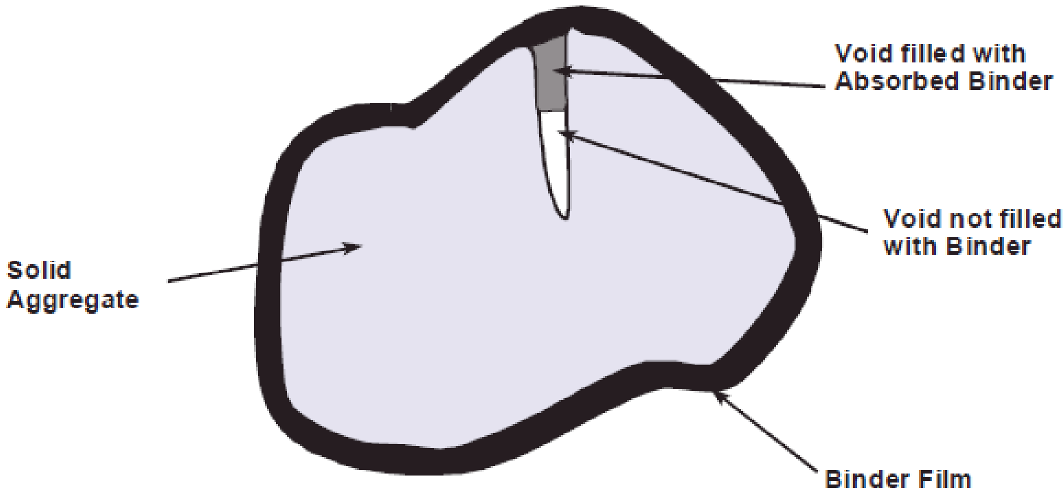


Figure 32: Schematic Illustration of Coated Aggregate with Absorbed Binder (IGHMA, 2001, SABITA Manual 24, 2019).

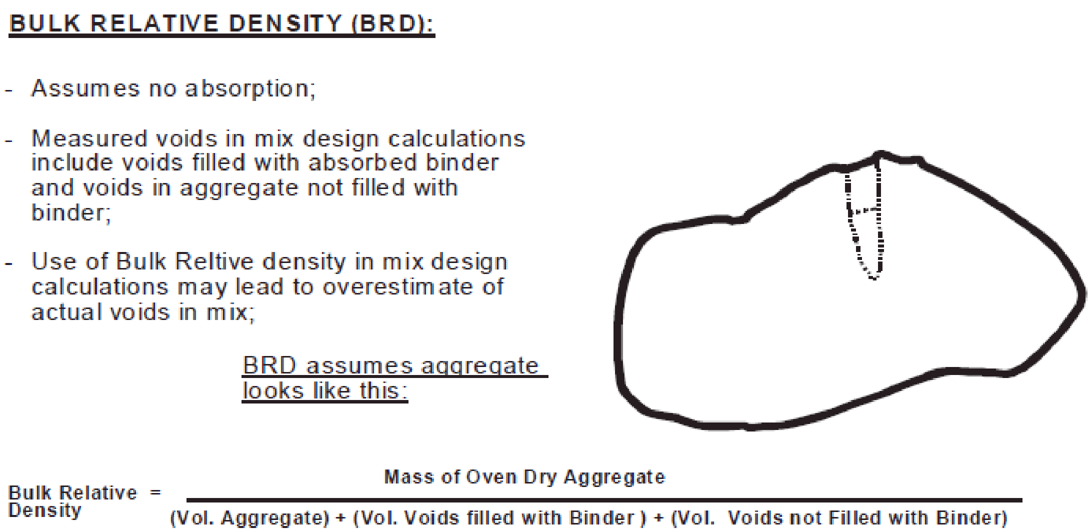


Figure 33: Definition and illustration of Bulk Density (IGHMA, 2001; SABITA Manual 24, 2019)

The VMA is primarily affected by:

a. Gradation

b. Aggregate characteristics

c. Compaction effort

The VMA that can be affected is summarised in Table 5.23. VMA compromises the voids filled with effective (unabsorbed binder), plus the voids between the coated particles. For most mixes, it is required that the void contents should be between 3% and 6%. This will ensure that rut resistance is met. This will also allow for thermal expansion of the binder during hot weather, as well as accommodate further reductions in VMA resulting from long-term traffic compaction (IGHMA, 2001).

Table 5.23: Relationship between HMA and Construction Parameters and VMA (IGHMA, 2001)

Property	**General Relationship with VMA**
Particle size and distribution	Complex, but denser gradations lead to decreased VMA
Maximum Aggregate Size	Larger aggregates reduce VMA
Aggregate Shape	Higher angularity increases VMA
Aggregate Texture	Rougher textures increases VMA
Aggregate Rugosity	Greater irregularity increases VMA
Filler content and type	Extremely fine particles (<10 microns) may function as a binder extender, causing the available VMA to decrease
Absorption Potential	For a given binder content, higher absorption will lead to increased VMA
Layer Thickness	Lower layer thickness generally leads to higher surface area to volume ratio. This cause the measured VMA to increase
Compaction Effort	More compaction (including by traffic) will lead to reduced VMA

In addition to minimum voids content, it is required that VMA be high to allow for enough binder into the mix to ensure that stability and workability are achieved and can be summarised as follows:

Optimum VMA = (Volume of effective binder required for workability/durability) plus (volume of voids required for stability)

$VMA = VIM + V_{BEF}$

VIM = Voids in the Mix expressed as a percentage of the MVD.

V_{BEF} = Volume of effective Binder expressed as a percentage of the volume of the bulk mix

Table 5.24 indicates the minimum VMA criteria for continuously graded mixes. The results for the Chrome Slag and Natural Aggregate is shown in Table 5.25 and 5.25A for the AE-2 binder, Table 5.26 and 5.26A for the Chrome Slag 50/70 mixture and for Natural Aggregate 50/70 mixture.

Table 5.24: Minimum Percentage Voids in Mineral Aggregate (VMA) (SABITA Manual 35, 2019)

Maximum Particle size (mm)	Minimum VMA for design voids		
	3%	4%	5%
10	14	15	16

Table 5.25: VMA for AE-2 mixtures versus Binder Content for Chrome Slag

Maximum Particle size (mm)	VMA versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	9,1	8,6	6	3,2
Chrome Slag	16	16,6	15,6	14,6

Table 5.25A: VMA for AE-2 mixtures versus Binder Content for Natural Aggregate

Maximum Particle size (mm)	VMA versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	6,2	5,3	4,3	1,5
Natural Aggregate	16,9	17,2	17,6	16,2

Table 5.26: VMA for the 50/70 mixtures versus Binder Content for Chrome Slag

Maximum Particle size (mm)	VMA versus Binder			
	4,5%	5,0%	5,5%	6,0%

Voids (%)	7	6	3,6	2,1
Chrome Slag	14,2	14,3	13,7	13,4

Table 5.26A: VMA for the 50/70 mixtures versus Binder Content for Natural Aggregate

Maximum Particle size (mm)	VMA versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	6,3	4,3	3,4	2,3
Natural Aggregate	16,2	15,3	16,7	17,1

5.4.12 Voids Filled with Binder (VFB)

As per VMA discussion above, aggregate surfaces contain cracks and cavities which may absorb a certain volume of binder and water or may remain filled with air. Binder which has entered such cavities is referred to as absorbed binder (IGHMA, 2001). This is also illustrated in Figure 34. The extent to which the voids between large aggregates are filled with binder plays an important role in determining rut resistance.

Most specifications require VFB between 70% and 80% at 4% air void content during the design phase but it is only for design phase and not a production requirement (CAPA, 2007; IGHMA, 2001). The specifications for the design traffic are shown in Table 5.27. HMA designed for moderate to heavy traffic may not pass the VFB requirement with relative low percentage air voids in the field, even though the air voids are within the acceptable range. Low air void contents may be very critical in terms of resisting permanent deformation. The VFB requirements help to avoid those mixes that are susceptible to rutting in heavy traffic situations. The purpose of the VFB is to avoid less durable HMA resulting from thin films of binder on the aggregate particles in light traffic situations (CAPA, 2007). The full design results for the VFB are shown in tables 5.28 for the Chrome Slag and 5.28A for the Natural Aggregate with 50/70 binder. The full design results for the VFB are shown in tables 5.29 for the Chrome Slag and 5.29A for the Natural Aggregate with AE-2 binder

Studies suggest that the most appropriate method for calculating bitumen absorption in aggregates is through RICE's method for measuring relative density (IGHMA, 2001, SABITA Manual 35, 2019).

Table 5.27: Specifications of the VFB according to E80 Design Traffic

Minimum	Maximum	Design Traffic E80

70	80	<0,3 Million
65	75	0,3 - > 30 Million

Table 5.28: VFB for AE-2 mixtures versus Binder Content for Chrome Slag

Maximum Particle size (mm)	VFB versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	9,1	8,6	6	3,2
Chrome Slag	43,2	48,1	61,2	77,9

Table 5.28A: VFB for AE-2 mixtures versus Binder Content for Natural Aggregate

Maximum Particle size (mm)	VFB versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	6,2	5,3	4,3	1,5
Natural Aggregate	63,5	69,3	75,7	91

Table 5.29: VFB for 50/70 mixtures versus Binder Content for Chrome Slag

Maximum Particle size (mm)	VFB versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	7	6	3,6	2,1
Chrome Slag	50,9	58,3	73,5	84,2

Table 5.29A: VFB for 50/70 mixtures versus Binder Content for Natural Aggregate

Maximum Particle size (mm)	VFB versus Binder			
	4,5%	5,0%	5,5%	6,0%
Voids (%)	6,3	4,3	3,4	2,3
Natural Aggregate	60,9	72	79,7	86,3

5.4.13 Moisture Sensitivity (Modified Lottman) Test

The test determines the potential moisture damage, to determine whether or not an anti-stripping additive is effective, and to determine what dosage of an additive is needed to maximise its effectiveness. Six (6) ITS briquettes are compacted within the design void content range and partially saturated with water. Three (3) of the samples are frozen for at least 15hrs and subsequently immersed for 24hrs in a water bath set at 60°C (ASTM D4867). The ratio of the ITS values of the conditioned and unconditioned samples, termed the Tensile Strength Ratio (TSR), is used to assess the susceptibility to moisture damage. The test measures the strength loss resulting from damage caused by "stripping" under laboratory controlled accelerated water conditioning. The results are used to predict long-term susceptibility to stripping of an asphalt layer (CAPA). Table 5.30 indicates the TSR criteria of the mix and the climate in which the mix will operate. For routine mix design purposes, TSR values of 0.7 are normally specified. The results are shown in Tables 5.31 for AE-2 binder and Tables 5.32 for 50/70 binder.

Table 5.30: TSR minimum Criteria based on mix permeability and climate (IGHMA, 2001).

Climate	**Permeability**		
	Low	**Medium**	**High**
Dry	0,6	0,65	0,7
Medium	0,65	0,7	0,75
Wet	0,7	0,75	0,8

Table 5.31: AE-2 Binder Modified Lottman Results

	AE-2			
	Natural Agg		Chrome Slag	
Binder %	5	5,5	5	6
Modified Lottman	0,905	0,946	0,908	0,957

Table 5.32: 50/70 Binder Modified Lottman Results

	50/70			
	Natural Agg		Chrome Slag	
Binder %	5	5,5	5,5	6
Modified Lottman	0,908	0,952	0,902	0,937

5.4.14 Model Mobile Load Simulator (MMLS)

MMLS is used to determine the permanent deformation and susceptibility of the asphalt mixture to moisture damage. The MMLS offers four (4) wheels consisting of 300mm diameter with a maximum inflation pressure of 690kPa and maximum load of 2.7kN. More than 10000 simulated axle loads per hour can be achieved. Samples are placed in a Test Bed and then conditioned to a predetermined temperature of 50°C ± 2°C.

The test is then run to one hundred (100), load applications is then run to ensure that the samples are properly Seated. Pre-trafficked cross sections are measured as reference before full testing.

The MMLS is stopped at pre-determined intervals and cross sections are then measured. The measurement intervals for testing is at 2500, 5000, 10000, 25000, 50000 and 100000 repetitions respectively.

Figure 36 shows typical layout of the MMLS.

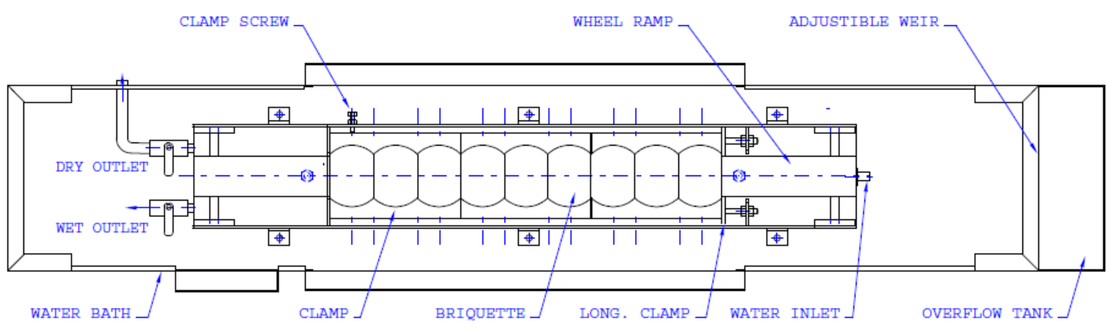


Figure 34: Typical layout of a MMLS (DPG1, 2008)

The results of the MMLS are evaluated according to the following main components:

1. Total Rut depth: Deformation from axle loads and tyre pressures applied by MMLS. It is measured as vertical distance between maximum and minimum surface evaluation of a cross section profile (See Figure 37).
2. Heave: Vertical distance between maximum surface evaluation and original surface profile prior to test start.
3. Down Rut Depth: Vertical distance between minimum surface evaluation and original surface profile prior to start of test.

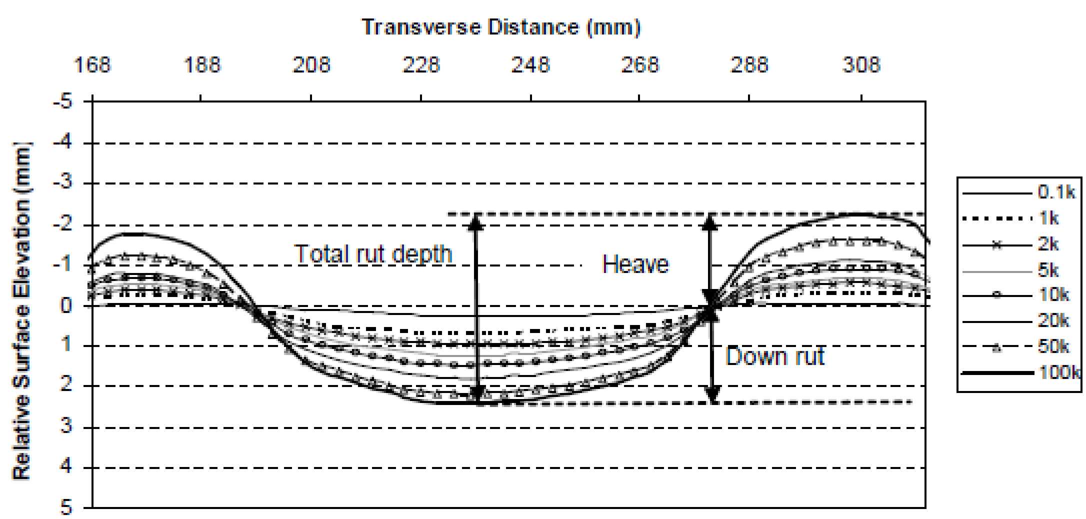


Figure 35: Typical rut graph information produced by the MMLS (DPG1, 2008)

The results are shown in the following Tables:

Table 5.4: AE-2 5% binder for Chrome Slag

Table 5.5: AE-2 6% binder for Chrome Slag

Table 5.6: 50/70 5% binder for Natural Aggregate

Table 5.7: 50/70 5.5% binder for Natural Aggregate

Table 5.8: 50/70 5.5% binder for Chrome Slag

Table 5.9: 50/70 6% binder for Chrome Slag

Table 5.10: AE-2 % binder for Natural Aggregate

Table 5.11: AE-2 % binder for Natural Aggregate

The rut graphs are shown in the following figures:

Figure 36: AE-2 5% binder for Chrome Slag

Figure 37: AE-2 6% binder for Chrome Slag

Figure 38: 50/70 5% binder for Natural Aggregate

Figure 39: 50/70 5.5% binder for Natural Aggregate

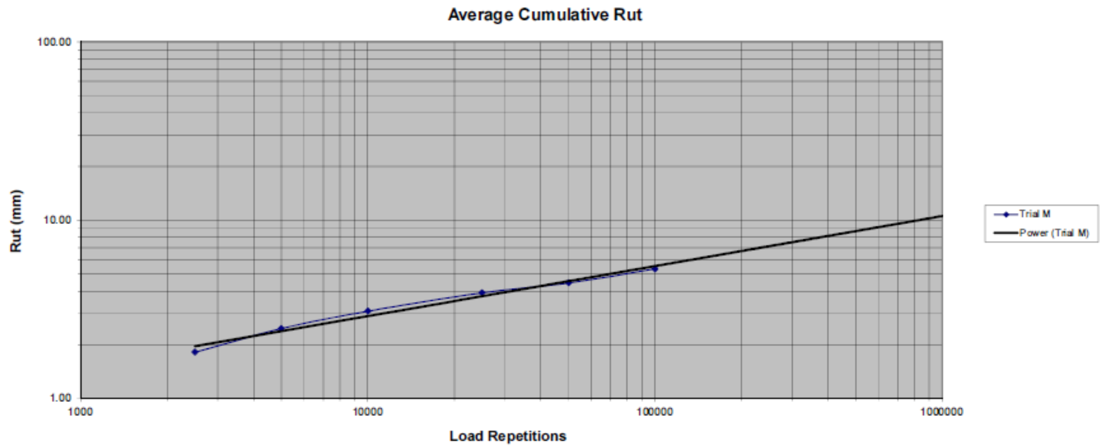
Figure 40: 50/70 5.5% binder for Chrome Slag

Figure 41: 50/70 6% binder for Chrome Slag

Figure 42: AE-2 % binder for Natural Aggregate

Figure 43: AE-2 % binder for Natural Aggregate

Table 5.4: AE-2 5% binder for Chrome Slag



Axle load Repetitions (RUT)							
Position	0	2500	5000	10000	25000	50000	100000
0100	0	2.17	2.65	3.22	3.91	4.52	5.05
0200	0	1.73	2.39	2.99	3.88	4.49	5.57
0300	0	1.85	2.67	3.58	4.66	5.26	6.71
0400	0	1.65	2.29	2.87	3.61	3.94	4.65
0500	0	1.67	2.32	2.74	3.47	3.99	4.62
Avg	**0**	**1.81**	**2.46**	**3.08**	**3.91**	**4.44**	**5.32**
Stdev	**0.00**	**0.22**	**0.19**	**0.33**	**0.46**	**0.53**	**0.87**

Average Rutting @ 100000 axles : 5.32

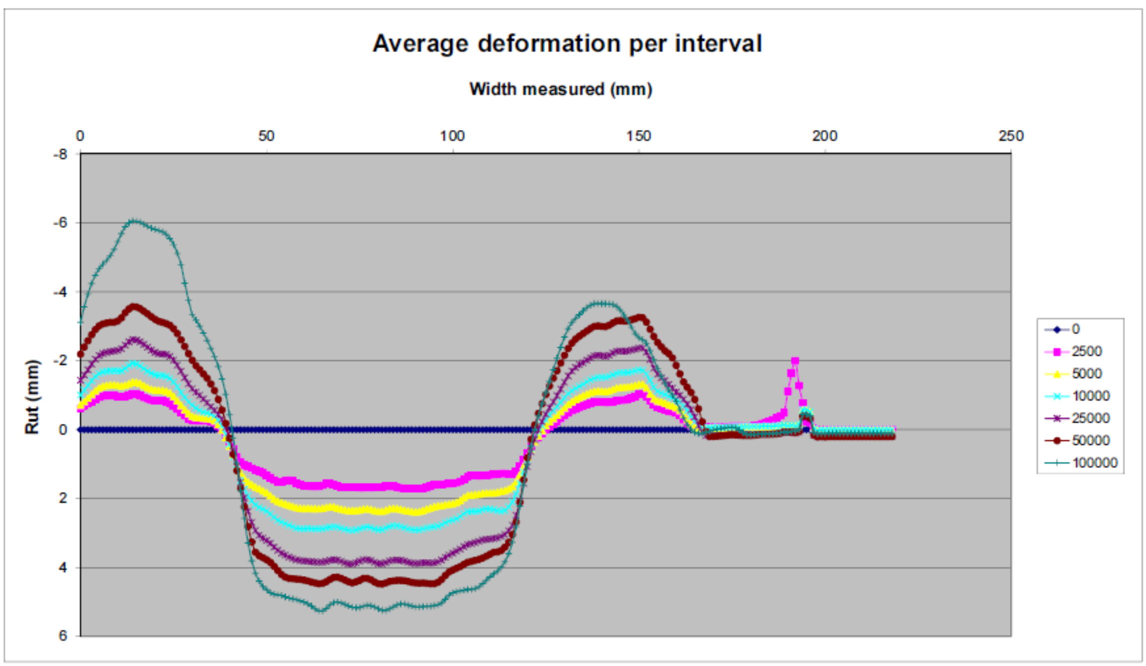
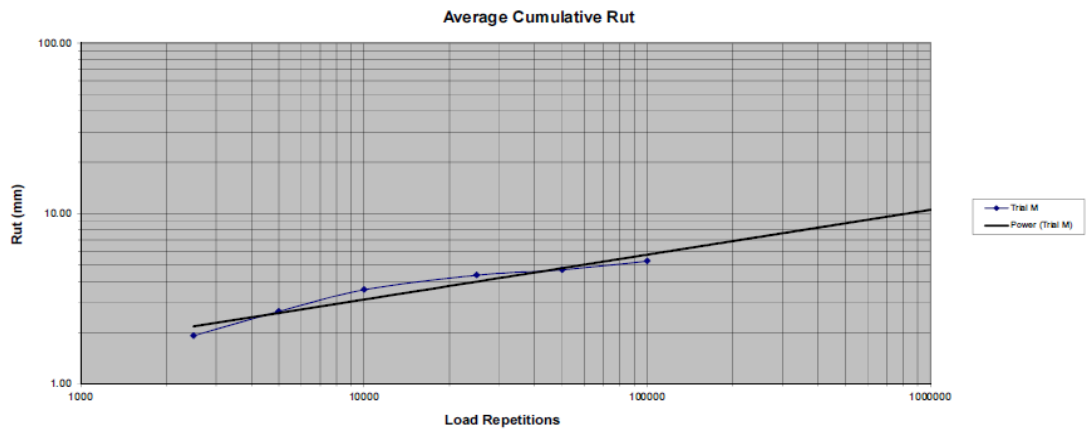


Figure 36: AE-2 5% binder for Chrome Slag

Table 5.5: AE-2 6% binder for Chrome Slag



Axle load Repetitions (RUT)							
Position	0	2500	5000	10000	25000	50000	100000
0100	0	2.41	3.58	4.88	5.65	6.11	6.81
0200	0	2.42	3.18	4.24	5.42	5.79	6.45
0300	0	1.71	2.36	3.06	3.68	3.91	4.33
0400	0	1.67	2.32	3.13	4.00	4.41	5.12
0500	0	1.37	1.84	2.51	2.96	3.13	3.53
Avg	**0**	**1.92**	**2.66**	**3.56**	**4.34**	**4.67**	**5.25**
Stdev	**0.00**	**0.47**	**0.70**	**0.97**	**1.15**	**1.26**	**1.39**

Average Rutting @ 100000 axles : 5.25

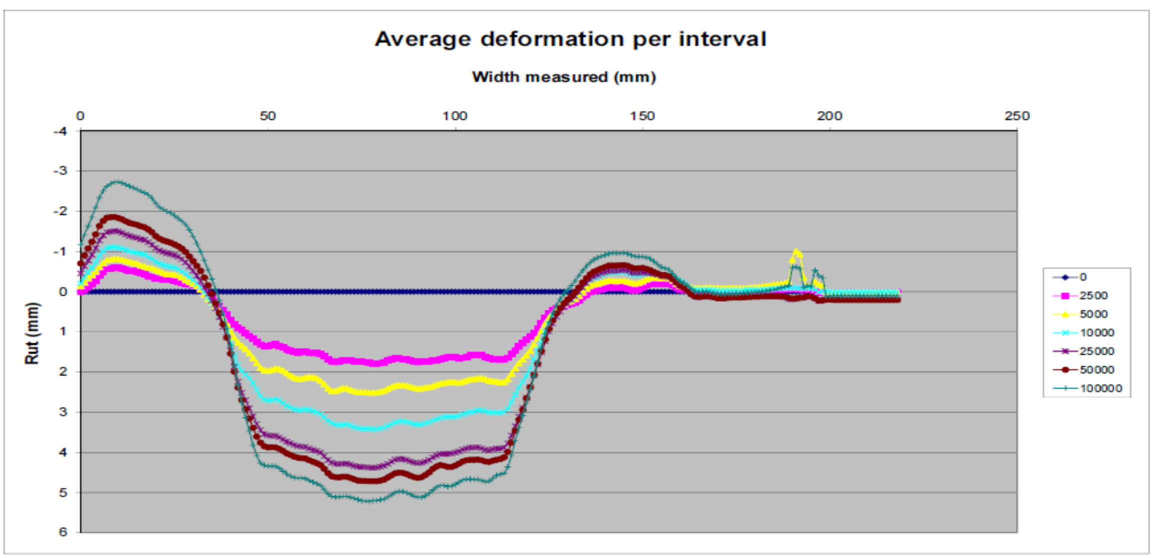
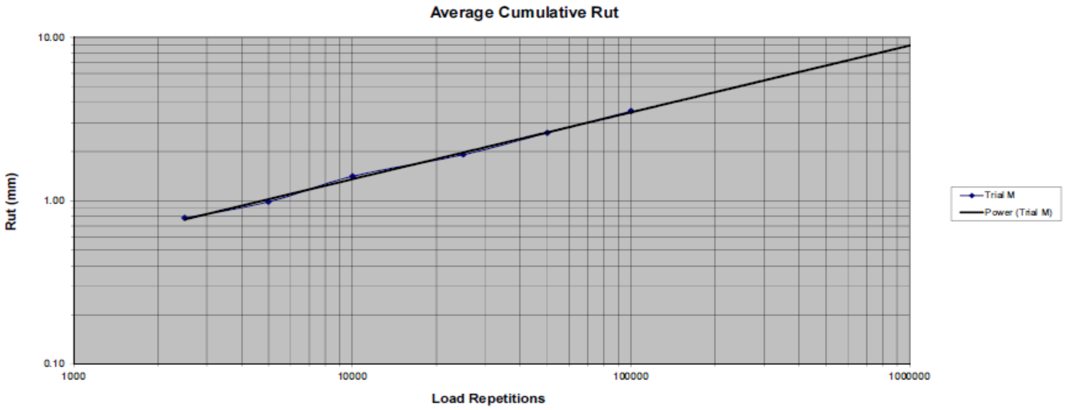


Figure 37: AE-2 6% binder for Chrome Slag

Table 5.6: 50/70 5% binder for Natural Aggregate



Position	Axle load Repetitions (RUT)						
	0	2500	5000	10000	25000	50000	100000
0100	0	1.15	1.44	2.03	2.60	3.10	3.56
0200	0	0.82	1.06	1.64	2.26	3.38	5.08
0300	0	0.81	1.08	1.61	2.21	3.12	4.18
0400	0	0.74	0.93	1.22	1.75	2.52	3.77
0500	0	0.39	0.41	0.54	0.75	0.88	1.07
Avg	**0**	**0.78**	**0.98**	**1.41**	**1.91**	**2.60**	**3.53**
Stdev	**0.00**	**0.27**	**0.37**	**0.56**	**0.71**	**1.01**	**1.49**

Average Rutting @ 100000 axles : 3.53

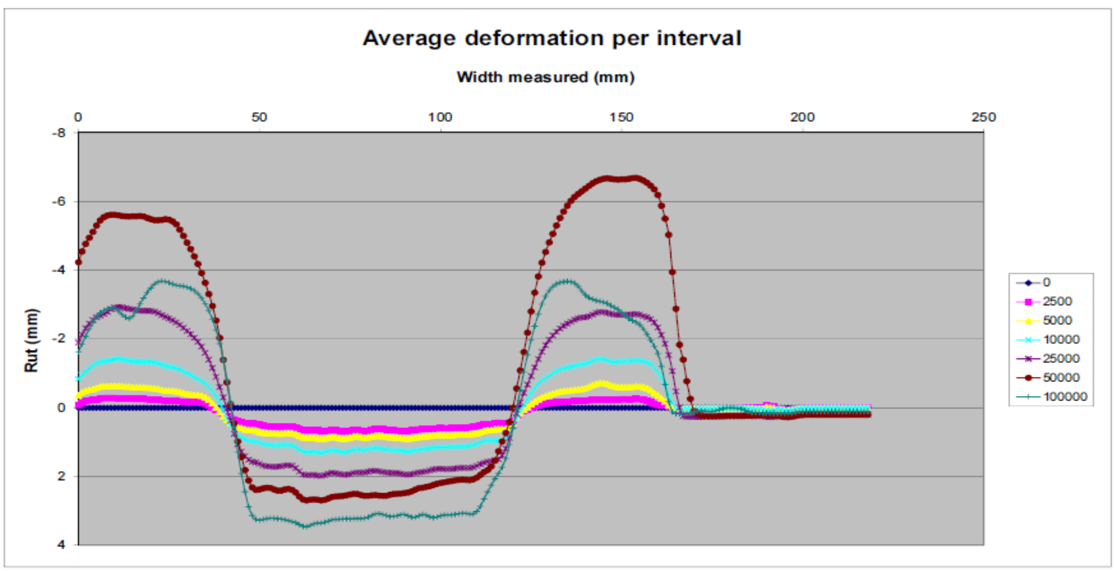
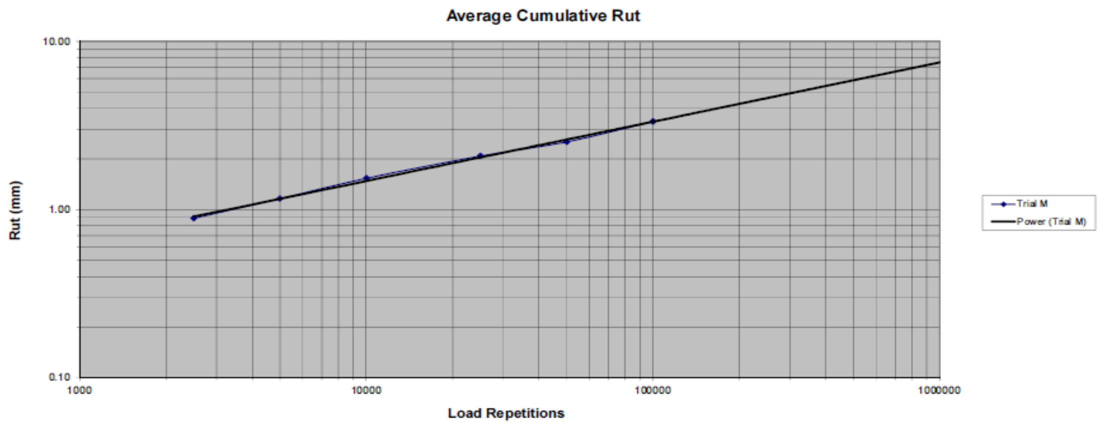


Figure 38: 50/70 5% binder for Natural Aggregate

Table 5.7: 50/70 5.5% binder for Natural Aggregate



Axle load Repetitions (RUT)							
Position	0	2500	5000	10000	25000	50000	100000
0100	0	0.99	1.37	1.91	2.46	2.78	3.18
0200	0	0.97	1.18	1.49	1.94	2.27	2.77
0300	0	0.84	1.13	1.52	2.10	2.56	3.48
0400	0	0.92	1.15	1.48	2.10	2.80	4.02
0500	0	0.70	0.98	1.28	1.81	2.20	3.23
Avg	**0**	**0.89**	**1.16**	**1.53**	**2.08**	**2.52**	**3.33**
Stdev	**0.00**	**0.12**	**0.14**	**0.23**	**0.24**	**0.28**	**0.46**

Average Rutting @ 100000 axles : 3.33

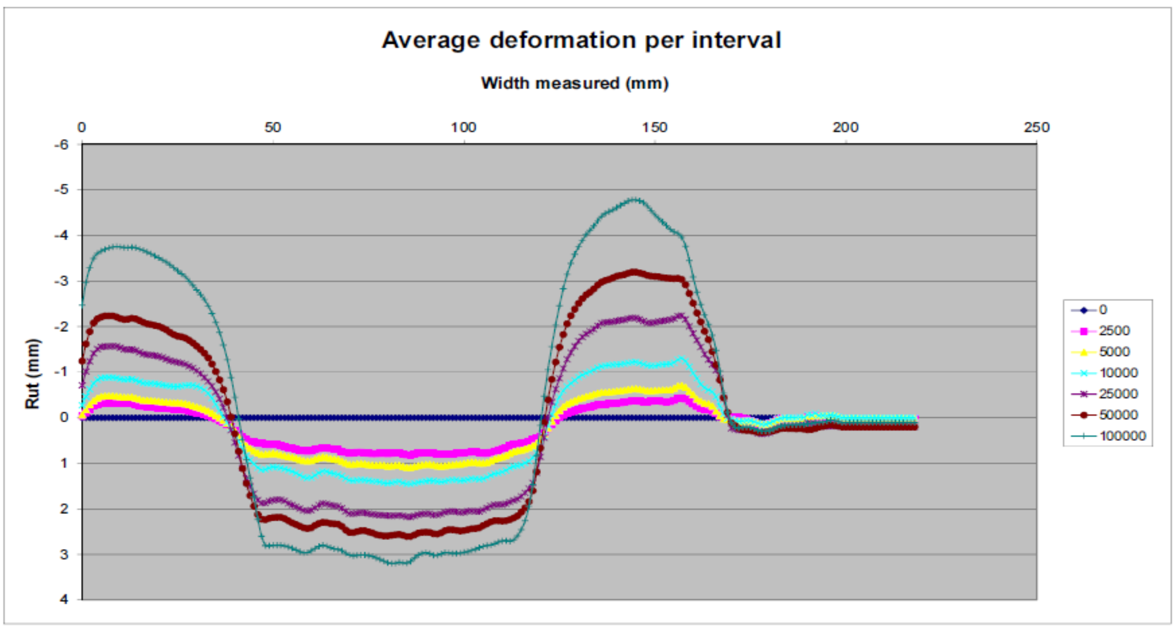
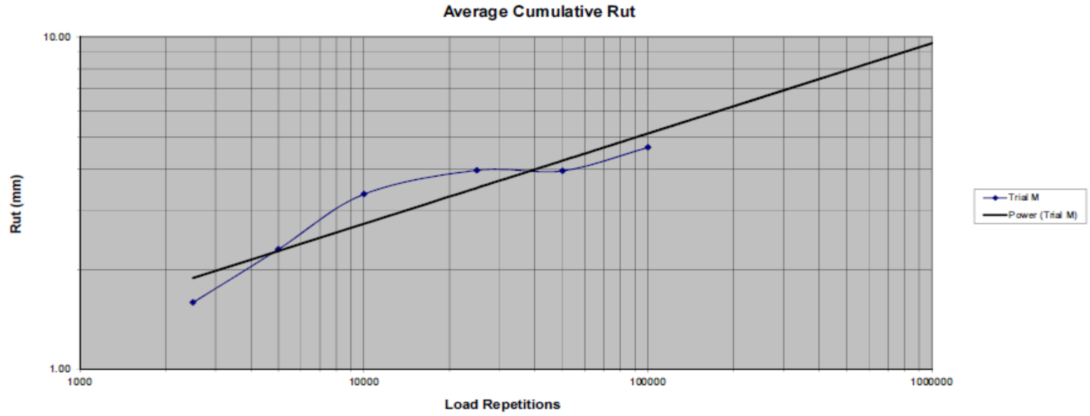


Figure 39: 50/70 5.5% binder for Natural Aggregate

Table 5.8: 50/70 5.5% binder for Chrome Slag



Axle load Repetitions (RUT)							
Position	0	2500	5000	10000	25000	50000	100000
0100	0	1.94	2.89	4.81	5.96	6.01	7.13
0200	0	1.42	1.85	2.65	3.18	3.14	3.81
0300	0	1.56	2.40	3.53	4.21	4.22	4.99
0400	0	1.62	2.35	3.05	3.40	3.32	3.85
0500	0	1.40	2.00	2.79	3.10	3.07	3.45
Avg	**0**	**1.59**	**2.30**	**3.36**	**3.97**	**3.95**	**4.65**
Stdev	**0.00**	**0.22**	**0.40**	**0.88**	**1.20**	**1.24**	**1.50**

Average Rutting @ 100000 axles : 4.65

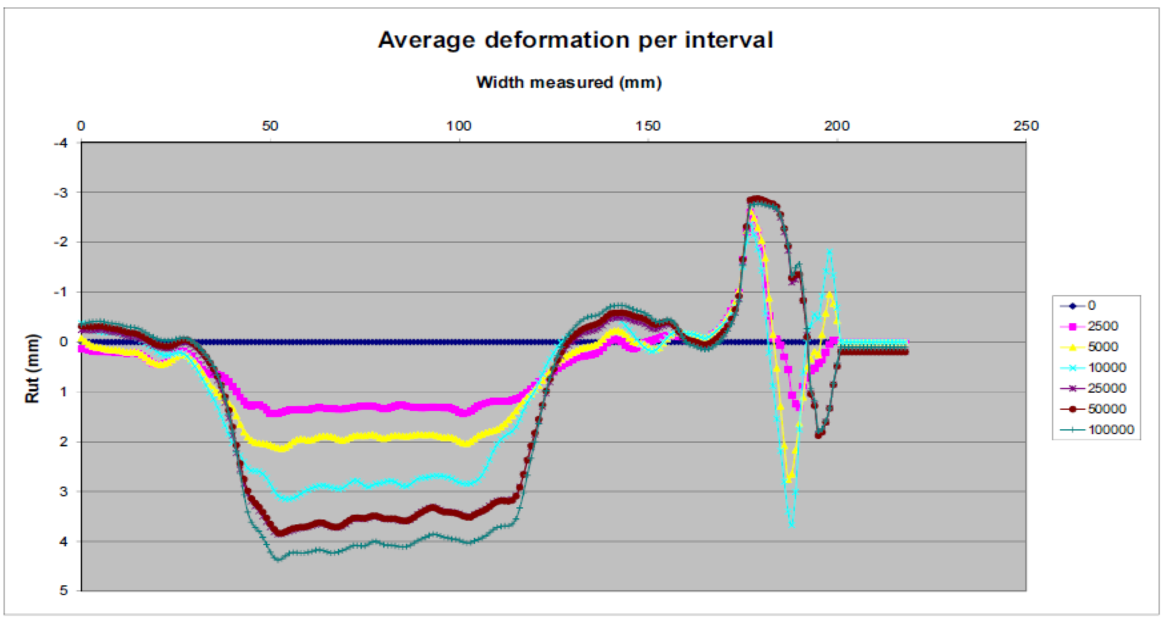
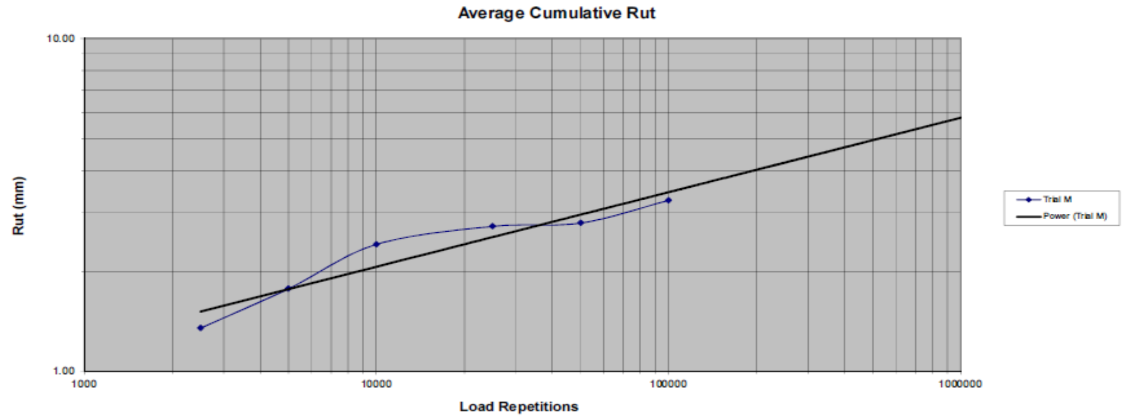


Figure 40: 50/70 5.5% binder for Chrome Slag

Table 5.9: 50/70 6% binder for Chrome Slag



Position	Axle load Repetitions (RUT)						
	0	2500	5000	10000	25000	50000	100000
0100	0	1.40	2.00	2.79	3.10	3.07	3.45
0200	0	1.43	1.89	2.52	2.94	3.00	3.28
0300	0	1.42	1.84	2.45	2.77	2.77	3.26
0400	0	1.22	1.51	2.17	2.47	2.43	2.99
0500	0	1.28	1.62	2.11	2.35	2.68	3.32
Avg	**0**	**1.35**	**1.77**	**2.41**	**2.73**	**2.79**	**3.26**
Stdev	**0.00**	**0.09**	**0.20**	**0.28**	**0.31**	**0.26**	**0.17**

Average Rutting @ 100000 axles : 3.26

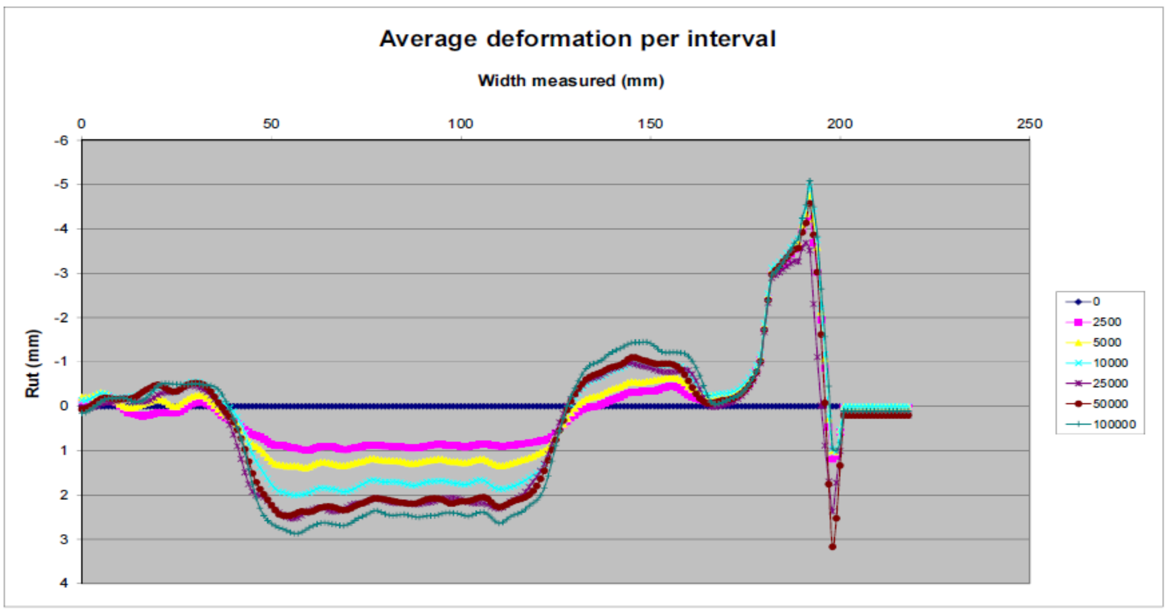
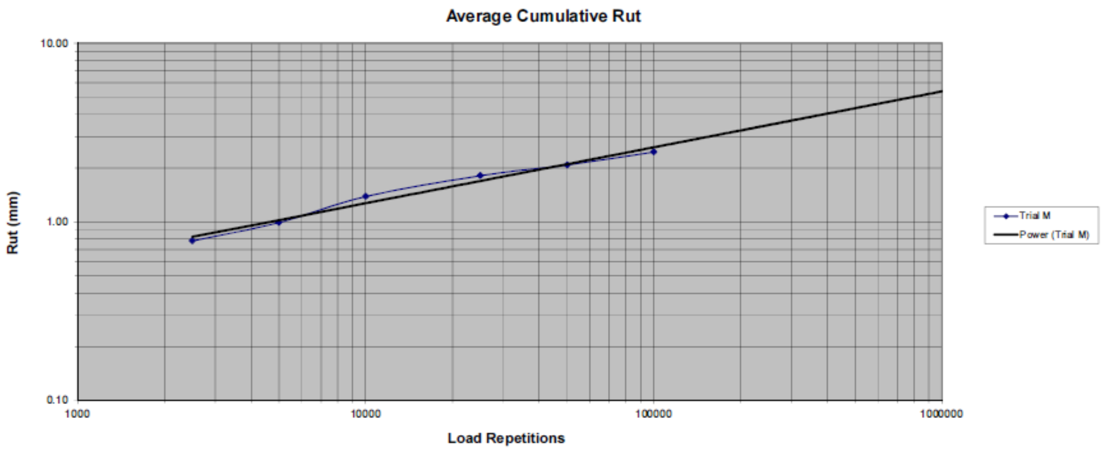


Figure 41: 50/70 6% binder for Chrome Slag

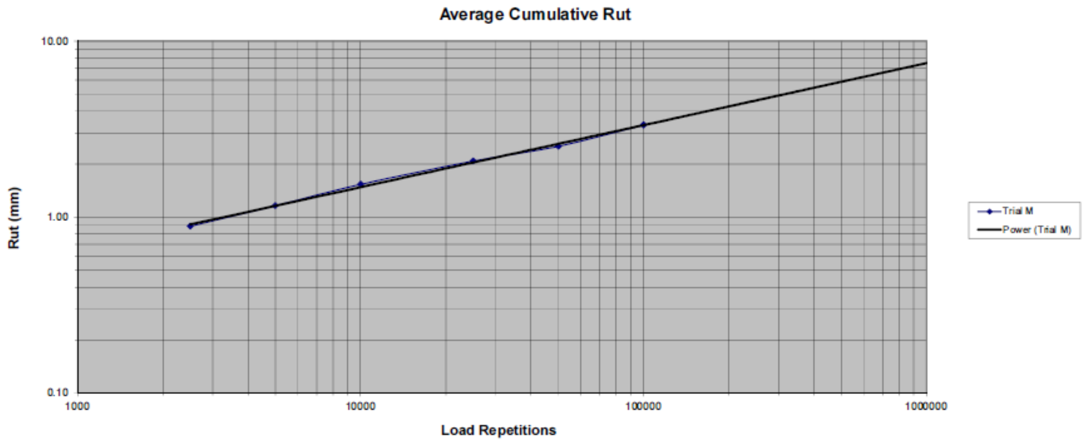
Table 5.10: AE-2 5% binder for Natural Aggregate



Axle load Repetitions (RUT)							
Position	0	2500	5000	10000	25000	50000	100000
0100	0	0.91	1.08	1.37	1.78	2.13	2.53
0200	0	0.48	0.60	0.98	1.26	1.54	1.96
0300	0	0.40	0.51	0.75	1.03	1.13	1.32
0400	0	0.23	0.41	0.80	1.21	1.46	1.87
0500	0	1.89	2.34	3.03	3.78	4.15	4.63
Avg	**0**	**0.78**	**0.99**	**1.39**	**1.81**	**2.08**	**2.46**
Stdev	**0.00**	**0.67**	**0.80**	**0.95**	**1.14**	**1.21**	**1.28**

Average Rutting @ 100000 axles : 2.46

Table 5.11: AE-2 5.5% binder for Natural Aggregate



	Axle load Repetitions (RUT)						
Position	0	2500	5000	10000	25000	50000	100000
0100	0	0.99	1.37	1.91	2.46	2.78	3.18
0200	0	0.97	1.18	1.49	1.94	2.27	2.77
0300	0	0.84	1.13	1.52	2.10	2.56	3.48
0400	0	0.92	1.15	1.48	2.10	2.80	4.02
0500	0	0.70	0.98	1.28	1.81	2.20	3.23
Avg	**0**	**0.89**	**1.16**	**1.53**	**2.08**	**2.52**	**3.33**
Stdev	**0.00**	**0.12**	**0.14**	**0.23**	**0.24**	**0.28**	**0.46**

Average Rutting @ 100000 axles : 3.33

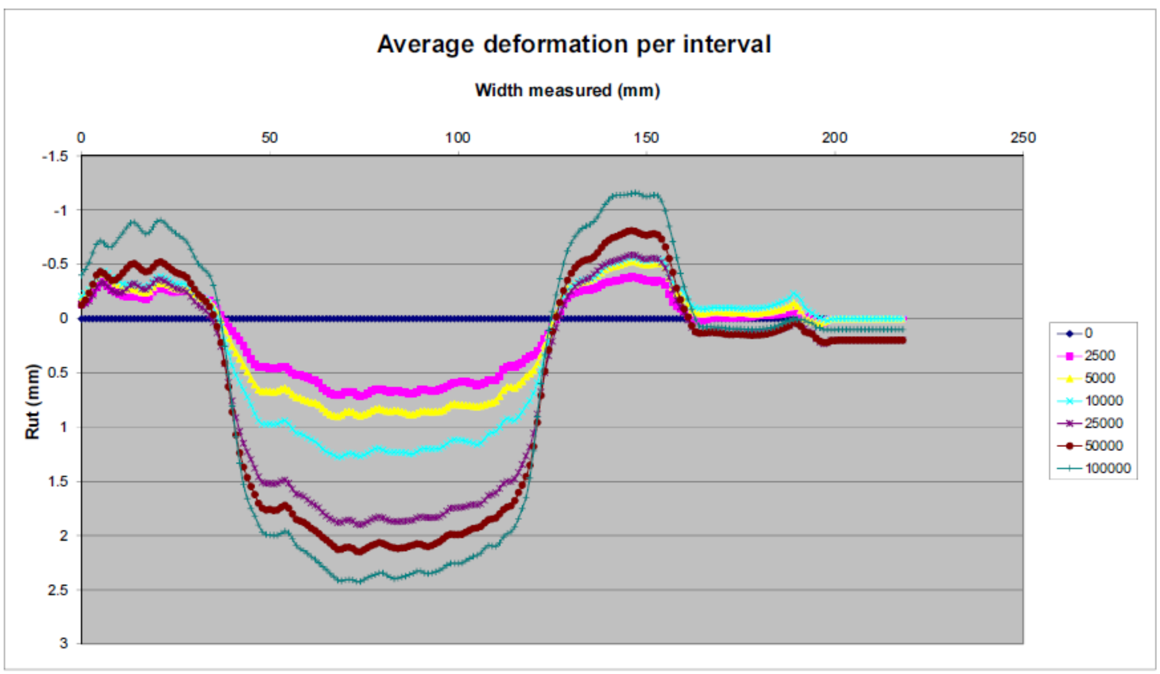


Figure 42: AE-2 % binder for Natural Aggregate

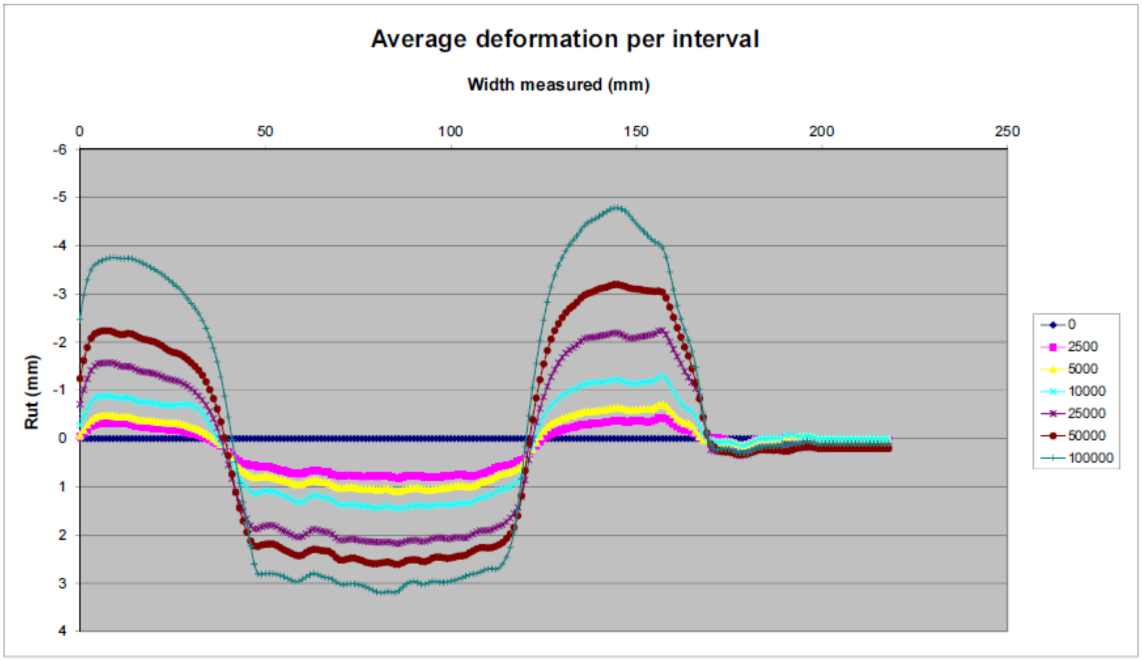


Figure 43: AE-2 % binder for Natural Aggregate

5.4.15 Gyratory Compaction

The gyratory was developed that would realistically compact trial mix specimens to the required densities that would be comparable to actual pavement climate and loading under traffic. This test gives the design engineer an insight into the mix compatibility and helps to avoid mixes that exhibit tender mixes or mixes that tend to densify dangerously to low air void content under long term action of traffic. Figure 44 shows typical gyratory testing equipment. As stated in this study, the Superpave design did not take off well in South Africa although the gyratory testing has been accepted and is used for evaluation of the mixes under heavy traffic loads. The gyratory has been set at 300 gyrations at an angle of 1.25°, 600kPa, and timed to 30 gyrations per minute.

Figure 44: Typical Gyratory compactor (Roberts, 1996)

The results are shown in Table 5.12 for AE-2 binder and Table 5.13 for 50/70 binder. The gyrations with acceptable limits for heavy to very heavy is min 1.5% and 2.5% void content after 300 Gyrations respectively.

Table 5.12: Gyratory results after 300 Gyrations with AE-2 Binder

	AE-2			
	Natural Agg		Slag	
Binder %	5	5,5	5	6
BRD Marshall	2517	2542	2691	2667
MTRD Rice	2653	2691	2700	2705
Marshall Voids	5,1	5,5	3,2	1,3
% Compaction	94,9	94,5	96,8	98,6

Table 5.13: Gyratory results after 300 Gyrations with 50/70 Binder

	50/70			
	Natural Agg		Slag	
Binder %	5	5,5	5,5	6
BRD Marshall	2516	2545	2659	2630
MTRD Rice	2616	2608	2747	2723
Marshall Voids	3,8	2,4	3,2	3,4
% Compaction	96,1	97,6	96,8	96,5

5.4.16 Indirect Tensile Strength (ITS)

The ITS have been used in the Marshall designs to evaluate the fundamental stiffness and fatigue properties of the mastic. The stiffness of asphalt determines its ability to carry and spread traffic loads to underlying layers. Resistance to fatigue is the ability of the mix to withstand repeated tensile strains without fracture. In this test, a cylindrical asphalt specimen is loaded on a diametral axis at a fixed rate until a significant loss in applied load is noted. The peak load is used to calculate the ITS. The test specifications are noted not to be between 900 Kpa and 1650kPa (SABITA, 2014). It has been noted that asphalt above 1500 kPa has the tendency to be brittle and hard to compact. Results of the tests are shown in Table 5.14 for 50/70 binder and Table 5.15 for AE-2 Binder.

Table 5.14: ITS for 50/70 binder

Binder	50/70							
Property	Chrome Slag				Natural Aggregate			
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6
ITS kPa	919	933	961	1169	907	950	1082	779

Table 5.15: ITS for AE-2 Binder

Binder	AE-2							
Property	Chrome Slag				Natural Aggregate			
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6
ITS kPa	1120	1170	1236	1245	1348	1275	1446	1357

5.4.17 Hamburg Wheel Tracking Test (HWTT)

The HWTT indicates and should be assessed according to the following:

1. Susceptibility to premature failure due to weak aggregate structure

2. Inadequate binder stiffness

3. Moisture damage

4. Inadequate adhesion between aggregate and binder

Samples are compacted to a diameter of 150mm and to a thickness of 60mm ±2mm. The samples are then cooled for 16h. The specimens are then placed in a mounting tray and fastened in a empty water bath. The bath is then filled with water to a test temperature of 50°C. The wheels are lowered, and the required criteria is loaded on the software and the test is then started.

The test results include post-compaction consolidation, which is usually assessed at 1000 wheel passes, creep slope, stripping slope and stripping inflection point as indicated in Figure 45 (SABITA MANUAL 35, 2020). Photographs of the apparatus is found in the Appendices of this study.

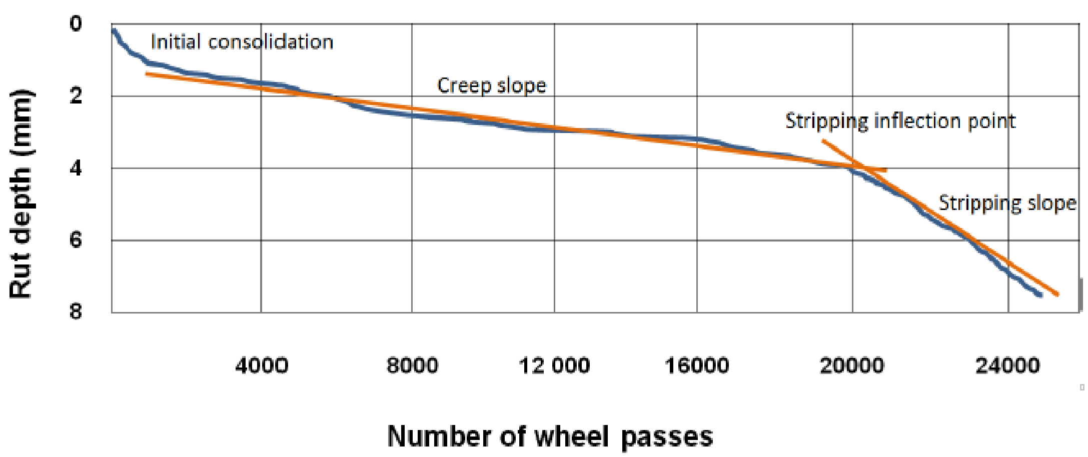


Figure 45: HWTT assessed at 1000 wheel passes (SABITA MANUAL 35, 2020)

The criteria used to evaluate the results for permanent deformation is found in Table 5.15A.

The HWTT test criteria is based on maximum temperature zone of 64 and 58 as found in the SABITA Manual 35.

Table 5.15A: Criteria for HWTT test results

Maximum Temperature Zone	Minimum number of passes to 6mm rut	Minimum number of passes to stripping point (min)

64	20000	10000
58	16000	10000

The tests completed was to evaluate the stripping point of the samples therefore the results shown in Table 5.15B and Table 5.15C are aimed to reach the minimum of 10000 passes only. The graphs are shown in Figures 46 to 49.

Table 5.15B: Natural Aggregate Hamburg results versus stripping point

Natural Aggregate	%Binder versus rut depression			
Passes	50/70		AE-2	
	5	5,5	5	5,5
10544	10,01	5,76		
10600			5	1,99

Table 5.15C: Chrome Slag Hamburg results versus stripping point

Chrome Slag	%Binder versus rut depression			
Passes	50/70		AE-2	
	5,5	6	5	6
6436	9,91	10		
10600			7,18	7,36

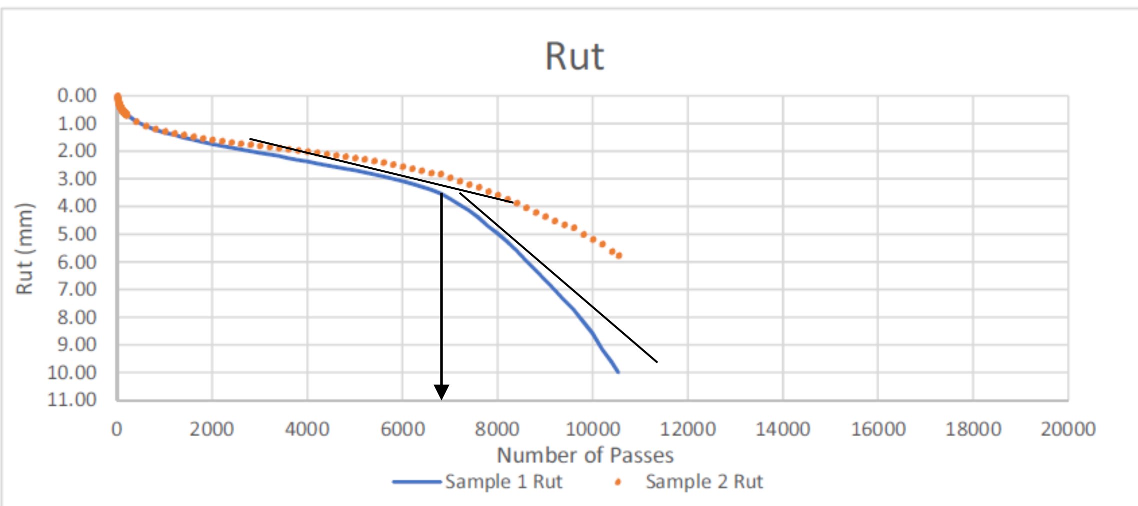


Figure 46: Natural Aggregate with 50/70 Binder, Sample 1: 5% Binder and Sample 2: 5.5% Binder

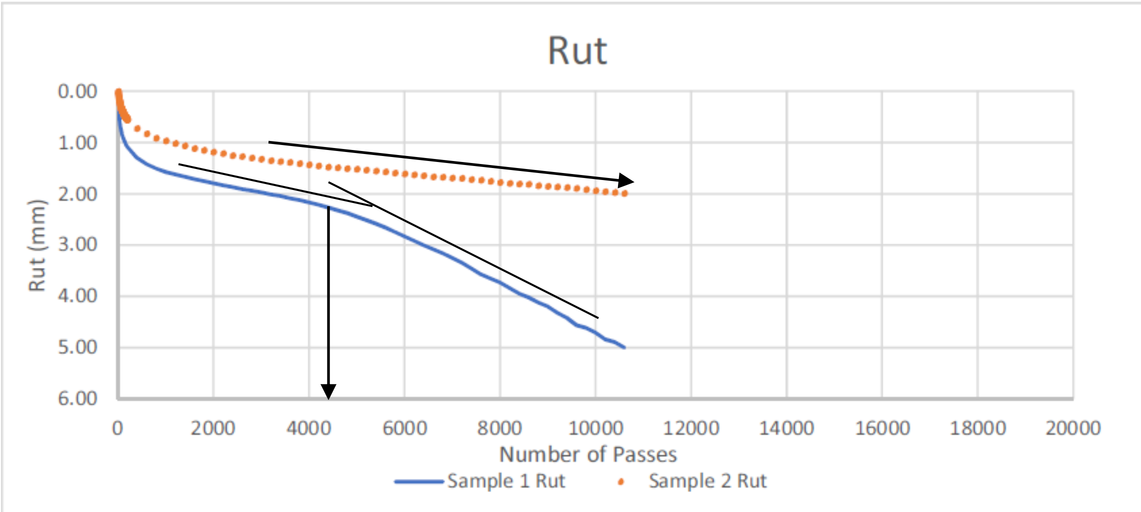


Figure 47: Natural Aggregate with AE-2 Binder, Sample 1: 5% Binder and Sample 2: 5.5% Binder

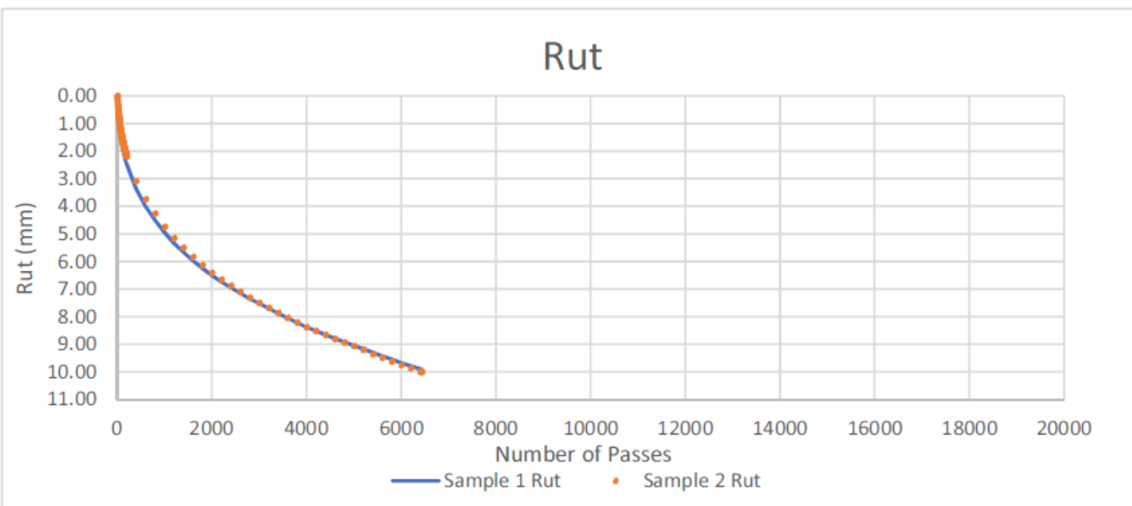


Figure 48: Chrome Slag with 50/70 Binder, Sample 1: 5.5% Binder and Sample 2: 6% Binder

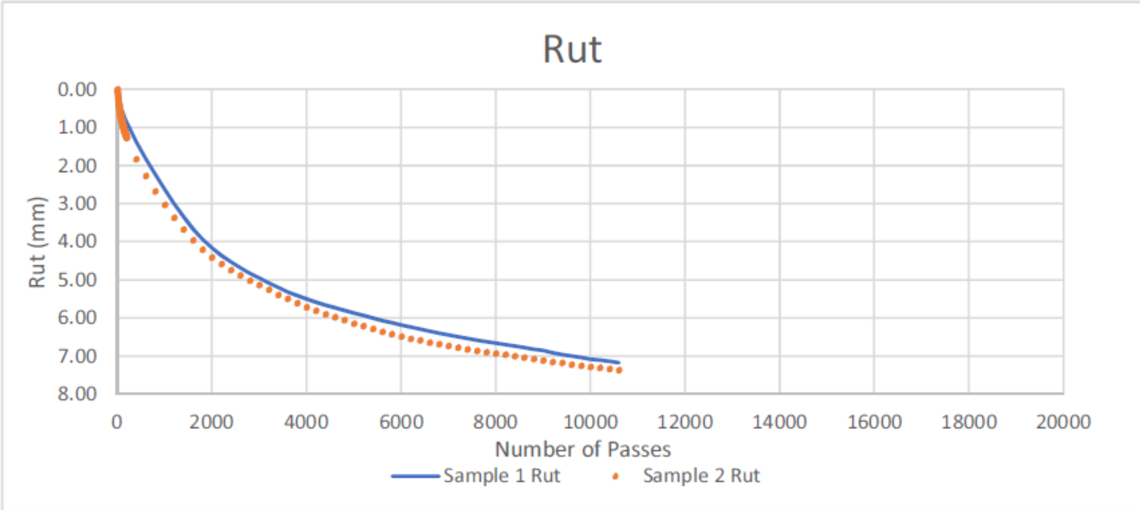


Figure 49: Chrome Slag with AE-2 Binder, Sample 1: 5% Binder and Sample 2: 6% Binder

5.5Discussion

Design of a suitable asphalt mixture is under continuous evaluation in South Africa and keeps evolving due to technologies that can better control the required parameters and obtain better, more reliable predicted and field performances of the mixtures. Various documents, as discussed, are used and combined to try and effectively obtain a mixture that conforms to all parameters and performance-based testing.

As stated in this study, it is critical to outline and complete the tests according to engineering properties evident in the guidelines used in this study, namely;

1. Durability
2. Resistance to cracking
3. Resistance to permanent deformation
4. Resistance to rutting
5. Resistance to Shrinkage
6. Flexibility
7. Skid Resistance
8. Permeability
9. Stiffness
10. Workability

The above is used for more aggressive designs as updated in the documents and noted in the study, namely;

1. IGHMA, 2001
2. SABITA Manual 24, 2019
3. SABITA Manual 35, 2019
4. SAPEM, 2013
5. TRH8, 1986

As per Figure 24 of the study, the engineering considerations need to take place for what the product is destined for and for what purpose.

As stated, fillers are defined as the materials that passes the 0.075mm sieve and are essential components for producing asphalt mixes which are dense, cohesive, durable, and resistant to damaging effects of moisture. There are two (2) types of fillers in the industry:

1. Inert fillers, natural rock dust or rock-flour
2. Active fillers, hydrated lime or cement

Fly Ash falls under the active fillers due to the amount of free lime available. Fillers have certain functions whereby the performance characteristics are affected, which are not limited to:

1. Effects the rheological properties of the mastic system.
2. Volumetric function to fill voids and bind aggregate together.
3. As with active fillers, improve the adhesion of the binder to the aggregate.
4. Fly Ash contributes to the improvement of compatibility of the asphalt layer.
5. The extender stiffens the binder therefore the stability is improved.

The filler-binder ratio is a critical element as the component will increase the viscosity of the mastic leading to compaction problems, especially with thin layers as they cool quicker.

The criteria is established for active fillers due to the variability of the fillers, which is envisaged by the supply. This has then created formulae to determine the correct ratio is applied and the proportions are determined. Sufficient filler in a mastic mixture will ensure:

1. The mixture has adequate cohesion.
2. The mixture provides sufficient internal tensile strength.
3. The mixture is resistant to shearing forces.

4. The mixture is durable.

5. The mixture has adequate resistance to permanent deformation.

It has been found in research that filler-binder ration of above 1.4 has proven to produce highly rut resistant mixes but does come at a cost, and compaction effort in the field is difficult to achieve. It is recommended that a ratio of 1.1 to 1.3 is more feasible for light trafficked roads (Pretorius *et al*, 2004).

The results have indicated the following:

The percentage passing the 0.075mm sieve is 80.7% which is above the minimum requirements of 70%. The ratio calculated for both 50/70 and AE-2 mixtures vary between 1:1.1 and 1:1.3. This falls within the required specification parameters as is noted for thin layer mixes. The results conform to 6% AE-2 and 6% 50/70 with 1:1.1 respectively.

The mix design is a laboratory design for the correct component selection and proportioning. It has been customary to categorise mixes in terms of set grading parameters which also include the consideration of volumetric or spatial concepts. The aggregate used for the study has a nominal size of 10mm. Detail characteristics were discussed in Chapter 4. The current design considerations for the 10mm nominal size aggregate have also included certain control points to further give guidance to the designer. It is spatial points as shown in Table 5.3, and the new combined blended grading must pass through these points. These points are also plotted in Figure 30 to 31. According to the Bailey Method, a primary control sieve (PCS) is a sieve that determines if the specific sample grading is coarse or fine. The PCS sieve for the 10mm nominal size materials is 2mm with a passing of 47% and is shown in Table 5.4. Both Chrome Slag and Natural Aggregate are specified as a fine mix as the materials passing the 2mm sieve on the combined grading is 45% and 42%, which is less than 47% passing the PCS.

Further, a ternary diagram can also be used to classify materials according to the relevant proportions of stone, sand, and filler (SAPEM, 2013). The proportions are divided into the following groups:

1. Coarse (Stone) is materials retained on the 5mm sieve.

2. Fine (Sand) is materials passing the 5mm sieve but retained on the 0.076mm sieve.

3. Filler is materials passing the 0.075mm sieve.

With this in mind, the following statements can be made:

For Natural Aggregate according to Table 5.5:

Coarse = 30%

Sand = 70% - 5.5% = 64.5%

Filler = 5.5%

For Chrome Slag according to Table 5.6:

Coarse = 33%

Sand = 67% - 6.4% = 60.6%

Filler = 6.4%

The indication of the ternary diagram also indicates that both the materials are classified as sand skeleton grading. This can be seen in Figure 50 and 51 for Chrome Slag and Natural Aggregate respectively. This also conforms to the fine mixture as stated by the PCS of the Bailey Method. Sand skeleton mixtures, the loads on the layer, are mainly carried by the finer aggregate fraction. The larger aggregate fractions provide the bulk and replaces a proportion of the finer aggregate as shown in Figure 52.

The combined grading is shown in Table 5.5 and 5.6 and is also plotted in Figures 30 and 31. The Table 5.5 and 5.6 is a representation of what the current laboratories are completing to combine materials to comply with a required grading specification as plotted on Figures 30 and 31. This is also shown on the D3 forms of the appendences. The required specifications used are found on Table 5.2 for the continuously medium graded mixture. The "% mix" in the columns, found in Table 5.2, is changed to adapt the combined grading to the specification. The percentage grading combination mix always needs to add up to 100%.

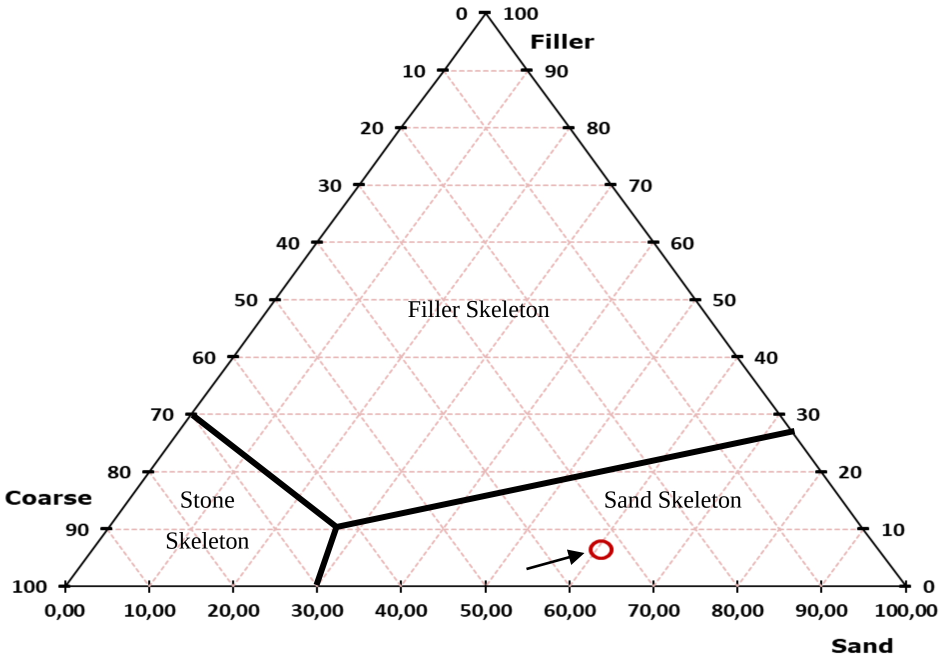


Figure 50: Ternary Diagram for Chrome Slag

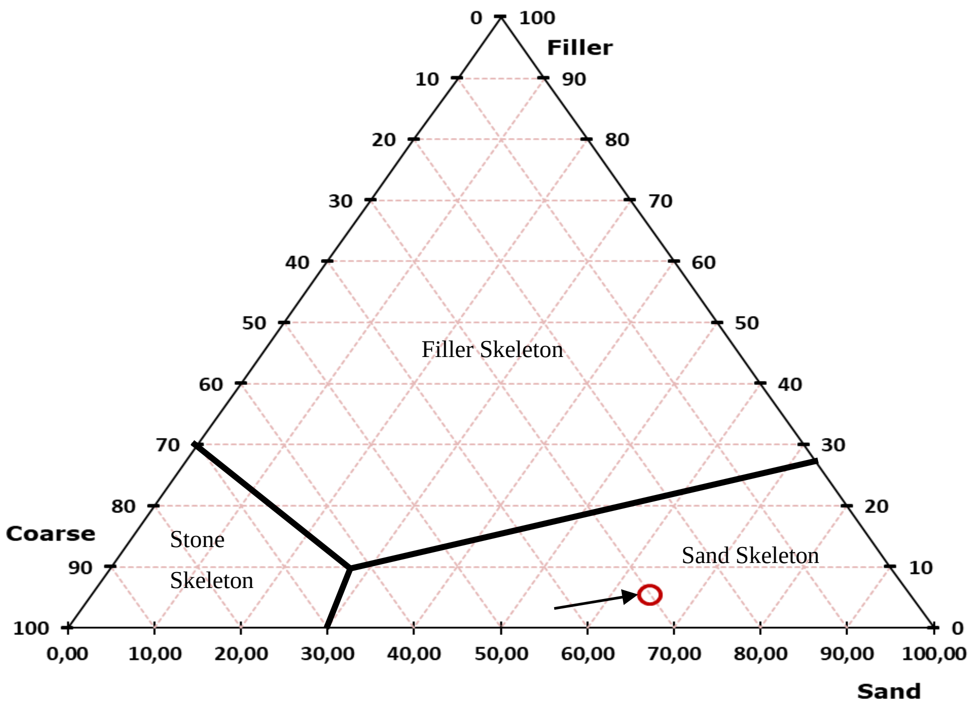


Figure 51: Ternary Diagram for Natural Aggregate

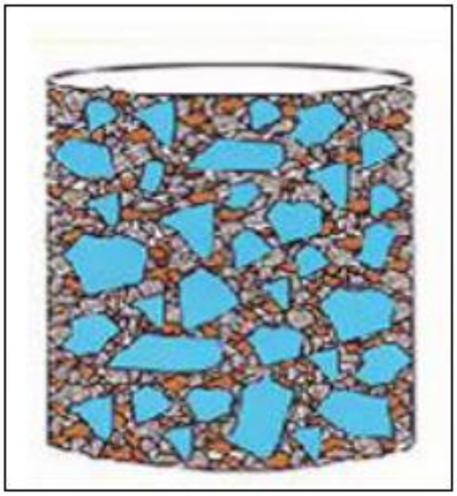


Figure 52: Diagram of Sand Skeleton Mixture (SAPEM, 2013)

The following can be assessed from figures 32 and 33 respectively;

1. Both gradings of Chrome Slag and Natural Aggregate pass through the control points as set out from Table 5.3.
2. The limits from Table 5.2 to produce an envelope in both figures show it is also within the control points. The gradings from each flow within the envelopes.
3. The gradings flow mostly on the upside of the specification envelopes, so it also indicates a fine grading specifications as discussed for sand skeleton mixes, which is also shown on the ternary diagram.
4. The fuller curve is on the upside of the specification envelope, which indicate that the best aggregate compaction density for the particular sieves is on the fine side.
5. Both the gradings on the figures follow the fuller curve closely from the 10mm sieve up to 0.6mm sieve, which indicates an ideally packed grading. The gradings then move away from the fuller curve from the 0.6mm sieve, indicating a coarser fine material. Although the gradings do move away, it still shows and even flow with the curve. The even flow show the adequate packing of the gradings can be achieved within the required guidelines.
6. The Chrome Slag display a better grading flow curve compared to the aggregate, and the more densely packed grading will be achieved. An "outlier" on the aggregate is on the 0.6mm sieve, which has dropped to outside of the specified envelope but is still within

the control points. It is envisaged that the grading will change under construction conditions and some materials on the 0.6mm will likely be "crushed" under compaction, thus raising the grading within the specified limits.

7. At the moment, the Chrome Slag shows a better density packing characteristic than the Natural Aggregates.

Laboratory Compaction of mixes essentially entails compacting specimens to try and simulate the volumetric characteristics and performance properties that will occur in the field. The compaction in most laboratories is to try and simulate the compaction in the field but it has been found that none of the laboratory equipment is capable of producing mixes with an aggregate packing that closely represents the packing obtained during the field compaction (IGHM, 2001).

There are three types of compaction that can be used in the laboratory:

1. Marshall Compaction – conventional method
2. Modified Marshall Compaction
3. Gyratory Compaction

The current Marshall compaction is used to process all continuously graded mixes using a uniform compaction procedure. The compaction takes place at 150 blows (75 blows on each side of the briquette), and this will indicate to the designer if the voids are closing. The number of blows is also to determine the optimum binder content. Any reduced or increased blows is only for the design purposes when the designer is satisfied that the blows will not produce any significant difference in density results (IGHM, 2001). Briquettes are compacted to a thickness of 64mm thick. It is noted that for every 10mm paving thickness less than 64mm, the designer is to add 0.1% additional bitumen to the target binder content (SAPEM, 2013).

Modified Marshall Compaction determines the void content after each blow of the Marshall hammer. This allows the designer to better assess the mix behaviour during compaction and traffic densification. It also differs from the conventional Marshall that uses five (5) binder contents where the Modified Marshall only uses three (3) (IGHM, 2001).

Modified Lottman tests indicate potential stripping of the binder from the aggregate. It is also an indication if any anti-stripping agents are required such as lime and cement. All results indicated in Tables 5.31and 5.32 show that the design is sufficient and is quite resistant to anti-stripping and well above the minimum of 0.8.

MMLS is sued for rutting potential of the material and is used for evaluation of materials under heavy traffic situations. The reason for this test in the study is to evaluate whether the Chrome Slag potential can be used for this purpose as well. Although no actual data is given for maximum rut after 100 000 axles for 20mm asphalt, it can be assumed that a higher rut is envisaged. The only rut resistance tables are found in the DPG1, which is a draft protocol and only stipulates for up to 40mm and not less. Under the laboratory conditions for the 40mm according to DPG1 the maximum rut after 100 000 axles should not be more than 2.5mm. While the results shown in Tables 5.4 to 5.11 indicate ruts of between 3.26 to 4.65 for 50/70 binder and between 2.46 and 5.35 for AE-2 binder. It has been noted that for every thickness of 10mm less than 40mm, 0.1% binder must be added to the design. Can this also be applicable to the MMLS for rural road application? This was taken into consideration as more binder can soften the mastic. Using the formulae, one can assume that 20mm difference equates to 2, therefore if we add it to the DPG1 Table for the 40mm, then the maximum rut for 20mm asphalt should be around 4.5mm. The results for the 50/70 is thus within specification but the AE-2 is within the specification for the Natural Aggregate but not for the Chrome Slag and Fly Ash mixture.

Gyratory compaction was developed in the United States of America (USA) as part of the Superpave mix design method. This method is similar to the Modified Marshall and can also monitor the increase in sample density with increasing compactive effort. This method produces compaction that more closely resembles field compaction. The gyratory compaction is completed to a maximum of 300 gyrations for sand skeletons. Gyratory compaction, the voids and density achieved at different gyrations, as well as the ultimate voids and density and this evaluation is likely to assess the performance of the mix in different designs and to determine the design binder content. This is why, on most of the design applications, the gyratory is the nominated test above the Modified Marshall test. In this study, the Gyratory is the preferred test and the Modified Marshall will not be used, but it is written in this study for information purposes (IGHM, 2001). All the results as found in Tables 5.12 and 5.13 have indicated good performance after 300 Gyrations and equates to the protocol for heavy traffic.

The Marshall Stability and Flow parameters were initially designed to serve as performance indicators but have been proven to be unreliable and have fallen out of favour, but it is still used in the design criteria (Pretorius *et al*, 2004). It has been found that little evidence suggests that these parameters exhibit a strong correlation with rutting or fatigue life (Jooste *et al*, 2000). The stability has been used to identify the optimum binder content.

Although the test has fallen out of favour, it can still be used to determine the bearing capacity of the layer to indicate whether the mixture has sufficient stability to resist displacement under traffic (Metcalf, 1969). All data collected on the Marshall Stability and Flow has indicated that possible relation to bearing capacity of a paving mix is envisaged. The results in Table 5.12 and 5.13 show that the % binders have psi that varies between 63psi and 108psi for the Chrome Slag on 50/70 binder and between 49psi and 126psi for the Natural Aggregate on the 50/70 binder. The AE-2 binder shows 87psi to 116psi for the Chrome Slag and between 104psi to 138psi for the Natural Aggregate. For a road with light traffic, acceptable stability can be concluded with the various mixes.

A question remains, can a check be developed between Marshall Stability and ITS of a design? A formula has been tried in this study to get an acceptable percentage value which must be achieved for acceptance of the Marshall Stability results and from the design, an estimated ITS for final proposal can also be determined. The formula is the following:

$$\text{Marshall Check} = \frac{\dfrac{(A\text{x}1000)}{6894{,}76} \quad \text{X} \quad 1000}{B} \quad \text{x} \quad 100$$

A = Marshall Stability in kN

B = The Actual ITS value – if the Marshall Stability value ends up greater than B, the following formulae must be used.

$$\text{Marshall Check} = \frac{B}{\dfrac{(A\text{x}1000)}{6894{,}76} \quad \text{X} \quad 1000} \quad \text{X} \quad 100$$

The results can also be seen in tables 5.16 and 5.17. The averages range between 80% and 90%.

Table 5.16: Marshall Stability check for 50/70 binder for both Chrome Slag and Natural Aggregate

Traffic Class	50/70								Average	
Property	Chrome Slag				Natural Aggregate				Chrome Slag	Aggregate
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6		
ITS kPa	919	933	961	1169	907	950	1082	779		
Marshall Stability kN	6,6	6,3	5	5	7,3	7,5	7,5	4,4		
% Stability check	96	97,94	75,46	62,03	85,67	87,33	99,47	81,92	83	89

Table 5.17: Marshall Stability check for AE-2 binder for both Chrome Slag and Natural Aggregate

Traffic Class	AE-2								Average	
Property	Chrome Slag				Natural Aggregate				Chrome Slag	Aggregate
Binder content %	4,5	5	5,5	6	4,5	5	5,5	6		
ITS kPa	1120	1170	1236	1245	1348	1275	1446	1357		
Marshall Stability kN	10,6	9,4	7,1	6,9	8	8,7	8	10,9		
% Stability check	72,85	85,82	83,31	80,38	86,08	98,97	80,24	85,84	81	88

The bulk density is for the compacted mixtures. The Chrome Slag does show that it is heavier than the Natural Aggregate but taking into consideration, it is not by much. On the AE-2 binder, the average difference is 62kg/m³ and on the 50/70 binder, the average is 97kg/m³. Although there is not much difference in the weight, it must be noted that Chrome Slag is porous, and consideration must be given to a higher binder, therefore an increase in weight is envisaged. This is not included in this study, due to the need to compare apples with apples at the moment, but for projects, this consideration needs to take preference thus field trials are critical.

The ITS results shown in Table 5.14 and Table 5.15 have indicated a better performance with the AE-2 binder as compared to the 50/70. It is shown that overall, on the selective % binder further studied, the results do conform to the requirements. The results are permissible on the 50/70 for the Chrome Slag from 5.5% binder and from 5% on the Natural Aggregate. The results have increased on the AE-2, which are within limits from 4.5% on the Chrome Slag and 4.5% on the Natural Aggregate. IGDHMSA states that pavements with low traffic volumes do not always warrant expensive performance parameters, the ITS test could be used to evaluate the risk of premature fatigue failure. Table 5.18 show the typical guidelines that can be used to evaluate the performance only for relatively thin wearing courses. It also indicates that for good performance against fatigue, the designer should strive for ITS of below 1000kPa. Another indication that the 50/70 is the more selective binder to use for the study.

Table 5.18: Guidelines for the interpretation of ITS results for fatigue performance evaluation (IGDHMSA, 2001)

Relative Fatigue Performance	ITS (kPa)
Good	<1000
Medium	1000 to 1400
Poor	>1400

Another remark to be shown is that the IGDHMSA also refers to the optimum aim of the ITS values to be between 1100 and 1500kPa. Table 5.19 also refers to a statistical parameter associated with relatively thin asphalt wearing courses.

Table 5.19: Statistical parameters for typical ITS results

Statistical Parameter	Typical ITS results (kPa)	Interpretation
95th percentile value	1650	Values above this may be indicative of brittleness or poor flexibility of wearing courses
75th percentile value	1200	Values close to this are indicative of good rutting performance
Average	1100	None
25th percentile value	900	Values below this may be indicative of poor rutting or stripping performance

The Hamburg results show that the only mixture that has made the specification is the Natural Aggregate on 5.5% AE-2 binder. The Chrome Slag did show improvement on the AE-2 binder, although all the other tests have confirmed a better reliability with the 50/70 binder. The high rut readings on the 50/70 Chrome Slag binder could show signs of moisture susceptibility. The reason is thus why MMLS was also completed for the high rut readings.

5.6 Summary

The main aim of asphalt mix design is to find a cost-effective combination of binder and mineral aggregate, that:

1. is workable in the field;
2. contains sufficient bituminous binder for durability and resistance to fatigue; and
3. has a suitable aggregate arrangement providing:
    - structure to the mix; and
    - space between particles to accommodate sufficient bituminous binder without flushing and / or bleeding.

One of the main factors contributing to well sustainable asphalt mix design is the consideration of a well-balanced aggregate packing. The degree of packing depends on the following factors:

1. Type and amount of compactive energy
2. Shape of the particles
3. Surface texture of the particles
4. Size distribution

Methods used in South Africa is based on the Fuller Curve and Bailey Method. Both curves were used to determine the optimal aggregate packing that can be achieved for the best mastic designs. The method of grading analysis considers the packing characteristics of individual aggregates, providing a quantified criterion that can be used to control mixture properties such as workability, segregation, and compatibility. Changing the grading of a mixture will influence the amount of void space in the aggregate skeleton.

The methods used in the study determine the coarse fraction as those particles that create voids, while the fine fraction is those particles that fit into the voids created by the coarse aggregate. The Bailey Method further creates the break point the determines the sieve sizes separating the coarse and fine aggregates and is designated as the primary control sieve (PCS). The PCS is the control sieve for the overall blend while the nominal maximum particle size (NMPS) is for the overall blend one sieve size larger than the first sieve to retain more than 10% of the aggregate. The PCS is indicated as per formula and the NMPS is based on the prescribed values in Table 5.4.

With the methods placed and grading mixtures created, the study has thus developed a continuous maximum density grading. The grading is plotted against the maximum density grading curve to the power of 0.45. The plots can thus be further evaluated to change certain portions of the grading, and this may help to bring the VMA within limits. Both the gradings for Chrome Slag and Natural Aggregate confirms the requirements. The compaction of the packing is also within the specifications of the envelopes and although the Natural Aggregate indicates problems in the finer material, it can be noted that this will be able to be adapted and changed for exact conformance. Consideration must also be taken that the Natural Aggregate can also be crushed in the compaction, thus changes to the area of concern in the grading envelope is envisaged.

In order to get an idea or check the correction of the optimum binder content of the mixtures, the surface area of aggregate is calculated to ensure that the parameters are met. This will also give an indication of the binder required to uniformly coat the aggregate particles. The best results indicated for the AE-2 Chrome Slag is between 5% and 6% binder and for 50/70 it was between 5.5% and 6%. The surface aggregate calculations indicated 5.862. This correlates with the results achieved for optimisation of the mixture. The same was shown for the Natural Aggregate with 5% and 5.5% for both AE-2 and 50/70 with the surface area indicating 5.297. It is also on this basis that further in-depth testing was chosen only on these parameters.

The VMA is stated in one of the corner stones to volumetric designs. A design voids is critical for a required thickness and to ensure that life span will be met. Also, it allows for enough compaction by traffic so that the voids are not closed even further. The Chrome Slag meets the requirements for the specification at 3% and 4% design voids. To summarise, the VMA on Chrome Slag does not issue a very confident design on the percentage binders., It can be acceptable if the results are rounded off but are close to the minimum limits as compared to the Natural Aggregate, which supersedes the expectations on all VMA results for both AE-2 and 50/70 binder. The Chrome Slag and Fly Ash mixture conforms mostly between 3% and 4% design voids. This is acceptable with 6% binder on the AE-2 and between 5.5% and 6% with the 50/70 binder with readings of 14.6, 13.7, and 13.4 respectively.

The VFB is the percentage of voids in the compacted aggregate mass that are filed with binder. The VFB is an important property not only as a measure of relative durability, but also because there is an excellent correlation between the result and the percentage density. VFB has been shown to be one of the volumetric parameters with the strongest relationship to rutting performance (IGHMA, 2001). The results are indicative that more binder is required for the

Chrome Slag and Fly Ash to meet the required parameters for the traffic class of <0.3 million E80. It is indicative to the absorbed binder as shown in Table 5.18 and 5.19 where the absorbed binder in the Chrome Slag is over 1% more than the Natural Aggregate. The AE-2 for the Chrome Slag and Fly Ash still indicates poor performance when compared to the 50/70 binder as 6% binder is required for the AE-2 and only 5.5% binder is required for the 50/70.

The immersion index has indicated that the selective binder % is well above the required specification, thus showing that the asphalt is not have issues with any moisture sensitivity. It must be noted that the Modified Lottman Test is the preferred test for any moisture sensitivity test.

The Modified Lottman Test have indicated very good performance for both Chrome Slag and Natural Aggregate on AE-2 and the 50/70 binders. It is noted that the Fly Ash, as stated in this study, contributes to anti-stripping agent and is seen in the results.

The Marshall Compaction test is to ensure that the permeability and density requirements are met after construction and, at the same time that the stability is met, based on minimum voids after trafficking. The Marshall Compaction in the filed uses the standard 150 blows to try and simulate the field compaction. Further compaction is induced by increasing the blows even further as shown in the Table 5.8 to try and simulate the voids after trafficking. With the further compaction, it is very difficult to determine simulation of the mastic due to human factors that effects the possible outcomes. It is with this that the Modified Marshall is not considered in this study and with the introduction of gyratory testing taking precedence. The gyratory is the more preferred testing apparatus as it is better controlled in the laboratory environment, although it must be noted that it also does not accurately simulate field compaction. It is, however, only utilised in South Africa when mixes are to be used for heavy trafficking as it provides a better indication of the likely ultimate density that may be achieved than the Marshall device.

The MMLS results have indicated poor performance after maximum rut was above the norm on the suggested tables of the DPG1, except for the AE-2 5% binder with the Natural Aggregate. It must be noted that the design of this study is to optimise the thickness of 20mm, for cost, and to obtain the possibility to use this mix on urban/rural roads. Can a factor be added to the DPG1 tables to complete creditability of the poor results? If so, as stated, the 50/70 outperforms the AE-2 and, as found in this study, performs better with the Chrome Slag and Fly Ash combination. Further in-depth study should be evaluated and adapted to the DPG1 (DPG1, 2008).

The results have indicated good durability with exceptional Modified Lottman Test results and good workability with the gyratory results. It must be noted that the 50/70 binder samples have outperformed the AE-2 binders in this category as well. It must be taken into consideration that the MMLS is for heavy vehicle load simulation, and for the purpose of this study, the application for rural/urban roads, the results have shown acceptable performance as very little heavy loads is envisaged on rural/urban roads. The same can be noted for the Hamburg test. The Hamburg test showed variable results for both Chrome Slag and Natural Aggregate mixtures. It can be that the thick compacted briquettes for the testing procedures are not suitable for the 10mm maximum size particles in the mixture. The increase in thickness for both MMLS and Hamburg have indicated that rutting is a concern with both products and binders thus the designer will have to apply further investigation research to conclude design for the required thin asphalt. With the results, it does show that the specialised testing like the MMLS and Hamburg will not be considered for the thin layered asphalts and the basic volumetric design should only be considered.

The Marshall stability test the stresses and fails the entire specimen during the test. Stability value is a measure of the resistance of the specimen to the development of internal shear. The resistance is considered directly to the degree to which masses of particles are bonded together mechanically or with the bituminous materials. The amount of asphalt required in a mix is more accurately determined by the Marshall test.

The ITS results have shown conformance on both 50/70 and AE-2 binders. Although the AE-2 binder performed better on the ITS results, both are still acceptable and the ITS is not the only parameter used to evaluate and choose the correct design. The design mixtures will perform on the required stiffness and have the fatigue resistance performance required. The minimum value for ITS in South Africa is stated at 800kPa, but studies have shown that the rutting potential increases for ITS below 1000kPa. It has also been shown that ITS values of above 1700kPa have the tendency to indicate brittleness and low flexibility. The ideal ITS results should between 1100 and 1500 kPa. Chrome Slag and Fly Ash Mastic performs well within the 1100 kPa and 1200kPa range at 6% binder. The results reported in this chapter indicate that the asphalt design consideration for Chrome Slag and Fly Ash only have performed well when compared to the Natural Aggregate counter. The parameters are met in most of the design parameters, although more binder is required for the mixture to be stable. The mastic design mixture allows for the following:

1. Durability
2. Resistance to cracking
3. Resistance to permanent deformation
4. Resistance to rutting

5. Stiffness

6. Workability.

7. Filler (Fly Ash) allows for better cohesion and anti-stripping agents

The results have indicated that 6% binder for Chrome Slag and Fly Ash is suitable in application in this study for both AE-2 and 50/70 binders, while the Natural Aggregate varies between 5 and 5.5%.

6. Conclusions and Recommendations

6.1 Introduction

This chapter is to conclude the thesis and make viable recommendations for the road construction industry using Fly Ash and Chrome Slag

6.2 Conclusion

Insight was provided in the aims and objectives such as:

1. Keep
2. Analyse the effectives of an asphalt mixture using the basic design principles
3. Evaluate the properties and the effectiveness of the asphalt mixtures
4. Evaluation of the characteristics of the Fly Ash/Chrome Slag combination

To achieve the objectives and aims, methodologies had to be completed:

1. Evaluation of the selected Fly Ash; chemical and physical
2. Evaluation of selected Chrome Slag; chemical and physical
3. Selection of a comparison material that is commonly used in South Africa for asphalt mixtures and completed full evaluation to set protocols
4. Combining the Fly Ash and Chrome Slag for a "fit for purpose" asphalt mixture design by using the standard protocols found in the set documents.

6.3 Fly Ash and Chrome Slag Environmental Effects

The Fly Ash chosen for the study was supplied by ULULA Class S and is a processed material. The Fly Ash was then subdued to the testing procedures to evaluate the characterisation chemically and physically. The evaluation of the data was to determine, if any, environmental impact related hazards and to classify the Fly Ash.

Class F Fly Ash is the only source produced in South Africa and is placed in landfill sites and has become a major concern especially with the impact the elements have on the drinking water. The evaluation of the impact was conducted by means of leach tests. Numerous studied completed on Fly Ash worldwide have revealed that once Fly Ash is *"entombed"* the risk of leching hazardous minerals is minimal. The Fly Ash used in this study have shown that when used in the asphalt mixture, only trace elements have leached and the risk to cause any risk to the environment is minimal.

The Fly Ash and Chrome Slag in the asphalt mixtures reduced the hazardous elements substantially.

In the determination of the leach test, variables such as particle size, pH are some factors that needs to be considered in selection of test and what the outcomes will be required.

The Chrome Slag used in this study is Ferrochrome Chrome Slag, which is produced on a daily process, and until 2003, it was placed in dumps without any pollution prevention, control, or remediation measures. The smelting process uses electrical energy to melt the feedstock, raising the melt to a temperature at which the mixture will chemically react. The net result of the chemical reaction is that carbon (C) combines with oxygen (O) from the ore to form CO and CO_2 gases that evolve from the melted mixture, leaving a Fe-Cr rich melt (ferrochromium), as well as a Chrome Slag (waste product) containing other residual materials.

Chrome Slag is formed through the addition of fluxes to strip impurities from iron ore, steel, and ferrous feeds. Most of the leachable with lower boiling points have been driven off. As stated, most of the residual compound are encased within the glassy matrix of the Chrome Slag. The compounds increase the pH values to between 10 and 11. This can be seen with the Chrome Slag under this study showing a pH result of 9.87.

Laboratory leaching sample results have indicated that Fly Ash and Chrome Slag constituents exhibit limited mobility. The study revealed that Fly Ash and Chrome Slag is an environmental option and has engineering advantages when used properly for road pavement techniques and in asphalt mixes. The Fly Ash and Chrome Slag in the asphalt mixtures shows a substantial reduction in leaching of elements.

Fly Ash and Chrome slag have shown in this study that they do have substantial harmful elements when compared to the allowable drinking water inorganic maximums. It is critical that leach testing be implemented at design stage to evaluate and mitigate risks accompanied by the use of Fly Ash and Chrome Slag. It must be kept in mind that when tests are performed with some methods, extraneous variables such as analytical sensitivity and sample inhomogeneity, may influence the reproducibility of the results. The Leach results of the asphalt mixtures have indicated that the possibility of the harmful elements to be leached into the environment is minimal and safe to use for an intended project. The overall conclusion is that Fly Ash and Chrome Slag used in this study is environmentally friendly.

The most important aspect is that all safety and regulations currently in place for handling of Fly Ash and Chrome Slag should be followed to minimise any health risks. The utilisation of Chrome Slag and Fly Ash in any application can be viewed as an environmental application, since the reuse or recovery of this material provides environmentally related benefits.

Fly Ash Analysis

The set standards used in this study was to evaluate and characterise the Fly Ash suitability to be used in asphalt designs. The standards were combined to try and provide a basic evaluation procedure in this study that can be followed for the purpose of asphalt designs. The following summarises the standards used:

1. SANS 1491 part 2
2. SANS 50196-1
3. SANS 50197-1 & 2
4. BS3892-1 & 2
5. COLTO
6. TRH8 & 14
7. TMH1
8. SABITA Manual 2, 24 & 35
9. Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa

The results produced form the standards was to evaluate the following:

1. Fly Ash Classification
2. Determine the cementing potential
3. Determine the LOI and SO_3 - although these items are only critical in concrete mixtures and in soil stabilisation
4. Evaluation of the amount of free lime
5. Complete the data analysis on the chemical composition of Fly Ash

Chemical Analysis

The Fly Ash in this study has a high value of SiO_2 and it indicates that it will form stable cementitious compounds with $Ca(OH_2)$. This reaction will allow the pozzolanic reaction to continue over a prolonged time. The ratio CaO/SiO_2 result show that the Fly Ash has a low cementing potential and will therefore need a cementing agent like cement or lime. This study compiled the following points of the Fly Ash:

1. LOI – LOI will not limit the strength as long as there is enough lime to react with. However, in the case of Class F Fly Ash, there is no sufficient lime, therefore it is critical to limit or keep the LOI as low as possible.
2. XRF to be able to classify the Fly Ash
3. The amount of free lime after reactions have taken place that will form $Ca(OH_2)$. When this reaction is mixed with water and come into contact with CO_2, it will form carbonates, which will cause carbonation.
4. Leaching tests to evaluate the potential harmful elements.

The composition of Fly Ash is determined by the parent coal and the amount of admixtures and type of processes, including pollution control technology, in the combustion facility producing highly variable Fly Ashes.

.

Physical Analysis

The following factors were identified:

1. Gradation analysis to determine the contribution to the asphalt mixture as an active filler
2. Colour of the Fly Ash

It can be said that Fly Ash has similar properties to silt when looking at the particles size distribution. The analysis that was completed on the gradation indicated:

1. For Fly Ash to gain early strength, at least 40% must pass the 10 micron sieve.
2. Fly Ash to continue with strength gain but at a reduced rate over an extended duration of time, the material is indicated between the 10 micron sieve and the 45 micron sieve.
3. The Fly Ash in this study will react over long period of time as most of the particle size distribution falls between the 10 micron and the 45 micron. This is an indication when being used in concrete mixtures and in road stabilisation methods.

4. Particles found above the 45 micron will not have any effect on reactions and will actually become inert and contribute to the gradation of the whole sample for the asphalt mix design.

Fly Ash in this study has glassy particles with various identifiable crystalline phases that contributes to Fly Ash being a heterogeneous material. Fly Ash has a colour that indicates the amount of unburned carbon and presence of iron. The colours vary form light grey to dark grey. The light colour is high in calcium and has a low carbon content. The Fly Ash in this study is processed and is light grey, indicating high quality material. The superior reactivity of high calcium Fly Ashes is related to the composition of glass and the presence of reactive crystalline phases.

Chrome Slag Analysis

Chrome Slag was evaluated to standards adopted for South Africa conditions and to obtain the suitability of using Chrome Slag in an asphalt mix design. The standards were combined in this study to create a procedure that can be followed for evaluating Chrome Slag for the possibility to use in an asphalt mix application. The standards used were:

1. COLTO
2. TRH8 & 14
3. TMH1
4. SABITA Manual 2, 24 & 35
5. Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa

The standards were used to determine the following points:

1. Physical analysis
2. Chemical composition

Physical Analysis

The physical aspect of Chrome Slag is a critical factor, as it will mostly contribute to the design of asphalt. The Chrome Slag as an aggregate component will typically constitute 92-96% of the asphalt by mass and will have a profound effect on the performance properties of the asphalt (Kandhal *et al*; 1997). Chrome Slag can be crushed into various required fractions as needed and is a very suitable material in road construction. The problem currently with Chrome Slag is the specific gravity of the material. Chrome Slag is mostly dark grey of colour with a density of about

$3470 Kg/m^3$, which makes it a heavy material compared to Natural Aggregates, thus transport of the material will be costly in some instances. Chrome Slag can be compared to volcanic rock such as basalt and granite. Just like the natural materials, Chrome Slag does contain trace elements, but which are mostly bound up within the crystal lattice, and therefore almost impossible to leach. Chrome Slag pH value various between 7 and 10 as shown in the study.

Chemical Analysis

Ferrochrome Chrome Slag samples have detected traces of heavy metals as shown in the study, mostly in the form of:

1. Cr_2O_3
2. SiO_2
3. Al_2O_3
4. MgO

Chrome Slag component of chromium (IV) oxide (Cr_2O_3) is very toxic and leachable. This component can restrict Chrome Slag for use and disposal, but this is only related to fresh Chrome Slag disposal dumps. Chrome Slag needs to go through the "weathering" processes, in order to use the material for intended purposes. This will diminish leaching elements rapidly over time as chemical compositions change during this process. These processes are mostly once off and, as it is noted by NSA, is an aesthetic issue and not harmful to the environment (NSA, 2003). As noted in the study, all other residual compounds found within the composition of Chrome Slag are mostly encased within Chrome Slag's glassy matrix. The lime in the Chrome Slag is a loose combination with silica, iron, and manganese. As a result, the Chrome Slag remains a stable form, where it will produce alkalinity over long periods of time. The Chrome Slag in this study compromises mostly of Chromite, Spinel, Quartz, Olivine, Clinopyroxene, and Amorphous. This is also indicated by the pH value of Chrome Slag and will increase to between 10 and 11 when it reacts with water. One of the main concerns of Chrome Slag is the expansiveness of the material. This is mostly due to the amount of MgO and CaO found within the Chrome Slag fragments. The formation of a white powder on the Chrome Slag is evident of the process, thus it needs to go through this process for up to 6 months. It has been noted in the study that Chrome Slag material size of 13mm and less can be used as is, and expansiveness of the material will not take place or can thus not be considered. Chrome Slag is acidic as described in the study, has strong bonding compounds, and is also evident to the low MnO results.

Material

Fly Ash and Chrome Slag cannot be ignored as this has become a valuable product as shown in the study. Fly Ash and Chrome Slag is readily available and can be used for modification, stabilisation and concrete purposes. With time, it can be envisaged that Fly Ash and Chrome Slag can be used predominately in projects for low volume roads.

Fillers are considered as an essential product for asphalt mixtures. Fillers consist of various products and are divided into inert or active fillers. The use of Fly Ash in the study is to show that another by-product can be used to further produce a more stable and long-lasting asphalt mixture. Adequate amounts of filler are to ensure cohesion which contributes to the resistance of deformation. Specific Fly Ash has shown to contribute to improve the mix compatibility and will help with “stripping”. The Fly Ash filler was also used to adjust aggregate gradations and volumetric properties which provided a dense, durable mix.

The Fly Ash is of a poor quality and all the tests conducted are completed as if a construction project is taking place. Most laboratories use rapid methods of testing and curing to complete the required testing in time and to ensure construction processes are not delayed. This study envisaged the same methods to understand what reactions will take place and if it is feasible to use Fly Ash with more advanced techniques and speed of construction currently taking place. The testing process of Fly Ash will take time and the method of analysing the material is shown in this study.

Chrome Slag and the Natural Aggregate is the main component in the asphalt mixture. It constitutes the larger portion of material used in the manufacturing of hot mix asphalt. The physical properties are generally regarded as the most important aspect of aggregate selection. The physical properties of aggregates are affected by the mineralogy of the parent rock, the extent to which the parent rock has been altered by leaching, oxidation, and other environmental factors, as well as by the processes required to produce graded and blended aggregate.
Dolerite is one of the most abundant and important natural road building materials for construction of high-quality pavement layers in roads in South Africa, seeing as it is associated with the basic crystalline group of rocks. Dolerite is a common type of felsic intrusive igneous rock that essentially contains feldspar, quartz, hornblende, and mica.

Chrome Slag is a constant and can be crushed according to the requirements. Chrome Slag is readily available, seeing as with quarries there are related problems of banks with changes to the mother rock due to the environment conditions. Looking at Chrome Slag, it is critical that the stockpiles go through weathering stages to minimise the potential of the swell properties linked to Chrome Slag.

It must be considered that for an effective asphalt layer, aggregates must display more rough angular material than smooth material. The properties of the aggregates must conform to the following set standards:

1. Hardness/ toughness
2. Durability
3. Shape and surface texture
4. Absorption and cleanliness

The Chrome Slag conformed well when compared to the Natural Aggregate. Ethylene Glycol testing was included in the hardness/toughness test, as the results must also conform to the set standard. Both Chrome Slag and the Natural Aggregate have performed well above the requirements of the hardness/toughness tests. However, the 6.7mm Chrome Slag fraction has shown that it is “softer” than the Natural Aggregate but still is within the required specifications. Both the Natural Aggregate and Chrome Slag conformed to the durability values of EGDI and Methylene Blue tests. All samples showed a zero (0) effect when soaked in the EGDI and that, there are no substantial deleterious clays found with results of 0.1 for the Natural Aggregate and 0.15 for the Chrome Slag which would affect the asphalt mixture. Both the materials in this study showed high durability for a required life span design. Shape and surface texture of the aggregates play an important role for work ability and compatibility of the asphalt mixture, therefore, it is critical that polish stone values and flakiness index are adhered to in the design process. The polish stone values are very close for both the materials in this study; values of 53 for the Natural Aggregate and 52 for the Chrome Slag, respectively. No problems are foreseen in the workability and compatibility of the materials as each has very low flakiness index results. Both are very close to each other, indicating that the Chrome Slag will have the same durability values required by the standards. The surface texture of these aggregates in this study affects the skid resistance of the layer. Both provide harsh textures, increasing the skid resistance at low speeds. Water absorption is another critical property, as this will indicate whether the aggregate is prone to exponential absorption that will affect the binding of the binder to the aggregate. It is critical that all results must be below 1% by mass. Calculating the average results obtained per grading, as shown in Table 3.22, the results are 0.5 for the Natural Aggregate and 0.7 for the Chrome Slag. It has been known that Chrome Slag will absorb more binder than aggregates as they do contain more pores, but this will not affect the mixture as the result is still below the required standard. The sand equivalent results show that very little clay-like materials are found with values of 79.2 for the Chrome Slag and 86.4 for the aggregate. This does indicate that the binder used for the specific mixture will have an affective bond, increasing the stability/durability of the mixture.

The most significant difference between Chrome Slag and most Natural Aggregates is its high particle density, which is the consequence of the presence of iron compounds. Chrome Slag is also known as a pozzolanic material as it has a significant quantity of calcium oxide, CaO.

The bitumen used in this study is the standard modified AE-2 and penetration grade 50/70. Modified binders offer more advantages as they are used for mixes that require high rutting resistance or above-average flexibility and durability. The cost of modified binders is high, but this was also to evaluate if the combination of Fly Ash and Chrome Slag can also be used for applications where traffic volumes are high. The bitumen tests completed in this study was to ensure conformity of the bitumen that will be used in the design of the asphalt mixtures.

A general guideline was used to pre-determine the type of bitumen. The modified binders are mainly used for heavy traffic applications where special attention is given to highly flexible mixtures or rut resistant mixtures. The penetration grade 50/70 is typically used for asphalt surfacings with light to medium traffic. AE-2 and 50/70 binders are used in most climatic zones in South Africa.

Design

Design of the mastic is an understanding of all properties of materials, fillers, and bitumen and bringing them together to form a product that is:

1. Durable
2. Resistant to cracking
3. Resistant to permanent deformation
4. Resistant to rutting
5. Flexible
6. Skid Resistant
7. Permeable
8. Workable

Most of the recent developments in asphalt design processes such as consideration of volumetric and spatial design concepts. Most modern designs rely entirely on volumetric design principles. With this statement, it was thus decided to complete a study using basic approach and design principles based on volumetric. In order to ensure the materials selected is suitable, basic design principles should be followed first with an exception on over the above specialised testing to ensure conformity.

The main component to any mastic mix is the grading. The grading is a means to an end. The grading is mostly a concept of a packing mechanism. The packing mechanism of the planned mix type will influence the volumetric design parameters.

The selection of a target grading and analysis of volumetric parameters should be relevant for a particular type of packing mechanism. The important performance parameters, which is resistant against permanent deformation and fatigue resistance, as well as mix permeability and compactability, are strongly related to the grading characteristics of the coarse aggregate. By combining most of the methods like the Baily Method, Fuller Curve, and NMPS, a grading specification can be developed to be suit the requirements and to ensure a dense packing mechanism that performs well against permanent deformation. The grading for the Natural Aggregate and Chrome Slag have indication that it is a fine type of material as the results are below the primary control sieve. Well packed mechanism can be achieved as the graphs follow close to the Fuller Curve for the best density on each sieve. All aspects of the grading with the necessary control points have been adapted to ensure proper grading requirements. Most of the laboratories have programmes that compiles best target grading suited for the design. Another example of this is shown in the appendices. All of the information after completion is placed on a D3 form, which is widely used throughout South Africa for asphalt design considerations.

The gradings does show that below the 0.6mm sieve the fines tend to be on the coarse side. Even with this grading, an even, gradual flow is seen on the Chrome Slag graph, and this is also due to the Fly Ash that contributes to the grading. There is an outlier on the Natural Aggregate graph but one can envisage that this is a material that will move into the required envelope once compacted. This can only be confirmed after compaction has taken place. With this in mind, the grading envelope for the Natural Aggregate is thus accepted. Both the materials are classified as sand skeleton gradings as indicated on the ternary diagrams on Figure 50 and 51. This also conforms to the fine mixture as stated by the PCS of the Bailey Method. Sand skeleton mixtures, the loads on the layer are mainly carried by the finer aggregate fraction. The larger aggregate fractions provide the bulk and replaces a proportion of the finer aggregate as shown in Figure 52.

To select the required percentage binder, the laboratories rely on experience, and they normally start with 4% going up to 6%. Another method is shown in SABITA where you calculate the surface area to get an idea of the required binder. The Natural Aggregate is round about 5.3%, while the Chrome Slag indicates a higher binder of 5.8%. The reason for the higher binder, as stated in the study, is that Chrome Slag has a higher absorption than Natural Aggregate.

The binder-with-filler component may stiffen the mix if the results are above the required ratio specified. The ratio is stated in this study that the standard is maximum of 1:1.5. It is also stated that for thin asphalt mixes less than 30mm, the ratio should not exceed 1:1.2. The filler retains heat, and it does cause compaction and workability problems for thin asphalt layers. Due to that, thin layers cool more rapidly. The ratio should thus be lower than the standard. The Fly Ash conforms to the ratio at 6% for both AE-2 and 50/70 binder content.

Volumetric design includes the Marshall compaction. The Marshall compaction is to try and simulate the envisaged voids after a certain number of blows. Currently the Marshall is set at 75 blows on each side and the target voids are set in documents as shown in Table 5.8. The Marshall will, however, indicate immediately to the designer if the current mix compacts easily, which means it will rapidly approach an ultimate density, and those which are less workable will gradually densify with compactive effort. In the design, ranges of initial and final void content are proposed as shown in Table 5.8. The Modified Marshall Compaction adds in additional compactive effort to try and simulate different classes of traffic. This gives an idea of voids closing and prevents any “floating” of the aggregate within the mastic, thus causing envisaged bleeding problems. There is a concern on the Modified Marshall that cannot actually be thoroughly used for these types of evaluations and should then only be used as a guide. For this reason, this method was not used in this study and no definite studies produced recommendations on appropriate levels of additional compaction.

The gyratory compaction was used as a replacement, which is currently the more reliable and acceptable method. The results of the gyratory indicated that the design does conform to the required specifications. It also confirmed that the mixtures conformed to the requirements for heavily traffic classes. The Chrome Slag does perform better with the 50/70 binder when compared to the AE-2 where the Natural Aggregate has a better performance as shown in Tables 5.12 and Table 5.13.

The following aspects of a volumetric design is critical to ensure proper packing mechanism, This entails the following:

1. Marshall Stability and Flow
2. Voids in Mix (VIM)
3. Binder Absorption
4. Voids in Mineral Aggregate (VMA)
5. Voids filled with Binder (VFB)

The Marshall Stability and Flow gives the resistance of the mix to permanent deformation. Although it has fallen out of favour in recent research studies, the stability is used to obtain the optimum binder content of the mixture. The results indicated that mostly all mixtures for both Chrome Slag and Natural Aggregate conforms to the E2 class specified in Table 5.9. The concerned item on all the mixes is that the stability/flow ration does not conform to the requirements of Table 5.9. It is close to the minimum requirement of 2, but further investigation needs to take place to determine the reasons. Taking consideration of the recent study stating the unreliability of the test, a further indication of this test is the calculation of load carrying capacity. The formulae are used to roughly calculate the tyre pressures of the vehicles using the pavement. Using the maximum imposed pressure of 100 psi as a reference, the following can be deduced: The Natural Aggregate out-performs the Chrome Slag and Fly Ash design as shown in Tables 5.12 and 5.13. The Chrome Slag results must only be taken into consideration once all volumetric design parameters have been met. The current design is leaning towards a mixture that can possibly use for heavy traffic pavements,

VIM, as stated, is the small spaces (voids) between the coated particles in the mastic. Air voids is crucial in all densely graded mixes to allow additional pavement compaction under traffic. The durability is a function of the air-void content. It is important to understand how the voids in the aggregate and related binder content are determined, to ensure that the binder will not fill all of the available voids and result in the aggregate "floating" in the binder. The Chrome Slag mastic shows conformity to 6% on the AE-2 binder and 5.5% on the 50/70 binder. This does indicate the better mastic is achieved for the Chrome Slag mastic, as previously stated in the Marshall Stability and Flow section. The Natural Aggregate shows conformity at 5.5% AE-2 binder and between 5 and 5.5% on the 50/70 binder.

Binder absorption indicates what is absorbed by the aggregate, which does not contribute to the particle adhesion. It is shown in this study that the absorption is relatively high on Chrome Slag but it was also noted in this study that this should not affect the properties of the design due to that Chrome Slag contains no fissures, although a higher binder content will be required when compared to the Natural Aggregate. The results display an average absorption of 1.81% for the

Chrome Slag compared to 0.11% for the Natural Aggregate on the AE-2 binder and 1.77% for Chrome Slag compared to 0.33% for Natural Aggregate on the 50/70 binder. This has an average difference on 1.57% between Chrome Slag and Natural Aggregate; this can also be seen on the results where the Natural Aggregate meets the requirements with less binder. Taking into consideration of binder absorbed and unabsorbed binder, we can discuss two (2) types: Total binder content and effective binder content. Total binder content is the amount that must be added to the mastic to produce the desired mix qualities. The effective binder content is the volume of binder not absorbed by the aggregate.

The VMA serves as a cornerstone of volumetric design. VMA is needed to ensure that adequate amount of asphalt could be added to the mixture without closing the voids and resulting in asphalt bleeding, in other words, VMA represents the space that is available to accommodate the asphalt and the volume of air voids necessary in the mixture. VMA is to ensure that bleeding does not occur, and that sufficient durability is achieved. VMA is affected by numerous properties of materials as stated in Table 5.23. Most of the voids' specifications to be achieved is between 3% and 6% for good rut resistance. It is also shown that VMA should be high to allow for enough binder into the mix to ensure that stability and workability are achieved. The Chrome Slag conforms to the requirements on 5.5% voids for the 50/70 and on 6% voids for the AE-2. The same can be said for the Natural Aggregate where it conforms to all 5.0% and 5.5% on the AE-2 and on the 50/70 binder. The aggregate gives a more flexible option than to the single option of the Chrome Slag.

VFB is binder absorbed by the cracks and cavities of the aggregate and is related to the frictional resistance of the mix. As noted and shown in this study, the Chrome Slag will have a higher absorption due to that it possess more cavities than Natural Aggregate. The required specifications are as per Table 5.27 but critically at 4% air voids. The designs are based on % binder and the voids are then calculated which then makes it difficult to obtain exactly 4% voids. Based on the results, the Natural Aggregate conforms to the specification at 5% binder for the 50/70 binder and at 5.5% binder for the AE-2 binder. The Chrome Slag, however, does not conform at all but taking the voids closer to 4%, it conforms to 5.5% binder on the 50/70 but exceeds the limits on 6% binder for the AE-2 binder. The results of the VFB must also be considered when a binder percentage is chosen, therefore if the correct binder is chosen, the VFB values will be acceptable.

The most critical damage to any pavement is mostly caused by water. Moisture sensitivity tests are compiled by the Immersion Index Test and the Modified Lottman Test. The Immersion Index

Test requires a minimum value of 75% and all requirements are met by both Chrome Slag and Natural Aggregate mixtures for 50/70 and AE-2 binders respectively with values varying from 80.4 to 89.3. The Modified Lottman Test tests the asphalt mixture to indicate if whether or not an anti-stripping additive is effective, and to determine what dosage of an additive is needed to maximise its effectiveness. The results have shown that all requirements are met by both Chrome Slag and Natural Aggregate mixtures for 50/70 and AE-2 binders respectively with values varying from 0.902 to 0.957.

Indirect Tensile Strength (ITS) is commonly used to determine the cohesion strength of the asphalt. The results are indicative of toughness and durability and rutting resistance. To achieve optimum good performance values, one must try and achieve ITS values of between 1100kPa and 1200kPa. On the 50/70 binder, the Chrome Slag shows a good ITS value at 6% binder, while the Natural Aggregate shows acceptable value at 5.5% binder. The AE-2 shows a very good results with all results above 1100kPa range. To analyse this further, the stability is taken into account to optimise the best binder content, which is then selected for further specialised testing.

Specialised testing was completed on selected binder percentage that conforms to most of the requirements and to indicate which of the mixtures will be suitable. The Natural Aggregate performed well with binders of 5% and 5.5% for 50/70 and AE-2. The Chrome Slag performed well with binders 5% and 6% on AE-2 and 5.5% and 6% on the 50/70. The decision for the binder percentage was based on the volumetric properties as discussed. The specialised testing in this study is the MMLS, Gyratory, and Hamburg wheel test.

The Gyratory testing was discussed in this section. As stated, MMLS is used to determine the permanent deformation and susceptibility of the asphalt mixture to moisture damage. The MMLS was introduced to evaluate the mixtures for heavy traffic conditions and adapt design principles to adjust the resistance to a requirement for heavy vehicles. The MMLS protocol shows acceptable design rutting after 100000 axles between 40mm and greater than 90mm thick asphalt layers. This study is producing a maximum thickness of 20mm for envisaged use on rural roads. Thus, the results will not be according to the required standard. The results are summarised in Table 6.1 for the AE-2 mixture and Table 6.2 for the 50/70 mixture.

Table 6.1: MMLS results for the AE-2 Mastic after 100 000 axles

	Chrome Slag (mm)		Natural Aggregate (mm)	
AE-2	5	6	5	5.5
	5,32	5,25	2.46	3.33

Table 6.2: MMLS results for the 50/70 Mastic after 100 000 axles

	Chrome Slag (mm)		Natural Aggregate (mm)	
50/70	5,5	6	5	5,5
	4,65	3,26	3,53	3,33

The results have indicated that the 50/70 is the preferred rutting resistance for the design mixtures.

HWTT is completed to determine various factors of the asphalt mixture such as:

- Creep slope
- Stripping Slope
- Stripping inflection point

The test was developed according to Performance Grade (PG) temperature zones. The maximum asphalt temperature zones are major determinants in classification of zones. Assessing the mix performance on the basis of the final data after 20 000 wheel passes, according to SABITA, might be misleading. It is therefore recommended that all the factors named above should be taken into consideration when evaluating the results. It has been stated that in the USA, stripping inflection point that occurs in less than 10 000 passes is an indication of moisture susceptibility.

Results indicating a rut in excess of 6mm needs to be further investigated by means of MMLS.

The MMLS showed a better rut resistant figures as shown in tables 6.1 and 6.2. Most of the results indicated have surpassed the 10000 passes but have not reached the 20 000 passes as recommended. This does indicate that there is a variable when it comes to the testing methods and needs to be properly considered when designer considers the products for a project. As stated, this is for a 20mm maximum asphalt thickness and according to the IGHMSA, the maximum allowed thickness for the nominal stone size is 4 times (x). Therefore, the maximum for 10mm stone/Chrome Slag is 40mm otherwise the characteristics of the mastic will change. This could also explain the high readings and variable readings that was indicative of a poor mix. It must be kept in mind that this study is for rural/urban roads therefore the use of Hamburg and MMLS is questionable for design parameters.

Summary

Industrial materials are the by-products of industrial processes. Many have chemical and physical properties that make them valuable resources when recycled or beneficially reused, but they are often disposed of as a waste. Industrial material recycling is helping to green the nation's infrastructure by making roadways more durable, conserving natural resources, decreasing energy use, and reducing greenhouse gas emissions.

Fly Ash and Chrome Slag contribution in asphalt mixtures as shown in this study gives a great benefit in engineering practice in the following manner:

1. Becomes as part of the engineering material that is environmentally friendly.
2. The Fly Ash and Chrome Slag has shown in all the required specified testing that it is a viable option for overlay projects.
3. The study has shown that short term curing, as done in South Africa, has not had a negative impact on the results but an improvement when compared to reference samples.
4. The Fly Ash and Chrome Slag has tremendous potential and ability to enhance pavement properties.
5. Fly Ash and Chrome Slag creates material that is durable and able to withstand shear forces, thus making it suitable for the design life period.

Fly Ash is readily available, and the reduction of landfill sites for the purpose of construction will also lead to reduction in greenhouse gases. This study has also shown various standards that can be adapted to evaluate the Fly Ash, and to improve on the use of it in the asphalt design process. It can be said that this study has created an outline for South Africa to follow when it comes to the design of asphalt when using Fly Ash, thus incorporating all the aspects obtained in this study into one specification document.

Although the Fly Ash has shown encouraging outcomes, it should be noted that the use of Fly Ash is unpredictable. This has a discouraging effect to the study as various factors need to be considered when one contemplates the use of Fly Ash.

The use of Fly Ash to enhance the performance of asphalt has been demonstrated in this study but has not yet been adopted on a commercial scale. The main factor of Fly Ash is the presence of free lime increases the resistance to stripping, increases the adhesion between aggregate grains and binder, therefore, contributing to higher durability of road surface. This also raises a sad point: it will come down to the cost of the products available, and whether the products used in this study will ever be used in a project of road construction.

Chrome Slag has shown that with Fly Ash, it can be combined to form an asphalt mixture combination to rival the use of Natural Aggregates. Although the Natural Aggregates did show a better performance on the tests than the Chrome Slag, it is still a viable option. This study also outlined the basic evaluation design procedures for the use of the combinations and can be followed as a guideline by designers. The study also indicated that the Chrome Slag is suitable for use for thin layered HMA and for use on roads with light traffic roads. It also showed that it can be possibly used on heavy traffic conditions, but this needs to be further investigated.

In this study the mixtures for thin layered HMA have conformed to the following parameters:

1. Materials have confirmed to the requirements
2. Grading analysis – combining all standards, new checks for optimum grading can be evaluated.
3. Volumetric properties
4. Specialised testing
    a. MMLS
    b. Gyratory
    c. Hamburg
    d. Modified Lottman

With the above, the designer can conclude the following engineering parameters will then be met:

1. Durability
2. Resistance to cracking
3. Resistance to permanent deformation
4. Resistance to rutting
5. Flexibility
6. Permeability
7. Stiffness

8. Workability

Overall, the following design can be used for thin layer asphalt mixtures:

1. Chrome Slag and Fly Ash – 6% AE-2 Binder
2. Chrome Slag and Fly Ash – 6% 50/70 Binder
3. Natural Aggregate – 5% AE-2 Binder
4. Natural Aggregate – 5.5% AE-2 Binder

The extra binder on the Chrome Slag is due to that Chrome Slag absorbs more binder as shown than Natural Aggregate. With the increase in binder, the weight in kg/m³ thus increases the cost in transport but with the low cost of Chrome Slag at the moment, it should equal out with the cost of quarry excavated materials.

The Chrome Slag and Fly Ash has actually performed better with the 50/70 binder. More parameters are met, and the materials performed better with the 50/70 binder. It can possibly be due to the binder being harder than AE-2 and not as flexible. In a way this does play an advantage to the use of Chrome Slag and Fly Ash as this type of binder is cheaper as well. It can be said that due to that, Chrome Slag is a softer material than the aggregate used in this study, the increase in rut readings on the Chrome Slag and Fly Ash mixture is envisaged.

6.3 Recommendations and Future Work

The use of industrial materials in roadways has the following benefits as shown in the study:

1. Environmental benefits
2. Economic benefits
3. Performance benefits

The purpose of asphalt mix design is to find a cost-effective combination of binder and aggregate that is workable in the field, with sufficient binder to ensure satisfactory durability, fatigue performance, and suitable aggregate configuration, providing structure and space between particles to accommodate the binder and prevent bleeding and permanent deformation.

The materials in this study are used to replace non-renewable virgin materials that must be mined and processed; using industrial materials conserves natural resources and reduces the energy use and pollution associated with these activities. Using by-products could, and probably will, make the roads more durable, therefore maintenance is envisaged to be less frequent which is good for the environment because it conserves natural resources and energy.

Using the industrial materials makes good economic sense for project owners and contractors. If industrial material use is planned from the beginning, the total project bid cost can be lower, allowing the project owner to accomplish more work with the same budget. Industrial materials are often less expensive than the virgin materials they replace, and recycling or reusing materials such as Fly Ash and chrome Chrome Slag reduces the need for new or expanded landfills, saving valuable landfill capacity.

It has been shown that industrial materials offer significant performance enhancement benefits. Chrome Chrome Slag in the asphalt layer has a high-friction surface that makes driving safer. Fly Ash enhances the durability, and the asphalt is less prone to cracking than standard asphalt.

The use of Fly Ash is not new, but standards and specifications need to be adapted for the purpose for the use of Fly Ash. Fly Ash is a valuable commodity and needs to be utilised efficiently.

The physical and chemical characteristics of Fly Ash need to be studied more comprehensively to be utilised more effectively. This will make the Fly Ash more predictable for future pavement design studies. In construction in South Africa, clients are not always open for new developments to construction, seeing as not enough studies and information are available. This study will need to be taken further and it will take time to convince authorities for the use of renewable products that are cost effective and require less maintenance. It is therefore a recommendation that the processed Fly Ash, as analysed in this study, needs to be considered and a trial project in South Africa will be ideal to study the long-term effects, durability, and cost. The trial project will have a major impact on construction once it has shown that using such products available is cost effective.

The use of Fly Ash has many advantages in the construction industry. It is just a matter of time and proper research to adjust the methods of evaluation, testing, and to improve the recycled material for better road construction practices, thus reducing landfill sites and greenhouse gasses.

Based on the worst case exposure, Chrome Slag poses no meaningful threat to human health or the environment when used in a variety of construction applications. The Chrome Slag matrix are not readily available for uptake by humans, other animals, or plants, and do no bioaccumulation in the food web and are not expected to bio concentrate in plant issue.

Chrome Slag has been safely and successfully used as a construction aggregate in many applications.

Asphalt design is a complex decision on what materials is available and what can be achieved during construction. Basic principles in design states that a designer should not specify properties that are unfamiliar to the industry as this may lead to undue risk being incurred by the contractor during tender process with consequent increases in the tendered rates or, alternatively, may lead to tenderers making assumptions that cannot be met when the final mix design is produced. One should be made aware of the difficulties relating to the mix design processes to produce the specified mix actually produced. There are risks associated with design, and the main risk is the variability that may occur. Variability in aggregate shape and gradation may result in excess or insufficient voids during construction, even though the end product may still be within specification. Mix properties may also vary during the construction phase across the width and length of a paver-lane.

When the minimum layer thickness is specified, designers should take into account the absolute maximum stone size, as well as the quantity of this stone to prevent the instability of required mix. A rule of thumb is that the maximum layer thickness should not exceed four (4) times the nominal maximum stone size. This needs to be considered when specialized testing is completed such as the Hamburg and MMLS which uses briquettes in excess of 60mm thick. Resistance to stripping due to moisture damage cannot be overemphasized and is often neglected. Anti-stripping agents, including lime, should be considered when there is any doubt. Until a factor can be utilised in the results or testing equipment can be adapted to suit thin layered asphalt, the Hamburg and MMLS tests cannot be properly used for the testing, and it is recommended that the basic volumetric designs be kept with final application with the gyratory test to determine a suitable design for rural/urban roads.

Waste is a source of secondary raw materials but at the same time can negatively impact the natural environment and public health. The production of industrial by-products in South Africa is expected to increase tremendously in the coming years and will have a detrimental impact on the environment. Successful utilisation of industrial by-products in the construction industry would require detailed economic and environmental analyses as well as engineering design specifications. Using Chrome Slag and Fly Ash will help preserve our natural resources. Based on the numerous tests completed in this study, we now know that the waste products are safe and a valuable resource, and this will encourage its use as an environmentally friendly product.

The additional calculations incorporated in this study for Bearing Capacity, Marshall Checks and the Grading Design envelope incorporating all current standards into one spread sheet needs to be further evaluated as it does contribute to further decisions for designers to applications for the projects.

It must be noted that Fly Ash is an unpredictable material and needs to be thoroughly studied before it is to be used in an asphalt mix design. The same can be said for the Chrome Slag, although there are a lot of test results available which is more reliable when decisions are made to use the Chrome Slag.

This study has shown that the combination of Chrome Slag and Fly Ash in thin layer asphalt mixtures can be used without addition of Natural Aggregates. All the materials are readily available. The only negative aspect of these materials is that it is only found in areas where electricity and steel is produced. It can therefore, to be more viable, only be used in those areas.

APPENDENCES

D3 Form: 50/70 Binder mix design for Natural Aggregate (Dolerite)

ROADLAB
Civil Engineering Materials Laboratory
Established 1968

HEAD OFFICE
207 Rietfontein Rd Primrose Germiston 1401
P O Box 1476 Germiston 1400
Tel: 011 828 0279 Fax: 011 828 0273
E-mail: info@roadlab.co.za
www.roadlab.co.za

Designed by: ROADLAB

Date: **2018/07/18**

ASPHALT MIX DESIGN

Contract	Michiel Heyns
Route	
Section	
Layer	N/S
Mix	Continuously Graded Medium - AGG
Our Ref.	

Form **D3**

AGGREGATE PROPERTIES

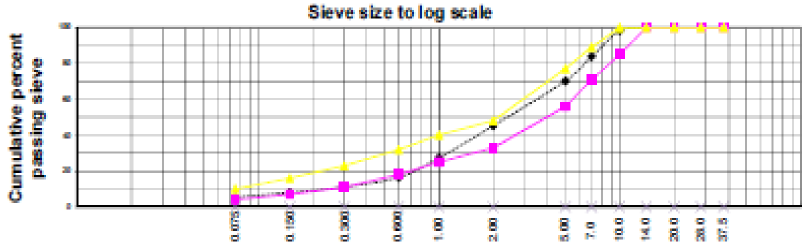
	Sample No	Nom. Size	Type and Source
1	1	13.2mm	Aveng
2	2	9.5mm	Aveng
3	3	6.7mm	Aveng
4	4	Super Sand	Aveng
5	5	Crusher Dust	Aveng
6			

Sieve Analysis [B 4] - % Passing Sieves

100.0

	Sample No. No.	1	2	3	4	5	6	COMBINED GRADING		
	% In Mix	0.0	15.0	8.0	26.0	51.0		Mix	Spec.	
Sieve Size (mm)	37.5	100	100	100	100	100		100	100	100
	28.0	100	100	100	100	100		100	100	100
	20.0	100	100	100	100	100		100	100	100
	14.0	89	100	100	100	100		100	100	100
	10.0	7	87	100	100	100		98	85	100
	7.0	0.3	6	79	100	99		84	71	89
	5.00	0.2	0.4	10	98	86		70	56	77
	2.00	0.2	0.2	0.3	64	56		45	33	48
	1.00	0.2	0.2	0	38	34		27	25	40
	0.600	0.2	0.2	0	24	20		16	18	32
	0.300	0.2	0.2	0	15	14		11	11	23
	0.150	0.2	0.2	0	9	11		8	7	16
	0.075	0.2	0.1	0.1	3.5	8.9		5.5	4	10
BRD		2.971	2.976	2.955	2.928	2.817		2.881		
Water absorp.		0.6	0.4	0.7					1.0 max	
Water absorp.					1.0	0.4			1.5 max	
ACV									25 max	
10 % FACT									160 min	
Flak. Index									25 max	
Sand eqv.									30 min	
PSV									50 min	

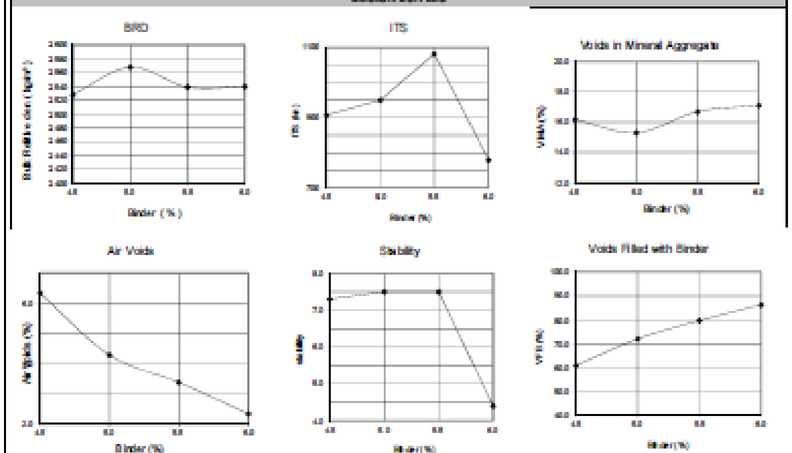
Sieve size to log scale



BINDER PROPERTIES

Type	50/70	Source	
Pen @ 25°C (0.1 mm)		Visc. @ 60 °C (Pa.s)	
Soft. Pt (°C)		Visc. @ 135 °C (Pa.s)	
RD	1.0250	Hot Flow (mm)	
Temp. (Mix) (°C)	155	Temp. (Comp)	137

DESIGN CURVES



DESIGN CRITERIA		1	2	3	4	5	PROPOSAL	SPECIFICATION	
Binder	%	4.5	5.0	5.5	6.0			MIN.	MAX.
Film thickness	μm	7.4	8.2	10.2	10.2				
Absorp. (Binder)	%	0.53	0.63	0.13	0.04				
Max. TRD (Rice)	kg/m³	2.699	2.683	2.628	2.601				
BRD (Marshall)	kg/m³	2.528	2.568	2.539	2.540				
Voids in Mix	%	6.3	4.3	3.4	2.3				
VMA	%	16.2	15.3	16.7	17.1				
VFB	%	60.9	72.0	79.7	86.3				
Immersion Index	%	87.2	80.4	81.5	84.3				
Dynamic Creep	kN								
ITS	kPa	907	950	1082	779				
Stab. (Marshall)	kN	7.3	7.5	7.5	4.4				
Flow (Marshall)	mm	3.9	3.6	4.0	5.1				
Stab. / Flow Ratio		1.9	2.1	1.9	0.9				
Air Perm.								1 x 10⁻⁸	

D3 Form: AE-2 Binder mix design for Natural Aggregate (Dolerite)

ROADLAB Civil Engineering Materials Laboratory — HEAD OFFICE, 287 Rietfontein Rd Primrose Germiston 1401, P O Box 1476 Germiston 1400, Tel: 011 828 0279 Fax: 011 828 0373, E-mail: info@roadlab.co.za, www.roadlab.co.za	Designed by: ROADLAB Date: **2018/07/18**	ASPHALT MIX DESIGN	Contract: Michiel Heyns Route: Section: Layer: N/S Mix: Continuously Graded Medium - AGG Our Ref.:

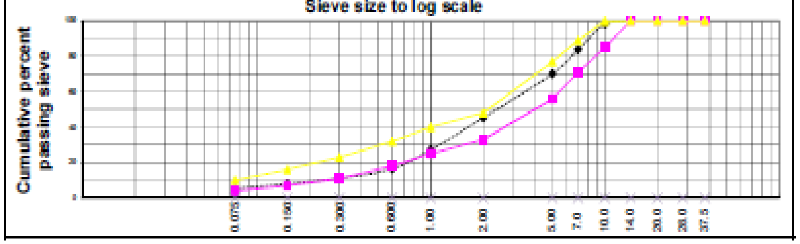
Form **D3**

AGGREGATE PROPERTIES			
	Sample No	Nom. Size	Type and Source
1	1	13.2mm	Aveng
2	2	9.5mm	Aveng
3	3	6.7mm	Aveng
4	4	Super Sand	Aveng
5	5	Crusher Dust	Aveng
6			

Sieve Analysis (B 4) - % Passing Sieves

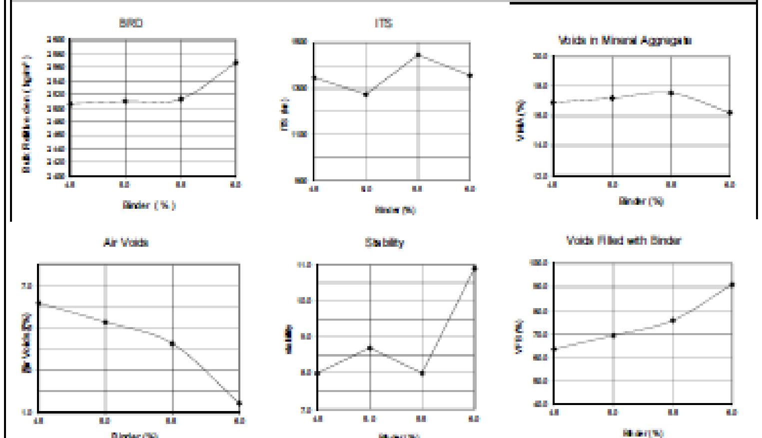
100.0

Sample No. No.	1	2	3	4	5	6	COMBINED GRADING		
% In Mix	0.0	15.0	8.0	26.0	51.0		Mix	Spec.	
Sieve Size (mm) 37.5	100	100	100	100	100		100	100	100
28.0	100	100	100	100	100		100	100	100
20.0	100	100	100	100	100		100	100	100
14.0	89	100	100	100	100		100	100	100
10.0	7	87	100	100	100		98	85	100
7.0	0.3	6	79	100	99		84	71	89
5.00	0.2	0.4	10	98	86		70	58	77
2.00	0.2	0.2	0.3	64	56		45	33	48
1.00	0.2	0.2	0	38	34		27	25	40
0.600	0.2	0.2	0	24	20		16	18	32
0.300	0.2	0.2	0	15	14		11	11	23
0.150	0.2	0.2	0	9	11		8	7	16
0.075	0.2	0.1	0.1	3.5	8.9		5.5	4	10
BRD	2.971	2.976	2.955	2.928	2.817		2.881		
Water absorp.	0.6	0.4	0.7					1.0 max	
Water absorp.				1.0	0.4			1.5 max	
ACV								25 max	
10 % FACT								160 min	
Flak. Index								25 max	
Sand eqv.								30 min	
PSV								50 min	



BINDER PROPERTIES			
Type	A-E2	Source	
Pen @ 25°C (0.1 mm)		Visc. @ 60 °C (Pa.s)	
Soft. Pt (°C)		Visc. @ 135 °C (Pa.s)	
RD	1.0250	Hot Flow (mm)	
Temp. (Mix) (°C)	160	Temp. (Comp)	145

DESIGN CURVES



DESIGN CRITERIA		1	2	3	4	5	PROPOSAL	SPECIFICATION	
Binder	%	4.5	5.0	5.5	6.0			MIN.	MAX.
Film thickness	µm	8.2	9.2	10.3	10.3				
Absorp. (Binder)	%	0.11	0.13	0.08	0.11				
Max. TRD (Rice)	kg/m³	2.671	2.650	2.625	2.605				
BRD (Marshall)	kg/m³	2.506	2.510	2.513	2.567				
Voids in Mix	%	6.2	5.3	4.3	1.5				
VMA	%	16.9	17.2	17.6	16.2				
VFB	%	63.5	69.3	75.7	91.0				
Immersion Index	%	81.3	83.6	87.8	89.3				
Dynamic Creep	kN								
ITS	kPa	1348	1275	1446	1367				
Stab. (Marshall)	kN	8.0	8.7	8.0	10.9				
Flow (Marshall)	mm	4.5	4.8	4.3	4.6				
Stab. / Flow Ratio		1.8	1.8	1.9	2.4				
Air Perm.								1 x 10⁻⁸	

D3 Form: 50/70 Binder mix design for Chrome Slag and Fly Ash mixture

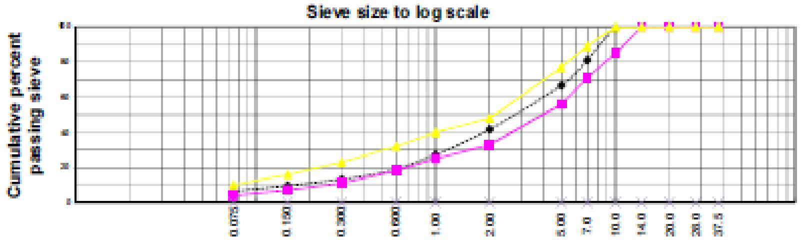
Designed by: ROADLAB	ASPHALT MIX DESIGN	Contract	Michiel Heyns	Form D3
Date: 2018/10/09		Route		
		Section		
		Layer	N/S	
		Mix	Continuously Graded Medium - SLAG	
		Our Ref.		

AGGREGATE PROPERTIES			
	Sample No	Nom. Size	Type and Source
1	1	13.2mm	Afrimat
2	2	9.5mm	Afrimat
3	3	6.7mm	Afrimat
4	4	4.75mm	Afrimat
5	5	-2mm	Afrimat
6	6	Fly Ash	Afrimat

Sieve Analysis [B 4] - % Passing Sieves

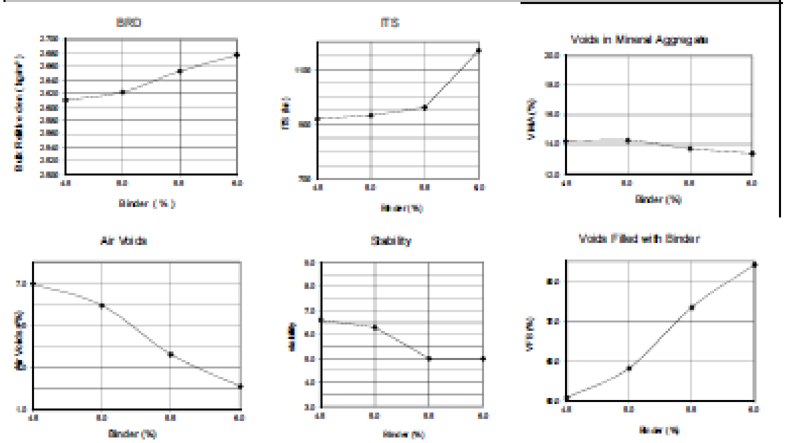
100.0

Sample No. No.		1	2	3	4	5	6	COMBINED GRADING		
% In Mix		0.0	17.0	15.0	10.0	52.0	6.0	Mix	Spec.	
Sieve Size (mm)	37.5	100	100	100	100	100	100	100	100	100
	28.0	100	100	100	100	100	100	100	100	100
	20.0	100	100	100	100	100	100	100	100	100
	14.0	89	100	100	100	100	100	100	100	100
	10.0	14	95	100	100	100	100	99	85	100
	7.0	2.0	15	70	100	100	100	81	71	89
	5.00	1.0	4.0	9	72	99	100	67	56	77
	2.00	1.0	2.0	2.0	7	66	100	42	33	48
	1.00	1.0	2.0	1	6	39	100	27	25	40
	0.600	1.0	2.0	1	5	23	100	19	18	32
	0.300	1.0	2.0	1	5	12	100	13	11	23
	0.150	0.4	1.0	0	3	6	97	9	7	16
	0.075	0.2	0.6	0.2	1.8	2.4	80.7	6.4	4	10
BRD		3.045	3.057	3.050	3.037	3.124		2.906		
Water absorp.		0.7	0.8	0.7					1.0 max	
Water absorp.					0.9	0.4			1.5 max	
ACV									25 max	
10 % FACT									160 min	
Flak. Index									25 max	
Sand eqv.									30 min	
PSV									50 min	



BINDER PROPERTIES			
Type	50/70	Source	
Pen @ 25°C (0,1 mm)		Visc. @ 60 °C (Pa.s)	
Soft. Pt (°C)		Visc. @ 135 °C (Pa.s)	
RD	1.0250	Hot Flow (mm)	
Temp. (Mix) (°C)	155	Temp. (Comp)	137

DESIGN CURVES



DESIGN CRITERIA		1	2	3	4		PROPOSAL	SPECIFICATION	
Binder	%	4.5	5.0	5.5	6.0			MIN.	MAX.
Film thickness	µm	4.6	5.3	6.5	6.5				
Absorp. (Binder)	%	1.74	1.84	1.70	1.79				
Max. TRD (Rice)	kg/m³	2.806	2.788	2.753	2.735				
BRD (Marshall)	kg/m³	2.610	2.622	2.653	2.677				
Voids in Mix	%	7.0	6.0	3.6	2.1				
VMA	%	14.2	14.3	13.7	13.4				
VFB	%	50.9	58.3	73.5	84.2				
Immersion Index	%	84.7	82.9	85.6	87.8				
Dynamic Creep	kN								
ITS	kPa	919	933	961	1169				
Stab. (Marshall)	kN	6.6	6.3	5.0	5.0				
Flow (Marshall)	mm	3.8	4.2	4.3	4.6				
Stab. / Flow Ratio		1.7	1.5	1.2	1.1				
Air Perm.								1 x 10	

D3 Form: AE-2 Binder mix design for Chrome Slag and Fly Ash mixture

ROADLAB Civil Engineering Materials Laboratory	Designed by: ROADLAB Date: 2018/10/09	ASPHALT MIX DESIGN	Contract: Michiel Heyns Route: Section: Layer: N/S Mix: Continuously Graded Medium - SLAG Our Ref.:	Form D3

HEAD OFFICE
287 Rietfontein Rd Primrose Germiston 1401
P.O.Box 1476 Germiston 1400
Tel: 011 828 8279 Fax: 011 828 5273
E-mail: info@roadlab.co.za
www.roadlab.co.za
Established 1963

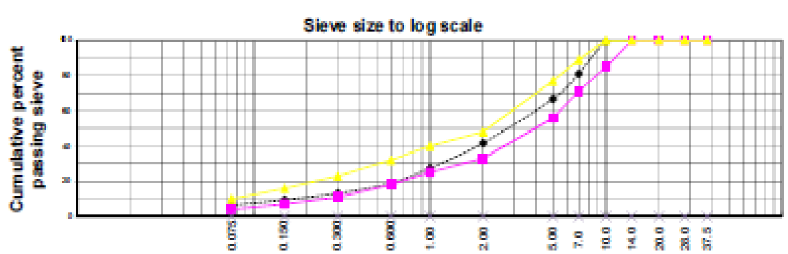
AGGREGATE PROPERTIES

	Sample No	Nom. Size	Type and Source
1	1	13.2mm	Afrimat
2	2	9.5mm	Afrimat
3	3	6.7mm	Afrimat
4	4	4.75mm	Afrimat
5	5	-2mm	Afrimat
6	6	Fly Ash	Afrimat

Sieve Analysis [B 4] - % Passing Sieves

100.0

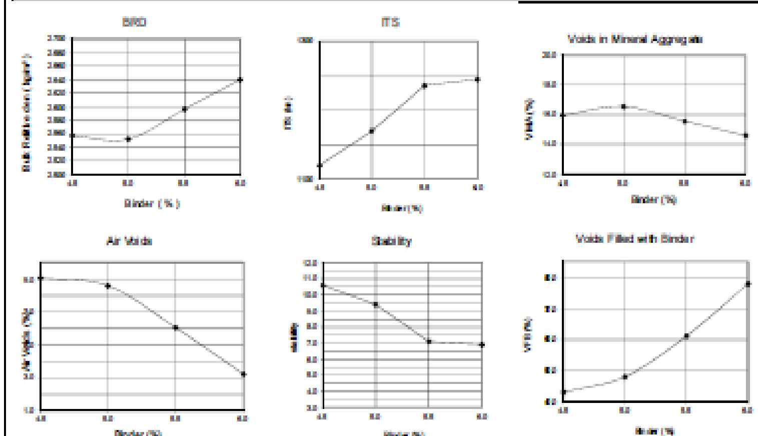
Sample No. No.	1	2	3	4	5	6	COMBINED GRADING Mix	Spec.	
% In Mix	0.0	17.0	15.0	10.0	52.0	6.0			
Sieve Size (mm) 37.5	100	100	100	100	100	100	100	100	100
28.0	100	100	100	100	100	100	100	100	100
20.0	100	100	100	100	100	100	100	100	100
14.0	89	100	100	100	100	100	100	100	100
10.0	14	95	100	100	100	100	99	85	100
7.0	2.0	15	70	100	100	100	81	71	89
5.00	1.0	4.0	9	72	99	100	67	56	77
2.00	1.0	2.0	2.0	7	66	100	42	33	48
1.00	1.0	2.0	1	6	39	100	27	25	40
0.600	1.0	2.0	1	5	23	100	19	18	32
0.300	1.0	2.0	1	5	12	100	13	11	23
0.150	0.4	1.0	0	3	6	97	9	7	16
0.075	0.2	0.6	0.2	1.6	2.4	80.7	6.4	4	10
BRD	3.045	3.057	3.050	3.037	3.124		2.906		
Water absorp.	0.7	0.8	0.7					1.0 max	
Water absorp.				0.9	0.4			1.5 max	
ACV								25 max	
10 % FACT								160 min	
Flak. Index								25 max	
Sand eqv.								30 min	
PSV								50 min	



BINDER PROPERTIES

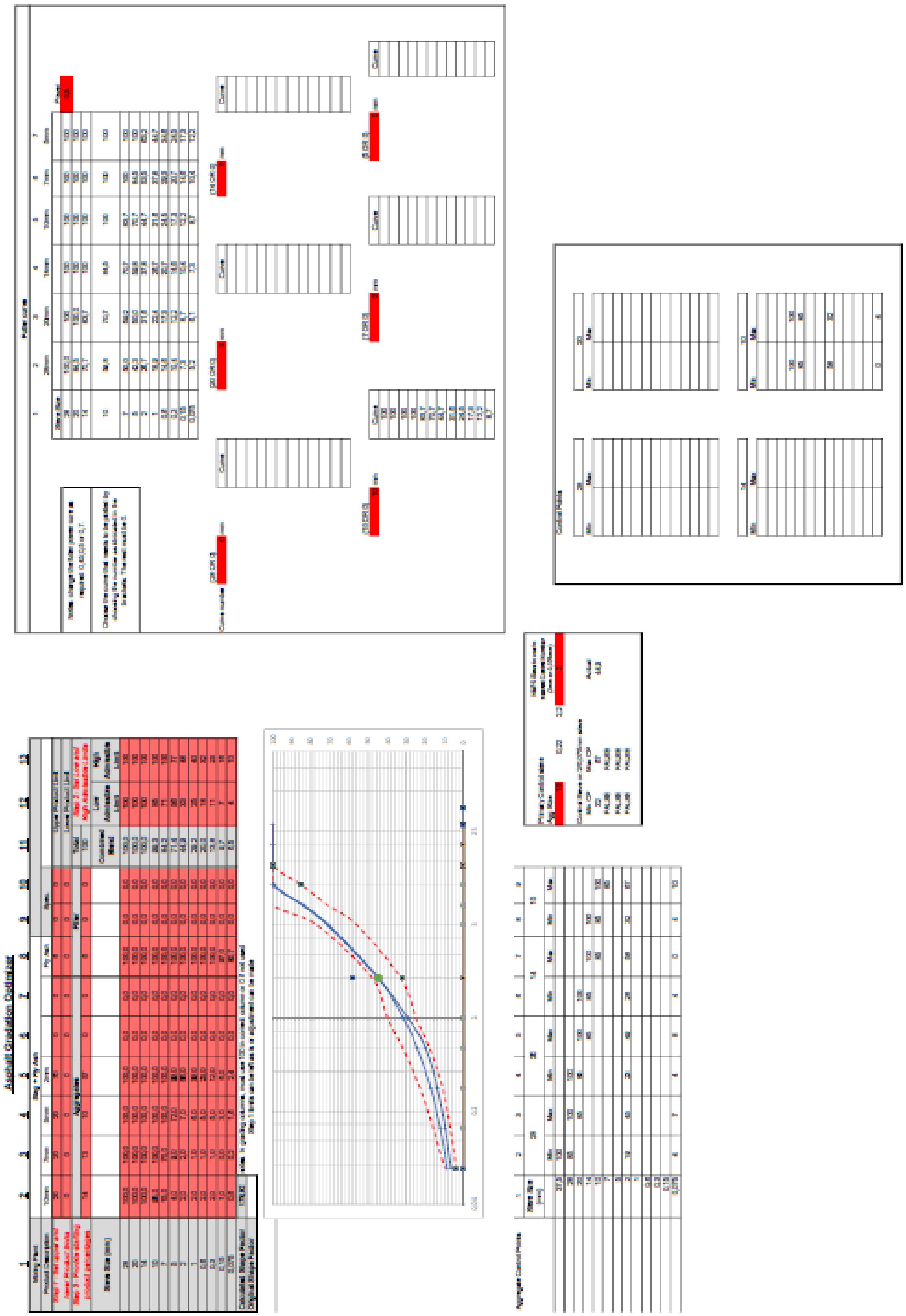
Type	AE2	Source	
Pen @ 25°C (0,1 mm)		Visc. @ 60°C (Pa.s)	
Soft. Pt (°C)		Visc. @ 135°C (Pa.s)	
RD	1.0250	Hot Flow (mm)	
Temp. (Mix) (°C)	160	Temp. (Comp)	145

DESIGN CURVES



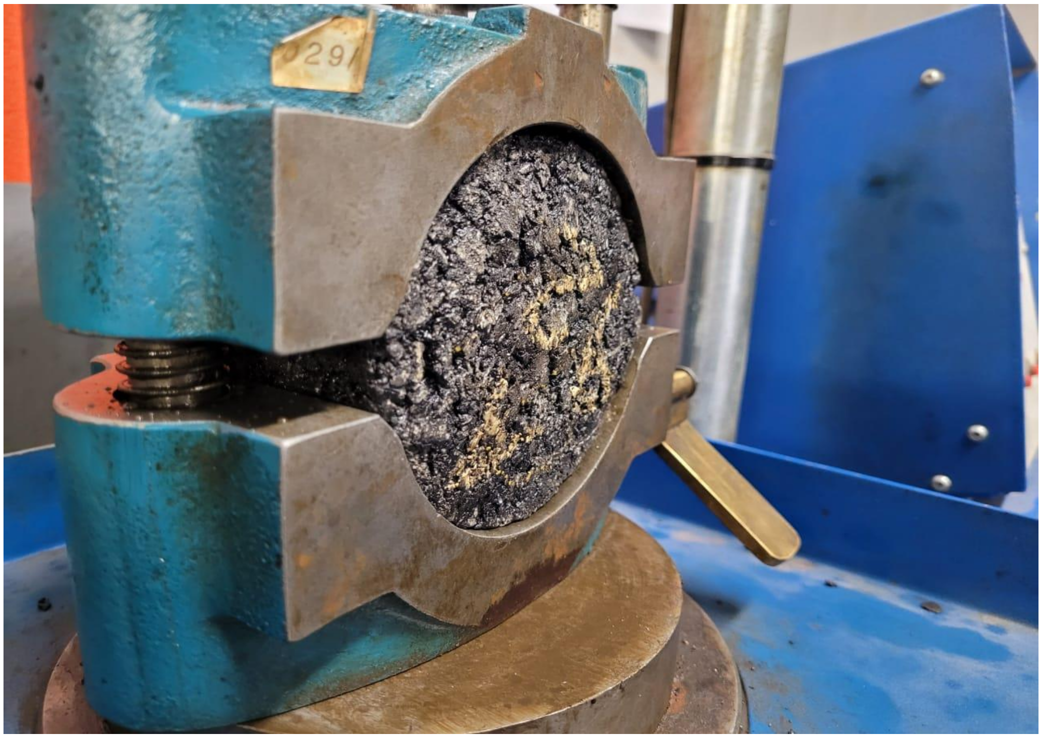
DESIGN CRITERIA		1	2	3	4		PROPOSAL	SPECIFICATION MIN.	MAX.
Binder	%	4.5	5.0	5.5	6.0			MIN.	MAX.
Film thickness	µm	4.5	5.2	6.2	6.2				
Absorp. (Binder)	%	1.82	1.89	1.84	1.69				
Max. TRD (Rice)	kg/m³	2.812	2.792	2.763	2.728				
BRD (Marshall)	kg/m³	2.557	2.552	2.596	2.640				
Voids in Mix	%	9.1	8.6	6.0	3.2				
VMA	%	16.0	16.6	15.6	14.6				
VFB	%	43.2	48.1	61.2	77.9				
Immersion Index	%	86.3	87.4	84.7	88.3				
Dynamic Creep	kN								
ITS	kPa	1120	1170	1236	1245				
Stab. (Marshall)	kN	10.6	9.4	7.1	6.9				
Flow (Marshall)	mm	5.2	5.2	4.2	4.6				
Stab. / Flow Ratio		2.0	1.8	1.7	1.5				
Air Perm.								1 x 10	

New Grading specifications incorporating all standards



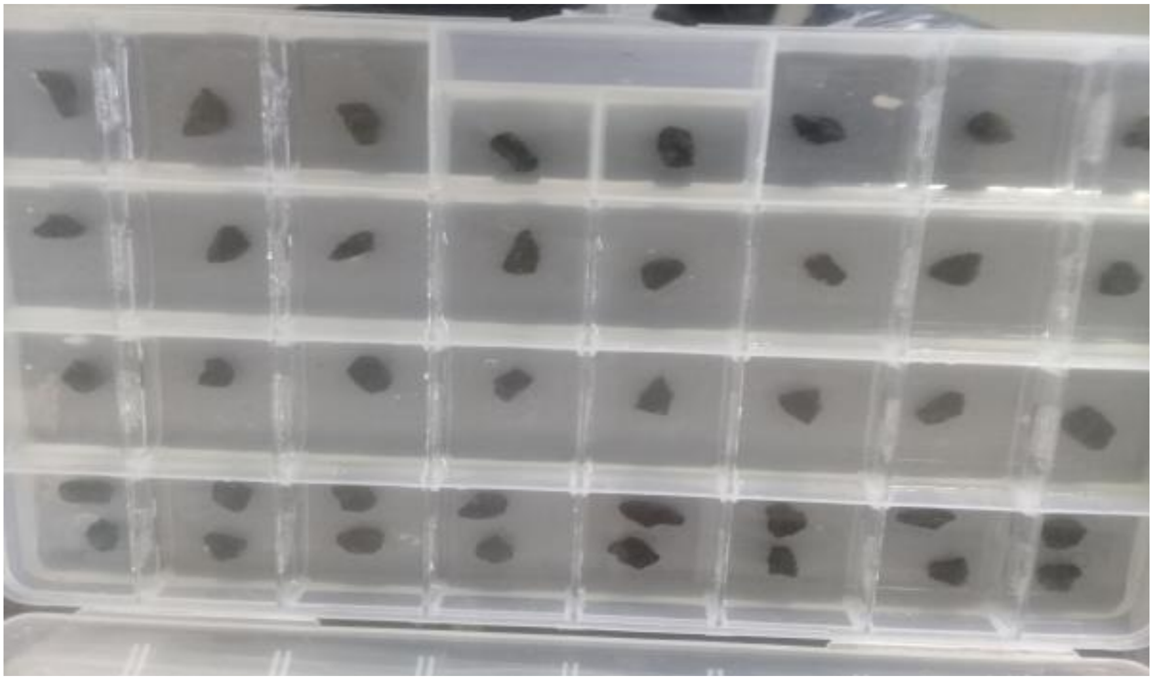
MMLS Testing

Marshall Stability and Flow

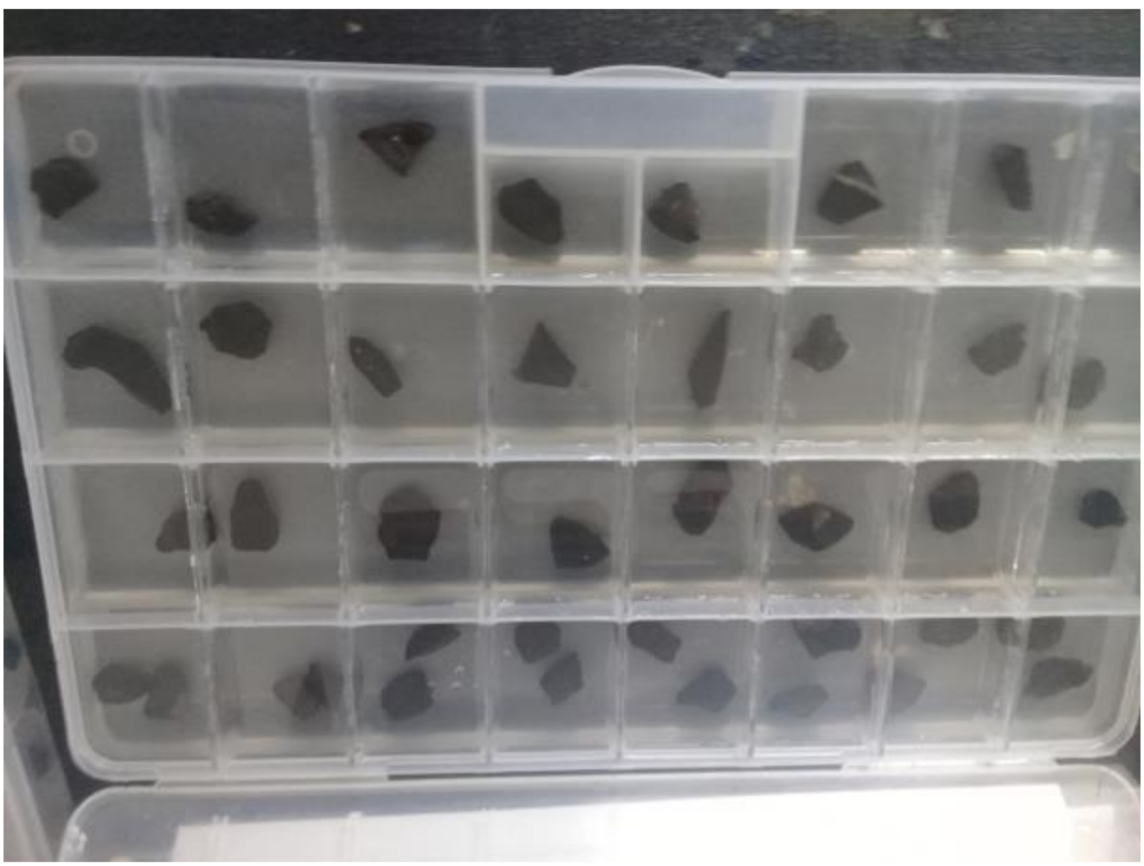


TMRD

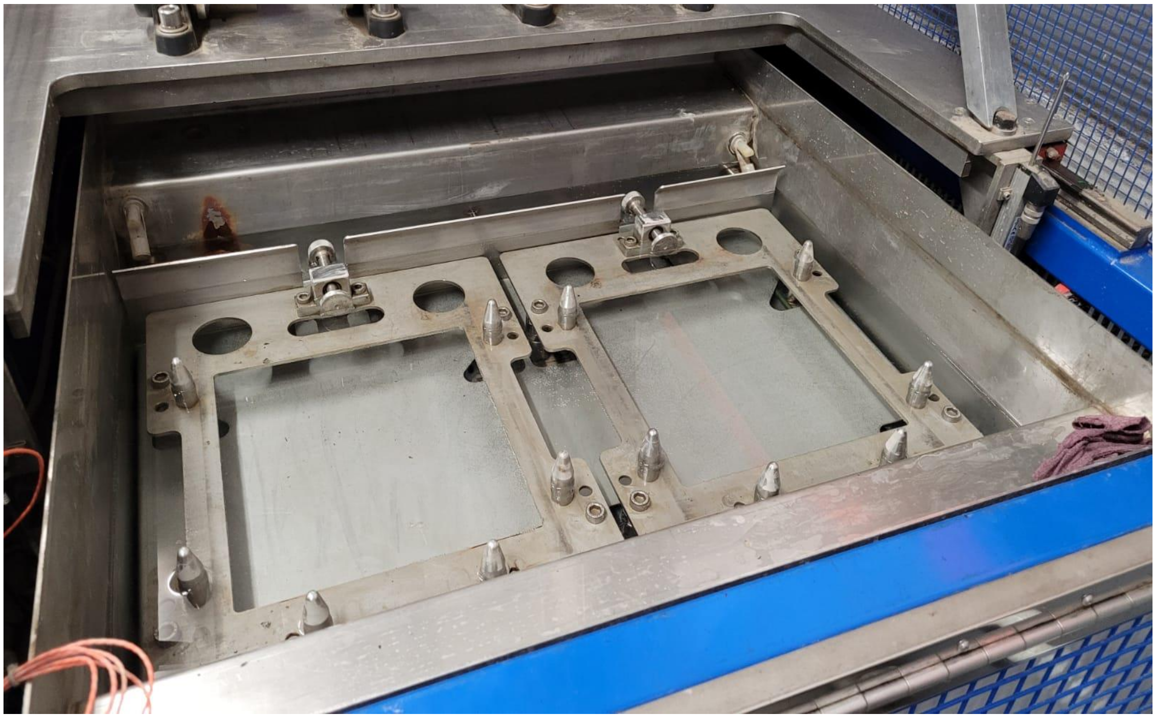
Ethylene Glycol – Natural Aggregate (dolerite)

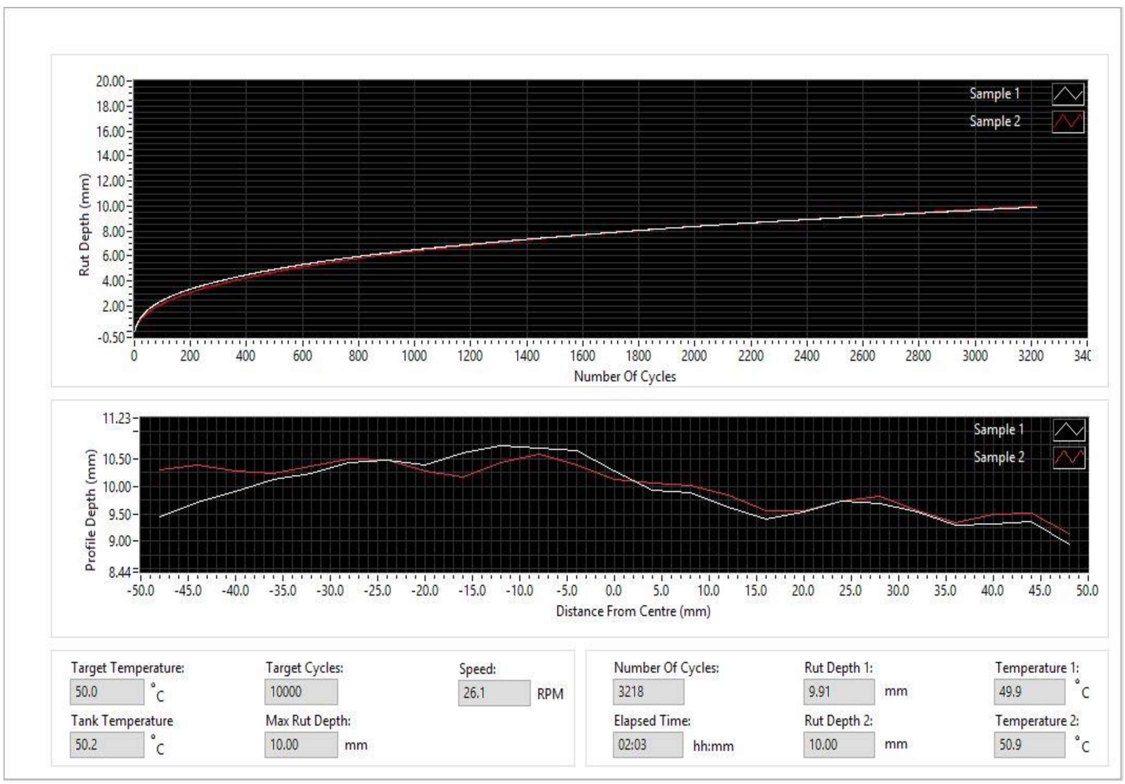


Ethylene Glycol – Chrome Slag

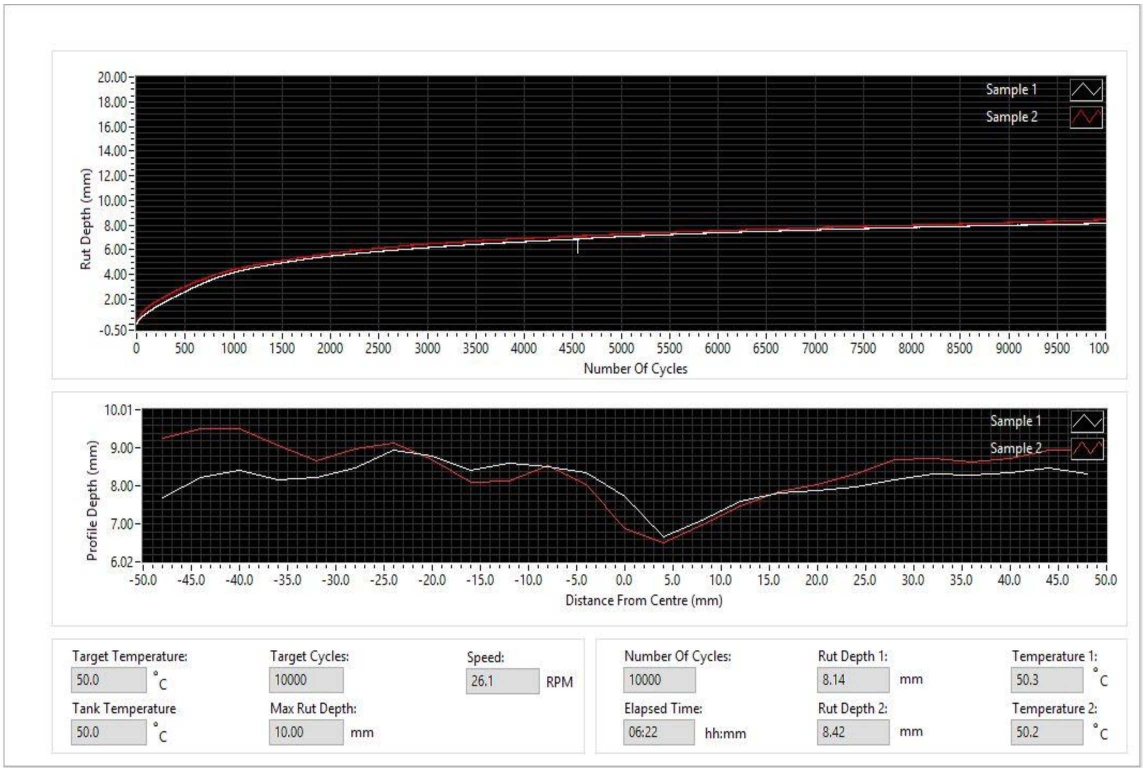


Hamburg Wheel Tests





Hamburg Software results Chrome Slag 50/70 5.5& 6% Binder



Hamburg Software results Chrome Slag AE-2 5& 6% Binder

Products and Services include:
Aggregates • Grit • Mineral Separation
Tel 013 699 0314/5 Fax 013 699 9425 34 Van Eck Street Ferrobank Witbank 1035 Private Bag X7260 Suite 209 Witbank 1035

AFRIGRIT
THE LINK to your BUSINESS PROCESS
Reg No: 2004/016729/07 VAT No: 4030237210

MATERIAL SAFETY DATA SHEET

All information in this MSDS is given in good faith and is accurate according to test results by accredited authorities. This MSDS is subject to revision when additional information comes to light.

1 PRODUCT AND COMPANY IDENTIFICATION

Supplier: Afrigrit
Postal: Private Bag X7260
Suite 209
Witbank

Address: 34 Van Eck Street
Ferrobank
Witbank

Telephone: 013 699 0314
Fax: 013 699 9425
e-mail: sales@afrigrit.co.za

Emergency telephone: 082 8949 097

Trade Name: Mineral slag based grit.
Chemical Family: Ferrochrome

2 COMPOSITION AND INGREDIENT INFORMATION

Hazardous components: Fine ferrochrome slag.
Common chemical name or generic name: Ferrochromium
Hazchem Code: Not applicable
UN / URG Number: Not applicable

CHEMICAL COMPOSITION

Calcium Oxide	2%	Titanium Dioxide	1%
Magnesium Oxide	20%	Iron Oxide	8%
Aluminium Oxide	26%	Chrome 3 oxide	12%
Silicon Dioxide	32%		

This is not free Silica

Date of origin	Originator	Revised by	Date of revision	Revision no	Name of doc.
10 Feb. 1997	Pat Pick	G. Venter	1-Apr-14	10	M.S.D.S.

3 HAZARDS IDENTIFICATION

Specific Hazards:	None.
Flammability:	None.
Chemical Hazard:	None.
Biological hazard:	None.
Reproductive Hazard	None.

Health effects:	
Eyes:	Same as any other foreign object or dust.
Skin:	Same as any other foreign object or dust.
Ingestion:	No known hazards.
Inhalation:	Same as for nuisance dust.
Carcinogenicity:	Not applicable
Mutagenicity:	No known hazards.

4 FIRST AID MEASURES

Product in eye: Wash with clean water until dust or particle is removed. If object could not be removed by this method seek medical attention.

Product on skin: Dust off or wash with water.

Product ingested: No need to administer any remedy although water will help rinse stomach.

Product inhaled: If person is overcome by dust cloud, introduction of clean fresh air is advised.

5 FIRE FIGHTING MEASURES

Extinguishing media: The substance is not flammable and inert to all fire fighting media.

Special Hazards: Not advisable for areas with a higher temperature than 1500 ^{o}c.

Protective clothing: Only necessary in the blasting application.

6 ACCIDENTAL RELEASE MEASURES

Personal precautions: None

Environmental precautions: Leaching may occur when in contact with organic compositions over a long period. Mix with a lime solution.

Suggested method of cleanup: Remove from organic material as soon as possible. Gather spilled material with brooms, spades, scoops etc.

7 HANDLING AND STORAGE

Handling:

No precautions needed, can be handled safely when loose or bagged.

Storage Precautions:

There is no unsafe storage for chrome based slag when suitable storage is being provided. (e.g. dry, undercover storage.) However, keep in mind that contact with organic material and acid rain may cause leaching over a period of time.

Date of origin	Originator	Revised by	Date of revision	Revision no	Name of doc.
10 Feb. 1997	Pat Pick	G. Venter	1-Apr-14	10	M.S.D.S.

8 EXPOSURE CONTROL AND PERSONAL PROTECTION

Occupational Exposure Limits (OEL): Total in-halable dust 0.5mg/m³
Engineering control measures: None

Personal protection during working application:

a	**Respiratory:**	Suitable dust masks of same nature as for nuisance dust.
b	**Hand:**	Leather or rubber gloves.
c	**Eye:**	Safety glasses or shield.
d	**Skin:**	Overall or other suitable clothing covering the whole body.
e	**Feet:**	Safety shoes or boots.
f	**Other protection:**	The end user for sandblasting operations must have a written Safe Working Procedure according to this MSDS.
g	**Risk assessment:**	The end user for sandblasting operations must have a risk assessment done by a competent person before commencing with the blasting operation.

9 PHYSICAL AND CHEMICAL PROPERTIES:

Appearance:	Dark Grey in colour, particle sizes ranging between 0.5mm-2.8mm.
Odour:	Slight dusty odour.
pH:	7.9
Boiling Point:	N/A
Melting Point:	1600 - 1700 ºC
Flash Point:	N/A
Flammability:	N/A
Spontaneous combustion:	N/A
Explosive properties:	Same as for any dust cloud mixed at the critical mixture with oxygen in closed confinement.
Oxidizing properties:	N/A
Vapour pressure:	N/A
Density:	3470Kg/m³
Solubility -water:	N/A
Solubility -coefficient:	N/A
Neurotoxicity:	None
Conductivity:	<100 μS/cm

Tested on 8 July 2003 by Secmet (Metallurgical and Corrosion Consultants) as follows:

Conductivity:	68	μS/cm	
Sulfate:	4.9	(mg/L)	
Nitrate:	0.3	(mg/L)	**All within the OEL**
Chloride:	19	(mg/L)	
Silica:	0.43	(mg/L)	

Date of origin	Originator	Revised by	Date of revision	Revision no	Name of doc.
10 Feb. 1997	Pat Pick	G. Venter	1-Apr-14	10	M.S.D.S.

10 STABILITY AND REACTIVITY

Conditions to avoid:

a Storage in contact with organic material over a long period of time.
b Highly acidic conditions.
c Dumping where leaching may occur.
f Protect from acid rain with suitable cover, e.g.. a tarpaulin.

Incompatible materials:

a Inorganic material.
b Acids.

Hazardous decomposition products: As listed above.

11 TOXICOLOGICAL INFORMATION

Acute toxicity:	Dust may cause irritation to nose, throat and lungs.
Skin and eye contact:	Redness and soreness of the skin and tearing of eye tissue.
Chronic toxicity:	Ulceration of the Central Nasal Septum of the nose, chronic dermatitis, over a prolonged period.
Carcinogenicity:	Level of Cr IV is non-detectable.
Mutagenicity	N/A.
Reproductive hazards:	None known.

12 ECOLOGICAL INFORMATION

Aquatic toxicity:	(fish:)	None.
Aquatic toxicity	(daphnia:)	None known.
Aquatic toxicity	(algae:)	None known.
Biodegradability:		Slow.
Bio-accumulation:		High.
Mobility:		None
German wgk:		

Date of origin	Originator	Revised by	Date of revision	Revision no	Name of doc.
10 Feb. 1997	Pat Pick	G. Venter	1-Apr-14	10	M.S.D.S.

References

AASHTO M295-06, 2006, “Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete”

Adriano, DC; Page, A; Elssewi, A; Chang, A and Straughan I; 1980, “Utilisation and Disposal of Fly Ash and other Coal Residues in Terrestrial Ecosystems: A Review”, Journal of Environmental Quality, V.9, n.3:333

AFRIGRIT, 2020; “Ferrochrome Uses and Material Specification Data Sheet”

Afrigrit, 2020; www.afrigrit.co.za

Al.ani AF, 2017, “Effect of Fly Ash on the Performance of Asphalt Concrete Mixes”, Journal of Babylon University/Engineering Sciences/No.5/Vol(25): 2017

Ali, N., Chan, J.S., Simms, S., Bushman, R., and Bergan, A.T. 1996; “Mechanistic evaluation of fly ash asphalt concrete mixtures”. Journal of Materials in Civil Engineering, 8(1): 19-25.

AMAR Ashtech Enterprises, 2013, “Fly Ash Handling”, www.amarashtech.com/handling.aspx

American Road and Transportation Builders Association Transportation Development Foundation (ARTB-TDF) (ARTB-TDF, 2011)

Arasan S, Yenera E, Hattatoglu F, Hinislioglue S and Akbuluta S, 2011; “Correlation between shape of aggregate and mechanical properties of asphalt concrete” Road pavement material design, Vol. 12, No. 2

Arcelor Mittal South Africa, 2016; “Technical Guideline For The Use Of Steel Chrome Slag In Road Construction”, June 2016.

Ash – valuable resource, 21-23 February 1994, “Second International Symposium, Vol 1 and Vol 2”, organized by the South African Coal Ash Association

Ash – valuable resource, papers S.387, 2-6 February 1987, “ Vol 1 – Productions and general Utilisation of Ash and Vol 2 – Concrete”

Ash Resources; 2007, “Technical Information Bulletin, Users’ Guide to Handling of Fly Ash Products”, Issue 1 No 1, www.ashresources.co.za

Ash Resources; 2012, “Material Safety Data Sheet (MSDS) for Fly Ash Products and Furnace Bottom Ash”, version: 2012/1, www.ashresources.co.za

Asi, I., and Assa'ad, A. 2005. "Effect of Jordanian oil shale fly ash on asphalt mixes." Journal of

Asphalt Academy, 2007; "Technical Guideline; The Use of Modified Bituminous Binders in Road Construction", TG1: Second Edition, November 2007

ASTM C618,1993, "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete," American Society for Testing and Materials, *Annual Book of ASTM Standards*, Volume 04.02, West Conshohocken, Pennsylvania.

ASTM D2487-06, 2006; "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)"

Australasian (iron & steel) Chrome Slag Association; "An Assessment of Iron and Steel Chrome Slag for Treatment of Stormwater Pollution",2006.

Ayanda, OS; Fataki, OS; Adekola, FA and Ximba, BJ; 2012, "Characterisation of Fly Ash Generated from Matla Power Station in Mpumulanga, South Africa", ISSN: 0973-4945; Coden Echjhao, E-Journal of chemistry, 9(4), 1788-1795

Lind B.B; A.M. Fallman; L.B. Larson; "Waste Management", 2001

Bahia H.U.; 2010. "Modeling of asphalt mixture in terms of filler–bitumen interaction," Int J Road Mater Pavement, 11: 281–303

Barisic I, Dimter S, Netinger I, 2010;"Possibilties of Application of Chrome Slag in Road Construction", Technical Gazette 17, 4, 2010, 523-528.

Beukes JP, Dawson NF and Van Zyl PG, 2010; "Theoretical and Practicla Aspects of Cr(VI) in the South African Ferrochrome Industry", Journal-South African Institute of Mining and Metallurgy

Bicki, TJ and Hirschi, MC; 1993, "Safe Drinking Water" Land and Water Number 17, Conserving Natural Resources in Illinois, University of Illinois at Urabana – Champaign, College of Agriculture, Cooperative Extension Service

Boral Fly Ash, 2013; www.boralana.com/flyash/faq.aspx

Bosch, GL; 1990, 'The mineralogy and chemistry of pulverized fuel ash produced by three South African coal-burning power stations", Unpublished MSc Thesis, University of Cape Town, South Africa

Bouwmeester M, Judd MD, Bedenhann SJ and Jones N, 2008; "The use of steel Chrome Slag in Hot-mix Asphalt in South Africa", South African Case Study, SAPEM Chapter 8.

Bowden L. Jarvis AP, Younger P and Johnson KL, 2009; "Phosphorous Removal from Waste Waters using Basic Oxygen Steel Chrome Slag", Environmental Science and Technology. 43(7): 2476-81, DOI: 10.1021/es 801626d

Button J.W., Perdomo D and Lytton R.L., 1990; "Influence of aggregate on rutting in asphalt concrete pavements" Transportation Research Record 1259. Transportation Research Board, National Research Council, Washington D.C. pp. 141 -152.

Campbell, AE; 1999, "Chemical, physical and mineralogical properties associated with the hardening of some South African fly ashes", Unpublished MSc Thesis, University of Cape Town, South Africa

Cement and Concrete Institute (C&CI), 2009; "Cementitous Materials for Concrete Standards, Selection and Properties", www.cnci.org.za

Churchill, E.V., and Amirkhanian, S.N.(1999). "Coal ash utilization in asphalt concrete mixtures."

Ciccu, R; Peretti, R; Zueca, A, 2001; "Heavy Metal Immobilisation using Fly Ash in Soils Contaminated by Mine Activity", International Ash Utilization Symposium

Colas: www.colas.co.za

Committee of Land Transport Officials (COLTO), 1998, Standard Specification for Road and Bridge for State Road Authorities, 1998 Edition

Concrete Technology, 2013; "Concrete Technology Fifth Edition", 2013 McGraw Hill Education (India) Private Limited

Conn, RE; Sellakumar, K and Bland, AE; 1999, "Utilisation of CFB Fly Ash for Construction Applications" Proceedings of the 15th International Conference on Fluidized Bed Combustion, Paper No. FBC99-0144

Cooperative Research centre for Coal in Sustainable Development (Australia), 2007; "Coal Combustion Products Handbook", edition 1 published in 2007 in English and held by Worldcat member libraries worldwide.

Department of Environmental Affairs South Africa, 2010, "National Waste Management Strategy", 4.7 Fly Ash and Coarse Ash Waste

Draft Protocol Guideline 1(DPG1), Dec 19, 2008: "Application of the MMLS3 for evaluating permanent deformation and moisture damage" (First Draft Version 3 Rev 1)

Electric Power Research Institute (EPRI) (EPRI, 1998)

Emry JJ, 1982;"Chrome Slag Utilization in Pavement Construction", Extending Aggregate Resources. ASTM Special Testing Publication 774, American Society for Testing and Materials, Washington, DC, 1982

European Norm Standards, EN450, 1994, "Fly Ash for Concrete – Definitions, requirements and quality control"

European Norm Standards, EN450, 2005, "Fly Ash for Concrete – Part 2, Conformity evaluation"

European Norm Standards, EN450-1:2007, "Fly Ash for Concrete – Definitions, specifications and conformity criteria, 2005 + A1:2007"

European Norm Standards, pr EN450-1, 2012, "Fly Ash for Concrete – Part 1, Definitions, specifications and conformity criteria"

European Standard; pr EN450-1; 2001, "Fly Ash for Concrete – Part 1: Definition, Specifications and Conformity Criteria", NABau 07.02.04 N0004

Fischer, GL; Prentice, BA; Siberman, D; Ondov, JM; Ragaini, RC; Bierman, AH; Mcfarland, AR and Powley, JB; 1978, "Size-dependence of the Physical and Chemical Properties of Coal Fly Ash"

Fly Ash Facts for Highway Engineers, 2003, Technical Report Document, Report No: FHWA-IF-03-019.

Fulton's Concrete Technology, Ninth Edition, 2009.

Gericke WA, 1995; "Environmental Aspects of Ferrochrome Production",INFACON 7, Trondheim, Norway, June 1995, Eds: Tuset, Tveit and Page, Publishers: FFF, Trondheim, Norway

Gitari, M.W; Fatabo, OO; Nyamihinura, A; Petrik, LF; Vadapalli, VRK; Nel, J; Dlamini, L; Gericke, G; Mahlaba, JS; 2009, "Chemical Weathering in Dry Ash Dump: An Insight from Physicochemical and Mineralogical Analysis of Drilled Cores", World of Coal Ash (WOCA) conference – May 4-7, 2009 in Lexington, KY, USA

Gradation and Size – Pavement Interactive, 2020; "Dynamic Compaction", https://pavementinteractive.org/reference-desk/materials/aggregate/gradation-and-size/

Groot DR, Kazadi DM, Pallmann H, De Villiers JPR, Redtmann T and Steenkamp J, 2013; "The recovery of manganese and generation of a valuable residue from ferro manganese Chrome Slags by a hydrometallurgical route", The Thirteenth International Ferroalloys Congress, Efficient Technologies in Ferroalloy Industry, June 9-13, 2013

Guyer, P.E., R.A, Fellow ASCE, Fellow AEI, 2011;"Introduction to Soil Stabilisation in Pavements" Course No: C03-028.

Hainin MR, Yusoff NI, Mohammad Sabri MF, Aziz MA, Hameed MAS and Reshi WF, 2012; "Steel Chrome Slag as an Aggregate Replacement in Malaysian Hot Mix Asphalt", International Scholarly Research Network, ISRN Civil Engineering, Volume 2012, Article ID 459016, 5 pages, DOI: 10.5402/2012/459016

Hall, I; 2011, "South African Coal Road Map – The SA Coal Industry: Present Context and Preliminary Future Scenarious", SANEA Lecture

Hassett, DJ and Heebink, LV; 2001, "JV Task 13 – Environmental Evaluation for Utilisation of Ash in Soil Stabilisation", Final Report No: DE-FC26-98FT40321; UND Fund 4715

Hattingh J, Friend JFC, 2003; "Envronmental and economic implications of Chrome Slag disposal practices by the ferrochromium industry/; A case study", ISSN 0378-4738 = Water SA Vol. 29 No. 1 January 2003.

Heebink, LV; Hassett, DJ; 2001, "Coal Fly Ash Trace Element Mobility in Soil Stabilisation", International Ash Utilisation Symposium, Center for Applied Energy Research, University of Kentucky, Paper ♯64, http://www.flyash.info

Heyns M, 2016; "Fly Ash as an Alternative Stabiliser for Road Pavement Materials" Master of Engineering Thesis, 2016

Heyns M, SO Abejide and M Mostafa Hassan (2018) "Sustainable Waste Alternative as Cement Replacement in Pavement Stabilization" JOURNAL OF CONSTRUCTION PROJECT MANAGEMENT AND INNOVATION; Vol 8, No 1, June 18, pp 1767 – 1778; ISNN: 2223-7852; https://hdl.handle.net/10520/EJC-10a49a808d

Hofko, B, Eberhardsteiner L, 2016; "Impact of maltene and asphaltene fraction on mechanical behaviour and microstructure of bitumen", Materials and Structures (2016) 49: 829-841; DOI 10.1617/s11527-015-0541-6.

Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa, September 2001

Ismail, KN; Hussin, K and Idris, MS; 2007, "Physical, Chemical and Mineralogical Properties of Fly Ash", Journal of Nuclear and Related Technology Vol.4, Special Edition, 47-51

Iyer, R; 2002, “The surface chemistry of leaching coal fly ash”, Journal of hazardous Materials B93:321-329

Jian-Shuih Chen, Shih-Hsiu Weis, 2016; “Engineering properties and performance of asphalt mixtures incorporating steel Chrome Slag” Construction and Building Materials 128(2016) 148-153.

Journal of Materials in Civil Engineering, 11 (4): 295-301.

Kadhim HA, Al-Humeidawi BH and Medhlom MK, 2018; “Production of High Modulus Asphalt Concrete with High Rutting Resistance”, ARPN Journal of Engineering and Applied Sciences, Vol. 13, No. 13, July 2018.

Kandhal PS, Parker F (1998), “Aggregate tests related to asphalt concrete performance in pavements”, NCHRP Report 405, Transportation Research Board, National Research Council, Washington DC, USA.

Kar D, Panda M and Giri JP, 2014; “Influence of Fly Ash as a Filler in Bituminous Mixes”, ARPN Journal of Engineering and Applied Sciences, VOL. 9, NO. 6, JUNE 2014

Khalifa S, 2018; “Research on the use of Ferro-Chrome Chrome Slag in civil engineering appliactions”, MATEC Web of Conferences 149, 01017, 2018.

Kim, AG; 2006, “Leaching Methods Applied to the Characterisation of Coal Utilisation By-Products”, National Energy Technology Laboratory, US Department of Energy

Komba JJ, O’Connel J, Paige-Green P, 2014;”Evaluation of the Performance of Aggregate in Hot-Mix Asphalt” Proceedings of the 33rd Southern African Transport Conference (SATC 2014), Proceedings ISBN Number: 978-1-920017-61-3.

Kruger, RA, 2013, “Business Development in the Fly Ash Industry”, Personal Communication

Kruger, RA, 2013, “Introduction to Coal Ash”, Personal Communication

Kumar P and Tanveer K, 2013; “Evaluation of physical properties of sulphur modified bitumen and its resistance to ageing”, Chemical Engineering, Elixir Chem. Engg. 55A (2013) 13104-13107

Lesueur D and Youtcheff J, 2013; “Chapter 29. Asphalt Pavement Durability”, Published in "Environmental Degradation of Advanced and Traditional Engineering Materials", Editor(s): Lloyd H. Hihara, Ralph P.I. Adler, Ronald M. Latanision, CRC Press, 2013 (http://www.crcpress.com/product/isbn/9781439819265#!)

Mahmoud E, Ibrahim A, El-Chabib H and Patibandla VC, 2013; “Self-Consolidating Concrete Incorporating High Volume of Fly Ash, Chrome Slag, and Recycled Asphalt Pavement”, International Journal of Concrete Structures and Materials, Vol.7, No.2, pp.155–163, June 2013, DOI 10.1007/s40069-013-0044-1, ISSN 1976-0485 / eISSN 2234-1315

Materials in Civil Engineering, 17 (5): 553-559.

Mehta,P.K.,1998, ”Role of Fly Ash in Sustainable Development – Concrete, Fly Ash, and the Environment – Proceedings” Forum held – Sponsored by EHDD Architecture and Pacific Energy Center.

Metcalf C, 1969; “Use of Marshall Stability Test in Asphalt Paving Mix Design”, Research Laboratory, Sheel Oil Co, HRB:OR-279.

Mikoc M, Markovic, 2010; “Influence of Chrome Slag, fly ash and silica fume on the mechanical and physical properties of asphalt” Technical Gazette 17, 4(2010), 505-514.

Mills, KC, Yuan L, Jones RT, 2011; “Estimating the physical properties of Chrome Slags”, The journal of the Southern African Institute of Mining and Metallurgy; Volume 111; October 2011

Mining Weekly, 2010; “A brief look at SA’s coal mining industry”, www.miningweekly.com/article/a-brief-look-at-sas-coal-mining-industry-2010-09-03

Mohammed N, Ramjattan V, Mharaj R, 2016; “Mechanistic Enhancement of Asphaltic Materials Using Fly Ash”, Journal of Applied Sciences, 16: 526-533, DOI: 10.3923/jas.2016.526.533, URL: https://scialert.net/abstract/?doi=jas.2016.526.533

Mohd Rosli Hainin, Nur Izzi Md. Yusoff, Mohd Fahmi Mohammed Sabri, Mohd Azizi Abdul Aziz, Mohd Anwar Sahul Hameed and Wasid Farooq Reshi; 2012: “Steel Chrome Slag as an Aggregate Replacement in Malaysian Hot Mix Asphalt”, International Scholarly Research Network, ISRN Civil Engineering, Volume 2012, Article ID 4592016, 5 pages, doi:10.5402/2012/459016 moisture damage of asphalt”, December 19, 2008 (First Draft Version 3 Rev1)

Molharta, VM and Mehat, PK; 1996, “Pozzolanic and Cementitous Materials” Volume 1 od advances in Concrete Technology Series, Gordon and Breach Publishers

Moolman, D; 2011, ‘Baseline Study of Kendal Power Station”, Thesis published for Magister Scientae Degree, In the Faculty of Natrual and Agricultural Sciences, Institute for Groundwater Studies, University of the Free State

Mukandile E, Steyn W, Milne T and Kannemeyer L, 2015; “Rheological Characteristics of South African Bitumen”, Conference: 11th Conference on Asphalt Pavements for Southern Africa (CAPSA).

Naik, TR and Singh, SS; 1997, "Permeability of Flowable Slurry Materials Containing Foundry Sand and Fly Ash", Journal of Geotechnical and Geoenvironmental Engineering

National Asphalt Pavement Association, 2009; "Thin Asphalt Overlays for Pavement Preservation", Information series 135, Produced 7/09.

National Inventory, 2001, "Discard and Duff Coal", Summary report

National Chrome Slag Association, 2003; "Leachate from Blast Furnace Chrome Slag", NSA, April 2003

National Chrome Slag Association; 'Environmental Technical Bulletin"; May 26, 2003

National Chrome Slag Association; 'Iron and Steel Making Chrome Slag – Environmentally Responsible Construction Aggregates"; May 26, 2003

National Chrome Slag Association; 'Iron and Steel Chrome Slags – Non-Hazards"; MF194-5; D. Lewis; December 14, 1980.

National Chrome Slag Association; 'Leachate from Blast Furnace Chrome Slag – What it is and How to Treat it"; April 8, 2003

Netterberg, F and Paige-Green, P; 1984, "Carbonation of lime and cement stabilised in road construction", National Institute for Transport and Road Research, CSIR, South Africa, Technical Report: RS/3/84

Niemela P, Kauppi M, 2007; "Production, Characteristics and Use of Ferrochromium Chrome Slags", Innovation in Ferro Alloy Industry, INFACON XI, 2007.

Ochla C; "Utilization Iron and Steel Chrome Slag's in Environmental Applications-An Overview", Tube City IMS

Ojo F, 2010, "Chemical interactions and mobility of species in fly ash-brine co-disposal systems" Thesis published for Doctoral in Chemistry, Department of Chemistry, University of Western Cape.

Oppenshaw, SC; 1992, "Utilisation of Coal Fly Ash" Thesis published for Master Degree in Engineering, University of Florida

Paige – Green, P; 2007, "Durability testing of basic crystalline rocks and specification for use as a road base aggregate", CSIR Built Environment

Paige-Green, P; 2013, "A revised ethylene glycol test for assessing the durability of basic crystalline materials for road aggregate", MRC-08, Geological construction materials – Part 1.

Pan T, Tutumluer E and Carpenter H, 2005; "Effect of coarse aggregate morphology on the resilient modulus of hot mix asphalt", TRB 84th Annual Conference, Washington D.C., USA, January 2005.

PAPP J (2000) Chromium. US Geological Survey. Chromium Association. http://www.chromium-asoc.com/thcrfl.htm [23 October 2000].

Pavement Materials: Aggrgates, 2010: "Lecture notes in Transportation Systems Engineering"; September, 2010; https://www.civil.iitb.ac.in/itvm/1100_LnTse/404/plain/plain.html

Pretorius FJ, Grobler JE and Onraet J, 2004; "Development of a Fit-For-Purpose Product Performance Specification System for Asphalt Mixes", Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04), ISBN Number: 1-920-01718-6, Proceedings produced by: Document Transformation Technologies cc, 12-16 September 2004, Sun City, South Africa

Principles of Geotechnical Engineering, 7th Edition, 2012

Priyaka BD, Kumar PUA, Dedeepya K, Shabuddin A and Rao SK, 2015; "Use of Fly Ash as Mineral Filler for Bituminous Paving Mixes", IJREI: International Journal of Research in Engineering and Technology, eISSN:2319-1163/pISSN:2321-7308

Proctor DM, Fehling KA, Shay EC, Wittenborn JL, Green JJ, Avent C, Bigham RD, Connolly M, Lee B, Shepker TO, Zak MO, 2000; "Physical and chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Chrome Slags", Environmental Science and Technology, Vol 34, No8, 2000.

Mistry R, T. K. Roy,2016; "Effect of using fly ash as alternative filler in hot mix asphalt", Perspectives in Science 8 (2016) 307–309.

Ramme BW, Covi A, Faheem A, Sobolev K, 2016; "Fly Ash – An Important Ingredient for use in Hot-Mix Asphalt Concrete", Fourth International Conference on Sustainable Construction Materials and Technologies, http://www.claisse.info/Proceedings.htm, Las Vegas, USA, August 7-11, 2016

Resource Conservation and Recovery Act as amended, 1998, Public Law 94-580, United States Congress, Washington, D.C, October 21, 1976

Reuter M, Xiao Y and Boin U, 2004; "Recycling and Environmental Issues of Metallurgical Chrome Slags Fluxes and Salts", VII International Conference on Molten Chrome Slag Fluxes and Salts. The South African Institute of Mining and Metallurgy, 2004

Reynolds, K; Kruger, R; Rethman, N and Truter, W; 2002, "The production of an artificial soil from sewage sludge and fly ash and the subsequent evaluation of growth enhancement, heavy metal translocation and leaching potential", ISBN 1-86845-946-2 – Water SA Special Edition: WISA Proceedings

Roberts, F.L.; Kandhal, P.S.; Brown, E.R.; Lee, D.Y. and Kennedy, T.W. (1996[1]). *Hot Mix Asphalt Materials, Mixture Design, and Construction*. National Asphalt Pavement Association Education Foundation. Lanham, MD.

Rotaru, Antcuta, Vasile Boboc, 2010;"A Material Used in Substructure and Road Works: Physical Characteristics of Pozzolona Fly Ash from Thermal Power Plant of Iasi, Romania" Issue 6, Volume 6.

Roy, W.R; Schuller, R; Suloway, J, 1981; "Coal Fly Ash: A Review of the Literature and Proposed Classification System with Emphasis on Environmental Impacts", Environmental Geology Notes, #96

Seshadri, B; Bolon, NS; Bradie, K; 2010, "The role of coal combustion products in managing the bioavailability of nutrients and heavy metals in soils".

Shen DH, Wu CM and Du Jc, 2009; "Laboratory Investigation of Basic Oxygen Furnace Chrome Slag for Substitution of Aggregate in Porous Asphalt Mixture", // Construction and Building Materials.23 (2009), 453 - 461

Simmons J, Ziemkiewicz P and Courtney Black D; 2001, " Use of Steel Chrome Slag Leach Reds for the Treatment of Acid Mine Drainage", Presented at the 2001 National Association of Abandoned Mine Lands Annual Conference, August 19-22, 2001, Athens, Ohio.

Sobolev K, Flores I, Bohler JD, Faheem A and Covi A, 2013; "Application of Fly Ash in Asphalt Concrete", World of Coal Ash Conference, April 22 – 25, 2013

Solc, J; Foster, HJ and Butler,RD; 1995, "Environmental impact of Fly Ash disposal of Colourado, Illinois and Ohio test sites – hydrogeological approach", Ground water quality: Remediation and Protection, Proceedings of the Prague Conference, IAHS Publ. no. 225

South Africa Bitumen Association (SABITA) Manual 2, 2012; "Bituminous Binders for Road Construction and Maintenance"

South Africa Bitumen Association (SABITA) Manual 24, 2005; "User Guide for the Design of Hot Mix Asphalt"

South Africa Bitumen Association (SABITA) Manual 8, 2003; "Guidelines for the safe and responsible handling of bituminous products" 2nd Edition, December 2003

South Africa Bitumen Association (SABITA), 2014; "Asphalt Mix Design for South Africa", Asphalt mix design manual for South Africa, provisional working document November 2014

South Africa National Standards (SANS) 1491-2, 2005, "Portland Cement extenders Part 2: Fly Ash"

South Africa National Standards (SANS) 1491-2, 2005; "Portland Cement Extenders Part 2: Fly Ash"

South Africa National Standards (SANS) 4001 BT1:2014; "Penetration Grade Bitumens"

South Africa National Standards (SANS) 50196-1:2006; "Methods of Testing Cement Part 1: Determination of Strength"

South Africa National Standards (SANS) 50197-1, 2000, "Cement Part 1: Composition, specifications and conformity criteria for common cements"

South Africa National Standards (SANS) 50197-2, 2000, "Cement Part 2: Conformity evaluation"

South Africa National Standards (SANS) 50450-1, 2011, "Fly Ash for concrete Part 1: definition, specifications and conformity criteria"

South Africa National Standards (SANS) 50450-2, 2001, "Fly Ash for concrete Part 2: Conformity evaluation"

South African National Standard Part AG10; SANS 3001-AG10:2012: ACV (aggregate crushing value) and 10 % FACT (fines aggregate crushing test) values of coarse aggregates

South African National Standard Part AG11; SANS 3001-AG11:2016: Tests for mechanical and physical properties of aggregates — Determination of the polished stone value

South African National Standard Part AG14; SANS 3001-AG14:2013: Determination of the ethylene glycol durability index for rock

South African National Standard Part AG15; SANS 3001-AG15:2012: Determination of rock durability using 10 % FACT (fines aggregate crushing test) values after soaking in ethylene glycol

South African National Standard Part AG20; SANS 3001-AG20:2014: Determination of the bulk density, apparent density and water absorption of aggregate particles retained on the 5mm sieve for road construction materials

South African National Standard Part AG21; SANS 3001-AG21:2014: Determination of the bulk density, apparent density and water absorption of aggregate particles passing on the 5mm sieve for road construction materials

South African National Standard Part AG4; SANS 3001-AG4:2015: Determination of the flakiness index of coarse aggregate.

South African National Standard Part AG5; SANS 3001-AG5:2015: Sand equivalent value of fine aggregates

South African National Standard Part AG9; SANS 3001-AG9:2015: Determination of the Treton impact value for aggregates and gravels

South African National Standard, 2008; "Deleterious clay content of the fines in aggregate (methylene blue adsorption indicator test", SANS 6243:2008

South African National Standard, 2008; "Polished-stone value of aggregates", SANS 5848:2008

South African Pavement Engineering Manual, 2011, Chapter 3, "Material Testing", Revision 1.(SAPEM, 2011).

South African Pavement Engineering Manual, 2011, Chapter 4, "Standards", Revision 1.(SAPEM, 2011).

South African Pavement Engineering Manual, 2011, Chapter 8, "Material Sources", Revision 1.(SAPEM, 2011).

South African Pavement Engineering Manual, 2011, Chapter 9, "Material Utilisation and Design", Revision 1.(SAPEM, 2011).

Surridge, AKJ; Van der Merwe, A; Kruger,R; 2009," Preliminary microbial studies on the impact of plants and South African fly ash on amelioration of crude oil polluted acid soils" World of Coal Ash (WOCA) conference – May 4-7.

Swami BL, Mehta YA and Bose S, 2004; "A Comparison of the Marshall and Superpave Design Procedure for Materials Sourced in India", The International Journal of Pavement Engineering, Vol. 5 (3) September 2004, pp. 163-173

Tapkın, S. 2008; " Improved asphalt aggregate mix properties by portland cement modification". Can. J. Civ. Eng. 35: 27-40.

Tau, P; 2005, "Occupational Hazards of Exposure to Coal Fly Ash", Thesis published for Magister Technologiae: Environmental Health, Department of Environmental Helath, Faculty of Health Sciences, Tshwane University of Technology

Technical Recommendations For Highways (TRH) 14, 1985; "Guidelines for road construction materials", 1985

Technical Recommendations For Highways (TRH) 8, 1987; "Design And Use Of Hot-Mix Asphalt In Pavements", 1987

The Federal Register, vol 45, No. 98, May 19, 1980

The Shell Bitumen Handbook sixth edition, 2015; ISBN 978-0-7277-5837-8

TMH1, 1986, Technical Methods for Highways, "Standard Methods of Testing Road Construction Materials"

Tuncer, B, 2006, "Green Highways Strategy for Recycling Materials for Sustainable Construction Practices", University of Wisconsin – Madison, Geological Engineering Program and Department of Civil and Environmental Engineering, Madison, WI, USA

Tuncer, BE; Acosta, HA and Benson, CH; 2006, "Stabilizing Soft Fine-Grained Soils with Fly Ash", Journal of Materials in Civil Engineering

Ululu Ash, 2021; www.ululaflyash.com

United States Environmental Protection Agency, 1999, www.epa.gov

Usmen, M; Bowders, J and Gidley, J; 1998, "Low Permeability Liners Incorporating Fly Ash" Proceedings from a Session of ASCE Noational Convention, Tennesse: Disposal and Utilisation of Electric Utility Wastes, ed. M. Usmen, (New York: ASCE), P.50-65

Verhaeghe BMJA, Jooste FJ, Taute A, Visser AT and Myburgh PA, 2000; "A New Hot-Mix Design Method for Southern Africa", South African Transport Conference, Action in Transport for the new Millenium, South Africa, 17 – 20 July 2000.

Verhaeghe BMJA, Myburgh PA and Denneman E, 2007; "Asphalt Rutting and its Prevention", 9th Conference on Asphlat Pavements for South Africa, September 2007.

Von Quintus, H.L., Scherocman, J.A., Hughes C.S., Kennedy, T.W. 1991; "Asphalt aggregate mixture analysis system". NCHRP report 338. Prepared for Transportation Research Board, Brent Rauhut Engineering Inc, Austin, Texas

Von Vliet K, 2006; "Mechanical Behaviour of Materials", MIT open course ware, ocw.mit.edu

Washington State DOT Construction Division Pavements Office, 2015; "WSDOT Strategies Regarding Use of Steel Chrome Slag Aggregate in Pavements", A report to the State Legsilature in Response to 2ESHB 1299, November 2015.

Washington State DOT, 2015; "WSDOT Strategies Regarding Use of Steel Chrome Slag Aggregate in Pavements"; Report to the state Legislature in Response to 2ESHB 1299; Prepared by Washington State DOT; Construction Division Pavements Office; November 2015.

Xie J, Wu S, Pang LM and Lin J, 2012; "Influence of Surface Treated Fly Ash with Coupling Agent on Asphalt Mixture Moisture Damage", Construction and Building Materials 30; 340-346 DOI: 10.1016/j. conbuidmant. 2011.11.022, May 2012

Yang R, Ozer H, Kang S and Al-Qadi I, 2014; "Environmental Impacts of Producing Asphat Mixtures with Varying Degrees of Recycled Asphalt Materials", Submitted to the International Symposium on Pavement LCA 2014.

Young, SC; 1993, "Physical and Hydraulic properties of Fly Ash and other by-products from coal ash combustion", Electri Power Research Institute, Palo Alto, EPRI pp 83

Ziemkiwicz PK and Skousen JG, 1998; "The Use of Steel Chrome Slag in Acid Mine Drainage Treatment and Control", In: Proceedings, Nineteenth Annual West Virginia Surface. Mine Drainage Task Force Symposium, Morgan town, West Virginia April 7 - 8

Zulkati A, Wong YD ad Sun DD, 2012; "Effects of Fillers on Properties of Asphalt-Concrete Mixtures", Journal of Transportation Engineering 138(7); 902 – 910; DOI: 10.1061/(ASCE) TE.1943-5436.0000395