Fly Ash as an Alternative Stabiliser for Road Pavement Materials: a case study in South Africa

By

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Declaration

I hereby declare that this dissertation, submitted for a Masters Technologiae 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

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ABSTRACT

Fly Ash is a by-product at thermal power stations, otherwise known as residues of fine particles that rise with flue gases. Coal is pulverised and blown with air into a boiler's combustion chamber. Fly Ash is the lighter finer ash particles that remain suspended in the flue gas. Fly Ash consists of silt sized particles which vary in size from 0,5 micron to 100 micron. The Fly Ash is spherical in shape and the size distribution makes it an acceptable mineral filler in various engineering applications. The Fly Ash varies in color and this is contributed by chemical and mineral constituents. Fly Ash has high amounts of silicone dioxide and calcium oxide which creates a by-product which is very cementitious, and thus Fly Ash has a pozzolanic property. Eskom is planning to expand its coal powered generated capacities, thus the quantity of Fly Ash dumps will increase. 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. By-products throughout the world are often used to enhance properties of traditional road pavement construction materials, and the combination generates a material with well-controlled and superior properties. It is in the context of this study to produce results to further motivate the use of by-products, such as Fly Ash, in road construction. Detailed design and investigations were completed to evaluate the use of Fly Ash as a suitable replacement for cement or partial replacement to reduce landfill sites and in the effect become an environmental option for road construction is South Africa. To understand Fly Ash, physical, chemical and mineralogical characteristics need to be understood before any further testing could be completed.

Fly Ash is classified according to the sum of total aggregate Alumina, Silica and Ferric Oxide. Two classes are identified: Class C and Class F. If the sum is between 50% and 70%, it is a Class C. If the sum is greater than 70%, it's a Class F. Three (3) Fly Ashes have been sourced for this study namely: DURAPOZZ, POZZFILL and Dump Ash. Two Fly Ashes are air classified Fly Ash and the other was sampled directly from the dump sites. All three Fly Ashes have been classified as Class F, as the sum was greater than 70% with DURAPOZZ 91.88%, POZZFILL 88.5% and Kendal Dump Ash 86.77%. Although the Fly Ashes have been classified as Class F, it is still known as a pozzolanic material, therefore the Fly Ash requires a reaction agent in the form of cement or lime to kick start the pozzolanic reaction. XRF tests were completed on the Fly Ashes to evaluate the elements that make up the Fly Ash particles. The study showed that all three Fly Ashes have a high Silica (SiO_2) content, which forms a cementitous compound reaction, but it was found that the ratio between Lime (CaO/SiO_2) is low therefore showing that a cementing agent will be required. The Loss of Ignition (LOI) was also taken into consideration as it is a critical characteristic of Fly Ash. LOI is

measurement of unburnt coal and high amounts could lead to entrainment problems and affect the durability. The test results revealed that the Fly Ashes conformed to the specification and are below the required 5% allowable. The gradation of the Fly Ashes also showed that DURAPOZZ and POZZFILL will react slowly over time. The Kendal Dump Ash will also react slowly over time but also has material that will become inert, which will add to the property of the material and not to the reaction process. The Fly Ashes have shown in this study that it has enough pozzolanic material available to continue with slow reactions which will occur continuously over time.

Environment is a concern when using Fly Ash in construction projects. Fly Ash is a residue generated by coal combustion, but due to potentially toxic elements found in the Fly Ash, it is considered harmful to the environment. To evaluate the potential harmful effects to the environment, the stabilised Fly Ash samples were subjected to leach tests. The chemical and physical properties of Fly Ash enabled it to be utilised to limit the environmental damage. The study revealed that using cement with Fly Ash achieves alkalinity and reduces the harmful leach elements to the environment. The pH values of the stabilised material varied between 10.29 and 10.82, which show that the material is alkaline. This will ensure continuous reactions, and the leach ability of certain elements will be decreased over a period. The pH values are also not high and this will reduce the leaching of arsenic over time. The Fly Ash leach samples were compared to the maximum allowed elements found in drinking water. The Leach results have shown that the material was "entombed" and the possibility of leachant releasing agents of a dangerous nature are minimal.

Cementing agent chosen for this study were two types of cement, developed by two different suppliers specially developed for stabilisation purposes namely; LAFARGE CEM II 32,5 VA(S-V) and AFRISAM CEM II 32,5 B-M(S-V). The cement is more effective for soils of low clay content, to gain early strengths. Fly Ash has a low early strength gain but continues to gain strength slowly over a longer period. General guidelines in South Africa are utilised to obtain desired properties of soil for design purposes. Classified G5 material was used in this study, due to that the material has been found to be coarse, and this will also be able to carry much heavier loads without deformation. The material was subjected to further testing for indication of any rapid weathering materials after exposure to the atmosphere. The G5 was subjected to Ethylene Glycol and Durability Mill Index tests. The material was found to be durable and suitable for the purpose of design and lifespan. Basic design steps were used as normal, followed during a construction program. Rapid methods of testing was completed, which are currently used in a construction project, and the reactions of the Fly Ash can be evaluated to see if it conforms to the current standards. Reference samples were completed by stabilizing the G5 with 1% cement respectively. All stabilised Fly Ash tests were compared to the standards and to the reference samples. This was to evaluate the impact Fly Ash has during a stabilisation project. Initial Consumption of Cement (ICC) was completed, but due to the poor quality of Fly Ash, it was expected that no constant results will be shown. Material stabilised with cement alone showed that the material will stabilise between 4% cement and 5% cement for both types of cement. This indicated that substantial amount of Fly Ash will be required to meet the demand of the material and to ensure proper cementation and durability. The G5 material was thus stabilised with the Fly Ash mixtures containing 18%, 20%, 22% and 24% respectively. Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) tests were completed on the mixtures and compared to the reference samples and to the required standard. All the results have shown an improvement to the UCS which varied from 1759kPa to 3830kPa when compared to the reference samples. The same can be seen for the ITS, even though the Dump Ash mixtures decreased the ITS values. The evaluation of the UCS and ITS results showed that lower Fly Ash percentages could be used for projects. The total amount of samples was thus reduced to, namely; 1% LAFARGE mixed with 16% Dump Ash, 1% LAFARGE mixed with 16% POZZFILL, 1% LAFARGE mixed with 16% DURAPOZZ, 1% AFRISAM mixed with 18% Dump Ash, 1% AFRISAM mixed with 18% POZZFILL, 1% AFRISAM mixed with 18% DURAPOZZ.

Further additional testing is required to ensure that the stabilised material will be adequate for the design life of the pavement. The main aim of durability testing is to ensure that the material durability will last for the duration of its design life, and to indicate whether the material will withstand natural forces if the top layers have failed, thus leaving stabilised layers exposed to the natural elements. The additional testing is evaluated by 3 tests, namely; Wet Dry Durability (WDD), CSIR Erosion Test, and Triaxial Tests. WDD is a specified test and can be found in most contract documents while the CSIR Erosion test is not. The referenced samples conformed to C4 classification with % loss of 20.1% and 23.7% respectively. Out of the 6 samples that were mixed with Fly Ash, 2 conformed to C4, 3 conformed to C3 and 1 totally failed the WDD test. The results indicate that the mixtures will have sufficient durability. The CSIR Erosion Test is not seen as a proper durability test for gravel road testing and is mostly used by researches and designers on asphalt surfacing, seal, and concrete overlays. The results do confirm this, as the results do not conform to the required specification. Triaxial tests were completed to calculate the safety factor of the material to deformation. The safety factor concept developed form the Mohr-Coulomb theory represents the ration of shear strength divided by the applied stress causing shear. Safety factor of above 1 was required to ensure deformation of a gradual nature and not a rapid failure in a short time. These were achieved well above the norm when compared to reference samples. The poor quality of Fly Ash has shown that no uniformity of the results could be seen nor can it be predicted, thus all testing needs to be completed thoroughly including durability testing. Most of the results conform to the standard testing available for durability and normal design process testing. The standards followed in this study showed the effectiveness of the Fly Ash mixtures when used as a stabilisation option.

Keywords: Fly Ash, Chemical, Environment, Stabilisation, Durability, Design, Standards

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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

CBR - California Bearing Ratio

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

Ga - Gallium

Ge - Germanium

H_2O - Water

Hf - Hafnium

Hg - Mercury

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

OMC - Optimum Moisture Content

OPC - Ordinary Portland Cement

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

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

UCS - Unconfined Compressive Strength

USCS - Unified Soil Classification System

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, Aims and Objectives, Scope and Research Approach and Outline of Subsequent Chapters.

1.2 Background

Fly Ash is a thermally altered mineral matter, which is a waste by-product generated from the combustion of coal for power generating. Coal is pulverized and blown with air into a boiler's combustion chamber. There are four basic types of coal-fired boilers: pulverized coal (PC), stoker-fired, cyclone, and fluidized-bed combustion (FBC) boilers. The PC is the most commonly used in South Africa. The combustion methods, coal source and particle shape, impacts the physical and chemical characteristics of Fly Ash (Fly Ash Facts for Highway Engineers (FA FACTS), 2003). Boiler tubes extract heat from the boiler, cool the flue gas and cause the mineral matter to harden and form ash. Fly Ash is the lighter, finer ash particles that remain suspended in the flue gas. Particle emission control devices, such as electrostatic precipitators or filter bags, remove the Fly Ash. It is also typically finer than PC and lime (Boral, 2013). Fly Ash consists of silt-sized particles, which are spherical in shape, and ranges in size from 0, 5 micron to 100 micron. The unique spherical shape and particle size distribution of Fly Ash makes it a good mineral filler in various engineering applications (FA FACTS, 2003). Fly Ash is commonly used as a pozzolan in ordinary Portland Cement applications. Pozzolans are siliceous and aluminous materials, which are of a finely divided form and, in the presence of water, react with calcium hydroxide at ordinary temperatures to produce cementitious compounds (Mehta, 1998).

Fly Ash colour vary from tan to dark grey, which is dependent on chemical and mineral constituents (FA FACTS,2003). Tan to light colours are associated with high lime contents while brownish colours are associated with iron contents. Dark grey to black is attributed to a high unburned carbon content. (Mehta, 1998).

Fly Ash is defined by South African Bureau of Standards (SABS) as a powdery residue obtained by the separation of the solids from flue gases during combustion of coal, 80% of the solid residue released from combustion of coal is released as Fly Ash.

Fly Ash has high amounts of silicon dioxide and calcium oxide, and as a result of these, Fly Ash is a very cementitious by-product of the coal burning process. The main component of Fly Ash is silicon dioxide, which is present in two forms:

a. Amorphous – rounded and smooth

b. Crystalline – sharp, pointed and hazardous aluminium oxide and iron oxide (Mehta, 1998; Ismail *et al.*, 2007; FA FACTS, 2003)

Fly Ash is heterogeneous, consisting of a mixture of glassy particles with various identifiable crystalline phases such as quartz, mullite and various iron oxides (Ojo, 2010). The pozzolanic property is directly proportional to the amount of free lime, and indirectly proportional to amount of unburnt Carbon. Fly Ash generated from power stations contains some soluble oxides such as CaO and MgO. The chemical composition of Fly Ash is typically made of major elements such as Si, Ca, Al, Mg, Fe, Na and K (Oppenshaw, 1992). Various trace elements also contained in Fly Ash are Co, Cd, As, Se, Zn, Mo, Mn, Pb, B, Cu and Ni (Ojo, 2010). The chemical properties and composition provide the greatest variability to Fly Ash. Studies have shown that Fly Ash samples from various areas do vary in pH levels (Oppenshaw, 1992, Gitari *et al.*, 2009).

After the thermal process, Fly Ash is placed in landfill sites. The management and disposal of the Fly Ash produced by coal-fired power plants has caused a major problem in many parts of the world, including South Africa. Disposal of Fly Ash constitutes a problem not only because of large volumes generated but also of the possibility of environmental impacts (National Inventory, 2001). The environmental impact studies for reutilisation of Fly Ash in construction have produced positive results, but these studies is seen as primarily trail studies until environmental impacts have been resolved (Oppenshaw, 1992). Fly Ash contains environmental toxins which vary according to the kind of coal burnt to form it. Fly Ash in its natural state is regarded as a hazardous material, but mixed with Bottom Ash falls in the category of non-hazardous material (Oppenshaw, 1992). A research project on trace elements mobility in soil stabilisation using coal Fly Ash have shown, if Fly Ash is used properly, it is not hazardous to the environment (Hassett *et al.*, 2001). Utilisation of Fly Ash will not only minimize the disposal problem but will also help in utilizing precious land in a better way. In stabilisation work, Fly Ash binds to the soil due to chemical reactions taking place hence the chances of pollution or contamination of water to the use of Fly Ash in roadworks are negligible (Hassett *et al.*, 2001).

Large quantities of Fly Ash is generated on a daily basis in South Africa, particularly in the Mpumalanga and Free State regions (Hall, 2011). The needs for safe disposal have been adopted not only in South Africa, but worldwide. The South African power stations employ two techniques for disposal of Fly Ash and these are the dry and dense slurry disposal techniques.

The dense slurry technique involves the Ash mixed with waste water to form slurries, which is then pumped to Ash dams. The Ash settles in the dam while water is drained to retaining dams via penstock pipes and membrane drains. The dry technique is when Fly Ash from precipitators is moistened with small amounts of brine to suppress dust from the Ash particles, and is then taken away to Ash dumps via conveyor belt for disposal. The Ash dumps are kept wet with water from treatment plants for dust suppression and disposing of brines (Gitari *et al.*, 2009). The dry disposal Ash system is typically used by South African power stations, which currently produces about 1.765MT of Fly Ash per annum (Gitari *et al.*, 2009). The dry disposal system is known to undergo dissolution on contact with an aqueous solution. Species released from this interaction may lead to cleaner effluents on significant pollutants over time. The major environmental concern is the release of contaminants to ground and surface water after disposal (Gitari *et al.*, 2009).

Fly Ash is classified, worldwide, into two classes namely: Class C and Class F. Class C is a result of burning of younger lignite or subbituminous coal. It is pozzolanic in nature but also contains self-cementing properties. Mixed with water, the Ash will harden and gain strength over time, and contains more than 20% lime. Class C primarily consists of calcium alumino-sulphate glass, quartz, tracalcium aluminate and free lime and is also referred to as high calcium Fly Ash (FA FACTS, 2003). Class F is a result of burning of old harder anthracite and bituminous coal. The Ash is pozzolanic in nature and contains less than 20% lime. It therefore needs a cementing agent such as ordinary Portland Cement (OPC), quicklime or hydrated lime with presence of water to react and produce cementitious compounds. Class F Fly Ash primarily consists of an alumino-silicate glass, quartz, mullite and magnetite, referred to as low calcium Fly Ash (FA FACTS, 2003).

Fly Ash is classified according to world standard test method ASTM 618 (ASTM618, 2011). In South Africa, Fly Ash is classified according to SANS 1491-2 (SANS 1491-2, 2005). The American Society for Testing and Materials (ASTM) is an accepted standard used worldwide. The South Africa National Standard (SANS) is a document that has adapted the ASTM to conform to local conditions although many of the SANS documents do reference back to the ASTM.

The public has not yet been convinced that Fly Ash is environmentally safe. Organizations such as Electric Power Research Institute and American Coal Ash Association have encouraged the use of Fly Ash in construction, mainly with regards to strength and cost.(Oppenshaw, 1992)

Usmen *et al.*, (1998) investigated the effects of stabilisation with Fly Ash by testing leachant of several Fly Ash specimens stabilised with Lime, Cement and Betonite. The results indicated Cadimium leaching can be reduced by methods of stabilisation. Stabilisation limits surface water and exposure of Fly Ash to any precipitation, run-off, etc. Once Fly Ash is entombed, there is less chance of leaching, which have been proven in most construction uses of Fly Ash.

Overall studies have confirmed that Fly Ash, if used properly, is not hazardous to the environment when used for soil stabilisation (Hassett *et al.*, 2001). Soil stabilisation causes chemical reactions which binds Fly Ash particles, therefore chances of pollution, due to use of Fly Ash in road works, are negligible.

1.3 Problem Statement

Several million tons of Fly Ash is being produced every day, globally, and the disposal of the Fly Ash represents a serious obstacle to the electricity industries. Accumulations of these Fly Ash landfill dump sites have reached alarmingly high levels, requiring immediate attention for its disposal. The global demand for coal has grown steadily over 30 years, but increased rapidly over recent years due to the influences of India and China. Coal growth has been the fastest fuel source than any other fuel in the last 10 years (Hall, 2011). Coal use for electricity is 41% (Hall, 2011) of the global demand, and with global urban populations expecting to increase the demand for energy will increase.

The Coal industry provides 80% of South Africa's total primary energy requirements and is core to economic development with 92.8% of coal use providing electricity. The production of coal is to grow significantly in the next decade (Hall, 2011). Table 1.1 currently shows the reserves of coal found in South Africa in a study done in 2009. 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.

According to research firm Frost & Sullivan, state utility Eskom's power generation capacity expansion plans will increase coal consumption needs by an additional 50 million tons per annum. Further, Sasol's synthetic fuels manufacturing capacity will also see its coal consumption rising by an additional 25 million tons per annum, essentially increasing domestic demand for coal by 75 million tons per annum over the next decade. Further investment in the coal sector will therefore be needed (Mining weekly, 2010).

Changes in legislation and the mining industry realization of this valuable source have changed how the discarded source is now being considered. The discarded sources are now compacted and rehabilitated to preserve the source, which includes the reduction of burning and smouldering dumps. (National Inventory, 2001).

In the past, Fly Ash produced from coal combustion was simply entrained in flue gasses and dispersed into the atmosphere. By the creation of environmental and health legislations, Fly Ash emissions have dropped to less than 1% of ash produced but has increased the area of landfill sites. (National Inventory, 2001)

Solutions to reduce landfill sites from waste by-products is becoming critical. The national government has also launched various programmes to study possible uses of the waste by-products. One of the main concerns is the Fly Ash landfill sites, which grows tremendously every year due to the fact that it is produced from one of the main sources found in South Africa, Coal. Fly Ash 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 utilizing the by-product for its own use in its own unique environment.

Table 1.1: South African Coal reserves in 2009 (Hall, 2011)

Coalfield	Recoverable (Mt)	%
Waterberg	6 744	20.4
Witbank	8 509	25.7
Highveld	9 475	28.6
Free State	-	
Ermelo	4 388	13.2
V-Sasolburg	1 708	5.2
Springbok Flats	-	
South Rand	716	2.2
Utrecht	541	1.6
Klip River	529	1.6
Vryheid	100	0.3
Kangwane	146	0.4
Nongoma	6	0.0
Soutpansberg	257	0.8
GRAND TOTAL	**33 119**	**100**

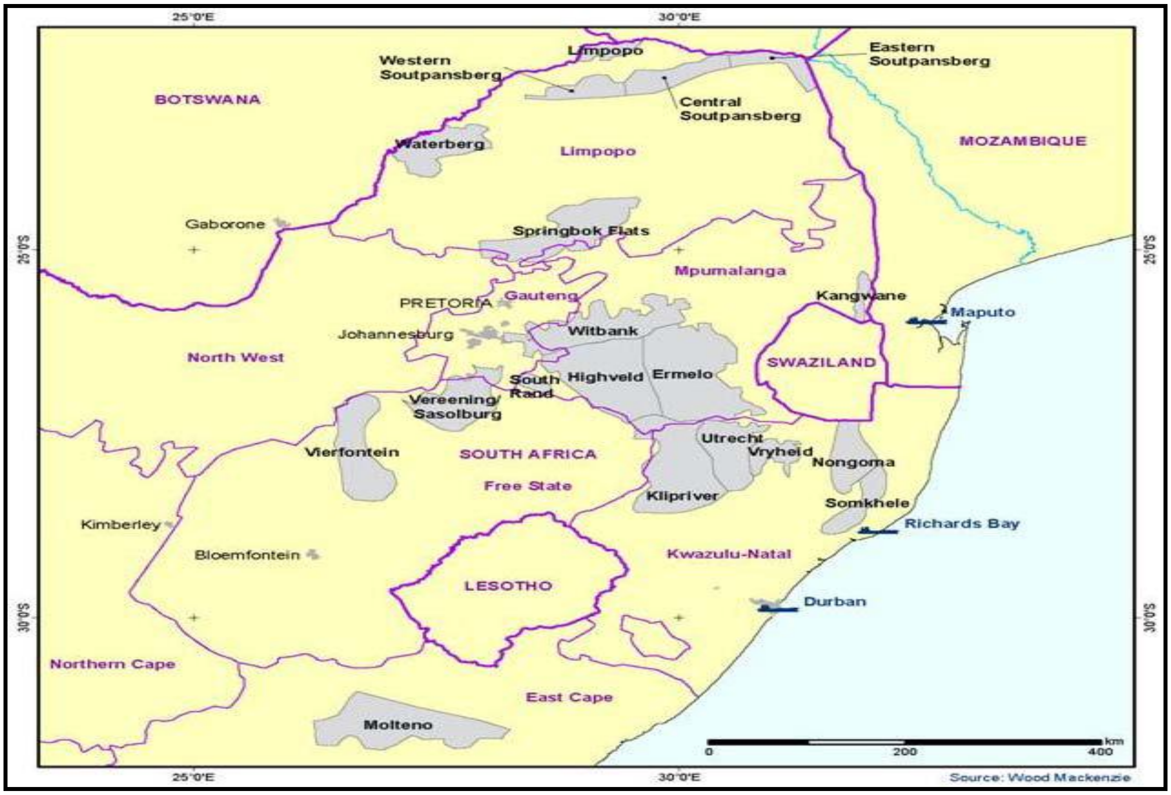


Figure 1: Coal Mines in South Africa (Hall, 2011)

1.4 Study Area

Two coal-fired stations were chosen and will be used in this study: Lethabo and Kendal. Lethabo is one of the largest coal-fired stations in South Africa. It is very unique as it burns low-grade coal with a calorific value of 16MJ/Kg and has an ash content of 42%. Lethabo has the largest electrostatic precipitators of their kind in the world, which removes 99.8% of Fly Ash. The Fly Ash removed is back-stacked into the mined area or stacked on dumps. (COP17 fact sheet, 2012).Kendal mine is situated near Witbank in the Mpumalanga region. Kendal is currently the largest coal-fired power station in the world and holds several Eskom performance records. Lethabo is situated in the Free State region. The choice was to choose two mines in the provinces where most of the coal is being mined. The Regions for this choice was Free State where Lethabo is based, and the Mpumalanga region where Kendal is based. The Fly Ash will be analysed accordingly to produce conclusions that supply of the Fly Ash can be from the Free State region and Mpumalanga region thus transport costs can be reduced depending where the construction projects are in the process. Figure 2 is a photo of the Ash Dumps typically found at Kendal power station.


Figure 2 Kendal Dump Ash (van der Walt, 2011)

1.5 Purpose of Study

Fly Ash is a lightweight material and causes lesser settlements. It is especially attractive for construction over weak subgrade such as alluvial clay or silt where excessive weight can cause failure. In road construction, Fly Ash is readily available and with negotiations, free of cost. The only actual cost will be transportation, laying and rolling.

The use of Fly Ash will be justified by actual savings achieved when considering environmental degradation costs due to the use of precious topsoil, aggregates from borrow areas, quarry sources and loss of fertile agricultural land due to ash deposits. Disposal of Fly Ash is of major environmental concern due to the possible release of contaminants to ground and surface water after disposal. When used in stabilisation work, chemical reactions take place which binds Fly Ash particles therefore the chances of pollution due to use of Fly Ash in road works is negligible (Hassett *et al.*, 2001).

The study will show various potential outputs where Fly Ash can be utilised to solve subgrade, subbase and base problems in areas where feasible material is not readily available and with increase in demand of cement/lime, that it will be a feasible alternative option.

The current use of reliable sources for treatment of soils or recycled materials in road construction is currently being depleted. 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 be dependent on virgin material only. The waste material and by-product can be allocated to new landfill areas, i.e. old quarries which then can be delivered to various road construction sites. This will develop and open up new economic opportunities, new job markets and revenue streams while addressing the problems relating to the construction industry and waste management (Sahu *et al.*, 2002).

The main focus of the study will be to show that Fly Ash can be used as a cement replacement in stabilisation of road pavement materials. The purpose is to provide conclusive results by using Fly Ash in road pavement layers in that little or no cement/lime is required as an additive. It will also provide an advantage in that Fly Ash, which is normally disposed of at a considerable cost, can now have an economic value.

This study will also concentrate on proper design and testing, as it is an important component of any stabilisation project. This study will establish design criteria and determine the proper chemical additive and admixture rate to be used to reach the desired engineering properties.

1.6 Research aims

The research aims are to develop a cheaper option by using Fly Ash as a higher percentage stabilisation agent with a partial mixture of cement/lime to reduce cost of cement/lime and reduce the landfill sites of Fly Ash. The use of the Fly Ash as a soil stabiliser will need to conform to specifications set out in specific standards that will be used in this study. The aim will be to induce that the Fly Ash is suitable as a soil stabiliser when results are evaluated from basic design steps that will be followed. The basic steps in the design is the laboratory design procedures for evaluation of the material for strength, workability and durability as specified in Committee of Land Transport Officials (COLTO) (COLTO, 1998).

1.7 Specific objectives

The use of Coal Fly Ash will cause a reduction in environmental pollution and construction methods, other than the use of cement or lime in current construction processes. With major landfill sites of Fly Ash readily available, it can be utilised immediately on construction sites therefore increasing the 6% reuse. Cement/Lime production demand have increased tremendously throughout South Africa and due to the increase in demand, the price has risen and the availability of the required source has caused various delays in major projects.

The specific objectives of the study are:

1. To determine if Fly Ash can be used as a partial replacement for cement/Lime and what will the cost difference be
2. To study the properties and effectiveness of the product in various test samples
3. To determine Ash characterisation and the effects of the chemical reactions when Fly Ash is used as stabiliser
4. To provide documentation on the effectiveness of stabilizing with coal Fly Ash

1.8 Methodology

1.8.1 Materials

Materials for testing will be sampled at the company Ash Resources, which will indicate the sources from where the samples were derived from. Ash Resources will be used for the establishment of the Chemical and Mechanical composition of the material to verify the different classes of the Fly Ash sampled. Samples will be taken from stockpiles that are older than 6 months. The Fly Ash can thus be evaluated to identify if it is feasible to use the Fly Ash from stockpiles with various time frames. The study will also compile a comparison of various Fly Ash products currently available on the market in South Africa. The current products chosen for the study is namely: Dura-pozz, Pozz-fill and Dump Ash, sampled directly from dumpsites. Dura-pozz is a classified Fly Ash according to SANS 1491- Part 2 (SANS 1491, 2011). Pozz-fill is a non-classified Fly Ash and is mostly used as a reactive cementitous filler. Dump Ash is not classified, however, it can be noted, that Dump Ash is from Kendal Dump Site, which is used to produce the Pozz-fill product and, that the characteristics would be similar, if not the same, except for the grading aspects of the samples. The choice of these Fly Ashes is due to that Fly Ash is mostly used for cement making and is readily available from the supplier, which also makes it a great advantage for any contractor to gain easy access to the product.

1.8.2 Testing Methods

The following test methods are conducted according to Technical Methods for Highways (TMH) (TMH1, 1986) during this study to compile various results and conclusions:

Method A1 – Wet preparation and sieve analysis of gravel, sand and soil samples
Method A2 – Determination of the liquid limit of soils by means of the flow curve method

Method A3 – Determination of the plastic limit and plasticity index of soils

Method A5 – Determination of the percentage of material passing a 0.075mm sieve in a soil sample

Method A7 – Determination of the maximum dry density and optimum moisture content of gravel, soil and sand

Method A9 – Determination of the California Bearing Ratio of untreated soils and gravels

Method A14 – Determination of the unconfined strength of stabilised soils, gravels and sand

Method A16T – Tentative method for determination of the indirect tensile strength of stabilised materials

Method A19 – The wet-dry durability test for cement treated materials

1.8.3 Mechanical Properties of Soil Mixtures

Apart from the standard test methods that were followed as mentioned in 1.8.2 above, below are some extra analyses that was carried out during the study.

1.8.4 Triaxal Tests

The conventional triaxial test is a common laboratory testing method widely used for obtaining shear strength parameters for a variety of soil types under drained or undrained condition.

Triaxial test data, in general, include evolution of axial and volumetric strain, deviatoric and isotropic stress, and pore pressure evolution. From the triaxial test results, it is possible to deduce the shear strength parameters, namely friction angle, cohesion, dilatancy angle and the other dependent parameters (Geotechdata, 2010).

1.8.5 Environmental Effects of Ash Mixtures

Fly Ash is recognized as an environmental pollutant. Fly Ash is alkaline and also consists of heavy metals that are detrimental to human health and the environments. 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). Coal Combustion Products (CCP) are used extensively in agricultural and construction industries. In agricultural, CCP is mostly used for the amendment of soils to improve the physical and chemical properties. CCP is a source of liming material to ameliorate soil acidity and as a nutrient source to supply calcium and sulphur. In construction, CCP are used for mostly concrete, and subsidiaries are for construction of fill and road stabilisation techniques. Another application of CCP is used for the remediation of contaminated environments, including acid mine drainage, mitigating phosphorus leaching in farm lands and immobilization of toxic metals in mine sites and agricultural soils (Seshadri *et al.*, 2010). Coal combustion residues can have a significant potential to contaminate soils and water. The rate of transport and chemistry leachant depend upon interrelated mineralogical, physical and chemical conditions, particularly on the initial quality of the combustion residues, climatic conditions, methods of deposit and containment, ash and soil permeabilities, and site geology and hydrogeology (Solc *et al.*, 1995).

1.8.6 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. The process itself is universal, as any material exposed to contact with water will leach components from its surface or its interior depending on the porosity of the material considered. 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 (Hassett *et al.*, 2001).

There are over 100 known leach testing methods. Therefore, no actual proper method has been identified to estimate the actual environmental consequences of the use or disposal coal utilisation by-products (Kim, 2006). Methods are basically classified accordingly to the following:

1. Batch Leaching, in which 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). These particles are a function of particle size of the feed coal, type of combustion and the particulate control device. The spherical shape of the Fly Ash particles results in a minimum surface area which reduces the potential number of leaching sites (Kim, 2006).

This study is about stabilisation of road pavements with Fly Ash. It is also the reason why the column leach test will be the preferred leach test to evaluate the leachants of stabilised material. The column leach test is designed to simulate the flow of percolating ground water through a porous bed of granular material.

1.8.7 Soil-Fly Ash Mixtures

Fly Ash will be mixed with the soil as per standard test methods followed for stabilisation mix designs in a civil engineering soils laboratory. Suitable COLTO classified G5 material will be used during this study. The G5 classified material is the material normally specified for the construction of stabilised sub bases throughout South Africa. The only Fly Ash available in South Africa is the Class F Fly Ash. A cementing agent will thus be required during the stabilisation process. Two cementing agents will be used for the stabilisation mixes namely, CEMII 32,5N and Lime. The G5 material chosen was crushed dolerite and the tests will be evaluated according to the effectiveness of the Soil-Fly Ash mixtures to stabilisation of soils with low active clay contents and the type of early age strengths.

1.9 Outline of subsequent chapters

Apart from chapter one, which contains the introduction to this study, the thesis consists of 5 chapters which is listed below.

Chapter 2 Literature Review

This chapter deals with literature review on studies completed worldwide on Fly Ash stabilisation as an alternative method to cement or lime stabilisation methods. It also deals with studies on further applications of Fly Ash in the construction industry.

Chapter 3 Environmental effects on Fly Ash

This chapter deals with the impacts Fly Ash stabilisation has on the environment. The chapter focuses on the leaching elements of the Fly Ash and handling methods of Fly Ash for safety purposes.

Chapter 4 Mechanical and Chemical properties investigation

This chapter deals with the materials used for this study. Descriptive details are given for each material with test completed to show the conformity to South African project specifications as well as to the South Africa National Standards (SANS).

Chapter 5 Stabilisation Methodology

This chapter deals with the evaluation of the test results of the classified material stabilised with Fly Ash using a small percentage of cement by following basic design steps according to set specifications.

Chapter 6 Conclusions, recommendations and future work

This is to conclude the thesis and make viable recommendations can be made for the road construction industry using Fly Ash.

Chapter 2 Literature Review

2.1 Introduction

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

2.2 Fly Ash

Fly Ash is a by-product as a result of burning coal at thermal power stations, moreover known as residues of fine particles that rise with flue gases. Fly Ash solidifies while suspended in exhaust gases and is collected by electrostatic precipitators or filter bags. They are spherical in shape and range in size from 0,5 micron to 100 micron (Rotaru *et al.*, 2010).

Fly Ash, as defined by the South African Bureau of Standards (SABS) (SABS, 2002), is a powdery residue obtained by the separation of the solids from the flue gases during combustion of pulverized coal. 80% of the solid residue released from combustion of coal is released as Fly Ash.

Several million tons of Fly Ash is produced every day, globally, and disposal of Fly Ash represents a serious obstacle to electricity industries. South Africa currently produces millions of tons of Fly Ash per annum of which only six percent (National Waste Management, 2010), is being utilised for different purposes.

The South African government is at a stage where it is strategically finding ways to reduce Fly Ash through treatment, reuse and beneficiation of Fly Ash (National Waste Management, 2010).

A wide range of potential uses have been identified, which includes:

1. Treatment of acid mine drainage
2. Commercial exploitation which is:
    a. Brick-making
    b. Cement production

During a survey that was completed in 2001 by Energy Department of Minerals and Energy (National Inventory Discard and Duff Coal, 2001), it was found that coal remains South Africa's prime energy resource, and 84.7 million tons was used by Eskom and 48.8 million tons used by SASOL per annum respectively. The Fly Ash is placed in dumps and the majority of these dumps are situated in the province of Mpumalanga with the average age of these dumps are between 15 years and 50 years (National Inventory Discard and Duff Coal, 2001).

Since Eskom is planning on expanding its coal powered generating capacity, quantities of Fly Ash waste will increase. Changes in legislation and mining industry and the realization of this valuable source have changed how this discarded source is considered. The discarded sources are now compacted and rehabilitated, to preserve the source, which includes the reduction and smouldering dumps (National Inventory, 2001).

Replacement of natural soils or minimization 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 of these inferior materials make it an attractive alternative if adequate performance can be achieved. By-products are often used to enhance the properties of traditional road pavement construction materials and the combination generates a material with well-controlled and superior properties (Tuncer, 2006).

2.3 Fly Ash Characteristics

Two types of Fly Ash; classified into (ASTM 618, 1994):

1. Class C
2. Class F

Classes F and C are classified by American Society for Testing and Materials (ASTM) according to their aggregate Alumina, Silica and Ferric Oxide contents. Distinction is made on the sum of total aggregate Alumina, Silica and Ferric Oxide (SiO_2 + Al_2O_3 + Fe_2O_3). If the sum is greater than 70%, then it is classified as Class F and if the sum is between 50% and 70%, it is classified as Class C (ASTM C618, 1994). The basic classification can be seen in table 2.1.

Class C is a result of burning younger lignite or subbituminous coal; it is pozzolanic in nature but also has some self-cementing properties. Mixed with water, the Ash will harden and gain strength over time and contain more than 20% lime (Boral, 2013).

Class F is a result of burning older harder anthracite and bituminous coal. The ash is pozzolanic in nature and contains less than 20% lime therefore, needs a cementing agent such as ordinary Portland Cement (OPC), quick lime or hydrated lime and the presence of water to react and produce cementitous compounds (Boral, 2013).

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

2.4 Physical Characteristics of Fly Ash

Fly Ash consists of very fine particles which range in size from 0.01µm to 100µm and is spherical in shape. Eighty to ninety nine percent of the Fly Ash samples by weight passes the No. 200µm sieve and this is then classified as “fine grained” under the Unified Soil Classification System (USCS) (ASTM D2487, 2006) if more than half of a sample weight passes the No. 200µm sieve (Oppenshaw, 1992; Conn *et al.*, 1999; Mehta, 1998).

Fly Ash is glassy and transparent due to the melting of silicate materials during the combustion process (Adriano *et al*; 1980, Young, 1993). During combustion, at a very high temperature, minerals become fluid after which the minerals are cooled rapidly at the post-combustion zone. The rapid cooling in the post-combustion zone results in the formation of spherical and amorphous particles of Fly Ash (Rotaru *et al.*, 2010). The fineness is dependent on the combustion temperature and the size of the pulverized coal introduced into the burners while the spherical shape of Fly Ash is the result of cooling and solidifying of molten droplets of inorganic coal residues after combustion (Ojo, 2010). It was found, that in some cases, Fly Ash is a smooth, hydrophilic surface and is extremely porous (Bosch, 1990; Campbell, 1999; Iyer, 2002).

The particle size distribution and specific surface area provide quantitative information that is utilised in evaluating the interactions between Fly Ash and aqueous solution (Ojo, 2010). The particle size and surface area is an important characteristic in determining the reactivity of Fly Ash (Mehta, 1998). It was also concluded that as reactions progress, changes in surface are important in long term leaching processes (Ojo, 2010).

Fly Ash is generally highly heterogeneous and consists of a mixture of glassy particles with various crystalline phases and a vitreous phase (Rotaru *et al.*, 2010). The vitreous phase is an important characteristic as Fly Ash that has large quantities of the vitreous phase have superior cementing properties.

Fly Ash colour may vary between tan and dark grey, which is dependent on the chemical and mineral constituents. Light to tan colours are associated with high lime content while dark grey to black is attributed to unburned carbon content (FA FACTS, 2003; Mehta, 1998; Ayanda *et al.*, 2012).

Particle size of Fly Ash has a large surface area in comparison to mass. The surface area increases as particle size decreases. This is due to smaller particles containing large surface concentrations of potentially toxic trace elements (Oppenshaw, 1992).

Particle size is most the important characterisation, especially in cement and concrete industry in which particle size determines the ability of Fly Ash to fill voids and workability of a resultant mix (Cooperative Research Centre for Coal in Sustainable Development (CCSD), 2007). Fineness is an important property of Fly Ash contributing to pozzolanic reactivity (FA FACTS, 2003; Mehta, 1998; Rotaru *et al.*, 2010).

The morphology of Fly Ash is defined as the form on structure of the particle (Oppenshaw, 1992). It has become clear that knowing the morphology of Fly Ash can help to understand the physical properties of Fly Ash and to understand the leaching behaviour of the Fly Ash.

Eleven morphological classes were identified and were based on opacity, shape and types of inclusions (Oppenshaw, 1992). The classes are as follows:

A) Amorphous, nonopaque
B) Amorphous, opaque
C) Amorphous, mixed nonopaque and opaque
D) Rounded, vesicular, nonopaque
E) Rounded, vesicular, mixed nonopaque and opaque
F) Angular, lacy, opaque
G) Cenosphere (hallow sphere), nonopaque
H) Plerosphere (sphere packed with other spheres), nonopaque
I) Solid sphere, nanopaque

J) Sphere, opaque

K) Sphere with either surface or internal crystals, nonopaque

Fischer concluded that Fly Ash has a very high percentage of spherical nonopaque particles (Class G & I). Class G dominates for particle sizes between 20µm to 74µm in diameter while Class I particles have less than 10µm in diameter (Fischer *et al*, 1978). Fischer *et al*, (1978) also indicated that the particle composition contributes to the level of opaqueness while combustion exposure time and temperature are responsible for the different shape characteristics (Fischer *et al*, 1978).

2.5 Chemical Composition of Fly Ash

Chemical Composition of Fly Ash is highly variable which is directly related to the source of coal; in other words, burning process or pre-treatment. It is recommended that individual characterisation is to be made for each source to be used in a project (Oppenshaw, 1992).

Major elements, in order of decreasing abundance, is as follows: Silicon (Si), Aluminium (Al), Iron (Fe), Calcium (Ca), Carbon (C), Magnesium (Mg), Potassium (K), Sodium (Na), Sulfur (S), Titanium (Ti), Phosphorus (P) and Manganese (Mn). Most of these major elements exist in the core of the Fly Ash, which is relatively stable as they have probably not been volatized in the combustion process (Oppenshaw, 1992; Rotaru *et al.*, 2010; Reynold *et al.*s, 2002). The surface layer becomes enriched when elements volatise during coal combustion and condenses on the fine Fly Ash particles as the temperature of the flue gas cools. This, therefore, contributes to that the smaller particles usually contain large surface concentrations, which are of potentially toxic trace elements.

Apart from Si which appears to decrease with decreasing particle size, major element composition of the fraction Fly Ash is relatively independent of particle size. Studies have been completed on Physical and Chemical characteristics of Fly Ash, which induces that both properties of coal Fly Ash are dependent on 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 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).

Fly Ash is pozzolanic in nature, which means that it has siliceous and aluminous material which in its natural state has a reduced or no capacity to cement. In the presence of water, it reacts with hydroxide to form cementing properties (Conn *et al.*, 1999).

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

Fly Ash components vary considerably but it contains a substantial amount of silicon dioxide and calcium oxide (Rotaru *et al.*, 2010; Amar Ash Tech Enterprises (AATE), 2013). Although Fly Ash varies from sample to sample, some generalisation can be viewed according to size distribution, surface area, morphology, hydraulic conductivity or permeability and density (Oppenshaw, 1992).

2.6 Mineralogical Composition of Fly Ash

The mineralogical composition refers to both amorphous and crystalline phases of Fly Ash, which includes other fractions. Most of the Fly Ash samples evaluated (Ojo, 2010) contains the following major elements: Quartz (SiO_2), Mullite ($Al_6Si_2O_3$), tricalcium aluminate ($Ca_3A_2O_6$), Alite (Ca_2SiO_5), Belite (Ca_2SiO_3), Magnetite (Fe_3O_4), Hematite (Fe_2O_3), Lime (CaO), Anhydrite ($CaSO_4$), Periclase (MgO), Melilite [$Ca_2(MgAl)(AlSi)_2O_7$], Merwite [$Ca_3Mg(SiO_4)_2$], Calcite $CaCO_3$, Pyrite (FeS_2), Thernadite (Na_2SO_4) and small amount of unburned coal. Fly Ash mineralogy is important aspect in analysing Fly Ashes as Fly Ash contains mostly 60% to 90% glass (Mehta, 1998). Calcium content has a great influence on type of glass content and recent studies have confirmed that modern Fly Ashes have glass content between 70% and 80% (Mehta, 1998).

Quartz in the coal is sand and silt which remained in Fly Ash due to it being resistant to thermal transformation during the combustion process.

South Africa produces Fly Ash that contains high quantities of mullite because of low Ca bituminous coal, which is rich in kaolinite utilised during combustion (Ojo, 2010). Moderate to high Ca Fly Ashes contain other calcium bearing minerals, which are reactive in the presence of water (Ayanda *et al.*, 2012).

Class C Fly Ash has a higher calcium content, but alteration of clay content of the coal in presence of calcium results in a suite of silicates, aluminosilicates and oxide phases instead of large amounts of glass. Small amounts of glass is visible that contains a high concentration of alumina which is chemically extremely reactive. This is also the reason why Class C Fly Ash is more reactive and gives higher early strength compared to Class F Fly Ash (Rifa, 2009).

Class F Fly Ash contains abundant of glass that results from melting of clays and subsequent exsolation of millite from the melt. Class F Fly Ash contains low calcium element which contains non-reactive crystalline minerals. 80% of Class F Fly Ash is glass with 20% remaining being non-reactive minerals (Mehta, 1998; Rifa *et al.*, 2009; AATE, 2013). Major elements in Class F Fly Ash are quartz, ferrite phase and mullite, which is an aluminium silicate (Ojo, 2010; AATE, 2013; Rifa *et al.*, 2009).

2.7 Utilisation of Fly Ash

Fly Ash is utilised globally for various purposes. The following are just some of the applications:

- Concrete Production
- Structural Fills/Embankments
- Fly Ash in combination with other recycled/waste materials

2.7.1 Concrete Production

Fly Ash is good quality pozzolan and has its uses in Fly Ash cement, masonry mortar, joint sealers etc. (Tanosaki *et al.*, 2011). Studies by Campbell, (1999); (1999); Reynolds *et al.*, (2002); Surridge *et al.*, (2009), have found that South African Fly Ash is a good additive to Portland Cement, which has a number of positive effects resulting in concrete that includes a decrease in water demand of concrete and decrease in the air entrainment in the concrete.

Concrete with Fly Ash has been proved to have the following advantages:

- Increases resistance to corrosion and ingress of corrosive liquids by reacting with calcium hydroxide in cement to form stable cementitous calcium silicate hydrate gel.
- Higher ultimate strength
- Reduced Bleeding
- Reduced heat of hydration
- Reduced permeability

- Increased resistance to sulphate attack
- Increased resistance to alkali-silica reactivity
- Lowered costs
- Reduced shrinkage
- Increased durability
- Fly Ash enhances properties of concrete as Fly Ash reacts with free lime presented during hydration process

The above mentioned benefits have been demonstrated through extensive research and highway and bridge construction projects. The benefits to the concrete does, however, depend on the type of Fly Ash used, the proportion used, mixing procedures and placement which includes field conditions at the placement time (FA FACTS, 2003; Boral, 2013; AATE, 2013).

2.7.2 Structural Fills/Embankments

Fly Ash in structural fill has the potential of providing a large market for high volume recycling of Fly Ash. In the United States of America (USA), fill projects have been completed successfully and received high praise from the construction and structural aspect (Oppenshaw, 1992).

Fly Ash in structural fills have, as well, potential problems such as wind erosion, surface – water erosion, dissolution in surface run-off and dissolution in rainfall percolating to groundwater. Most of these problems were eliminated by methods of entombment of Fly Ash with less permeable soil. Compaction is achieved by fewer vibratory passes which has a cost saving to the contractor (Oppenshaw, 1992).

Fly/Bottom Ash mixtures compared favourably with conventional sandy soils, but Fly Ash is more compressible than typical compacted soils at the same compaction levels. Moderately high compaction levels exhibited comparable or even higher shear strength than that of compacted sands of similar compaction levels. At 95% relative compaction, the effect of Fly/Bottom Ash mixture ratio on the peak shear strength was found to be relatively minimal. The values of critical state friction angle of the ash mixtures were found to be in the same range observed for typical sands (Kim *et al.*, 2005).

Fly Ash is light weight material, therefore it causes lesser settlements. Fly Ash is especially attractive for embankment construction over weak subgrades. Fly Ash can be compacted over a wide range of moisture contents and results in less variation in density with changes in moisture. Fly Ash ensures sufficient and efficient drainage. It has pozzolanic hardening property, and thus has better California Bearing Ratio (CBR) values as compared to standard soils which provide more efficient design of road pavements (Sahu *et al.*, 2002; Guyer, 2011).

2.7.3 Fly Ash in combination with other recycled/waste materials

The use of Fly Ash mixed recycled/waste materials is to improve mechanical properties of unsuitable subgrades to produce high performance in stabilisation of weak roads. This was achieved by mixing Fly Ash with a combination of carpet fibres or with foundry sand (Sahu *et al.*, 2002). In transportation applications Fly Ash is used to stabilise recycle asphalt pavement material. With combinations, significant higher CBR and Unconfined Compressive Strength (UCS) values were obtained. It was therefore an understanding that combinations are beneficial in terms of pavement capacity and service life (Li *et al.*, 2007). Combinations of Fly Ash with inert materials have reached 50% to 70% of the strength of the corresponding cementing inactive materials (Eskioglou, 2006).

Demonstration projects were completed using High Volume Fly Ash Cement (HVFA) to stabilise road bases. HVFA was made up of 58% Fly Ash and 42% Type 1 Ordinary Portland Cement. Tests completed showed that the bases exceeded the allowable classifications which also proved alternatives to conventional aggregates, which could significantly reduce materials cost in roadway construction (Saylak, 1999).

Combinations enhance the resilient response for soils, but the amount of enhancement depends on the type of soil. Test results have shown that combinations can help in delaying the failure of subgrade in pavement systems (Caughan, 2008).

2.8 Soil Stabilisation

Soil Stabilisation is the permanent physical and chemical alteration of soils to enhance the physical properties. Stabilisation is used to treat a wide range of materials including expansive clays to granular materials (Hasset *et al.*, 2001; Oppenshaw, 1992). Through stabilisation with Fly Ash, a financially viable and durable pavement is created (Eskioglou, 2006).

Soil stabilisation is the process of blending and mixing materials with a soil to improve the properties of the soil. The process may include the blending of soils to achieve the desired gradation or mixing of commercially available additives that may alter the gradation, texture or plasticity or act as a binder for cementation of the soil (Guyer, 2011).

Additive stabilisation is achieved by adding of proper percentages of cement, lime, bitumen, Fly Ash or combination of these to the soil. The selection of type and desired percentage of additive depends largely on properties of the soil and the improved quality desired. To modify the soil properties by means of gradation, workability and plasticity, small amounts of additives is added. The desire to improve strength and durability, large quantities is normally added (Guyer, 2011).

In the USA, a report (Energy and Environmental Research Center (EERC), 2011) was prepared to develop, educate and encourage the use of Fly Ash in roads, parking lots and in other construction. Many Fly Ash samples have exhibited moderate to high concentrations of calcium, thus showing that Fly Ash are cementitious and is suitable for construction applications such as soil stabilisation. Coal combustion products have properties that are beneficial in soil stabilisation applications, such as soil drying agent, amendment to increase strength properties, load bearing capacity of native soils, stabiliser in aggregate road base construction and pavement recycling (EERC, 2011).

Eskioglou showed (Eskioglou, 2006) the possibility of stabilisation on soils such as clay, crushed gravel, natural gravel and sand. Stabilisation was completed with various quantities of Ash so that any alteration of their mechanical properties can be recorded to benefit economy and the protection of the environment. The study reported that Ash with a high CaO content and the percentage passing the 75µm was 92%, contained hydraulic and pozzolanic properties. The soil under study was not fit for construction of embankments nor fit for the construction of road pavement layers but with the stabilisation with Fly Ash, mechanical properties were improved which resulted in reduction in moisture content (MC) and the material maintained stability with increasing MC. The optimum moisture content (OMC) during compaction tests decreased the specific weight due to the Fly Ash lower specific weight. Eskioglou did however comment that although the Fly Ash improved strength of the material after being cured for 90 days, the strength was not satisfactory and needed an addition of cement or lime to be acceptable to the relevant technical properties and classifications. Fly Ash was still proven as a successful operation in stabilisation of clays for road networks of a very low cost (Eskioglou, 2006).

In Botswana, the Kalahari sands were stabilised with Fly Ash as a successful project that met all the required technical standards (Sahu *et al.*, 2002). Considering three quarters of the country is covered by sand of the Kalahari Desert, it provides difficulty in providing adequate, good quality construction material for an adequate road pavement system. The sands have a lower water content and are rich in salts. Sands are often cemented by calcium carbonate to form calcrete. The sands are poorly graded, which means they are mostly single sized and causes a very loose structure. Fly Ash used in this study was supplied from the Morupule Thermal Power Station, which had typical chemical properties of Class F Fly Ash as seen in Table 2.2. It was found that by adding Fly Ash in large amounts greater than 32%, the maximum dry density (MDD) decreased and the OMC increased. The final verdict was that the Fly Ash had to be mixed with the sand in large volumes and cured for 21 days. This lead to the conclusion that material became suitable for subbase and base coarse for pavement layers, for a low traffic volume road (Sahu *et al.*, 2002).

The material used in the investigation was the "White Kalahari Sand", which belongs to a family of arid soils. The typical characteristics are the following:

a. Lower water content, thus they are unsaturated and have large pore water suctions

b. A crust that exists containing high volume of salts which forms during the moisture upward movement and evaporation at the top of the soil profile.

c. Cemented by calcium carbonate to form calcrete

d. Single size granules, due to that these soils are often transported and deposited by wind also causing a loos structure.

Table 2.2 Chemical Analysis of Fly Ash (Sahu *et al.*, 2002)

Fly Ash Analysis	Composition%
SiO_2	41.2
Al_2O_3	33.6
Fe_2O_3	5.08
CaO	6.45
MgO	3
K_2O	0.44
Na_2O	0.1
TiO_2	2.31
P_2O_5	<0.05

The proportions of the Fly Ash to be mixed with the sand was determined by previous work completed by (Sahu et al, 1998), which indicated that the strength characteristics of coarse grained soils were significantly improved with Fly Ash by more than 20%, shown in table 2.3.

All samples prepared were then subjected to two tests namely:

a. Unconfined Compression Test (UCS)

b. California Bearing Ratio (CBR)

Table 2.3 Test results produced (Sahu *et al.*, 2002)

Fly ash%	MDD kN/m^3	OMC%	UCS kN/m^2			CBR%			
			7days	14days	21days	0 day	7days	14days	21days
0	1765	5	--	--	--	--	--	--	--
20	1640	5	--	60	100	9	21	24	60
28	1552	8	80	90	70	12	27	52	71
32	1546	9.5	90	130	240	26	27	54	75
100	1310	20	--	--	--	--	--	--	--

The variation in Maximum Dry Density (MDD), seen in Table 2.3, was due to the fact that the proportion of solids found in the Fly Ash with lower specific gravity increases in the soil admixtures with increase in Fly Ash proportion. The same can be said for the variation in the Optimum Moisture Content (OMC), as it increases with the increase of Fly Ash mixture. During the test process, it was observed that as the OMC increases, the MDD decreases and this was constant for material with a grading from coarse to fine.

As indicated in Figures 3 and 4, for UCS and CBR respectively, the UCS shows a no gain to a very slow gain in strength up to 7 days, which then increases and gains strength over a period of 21 days. With CBR values showing the same consistency, it was found that the “White Kalahari Sand”, previously not even considered as an suitable material for subbase (Sahu *et al.*, 2002), was improved to a level where it could be considered for base coarse material of a low traffic road.

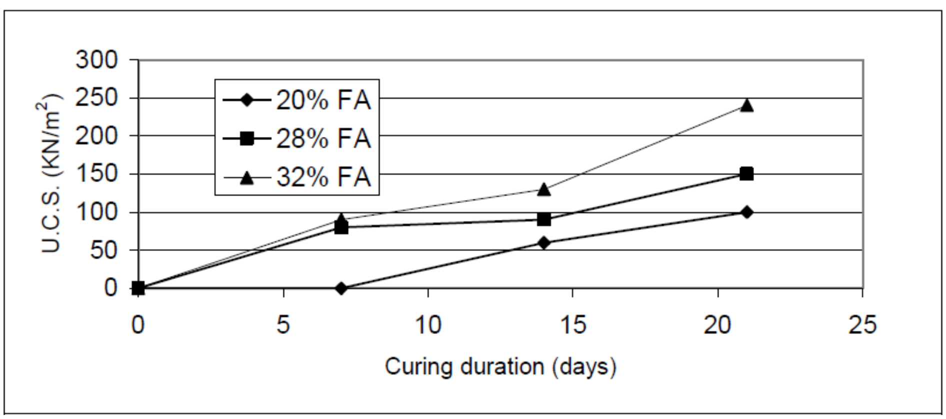


Figure 3 Variation of UCS with Fly Ash content (Sahu *et al.*, 2002)

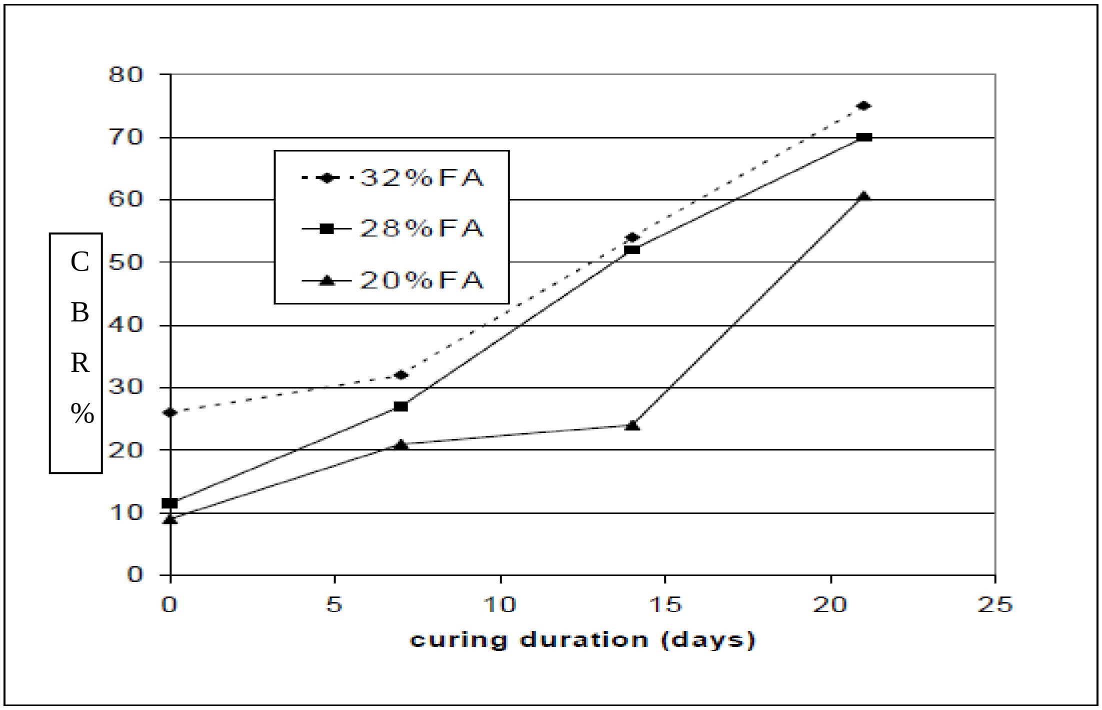


Figure 4 Variation of MDD with Fly Ash (Sahu *et al.*, 2002)

Fly Ash mixtures with sand of up to 32% of Fly Ash had a significant improvement although this may increase cost in projects and should only be considered where the haulage distance for Fly Ash are not large, and where water is not scarce (Sahu *et al.*, 2002).

Fly Ash mixtures compared favourably with conventional sandy soils, due to it being more compressible than sands compacted at same compaction levels. At higher compaction levels they exhibit comparable or even higher shear strength than that of sands at similar compaction levels (Kim *et al.*, 2005).

Studies have shown that 10 to 25 percent of Fly Ash can be mixed successfully with well graded materials. Normal construction methods can be utilised during stabilisation process, but the Fly Ash stabilisation had to be completed before winter months as the pozzolanic reaction ceases in temperatures below forty Fahrenheit (Oppenshaw, 1992).

Fly Ash has been utilised in numerous projects in the USA, and a recent study has been completed on the field performance of Fly Ash stabilised subgrades (Parsons *et al.*, 2005). The study was compiled by Parsons and Kneebone and was conducted to:

a. Confirm that the introduction of Class C Fly Ash provides statistically significant improvement of soil properties

b. Quantify the improvement and determine whether there is a deterioration over time of the Class C Fly Ash treated subgrades.

The methodology included a selection of twelve roads that varied between Fly Ash treated and untreated subgrades. Various testing was completed, where higher strengths of treated subgrades were evaluated and then compared to untreated subgrades. The age of these roads in the study varied between zero and nine years. During the study, no deterioration of subgrades was evaluated.

Subgrade soils are a essential component of pavement structures, and inadequate subgrade performance is cause of many premature pavement failures, especially in soils that contain clay as they provide inadequate support when saturated. This type of material has high plasticity and may cause reduction in density and strength of subgrade, thus accelerating pavement deterioration (Parsons *et al.*, 2005).

Three benefits were identified using Class C Fly Ash:

a. Drying agent: Fly Ash hydrates when exposed to water, thus consuming the water.

b. Control volume of change: Fly Ash reduces shrink/swell and does not experience significant change itself, so it dilutes the effects of swelling clays that are present.

c. Increase in strength: Fly Ash acts as a weak cementing agent that increases strength, fast in the beginning of the hydration process then slows over time to pozzolanic reactions as with lime.

Series of laboratory testing was completed where subgrades were stabilised with amount of Class C Fly Ash between 12% and 16%. The subgrades had the following specifications:

a. Liquid Limit (LL) of greater than 40

b. Plastic Index (PI) of greater than 25

The laboratory tests showed that Class C Fly Ash improves strength and modulus of subgrade soils. Fly Ash caused a reduction in PI although the subgrades under the study still retained some PI, but the swell of subgrades was significantly reduced. The study did show that although the PI and swell was reduced after the addition of Class C Fly Ash, amount of swelling was still significant. The Figures 5 and 6 show the reduction in PI and swell as tested in the laboratory respectively.

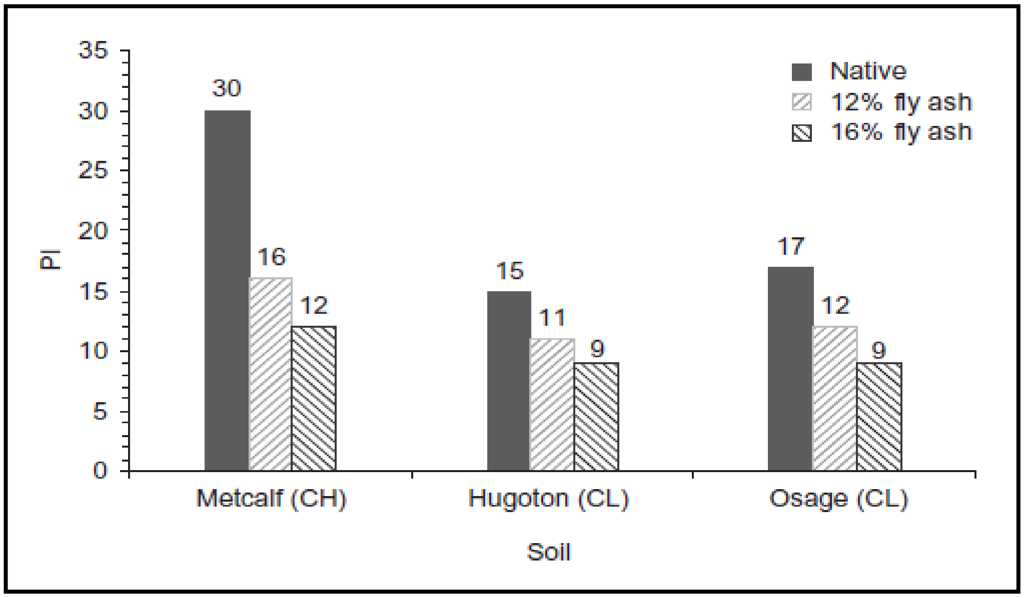


Figure 5 Reduction in the PI with addition of Fly Ash (Parsons *et al.*, 2005)

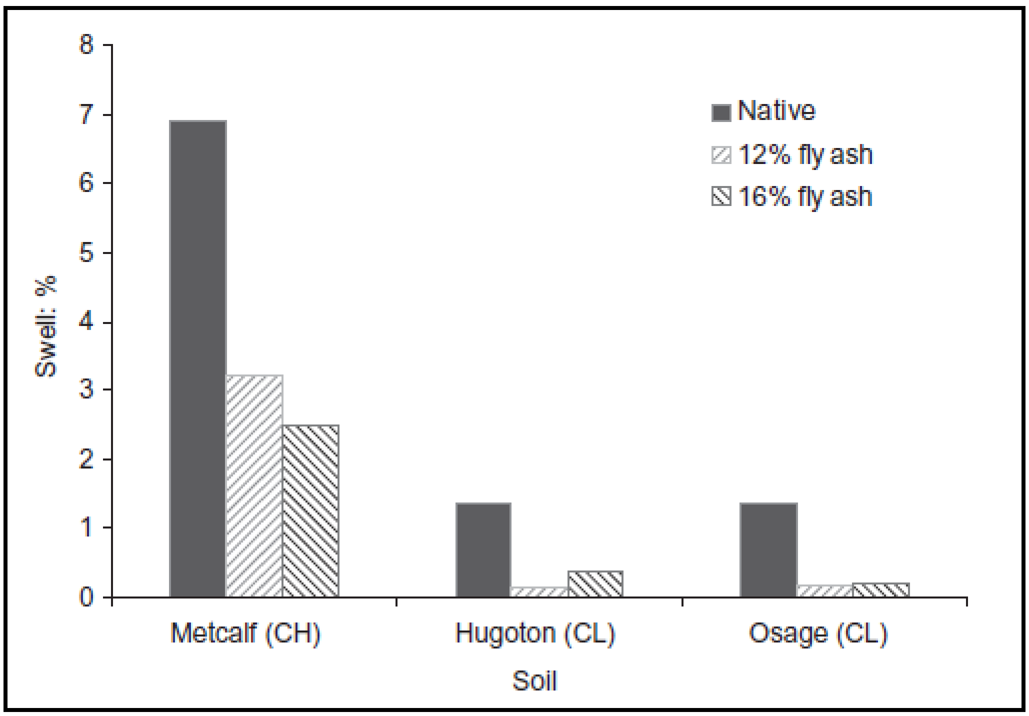


Figure 6 Reduction in swell potential for three soils with Fly Ash (Parsons *et al.*, 2005)

The field study also showed higher strength results than those compared to the laboratory tests. The field study showed that the Fly Ash treated subgrades had an increase in stiffness of up to

93%. Dynamic Cone Penetration (DCP) was used in the field study to compare the resistance of the Fly Ash treated subgrades and the un-treated subgrades. The Fly Ash treated subgrades showed values increased by 40% - 250% over the un-treated subgrades. The CBR values calculated from the DCP values showed that Fly Ash treated subgrades had a CBR of 24, while the un-treated subgrades was 9. Figure 7 showed the study of the CBR values between Fly Ash treated and un-treated subgrades.

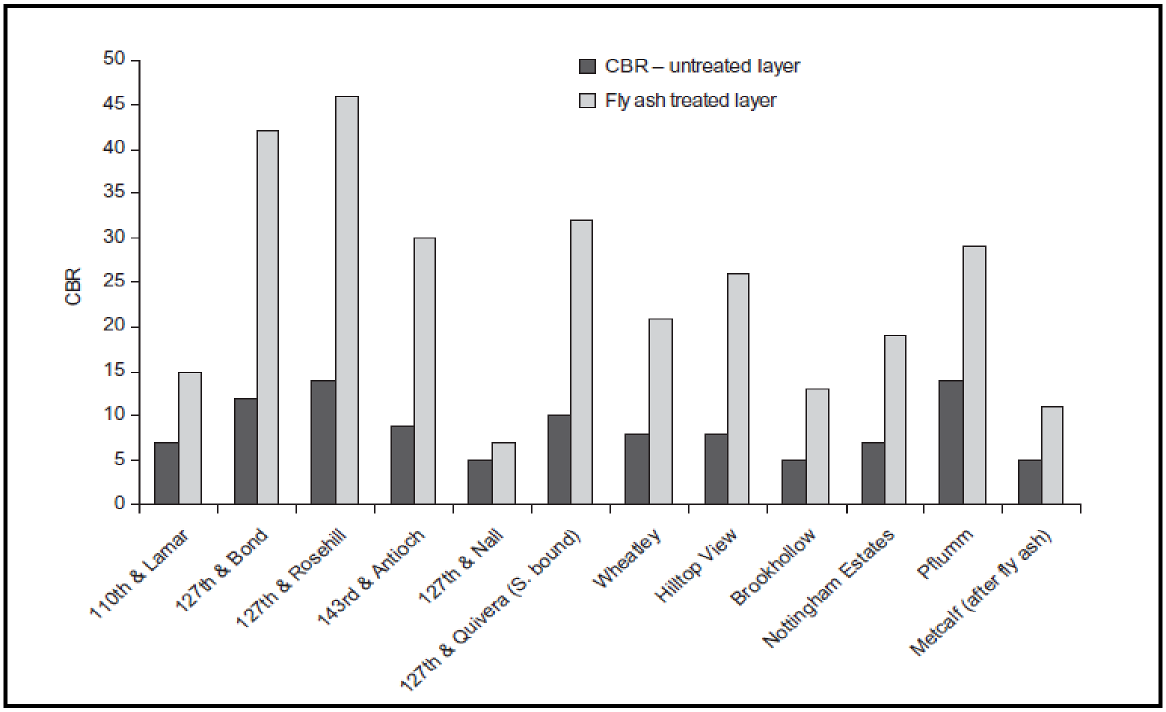


Figure 7 Average CBR Values for Fly Ash treated subgrade (Parsons *et al.*, 2005)

The Fly Ash treated subgrades showed no deterioration compared to the un-treated subgrades. Once again this showed the resistance to penetration of Fly Ash treated subgrades.

Average age of the streets tested was 9 years, and the Fly Ash treated subgrades showed a 220% increase in strength. One of the most crucial conclusions made in this study was that Fly Ash treated subgrades may provide for savings through reduction in the thickness of the asphalt overlay.

An extensive research was completed on stabilizing soft fine grained soils with Fly Ash (Edil, *et al*, 2006). This study was completely a laboratory study to evaluate the improvement in mechanical properties relevant to highway design and construction that can be obtained when soft grained subgrades soils are stabilised with Fly Ash.

Two crucial tests were identified:

a. California Bearing Ratio (CBR) for a working platform during highway construction

b. Resilient Modulus (M_r) – important for supporting long-term vehicular traffic loads.

Four types of Fly Ash were used with the physical composition, including classification summarised in Table 2.4 and 2.5.

Table 2.4 Chemical Composition and Index Properties of Fly Ash (Edil, 2006)

	Percent of composition					
Parameter	Columbia	Dewey	Edgewater	King	Typical[a] Class C	Typical[a] Class F
CaO	23.1	9.8	20.8	23.7	24.3	8.7
SiO_2	31.1	19.8	38.7	27.3	39.9	54.9
Al_2O_3	18.3	13.0	15.8	16.3	16.7	25.8
Fe_2O_3	6.1	6.0	7.8	5.9	5.8	6.9
MgO	3.7	3.1	3.4	1.8	4.6	1.8
SO_3	3.7	11.8	1.0	6.4	3.3	0.6
CaO/SiO_2 ratio	0.74	1.15	0.54	1.08	0.61	0.16
Loss on ignition (%)	0.7	53.4	0.1	5.4	6	6
Specific gravity	2.70	2.53	2.71	2.68	—	—
Percent fines (%)	95.3	39.6	92.8	91.9	—	—
Classification (*ASTM 618*)	C	Off specification	C	Off specification	C	F

All four Fly Ashes were taken from combustion of sub-bituminous coal and collected using electrostatic precipitators.

Seven subgrades soils that represented range of soft subgrades were used in the study. Properties of the soils are shown in Table 2.5.

Table 2.5 Index properties of soils (Edil, 2006)

						Classification					
Soil name	LL	PI	Percent fines	G_s	LOI (%)	USCS	AASHTO	CBR	w_N (%)	γ_d (kN/m^3)	w_{OPT} (%)
Org. Theresa silt loam	61	19	97	2.24	10	OH	A-7-5	0.3	35	13.5	29
Theresa silt loam	45	19	99	2.58	2	CL	A-7-6	3	19	15.9	18
Brown silt	60	35	97	2.58	4	CH	A-7-6	0.4	32	16.4	19
Lacustrine red clay	69	38	97	2.71	2	CH	A-7-6	2	35	15.7	24
Red silty clay till	47	22	71	2.69	2	CL	A-6	5	19	18.4	13
Joy silt loam	39	15	96	2.70	1	CL	A-6	3	25	16.5	19
Plano silt loam	44	20	96	2.71	2	CL	A-7-6	1	27	16.2	20

Note: LL=liquid limit; PI=plasticity index; Percent fines=percentage passing No. 200 sieve; G_s=specific gravity, LOI=loss on ignition; CBR=California bearing ratio (performed approximately 7% wet of optimum water content); w_N=in situ water content; γ_d=maximum dry unit weight; and w_{OPT}=optimum water content (*ASTM D 698*).

All soils are fine grained and classified as CL, CH or OH according to the Unified Soils Classification System. The soils have a similar particle size distribution and contain at least 90% fines. The in situ water contents of the soils were at 7% of optimum water content, it was then decided the soils shall be compacted to 7% of optimum water content to simulate the field conditions.

Unsoaked CBR were compacted but the soil water content was used instead of soil-Fly Ash mixture, due to the fact that the engineer uses the existing in situ water content of the soil in the design. To simulate construction methods of blending and adding water, the laboratory testing were delayed for 2 hours between adding water, blending and compaction. The soil specimens were tested immediately after compaction but the soil-Fly Ash mixtures were left in the moulds, covered in plastic and cured for seven days at 25 degrees Celsius and 100% relative humidity.

CBR test results for the untreated soil ranged between zero and five which indicated very poor subgrades. The soil-Fly Ash mixtures ranged between 10 and 20, suggesting that stabilisation with Fly Ash has similar benefits in terms of bearing strength as drying and compaction of the soil. CBR gain ratio was used to compare the CBR values to % of Fly Ash mixture. The CBR gain ration is the CBR of Fly Ash mixture normalized by CBR of untreated soil. With Fly Ash mixture of 10% a factor of increase was calculated of 4 and at 18% an increase factor of 8 was calculated.

The Resilient Modulus (M_r) test specimens were prepared using the same compaction effort as specimens prepared using standard proctor. Soil samples were prepared as per CBR specimens described above, but the soil-Fly Ash mixtures were extruded from the moulds, sealed in plastic and cured for 14 days at 25ºC and 100% humidity. Some specimens were cured for 56 days to evaluate how the resilient modulus changes as curing occurs.

M_r curves for soils usually has a characteristic shape for cohesive soils. With Fly Ash mixtures, it shows less dependency on deviator stress for the range of deviator stresses employed. The cementing particles were believed to be the primary factor responsible to reduce effects of the stress on M_r of Fly Ash mixtures. At 18% Fly Ash mixtures, the modulus of the soil-Fly Ash mixtures ranged between 0,8 and 2,5 times Mr of soils compacted at optimum water content.

Table 2.6 show results for resilient moduli in MPa of soil and soil-Fly Ash mixtures (Deviator stress = 21kPa).

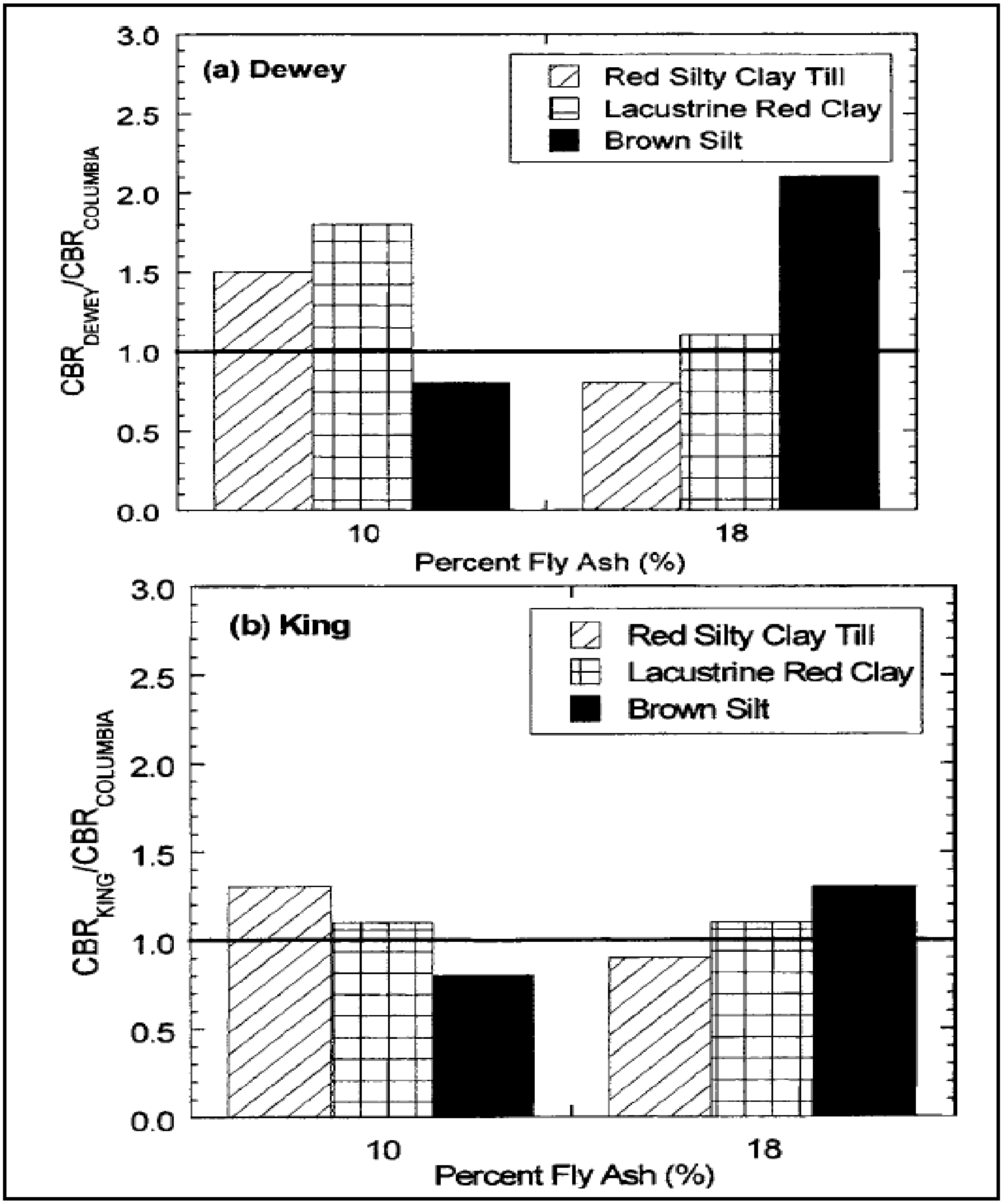
Table 2.6 Resilient Moduli (MPa) of Soil and Soil-Fly Ash Mixtures (Edil, 2006)

Soil name	Curing time (days)	w_{OPT} Soil alone	w_{OPT} Columbia Fly ash content (%)	Curing time (days)	7% wet of w_{OPT} Soil alone	7% wet Columbia			Dewey		King		Curing time (days)	Very wet condition Columbia		Dewey		
		0	12		0	10	12	18	10	18	10	18		10	18	10	18	30
RSCT	—	72.7 (−0.1)	—	14	15.0 (7.0)	12.1 (7.0)	—	65.0 (7.0)	21.1 (7.0)	76.3 (7.0)	22.0 (7.0)	90.9 (7.0)	7	14.2 (9.0)	20.7 (11.0)	15.2 (9.0)	41.8 (11.0)	—
LRC	—	43.3 (−1.0)	—	14	6.0 (7.0)	28.3 (7.0)	—	50.6 (7.0)	47.7 (7.0)	74.2 (7.0)	31.3 (7.0)	106.3 (7.0)	7	10.1 (10.0)	11.7 (13.0)	15.2 (10.0)	25.4 (13.0)	—
													14	22.9 (10.0)	41.6 (13.0)	—	—	—
BS	—	79.0 (−1.2)	—	14	9.0 (7.0)	49.4 (7.0)	—	71.4 (7.0)	60.0 (7.0)	82.8 (7.0)	18.7 (7.0)	68.3 (7.0)	—	—	—	—	—	—
OTSL	—	14.1 (−0.9)	—	—	0.9 (7.0)	—	—	—	—	—	—	—	7	F (10.6)	F (13.5)	F (10.6)	F (13.5)	25.6 (9.0) 7.8 (18.0)
TSL	—	13.3 (1.0)	—	—	9.0 (7.0)	—	—	—	—	—	—	—	—	—	—	—	—	—
JSL	—	—	—	—	9.0 (7.0)	—	—	—	—	—	—	—	—	—	—	—	—	—
PSL	7	34.0 (−3.0)	422.5 (−1.0) 226.1 (3.0)	7	3.0 (7.0)	—	144.9 (5.0)	—	—	—	—	—	—	—	—	—	—	—

Note: RSCT=red silty clay till; LRC=Lacustrine red clay; BS=brown silt; OTSL=organic Theresa silt loam; TSL=Theresa silt loam; JSL=Joy silt loam; and PSL=Plano silt loam. Number in parenthesis indicates water content of the soil prior to fly ash addition relative to the soil optimum water content (w_{SOIL}-w_{OPT}). F=Failed during testing.

The study also provided a comparison on types of Fly Ash used. As per graph shown below, it shows CBR of soil-Fly Ash mixtures prepared with the off-specification. Dewey and King Fly Ash normalised by CBR of similar mixtures approved by Class C Columbia Fly Ash. The off-specification Fly Ash have shown to be similar or produced even higher results than obtained by the Class C Columbia, this proved that off-specification Fly Ash is as effective for stabilizing soft soils.

Figures 8(a) Dewey and 8(b) King – CBR values of Soil-Fly Ash mixtures prepared with Dewey and King Fly Ashes normalised to CBR for Soil-Fly Ash mixtures prepared with Columbia Fly Ash. Contents of 10% and 18% used. Specimens compacted to 7% wet of optimum water content.



Figures 8 (a) and (b) CBR values over percentage Fly Ash Mixtures (Edil, 2006)

The effectiveness of Fly Ashes is related to the CaO/SiO_2 ratio as per table 2.7. It has been found that the higher the ratio, the higher the results will be for CBR and M_r respectively. Fly Ash stabilisation results in a more comparable CBR and $M_{r,}$ regardless of soil type.

Table 2.7 CBR of soil-Fly Ash mixtures compacted 2h after mixing and cured for 7 days (Edil, 2006)

Soil name	Soil optimum water content (w_{OPT})													7% wet of w_{OPT}						
	Soil alone	Columbia							Dewey			Edgewater		Soil alone	Columbia		Dewey		King	
		Fly ash content (%)													Fly ash content (%)					
	0	6	10	12	14	16	18	20	10	14	18	10	18	0	10	18	10	18	10	18
RSCT	26 (−1.0)	—	33 (2.0)	—	—	—	35 (4.0)	—	24 (2.0)	—	20 (4.0)	—	—	5 (4.7)	11 (7.0)	30 (7.0)	17 (7.0)	23 (7.0)	14 (7.0)	26 (7.0)
LRC	17 (−0.9)	—	19 (2.0)	—	—	—	20 (4.0)	—	25 (2.0)	—	20 (4.0)	—	—	2 (7.0)	8 (7.0)	24 (7.0)	14 (7.0)	26 (7.0)	9 (7.0)	27 (7.0)
BS	17 (1.0)	—	-	—	—	—	—	—	20 (2.0)	20 (3.0)	25 (3.0)	—	—	3 (5.0)	12 (7.0)	15 (7.0)	10 (7.0)	31 (7.0)	9 (7.0)	20 (7.0)
OTSL	2 (0.5)	—	2 (2.0)	—	—	—	5 (4.0)	—	4 (2.0)	—	10 (4.0)	2 (2.0)	2 (4.0)	0.3 (6.9)	—	—	—	—	—	—
TSL	12 (−0.4)	15 (2.0)	25 (2.0)	—	23 (3.0)	—	30 (3.0)	—	—	—	—	—	—	3 (6.3)	—	—	—	—	—	—
JSL	5 (1.0)	—	32 (2.0)	—	36 (2.7)	—	38 (3.4)	—	—	—	—	—	—	3 (6.0)	—	—	—	—	—	—
PSL	5	—	-	34 (2.4)	—	51 (3.2)	—	56 (4.0)	—	—	—	—	—	1 (7.0)	—	—	—	—	—	—

Note: RSCT=red silty clay till; LRC=Lacustrine red clay; BS=brown silt; OTSL=organic Theresa silt loam; TSL=Theresa silt loam; JSL=Joy silt loam; and PSL=Plano silt loam. Number in parenthesis indicates water content of the soil prior to fly ash addition relative to the soil optimum water content ($w_{SOIL}-w_{OPT}$).

Curing time of the samples was completed at different intervals to see how curing time affects the resilient modulus. The resilient modulus is a property relevant to long-term performance under service loads. As previous studies have shown (Parsons, 2005), there is hardly to no increase in strength between zero and seven days. As in this study, resilient modulus did not significantly increase between seven and fourteen days but larger increase occurred between fourteen and twenty eight days, and an even greater increase after day twenty eight (28).

In numerous studies, and mentioned in this literature, Fly Ash can be used in soil stabilisation applications but most studies have included an addition of a cementitous agent like lime, lime kiln dust, cement kiln dust and cement.

In Fly Ash Facts for Engineers (FA FACTS) (FA FACTS, 2003), Class C Fly Ash was used to study the possibility of soil improvement. A standard test was used to determine behaviour of Fly Ashes according to ASTM D5239 (ASTM D5239, 2004).

The test provides self-cementitous which are ranked as shown below:

Very self-cementing > 500psi (3400kPa)

Moderate > 100-500psi (700-3400kPa)

Non self-cementing < 100psi (700kPa)

It should be noted that the test mentioned above will not provide a basis to evaluate the interactions between the Fly Ash and soil or aggregate. The use of Fly Ash in soil stabilisation/modification, as mentioned before, is to improve the compressive and shearing strength of soils. The compressive strength of Fly Ash treated soils is dependent on:

a) In-place soil properties

b) Delay Time

c) Moisture content of time of compaction

d) Fly Ash addition ratio

The compressive strength of stabilisation is highly dependent on delay time. Both densities and strength are reduced with increases in delay in compaction time. Delay time is critical due to the rapid nature of the tri-calcium aluminate (CSA) reaction that occurs when Fly Ash is mixed with water.

The moisture content affects the strength, it has been recorded that the maximum strength is normally obtained of moisture contents below OMC, which for granular soils is generally one to three percent below OMC.

Studies have shown that addition rates of Fly Ash to soil is normally between 8 percent and 16 percent, which is based on dry weight of soil. Fly Ash designs are usually specified to meet AASHTO M295 (AASHTO M295, 2006) specifications although it has been found that non-AASHTO M295 compliant materials are being successfully used. It has been clearly stated, that any type of Fly Ash that has at least some self-cementing properties can be engineered to perform in transportation projects (FA FACTS, 2003).

Soil properties play an important role in use of Fly Ash as it has been found that organic soils and soils that contain more than 10 percent sulphates are difficult to stabilise using Fly Ash. Fly Ash reduces the potential soil to undergo volumetric expansion. Fly Ash controls the shrink swell properties of soil by cementing soil grains together, much like a Portland Cement that bonds aggregates together to make concrete. This bond restricts soil particle movements. The evaluation of these blends are tested with a soil expansion test such as ASTM D4289 (ASTM D4289, 2003) and ASTM D1883 (FA FACTS, 2003).

Characterisation of Fly Ash by X-Ray analysis explains the behavioural characteristics of Fly Ash. The X-Ray analysis plays an important role for a better understanding of Fly Ash reaction mechanisms. X-Ray diffraction analysis is be used to set out standards and specifications. The study completed highlighted three important criteria namely:

a. Elemental analysis

b. Quantitative Component Analysis

c. Hydration Reactions

Elemental Analysis was completed to identify chemical and physical properties of Fly Ash under the study, the basic table below shows the representative results of the Elemental Analysis.

Quantitative Component Analysis is to develop the methodology for quantitative assessment of crystalline compounds present in the Fly Ash and to define qualitatively the expected mineral composition.

The results on the study showed two important results:

a. The self-cementing properties of Fly Ash under the named study contained a combined 7.5% of tri-calcium aluminate and calcium aluminate sulphate, both of which are hydraulic cements

b. The crystalline compounds have significant effect on pozzolanic reactions, which are the essence of Fly Ash reactions.

Hydration Reactions analysis was to provide additional information about the chemical properties of the constituents in a reactive type Fly Ash. The X-Ray diffractometer was used to monitor compound growth and consumption over time.

It was also found that free calcium oxide was not present in significant quantities but appeared to be hard burned (Transportation Research Board (TRB), 1983).

Further studies undertaken by K.L. McManis and A. Arma (McManis *et al.*, 1989), was to evaluate the stabilisation or modification of sands and clays using ASTM Class C Fly Ash. The study aim was to use Class C Fly Ash as a full or partial replacement for Portland Cement or Hydrated Lime. The study was part of a full laboratory testing program undertaken for evaluation purposes. Tables 2.8 and 2.9 show the soil properties analysed for the study and the type of Fly Ash chemical and physical analyses.

Table 2.8 Soil Properties (McManis *et al.*, 1989)

	Soil			
Variable	A-3	A-2-4	A-7-6(20)	A-6(20)
Coarse Sand (Ret 40 sieve) (%)	40	3	0	1
Fine Sand (Ret 200 sieve)(%)	52	62	14	3
Clay and colloids (%)	3	17	55	34
Liquid Limit (%)	NP	21	60	31
Plastic Index (%)	NP	7	40	13
Max. dry wet density (pcf)	109.7	119.7	98.8	104.9
Optimum Moisture (%)	13	12.1	23.1	19
R-Value			<5	30

Note: NP=nonplastic

Table 2.9 Chemical and Physical Analyses of Fly Ashes (McManis *et al.*, 1989)

	Fly Ash Source		
Variable	Cajun	Rodemacher	Nelson
Retained on 325 sieve (%)	9.2-7.6	12.0-11.0	13.9-18.3
Loss on Ignition (%)	1.3-0.5	0.5-1.9	0.7-1.0
Total Oxides (%)	65.8-66.5	62.3-64.7	51.5-62.9
Calcium oxide (%)	21.5-24.5	27.2-24	25.2-25.8
Magnesium oxide (%)	4.4-4.7	4.9-4.5	4.9-2.9
Sulfur trioxide (%)	2.8	2.7-2.9	3.1-3.3
Alkalies (%)	1.34-0.66	1.49-1.06	1.45-1.74

Minimum proportions of stabilizing agents with sands are used to satisfy the standard acceptance criteria (250psi compressive strength with a 7 day cure), Table 2.10

Table 2.10 Percentage proportion of stabilisation agents (McManis *et al.*, 1989)

Stabilizing Agent	**A-3 Sand (%)**	**A-2-4 Silty Sand**
Fly Ash	20-25	None meeting criteria
Lime + Fly Ash	4-6 Lime + 15 Fly Ash	None meeting criteria
Cement + Fly Ash	All proportions acceptable except 4 cement + 5 Fly Ash	All acceptable
Cement	8	All acceptable

The density results have shown that the Fly Ash gave a similar result. The Fly Ash increased the maximum density and decreased the OMC throughout the range of Fly Ash percentages tested. The spherical shape of Fly Ash particles in the sand lubricates the mix and aids in the densification efforts thus the reduction in OMC. The Fly Ash addition percentage to the test samples was between 15% and 20%, which produced the maximum density results. It was found that the addition of above 20% Fly Ash reduced the density values. The other mix combinations, cement + Fly Ash and Lime + Fly Ash also produced gains in density. The gains were shown at different percentages.

In Figures 9 and 10, the gradation of the different sands with and without the types of Fly Ash used, are shown. The additional increase of the Fly Ash in the sand samples showed a gradation moving closer to the ideal curve for maximum density, which was due to the Fly Ash filling the voids between the sand particles creating fines and providing a matrix for the sand particles. On the silty sand samples, it was found that less percentage of the Fly Ash was to be added to get the gradation to move closer to the ideal gradation curve as illustrated in the Figures 9 and 10.

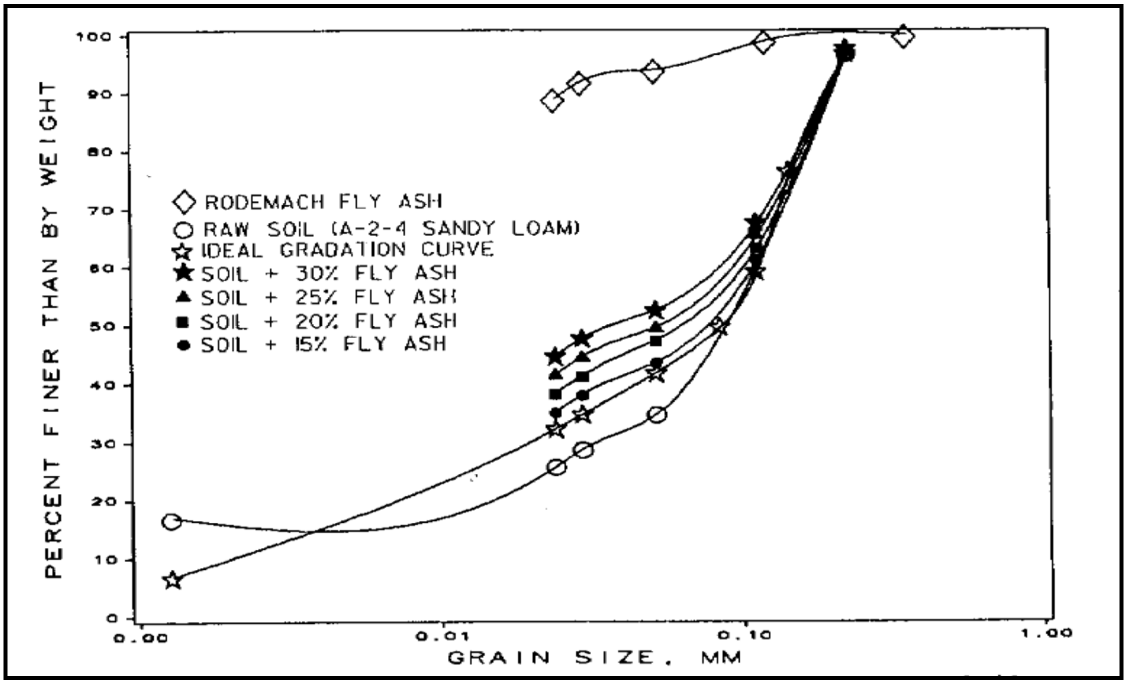


Figure 9: Comparison of gradation curves for sand A-2-4 with and without Fly Ash (McManis *et al.*, 1989)

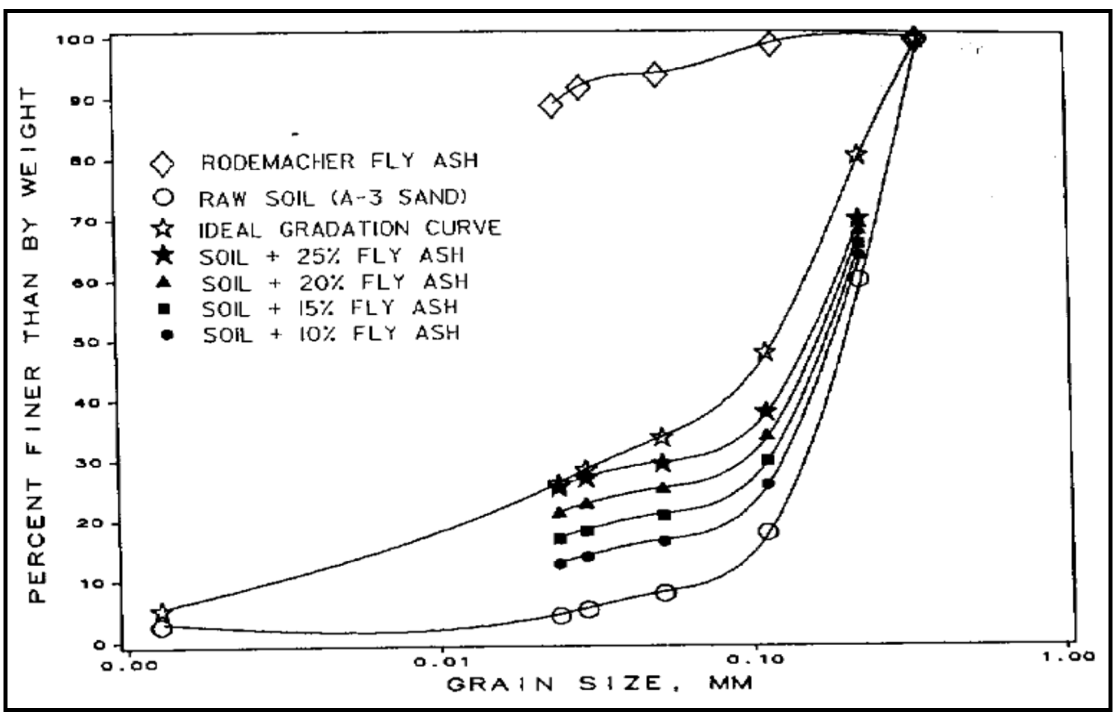


Figure 10: Comparison of gradation curves for sand A-3 with and without Fly Ash (McManis *et al.*, 1989)

The unconfined compressive strength variations were also observed with the various percentages of Fly Ash mixed into the samples. The tests showed that a 25 percent of CaO concentration in the sand samples appose to the 10.4 percent in the silty sand mixes. Additional gains in strength were observed with addition of lime or cement to the Fly Ash. The gain with addition of lime was not significant with the silty sand as the clay and sieve size fractions did not appear to have a strong pozzolanic characteristic. This might have been that the fines of the natural soil may interfere with and produce discontinuities in the cement formed within the matrix by the Fly Ash and Fly Ash combinations of additives.

For Curing times and durabilities, the tests showed that Fly Ash appeared to be competitive as a replacement for cement in sand and that no consideration in loss of strength was found over time although the silty sand did demonstrate a consistent loss in strength in the vacuum saturation test.

All tests completed during this study have shown that the ASTM Class C Fly Ash can be used as a full or partial replacement of Portland Cement in sands, but it all depends mostly on the gradation characteristics. On silty sand, success in stabilizing will depend on quantity and reactive properties of the fine grained material (Transport Research Report (TRR), 1989).

During the years of Steam Locomotives, stockpiles of clinker ash were spoilt in areas across the country. It was decided to do a study of using locomotive ash, otherwise known as clinker ash, to stabilise earthworks layer in Railway construction. Clinker Ash is a course material remaining on boiler grates after the burning of a lump of coal (Giles, 1994).

Previous studies have shown that the breakdown of material during compaction and under traffic in a road can be estimated from gradings before and after the maximum dry density AASHTO compaction test (Giles, 1994).

Two co-operate bodies have allowed for the use of Clinker Ash:

a. Transvaal Roads Department

b. American Railroad Engineering Association

The Transvaal Roads Department allowed waste Clinker Ash in lower layers of roadworks where natural material was not available. The Clinker Ash was restricted to fill and selected subgrade layers. This was accepted because the Ash had a low elastic modulus and can result in high deflections of the road.

The American Railroad Engineering Association placed a specification for the use of the Ash for use in Cinder Ballast; some are named:

a. Cinder Ballast shall contain Clinker Ash as result of burning of hard or soft coal in locomotive furnaces.

b. Clinker Ash should be brought to sufficient heat to bring condition into fusion.

c. Clinker Ash is used on branchlines with light traffic, sidings and yard tracks.

Research was completed in 1954 by Wilson (South African Railways (SAR), 1954), investigated properties of Ash as construction material. The railways started using the Ash in earthworks construction and specified the Ash in 1966.

Spoornet in South Africa have adopted the following applications for the construction material:

a. Ballast

b. Subballast

c. A Layer

d. B Layer

e. Bulk Earthworks

The Ash applications was used in the following layers:

a. Bulk Earthworks – Ash was used as a light weight fill when required when suitable fill material was not available

b. Subballast

   Ash was used as a separation layer between the coarse grained Ballast and fine grained subgrade. Strength and grading is the important factor while grading must fulfil the following requirements:

   1. Material below must subballast layer must be prevented from pumping through under dynamic loading

   2. Coarse Ballast particles must not penetrate into the formation

One important aspect of Ash as a subballast layer is that the grading must be maintained throughout the life span of the line despite the demise of the steam engine, locomotive clinker ash has diminished and therefore new ways of use of Ballast will have to be found as alternative to traditional Ballast for railway lines (Giles, 1994).

A case history was completed in the USA were the use of Fly Ash was used to stabilise gravel road surfaces. The study was part of a sustainable construction-green highways initiative project.

This initiative was implemented due to the increase in developments along gravel roads in the USA and associated with this was increase in traffic and traffic loads which placed a tremendous pressure on the local governments to upgrade the roads at an considerable cost. The solution to this was to stabilise the in-situ unpaved roadway with self-cementing Fly Ash (Class C) and then to overlay with hot mix asphalt (HMA).

Several advantages were identified over traditional upgrade methods to convert unpaved roads to paved roads:

1. A disposal area is not necessary as road material is not removed.
2. Little change in grade from original surface therefore road narrowing is avoided.
3. Scarce aggregate sources are not required.
4. Fly Ash used does not require disposal.
5. Construction progresses quickly.
6. Rutting is not a problem and the final material has a high modulu to have a good durability against frost action.
7. Construction can be done at a lower cost.
8. Life cycle costs are also lower and longer lasting roads are obtained.

The pavement structure under study consisted of a thick gravelly clayey sand fill which formed the pavement structure, while the under laying layers consisted mostly of a silty sands and low plasticity clays with CBR values ranging between 5 and 33 with an average of 14. The sand content consisted mostly of 60% fines and the gravel content was about 25%. After construction completion, the results obtained showed a significant improvement in stiffness and strength of the material after 7 days of curing. The CBR ranged between 48 and 90 and the unconfined compressive strengths was between 197kPa and 812kPa compared to the natural granular material which had test results of the CBR of 24. The most important test result for this study was the resilient modulus (Mr) as this indicates how deformable the material is under load. This Mr is considered as the primary pavement design property (Tuncer *et al.*, 2006). Overall moduli were higher than the modulus of crushed rock a year after construction. After monitoring a period of one year, chemical analysis of the draining leachate from stabilised layer showed that the concentrations of many trace elements were steady although the material could result in more leaching due to the fineness of Fly Ash compared to natural soil fines (Tuncer *et al.*, 2006).

Lin Li presented a paper on the properties of pavement geomaterials stabilised with Fly Ash (Li *et al.*, 2009), where the paper describes the evaluation of the mechanical performance of Fly Ash stabilised materials. Six roads were chosen for stabilisation with Class C Fly Ash exercise which material consisted of soft clay subgrade soil, recycled pavement material and existing road surface. This was to create working platforms for flexible or rigid pavements. The materials were then cured for seven (7) days after which an overlay was constructed. The Fly Ash content was mixed in by dry unit weight with an average percentage of 10 for each site. CBR tests were completed on disturbed samples before the stabilisation process, which show that the subgrades CBR values varied between 2 and 24 which increased the CBR values tremendously after stabilisation between 29 and 65 on average. The existing road surface produced CBR values of 24 before stabilisation and after stabilisation showed laboratory tested values of above 154.

It has been found that the laboratory stabilisation mix test results produced much higher CBR values than the field mix CBR values. Similar differences have been reported between the laboratory mix results and field mix results for fine-grained subgrade soil (Li *et al.*, 2009). The differences observed were, on average, between 30 and 66 percent and these will need to be considered when pavement design is based on data obtained from laboratory blended mixtures. Fly Ash stabilised materials do still provide conclusive results in terms of increasing pavement capacity and service life (Li *et al.*, 2009).

In numerous studies mentioned in this literature, Fly Ash can be used in soil stabilisation applications but most studies have concluded addition of a cementitous agent like lime, lime kiln dust and cement.

2.9 Environmental Impact

Fly Ash is one of the substances that causes air, water and soil pollution; disruption of ecological cycles; and set off environmental hazards. Mobilization of toxic elements and subsequent contamination of the groundwater is one of the greatest environmental concerns. Leaching tests, however, provided positive results showing that cadmium leaching is reduced by methods of stabilisation. Stabilisation with Fly Ash and construction of embankments have shown some tendencies of Fly Ash leachant to contaminate groundwater but through studies, have shown that it did not spread beyond 200m. Studies have also shown that if Fly Ash is contained there is less chance of leaching (Oppenshaw, 1992).

Fly Ash dumps are the real pollutant as potential environmental factor causing accidents with serious consequences. Fly Ash dumps also cause groundwater and soil pollution (Rotura *et al.*, 2010).

In South Africa, Fly Ash is mostly disposed of in form of slurries into settling ponds, or stockpiled on land, which often results in the loss of huge areas of land that was originally used 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 and that is called the dry method, and entails that Fly Ash is conditioned with waste water 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.

2.9.1 Use of Fly Ash Worldwide

Fly Ash is recognized as a suitable pozzolanic material and can be used in construction materials on a large scale. Fly Ash utilisation has significant 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

In the United States, the Environmental Protection Agency (EPA) (EPA, 1999) issued numerous reports from 1970 to date on guidelines on Fly Ash and encourage its use as an environment friendly material. In 1976, a legislation was approved that the beneficial use of Fly Ash be protected under the Bevill Amendment to the Resource Conservation and Recovery Act (RCRA) (RCRA, 1976). This legislation protects Fly Ash from being used as a hazardous waste. A study completed by the American Road and Transportation Builders Association Transportation Development Foundation (ARTB-TDF) (ARTB-TDF, 2011) have noted that over the years, Fly Ash has been used in transportation projects successfully in Europe. European countries design pavements with the focus on total lifespan of the pavement. An important key to this focus is the great attention to material and mixture properties. Fly Ash is regarded as an important component of most of the high performance designs in Europe (ARTB-TDF, 2011).

In South Africa, the public has not yet been convinced that Fly Ash is environmentally safe. Organizations, like Electric Power Research Institute, have encouraged the use of Fly Ash. Most of the researches so far were to encourage the use of Fly Ash in construction mainly with regards to strength analysis and to save cost. Using Fly Ash is the sustainability of providing a viable alternative to non-renewable primary aggregates. Fly Ash products are recognized worldwide as an environmentally friendly benefit for the construction industry. Each ton of Fly Ash used in South Africa saves approximately one ton of CO_2 emissions (National Inventory, 2001). It has been estimated that the use of Fly Ash in cement for concrete has saved in excess of 6 million tons of harmful greenhouse gas emissions in South Africa (Ash Resources, 2012). As previously stated, South Africa produces millions of tons of Fly Ash per annum and only about six (6) percent is utilised (National Inventory, 2001). Fly Ash landfill sites are an environmental concern due to that the release of contaminants to the ground and surface water after disposal. When used for stabilisation, chemical reactions take place, binding the Fly Ash particles and thus the chances of pollution is negligible (Heebink *et al.*, 2011).

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 ground water, it is to prevent water intrusion which could dissolve some trace elements of the Fly Ash dump sites.

Electric Power Research Institute (EPRI) (EPRI, 1998) also studied the health and environmental effects of Ash used in various applications over different regions in the USA. The results concluded that the health risks from ingesting Ash were generally miniscule therefore trace elements from coal 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 Ash are both localized and minimal (EPRI, 1998).

2.9.2 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.

It has been found that Fly Ash leachant samples were highly variable and were found in some cases to be higher than the United States Environmental Protection Agency (USEPA) drinking water quality levels (Oppenshaw, 1992). Related studies to leachant have shown that some Fly Ash dumps found in South Africa have been comparable to the standard quality of water fit for Human Consumption (P.Tau, 2005).

Low pH values encourage leaching trace elements, while leachibility of certain elements decreased as the material aged. It was found that the Fly Ash behaviour of elements; Si, Ca, Al, Mg, Fe, Na and K, remains constant, which meant that after 10 years more than 90% of the elements remained in the deposits and did not leach out (Gitari *et al.*, 2009; Usmen *et al.*, 1998). Different types of Fly Ash can change the pH value of the soil. The pH has a major influence of the mobility of toxic elements. The soil and pH of Fly Ash could determine the available concentration of these elements and in turn could lead to desirable results (Oppenshaw, 1992, Ayanda *et al.*, 2012).

2.10 Summary

Literature indicates that uses of Fly Ash in construction is a fairly common practice and has been successfully used worldwide, namely:

1. Fly Ash is a suitable filler for single sized aggregates and improves soil that was considered unreliable for road pavement construction.
2. The CBR increased by a greater factor when Fly Ash is added to wetter or more plastic fine grained soil.
3. Soil-Fly Ash mixtures will have a lower resilient modulus than soil alone compacted at optimum water content.
4. Larger increases in resilient modulus should be expected for wetter or more plastic fine grained soils.
5. Stabilisation with Fly Ash results in comparable CBR and M_r regardless of soil type.
6. Fly Ash stabilised subgrades should stiffen over time, resulting in increased pavement support.
7. Off-specification Fly Ashes has been proven just as suitable for stabilisation as Class C and Class F Fly Ashes.
8. The use of Fly Ash in soil stabilisation and soil modification may be subject to local environment requirements pertaining to leaching and potential interaction with ground water and adjacent water courses. Typical stabilised soil depths are 150mm to 300mm.
9. The primary reason for Fly Ash use in soil stabilisation is to improve the compressive and shearing strength of soils.

The compressive strength of Fly Ash treated soils is dependent on:

1. In-place properties
2. Delay time
3. Moisture content at time of compaction
4. Fly Ash addition ratio

It should be noted that, virtually, any Fly Ash that has at least some self-cementitous properties can be engineered to perform in transportation projects. The Fly Ash dries the soil by two mechanisms: chemical reactions that consume moisture in the soil and simple dilution. The drying effect of fly ash is rapid and immediate, making the soil more resistant to additional of water infiltration which provides additional traffic support, creates a stable work platform and reduces dusting from construction traffic.

Utilisation of Fly Ash has been investigated by many researchers in order to facilitate its disposal and minimize its negative environmental impacts by considering the chemical composition and leaching characteristics of the Fly Ash before utilisation.

Fly Ash varies in colour which is influenced by the iron-rich fractions of Fly Ash. The colour mostly depends on the amount of unburned carbon in the ash. The lighter the colour, the lower the carbon of Fly Ash.

Environmental Impact of Fly Ash is of a major concern but it has been proven that if Fly Ash is used properly, and through stabilisation methods, it will not have an effect on environmental issues. However, the controlling and handling of Fly Ash in the construction industry should be properly studied for Health and Safety concerns.

In the past, Fly Ash produced from coal combustion was simply entrained in flue gases and dispersed into the atmosphere. By the creation of environmental and health legislations, Fly Ash emissions have dropped to less than 1% of ash produced but has increased the area of landfill sites.

Chapter 3 Environmental Effects of Fly Ash

3.1 Introduction

This chapter presents studies related to the effects of Fly Ash on the environment with a main focus on Leaching properties of Fly Ash.

3.2 Environmental Impacts from Leaching

Key potential hydrological impact is the collection of contaminants by water as it percolates through or over a material. The use of leachant tests are conducted to analyse the solubility of Fly Ash (Oppenshaw, 1992; Solc *et al.*, 1995). Studies show that leachate is highly variable as a result of type of coal and plant process. Roy et al (1981), have shown that leachability of certain elements decreased as the material aged. The pH levels of Fly Ash encourages leaching of trace metals, although it has been found that high pH levels favours leaching of arsenic (Solc *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

Arsenic is found in all pH levels of Fly Ash but is in the non-toxic form (Oppenshaw, 1992; Solc *et al.*, 1995; Moolman, 2011). The metals of concern to toxicity were evident but they are within the RCRA limits, although it has been stated that the results does not mean that Fly Ash does not have any toxic effects (RCRA, 1980).

A number of studies have addressed the leaching of Fly Ash residue and what impact it has on the environment. The studies have revealed that when Fly Ash is used in concrete, there is a minimal risk of leaching. Fly Ash, when used in road stabilisation projects, has been proven to only leach trace amounts of minerals that are not harmful to the environment. Coal Fly Ash has proven to yield from agricultural land and used as a pollution control agent for soil decontamination, sludge and effluent treatment and hazardous waste stabilisation (MoolMan, 2011). Environmental changes as a result of pollution formed through energy production and use, affect soil pH, structure fertility and microbial communities. Soils become relatively sterile to all but resistant microbial life forms. Micro-organisms are able to degrade pollutants in soil leading to insitu rehabilitation of pollutant soils (Surridge *et al.*, 2009). As already stated in this study, Fly Ash consists of fine, powdery particles that are spherical in shape and is mostly glassy (amorphous) in nature. Bituminous coal Fly Ash is silica, alumina, iron oxide and calcium with various amounts of carbon. Fly Ash is alkaline product of fossil fuel power generated stations. It has pH of approximately 11.5 when fresh and due to weathering, pH reduces and stabilises to pH value of about 8.5 (Surridge *et al.*, 2009; Ayanda *et al.*, 2012). Table 3 shows the pH value of the stabilised material, which shows that material stays an alkaline product. Further, in detail studies can thus be induced.

Table 3, pH values of stabilised material with Class F Fly Ash and Cement

Description	Leachate		
	pH	**Alkalinity**	**Acidity**
		mg/L CaCO3	**mg/L CaCO3**
1% OPC AFRISAM	10.56	51.47	0
1% OPC LAFARGE	10.54	51.47	0
1% OPC + 16% D.POZZ LAFARGE	10.77	66.49	0
1% OPC +16 POZZFILL LAFARGE	10.82	71.92	0
1% OPC + 16% D.ASH LAFARGE	10.57	60.2	0
1% OPC + 18% DURAPOZZ AFRISAM	10.77	60.05	0
1% OPC + 18% POZZ FILL AFRISAM	10.65	60.05	0
1% OPC +18% D.ASH AFRISAM	10.29	42.89	0

Fly Ash has the potential to make positive contributions to agriculture and land reclamation as a liming agent (Surridge *et al.*, 2009). Heavy metals in Fly Ash can exhibit a broad range of toxic effects to humans, terrestrial and aquatic life and plants (Ayanda *et al.*, 2012). Benefits of using Fly Ash in cultivation of plants are extensively investigated as to its use in the forestry sector (Reynolds *et al.*, 2002). Most of the elements in Fly Ash occur as silicates, oxides, sulphates and alumino silicates. These elements cannot be broken down or destroyed in the environment but they can change form (Ayanda *et al.*, 2012). Fly Ash releases large quantities of heavy metals into the localized area and the heavy metals can also enter the aquatic environment and, therefore, lead to a steady back ground level in aquatic environment (Anyanda *et al.*, 2012). 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 3.1 show the elements found in common South African Class F Fly Ash conducted under an X-Ray spectrometry test. In order to understand some of these elements, another comparison must be conducted to show the impact of these elements on the environment, if any. Water is the main source for human and environment survival; therefore, elements are compared to the maximum allowable concentrations in water fit for human consumption (Bicki *et al.*, 1993). Table 3.2 show the comparisons of required maximum allowable elements also found in Fly Ash with possible health effects. It must be noted that these results are for the ash found in the dumps without any further other treatment. It is thus critical that leach tests be conducted so potential hazards can be red flagged for the use of Fly Ash 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.

Fly Ash goes through to a long-term dissolution, the neutralization capacity of Fly Ash is extended, offering a liming potential that lasts longer and is less dramatic than agricultural liming (Surridge *et al.*, 2009). This slow transmission of pH change allows for adaptation of the microbial communities and plants within the polluted soils (Surridge *et al.*, 2009).

As previously stated, it is critical that leach tests are conducted to raise points of concern if Fly Ash is to be used for a required product/project. For the purpose of this study, leach tests were completed on the chosen Fly Ash percentages with cement. The chosen mixtures for this study were subjected to leach testing and comparison tables could be drawn up to compare to Tables 3.1 and 3.2.

Table 3.2 shows the leach elements of the Fly Ash 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 ground water system.

The results in Table 3.3, is compared to the typical class F analysis found in Table 3.1, but one must also consider that the results in Table 3.3 are shown as Parts Per Million (ppm) and not as in Table 3.1 Parts Per billion (ppb). The same is for Table 3.4 which is the comparison for Table 3.2. The results in both Tables 3.3 and 3.4 shows a tremendous reduction when the samples are stabilised, which is due to the reaction between cement, Fly Ash and soil. The reason on the choice of % of Fly Ash with cement is described in detail in chapter 5 of this study.

Table 3.1 X-Ray spectrometry tests on typical Class F Fly Ash (Ash Resources, 2012)

Parameter	Range (ppb)
As	20
Ba	1502
Bi	3.8
Br	<2
Ce	235
Co	16
Cr	190
Cs	7.8
Cu	49
Ga	50
Ge	6.9
Hf	13
La	132
Mo	4.5
Nb	41
Nd	100
Ni	40
Pb	54
Rb	53
Sc	31
Se	2.8
Sm	25
Sr	1474
Ta	4.8
Th	45
TI	<3
U	9.2
V	129
W	8.6
Y	82
Yb	6.8
Zn	49
Zr	476

Table 3.2 Maximum allowable inorganics accepted in drinking water (Bicki *et al.*, 1993)

Material	Fly Ash Results (ppb)	Maximum Acceptable Level (parts per billion)	Possible Effects of Higher Levels
As	20	50	Lung Cancer, kidbey damage
Ba	1502	1000	Heart damage
Cr	190	50	Liver, kidney damage
Pb	54	50	Brain damage
Se	2.8	10	Growth inhibition
Cu	49	49	Metallic taste, blue-green stains on fixtures
Zn	49	N/A	Metallic taste

Table 3.3 Leach testing results compared to Typical Class F Fly Ash

Description	Leachate (ppm)								
	As	Ba	Bi	Co	Cr	Cu	Pb	Se	Zn
Typical Class F Fly Ash (ppb)	20	1502	3.8	16	190	49	54	2.8	49
1% LAFARGE + 16% DURAPOZZ	15.30	< 4	1.76	< 0.2	46.35	14.24	< 6	< 0.4	< 60
1% LAFARGE +16 POZZFILL	13.65	< 4	1.72	< 0.2	58.11	14.88	< 6	1.56	< 60
1% LAFARGE + 16% DUMP ASH	7.59	< 4	1.70	< 0.2	23.97	16.39	< 6	< 0.4	< 60
1% AFRISAM + 18% DURAPOZZ	19.41	< 4	1.68	< 0.2	50.29	14.20	< 6	2.33	< 60
1% AFRISAM + 18% POZZFILL	15.04	< 4	1.76	< 0.2	59.14	17.14	< 6	< 0.4	< 60
1% AFRISAM +18% DUMP ASH	8.19	< 4	1.67	< 0.2	8.89	17.11	< 6	< 0.4	< 60
1% AFRISAM	5.32	< 4	1.70	0.44	8.18	15.91	< 6	< 0.4	< 60
1% LAFARGE	5.36	< 4	1.70	0.29	8.56	18.89	< 6	< 0.4	< 60

Table 3.4 Leach results compared to drinking water allowable Table 3.2

Description	Leachate (parts per million)						
	Cr	Cu	Zn	As	Se	Ba	Pb
	ppm	ppm	ppm	ppm	ppm	ppm	ppm
1% OPC AFRISAM	8.18	15.91	< 60	5.32	< 0.4	< 4	< 6
1% OPC LAFARGE	8.56	18.89	< 60	5.36	< 0.4	< 4	< 6
1% OPC + 16% D.POZZ LAFARGE	46.35	14.24	< 60	15.30	< 0.4	< 4	< 6
1% OPC +16 POZZFILL LAFARGE	58.11	14.88	< 60	13.65	1.56	< 4	< 6
1% OPC + 16% D.ASH LAFARGE	23.97	16.39	< 60	7.59	< 0.4	< 4	< 6
1% OPC + 18% DURAPOZZ AFRISAM	50.29	14.20	< 60	19.41	2.33	< 4	< 6
1% OPC + 18% POZZ FILL AFRISAM	59.14	17.14	< 60	15.04	< 0.4	< 4	< 6
1% OPC +18% D.ASH AFRISAM	8.89	17.11	< 60	8.19	< 0.4	< 4	< 6

Fly Ash is used for various environmental applications that include:

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

Application of Fly Ash to soil influences the biovailability of nutrients and heavy metals. Biovailabiltiy refers to how much of a chemical is available to a living biota including plants and soil micro-organisms (Seshadri *et al.*, 2010). Bioavailability of chemical defines relationship between the concentration of chemical in the terrestrial environment and the level of the chemical that actually enters the receptor causing either a positive or negative effect on the organism (Seshadri *et al.*, 2010). Chemical bioavailability is considered an important issue in the environment because of the availability of chemicals that may be mitigated once the chemicals come in contact with soil and sediment (Seshadri *et al.*, 2010).

Seshadri et al, (2010) also noted that the ashes contain nutrient elements which included Si, Al, Fe, Ca and S. For plant nutrition, two major sources where identified namely S and Ca. Boron is essential mineral nutrient for all vascular plants. Selenium is essential for animals but not for plants. The presence of S as an anhydrite ($CaSO_4$), after hydration, makes the ashes a successful user as an S fertilizer to increase the yields of winter wheat, rice and posture (Seshadri *et al.*, 2010).

Reynolds et al, (2002), completed a study with production of artificial soil using Fly Ash, lime and sewage sludge. The high heavy metal and toxic element concentration of sewage sludge is classified as a toxic waste. With addition of Fly Ash forms a reaction where the heavy metals in the sludge are expected to be bound in the form of insoluble metal hydroxides in the ash. The combination improved the soil texture and fertility, and thus resulted in better crop yields. Positive results obtained led to a series of grain and cereal crops being planted.

Ciccu et al, (2001), presented a paper using soil from an Italian mine site contaminated with heavy metals. The study showed a decrease in levels of heavy metals in percolating water from Fly Ash mixed with soil, indicating that Fly Ash in such soils can lead to immobilization of heavy metal ions.

Germany Fly Ash power plants generates no water pollution as this was proved with tests on fish, aquatic creatures, aquatic plants and micro-organisms. A 1:1 mixture of Fly Ash and water was used to perform these tests and results concluded showed no permanent and no adverse effects on any of the test subjects (Moolman, 2011).

In the United Kingdom, the environmental agency has assessed Direct Toxicity Assessment for monitoring and controlling the discharge at industrial effluents into surface waters. The study has shown that water discharged from Fly Ash disposal dump sites needs no dilution in order for it to have no impact on fresh water. It also concluded that sediments in the vicinity of Fly Ash disposal site have no marked toxicity, despite them operating for substantial amount of years (Moolman, 2011).

Laboratory leaching and field run-off sample results have indicated that Fly Ash constituents exhibit limited mobility. The study revealed that Fly Ash is an environmental option and has engineering advantages when used properly for soil stabilisation techniques (Heebink *et al*, 2011)

Usem (1988) investigated the effect of stabilisation by testing leachant of several Fly Ash specimens stabilised with lime, cement or betonite. The results indicated cadmium leaching can be reduced by methods of stabilisation.

3.4 Handling of Fly Ash

Fly Ash is a fine powder that mainly consists of glassy particles (Mehta, 1998; Oppenshaw, 1992; FA FACTS, 2012). The Fly Ash poses little immediate hazard and short term exposure to the dry powder Fly Ash and is not likely to cause serious harm (Ash Resources, 2012). Various important precautions should be taken when handling the Fly Ash, seeing as the powder is alkaline when wet and may cause the following health problems, depending on the length of exposure:

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

Various safety rules and regulations have been put in place for personal protection. Fly Ash is often handled in association with Portland Cement, and prevention matters are handled in the same way (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 DURAPOZZ, 2.13 for POZZFILL and 1.86 For Kendal Dump Ash. The RD for cement is 3.15. It is mostly for practical reasons the RD plays an important role and that 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).

3.5 Summary

Fly Ash is utilised worldwide, and substation documents are in place for environmental protection namely; RCRA and the EPA. Fly Ash is constantly evaluated and studied to produce reports, namely:

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

These reports are constantly updated and are readily available for further, future studies.

As previously stated, South Africa has not yet been convinced that Fly Ash is environmentally safe. In-depth studies have revealed the ages of the landfill sites, contamination of groundwater in and around the landfill sites due to surface run-off. Studies have also been completed on how to plan landfill sites. The most important study was the classification of the South African Fly Ash produced. The actual study was of using the Fly Ash in cement production, therefore, all safety and environmental studies have been based around cement production.

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. Immobilize of heavy metal ions from contaminated soils

Elements in Fly Ash vary from different classes. Common Class F Fly Ash in South Africa have some potential hazardous material when compared with water's maximum inorganic allowable. A full comparison can only be conducted after the Fly Ash has been utilised to compare what hazardous materials are leached and at what toxic level it represents.

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

The Leach results have shown that the material was "*entombed*" and the possibility of leachant releasing agents of a dangerous nature are to a minimal. The results have shown a tremendous reduction in leach agents and that if minor leach agents do enter the drinking water tables, it is not hazardous. The leach tests in this study have shown that the Fly Ash stabilisation is environmental friendly. It also shows that the Fly Ash particles that are normally released are bound within the soil, due to chemical reactions, and will continue to be bound as long as reactions take place.

The selection of a leaching method is not simple. The project objective, type of material and type of data desired will determine the most appropriate method. Critical variables include the sample size and particles size distribution, leachant volume and pH, and duration of leachant test. 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 most important aspect of this chapter is that all safety and regulations currently in place for handling of Fly Ash should be followed to minimize any health risks that could be obtained from long duration exposure to the Fly Ash.

Chapter 4 Materials

4.1 Introduction

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

4.2 Stabilisation in the pavement 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, excessive deflections that will cause fatigue cracking within the layer or in the overlying layers and prevent permanent deformation through densification (Guyer, 2011).

In the selection of a stabiliser, the following factors need to be considered:

1. Type of soil to be stabilised
2. Purpose for which the layer will be utilised
3. Type of soil improvement to be desired
4. Required strength and durability of stabilised layer
5. Cost and environmental conditions

General guidelines of the type of additive to be added to soils are well published in South Africa. The common books is the TRH3; Technical Recommendations for Highways, Design and construction of surfacing seals (2007), TRH4; Structural Design of Flexible Pavements for inter-urban and rural roads guideline document (1996), Committee of Land Transport Officials (COLTO) (1998) and TRH14; Guidelines for Road Construction Materials (1985), which mostly give details on stabilisation methods and guidelines to what additives are suitable for the type of desired soil property . Type of guidelines is published tables and formulae for quick reference and decisions during a pavement design stage.

Portland Cement, for example, is generally used on well graded granular materials and with relatively low plasticity levels. The pH of the soil must also be below 12 (Guyer, 2011). Lime, for example, is generally used for materials with high plasticity levels and pH levels of above 12, and used to transform "*weak soils*" into "*working tables*". Although Portland Cement and lime is used for various applications, both can be used throughout the road prism during construction phase (Guyer, 2011).

4.3 Fly Ash

Studies around the world have shown that Class F Fly Ash is a pozzolanic material, i.e. it reacts with lime/cement to form cementitous compounds (Guyer, 2011; Mehta, 1998). The Fly Ash undergoes a "*pozzolanic reaction*" with the calcium hydroxide ($Ca(OH)_2$) created by the hydration of cement and water. Fly Ash is not a homogenous product and the individual particles differ in size, density, mineralology, chemical composition and morphology (Kruger, 2013). South Africa has abundant Fly Ash resources that are processed for commercial use, mainly for cement extension and in concrete mixes. For the purpose of this study, three sources of Fly Ash have been used, two from Kendal power station and one from Lethabo power station. Two of the Fly Ashes are air classified and one type is directly sourced from the ash dump at Kendal power station. Figure 11 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 three Fly ashes selected are namely:

1. DURAPOZZ – Air classified fly ash from Lethabo power station
2. POZZFILL – Air classified fly ash from Kendal power station
3. Dump Ash – directly sampled from the ash Dumps at Kendal power station

The choice of these Fly Ashes provides a variation in composition and particle size.

4.4 Fly Ash Standards

There are currently no specified standards for the use of Fly Ash as a soil stabiliser in South Africa. The standards that are fairly 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 a soil stabiliser (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 is also still followed. Compliance with various requirements assures the user that unsuitable Fly Ash is not utilised for stabilisation.

The following main standards were applied to evaluate the physical and chemical properties of the three (3) individual Fly Ashes used for this study:

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

The characteristics for each of the 3 Fly Ashes are compared to the value specified in these standards. The performance of a particular Fly Ash is determined by its chemical and mineralogical composition as well as its morphology and granulometry. To assess the stabilisation 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. Evaluation of the pozzolanic potential to predict whether the reaction will continue for a long period.
4. Determination of Sulphur content (SO_3) for the potential formation of ettringite.
5. Determination of the amount of free lime (fCaO)
6. Determining the effect of fineness on performance.

4.4.1 DURAPOZZ

DURAPOZZ is an internationally recognized high quality Fly Ash. DURAPOZZ is mostly used in concrete mixes where it contributes to a reduced carbon dioxide (CO_2) footprint. DURAPOZZ is spherical in particle shape, has a fine particle size and is pozzolanically reactive (Ash Resources, 2012). Table 4.1 shows the results for compliance to SANS 50197-1(2000), SANS 50450 (2011) and EN450-1 (2001).

Table 4.2 shows the XRF analysis and Table 4.3 shows the weekly sampling checks that were completed. All the parameters of the test results confirms that Lethabo DURAPOZZ Fly 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. It needs to be noted that the total calcia (TCaO) is not necessarily the reactive calcia (RCaO).

Table 4.1 DURAPOZZ Fly Ash test results according to specifications

Method	Description	Specification	DURAPOZZ
SANS50450 (Category A)	LOI	<5.0	0.46
SANS50450	LOI	<5.0	0.88
SANS50450	Sulpur content	<2.5	0.03
EN451-1	FCaO	<1	0.08
SANS50450	Total Alkalies	<5	0.11
SANS50450 (Category N)	Finess	<40	11.47
SANS50450 (Category S)	Finess	<12.0	10.8
SANS50450/SANS 50197-1	RSiO2	>25	36.6
SANS50450/SANS 50197-1	RCaO	<10	4.68

Table 4.2 XRF Analysis for DURAPOZZ Fly Ash

Parameter	Unit	Result
SiO_2	(%)	54.28
Al_2O_3	(%)	34.14
Fe_2O_3	(%)	3.46
CaO	(%)	4.12
MgO	(%)	1.08
K_2O	(%)	0.57
Na_2O	(%)	0.11
TiO_2	(%)	1.59
Mn_2O_3	(%)	0.04
P_2O_5	(%)	0.64
Cr_2O_3	(%)	0.01
SrO	(%)	0.12
ZnO	(%)	0
SO_3	(%)	0.03
LOI	(%)	0.46
CaO/SiO_2	ratio	0.08
SiO_2 + Al_2O_3+Fe_2O_3		91.88

Table 4.3 Weekly sampling report

Day	Date	% Retained on a 45µm sieve (Wet)	% LOI
		Standard: Max: 12.5% (SANS 1491:2)	**Standard: Max:5.0% (SANS 1491:2)**
Sunday	15-Jul-12	9.70%	0.55%
Monday	16-Jul-12	9.90%	0.60%
Tuesday	17-Jul-12	9.80%	0.53%
Wednesday	18-Jul-12	10.80%	0.49%
Thursday	19-Jul-12	11.10%	0.72%
Friday	20-Jul-12	10.30%	0.63%
Saturday	21-Jul-12	9.80%	0.59%

Average	10.20%

4.4.2 POZZFILL

POZZFILL does conform to some of the requirements of SANS 50450 (2011), SANS 50197-1 (2000) or EN450-1 (2001). POZZFILL is, extensively used as a reactive cementitious filler in South Africa. The unique combination of chemical and physical properties enables the product to impart significant features and benefits in cementitious systems (Ash Resources, 2012). POZZFILL for this study was sourced from Kendal power station. POZZFILL is also proven in road subbase, asphalt and refractory applications. Table 4.4 shows the results for compliance to SANS 50197-1 (2000) and EN450-1 (2001). Table 4.5 shows the XRF analysis while Table 4.6 shows the weekly sampling test report.

4.4.3 Kendal Dump Ash

Apart from DURAPOZZ and POZZFILL, an untreated sample was taken directly from the landfill dumpsite at Kendal power station. Table 4.7 shows the results for the XRF Analysis while Table 4.8 shows the LOI in conjunction with the weekly sampling report.

Table 4.4 POZZFILL Fly Ash test results to Specification

Method	Description	Specification	POZZFILL
SANS50450 (Category A)	LOI	<5.0	2.81
SANS50450	LOI	<5.0	1.02
SANS50450	Sulpur content	<2.5	
EN451-1	FCaO	<1	0.28
SANS50450	Total Alkalies	<5	
SANS50450 (Category N)	Finess	<40	35.2
SANS50450 (Category S)	Finess	<12.0	35.2
SANS50450/SANS 50197-1	$RSiO_2$	>25	34.55
SANS50450/SANS 50197-1	RCaO	<10	5.38

Table 4.5 XRF Analysis for POZZFILL Fly Ash

Parameter	Unit	Result
SiO_2	(%)	53.76
Al_2O_3	(%)	31.22
Fe_2O_3	(%)	3.37
CaO	(%)	5.38
MgO	(%)	1.67
K_2O	(%)	0.78
Na_2O	(%)	0.16
TiO_2	(%)	1.67
Mn_2O_3	(%)	0.04
P_2O_5	(%)	0.63
Cr_2O_3	(%)	0.01
SrO	(%)	0.19
ZnO	(%)	0
SO_3	(%)	0.13
LOI	(%)	1.02
CaO/SiO_2	ratio	0.10
$SiO_2 + Al_2O_3+Fe_2O_3$		88.35

Table 4.6 Weekly sampling report

Day	Date	% Retained on a 45µm sieve (Wet)	% LOI
		Standard: Max: 12.5% (SANS 1491:2)	**Standard: Max:5.0% (SANS 1491:2)**
Sunday	15-Jul-12	33.40%	0.52%
Monday	16-Jul-12	35.20%	0.67%
Tuesday	17-Jul-12	35%	0.53%
Wednesday	18-Jul-12	32.90%	0.63%
Thursday	19-Jul-12	32%	0.55%
Friday	20-Jul-12	34.80%	0.62%
Saturday	21-Jul-12	33.30%	0.57%

Average	33.80%

Table 4.7 XRF Analysis for Kendal Dump Ash

Parameter	Unit	Result
SiO_2	(%)	52.16
Al_2O_3	(%)	30.99
Fe_2O_3	(%)	3.62
CaO	(%)	5.16
MgO	(%)	1.62
K_2O	(%)	0.73
Na_2O	(%)	0.35
TiO_2	(%)	1.62
Mn_2O_3	(%)	0.04
P_2O_5	(%)	0.6
Cr_2O_3	(%)	0
SrO	(%)	0.18
ZnO	(%)	0.001
SO_3	(%)	0
LOI	(%)	2.81
CaO/SiO_2	ratio	0.10
$SiO_2 + Al_2O_3+Fe_2O_3$		86.77

Table 4.8 Weekly sampling report

Day	Date	% Retained on a 45µm sieve (Wet)	% LOI
		Standard: Max: 12.5% (SANS 1491:2)	Standard: Max:5.0% (SANS 1491:2)
Sunday	15-Jul-12	48.3%	0.97%
Monday	16-Jul-12	27.9%	1.58%
Tuesday	17-Jul-12	42.0%	1.17%
Wednesday	18-Jul-12	43.5%	0.86%
Thursday	19-Jul-12	29.7%	1.40%
Friday	20-Jul-12	33.8%	0.99%
Saturday	21-Jul-12	Plant Closed	Plant Closed

Average	37.5%

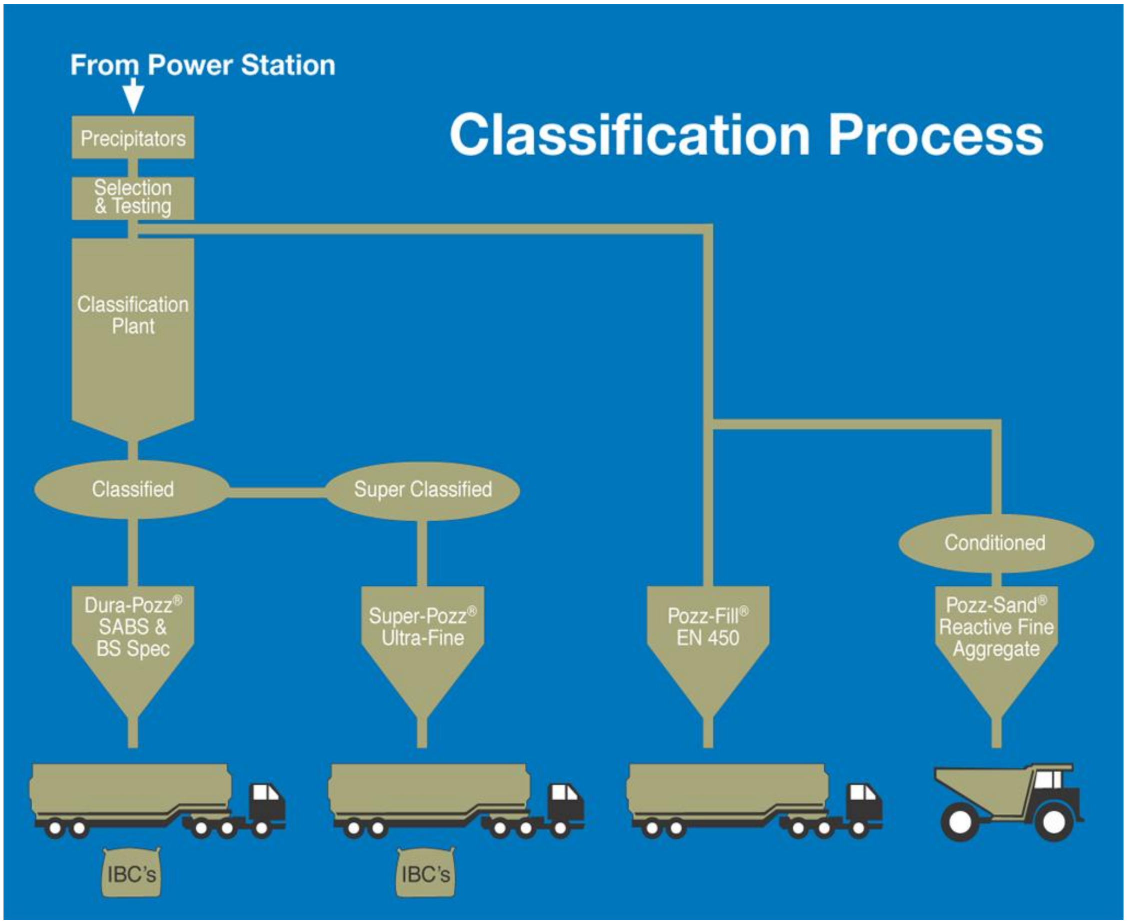


Figure 11: Air classification process of South Africa Fly Ash (Ash Resources, 2012)

4.5 Cement

The use of cement in this study is due to that South Africa only has Class F Fly Ash and these types of Fly Ashes require a cementing/reaction agent. The material as tested, see Table 4.13, is rated as non-plastic and cement is more effective for soils of low active clay content and to gain early strengths (Ventura, 2003). South Africa's cement is certified by SANS 50197-1(2000), Cement Part 1: composition, specification and conformity criteria for common cements. The cements produced generally consist of a combination of:

1. Milled Clinker (Portland Cement)
2. Ground granulated blast furnace slag
3. Fly Ash
4. Limestone
5. Silica Fume

Table 4.9 shows the common cement types and composition proportions by mass found in the typical South Africa. Cements have various descriptions according to SANS 50197-1. The type and composition is basically, labelled as CEM I, II, III, IV and V with the percentage mineral written next the composition for example: CEM II B-L 32.5N. The mineral composition is made of various values, which is namely:

1. S – Slag from blast furnace
2. B – indicate extension level (for CEM II a minimum 21%, maximum 35%)
3. M – indication that more than one extended is used
4. V – silicesous Fly Ash
5. W – calcereous Fly Ash
6. L – milled limestone
7. D – silica fume

The number, for example: 32.5, is the 28 day European Norm (EN) prism strength class as set out in the SANS 51096-1 (2006) test method. The alphanumerical values "N/R" is the indication of early age strength gain where the alphanumerical value N is for normal and the alphanumerical value R is for high early strength. According to the test method SANS 51096-1 (2006), 32.5N will have to achieve a minimum of 16 megapascal (MPa) EN prism strength on 7 days, where

32.5R will have to achieve a minimum of 10 MPa EN prism strength in 2 days (SANS 51096-1, 2006). South Africa has three strength classes namely; 32.5, 42.5 and 52.5. South Africa can produce a possible of 162 cement products with a combination of the allowable compositions (AFRISAM, 2012). Table 4.10 shows the branded names of South Africa common cements complying with SANS 50197-1 (2000).

In stabilisation projects, COLTO Section 3500 (1998), normally have a special clause written in the project contract document stating that all cements used for chemical stabilisation shall be SANS 50197-1:2000 approved and that the strength classes shall not be greater than 32.5. Figure 12 shows a typical project written specification for chemical stabilisation. Most of projects in South Africa do not allow strength class higher than 32.5 as higher thermal influences are obtained during hydration, which may lead to cracking (Fulton, 2009).

The following points are important when selecting the optimum cement for stabilisation:

1. Ability to modify quickly by reducing plasticity
2. Improve strength characteristics of the soil
3. Slow strength gain to allow for sufficient working time on site
4. Availability of the required product in the construction area.
5. Product application, bulk tanker or bags
6. Price

Companies in South Africa that produce cement products required for chemical stabilisation purposes is LAFARGE and AFRISAM. The products produced by each company for road stabilisation projects, is the following: LAFARGE Roadcem CEM II/B-M (V-S) 32.5N and AFRISAM CEM II VA (S-V) 32.5N. Each of these products is designed specifically to:

1. Improve engineering properties of road construction purposes
2. Reduce plasticity
3. Ensure strength and durability
4. Be effective across a wide range of material types

Both LAFARGE and AFRISAM products are available throughout South Africa and the main extension levels are 13% slag and 20% Fly Ash for LAFARGE and 27% slag and 30% Fly Ash for AFRISAM. Both products use the DURAPOZZ from Ash Resources in the products produced. In Table 4.11 the chemical properties are shown for both products LAFARGE and AFRISAM.

Table 4.9 Common Cement Types and Composition: proportions by mass (Fulton, 2009)

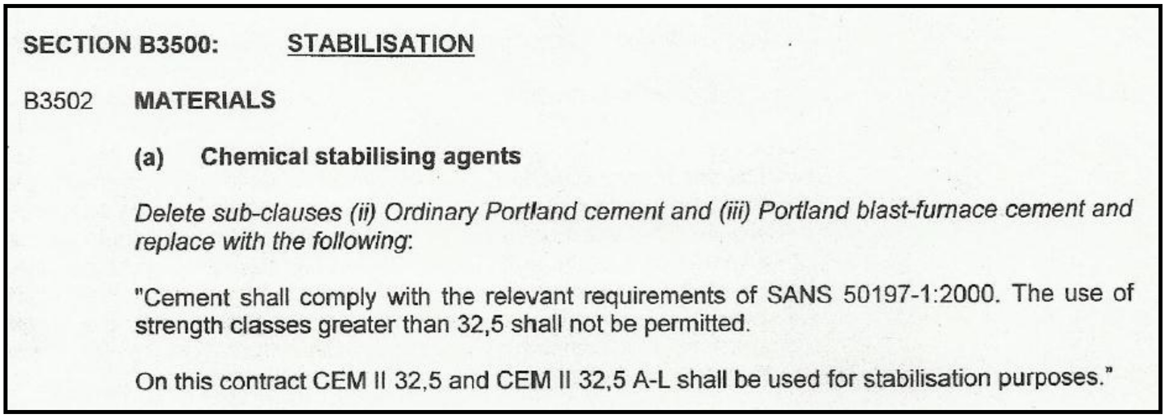
Main types	Notation of products (types of common cement)		Composition, percentage by mass[a]										
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		Minor additional constit-uents
						natural	natural calcined	siliceous	calca-reous				
			K	S	D[b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95 - 100	-	-	-	-	-	-	-	-	-	0 - 5
CEM II	Portland-slag cement	CEM II A-S	80 - 94	6 - 20	-	-	-	-	-	-	-	-	0 - 5
		CEM II B-S	65 - 79	21 - 35	-	-	-	-	-	-	-	-	0 - 5
	Portland-silica fume cement	CEM II A-D	90 - 94	-	6 - 10	-	-	-	-	-	-	-	0 - 5
	Portland-pozzolana cement	CEM II A-P	80 - 94	-	-	6 - 20	-	-	-	-	-	-	0 - 5
		CEM II B-P	65 - 79	-	-	21 - 35	-	-	-	-	-	-	0 - 5
		CEM II A-Q	80 - 94	-	-	-	6 - 20	-	-	-	-	-	0 - 5
		CEM II B-Q	65 - 79	-	-	-	21 - 35	-	-	-	-	-	0 - 5
	Portland-fly ash cement	CEM II A-V	80 - 94	-	-	-	-	6 - 20	-	-	-	-	0 - 5
		CEM II B-V	65 - 79	-	-	-	-	21 - 35	-	-	-	-	0 - 5
		CEM II A-W	80 - 94	-	-	-	-	-	6 - 20	-	-	-	0 - 5
		CEM II B-W	65 - 79	-	-	-	-	-	21 - 35	-	-	-	0 - 5
	Portland-burnt shale cement	CEM II A-T	80 - 94	-	-	-	-	-	-	6 - 20	-	-	0 - 5
		CEM II B-T	65 - 79	-	-	-	-	-	-	21 - 35	-	-	0 - 5
	Portland-limestone cement	CEM II A-L	80 - 94	-	-	-	-	-	-	-	6 - 20	-	0 - 5
		CEM II B-L	65 - 79	-	-	-	-	-	-	-	21 - 35	-	0 - 5
		CEM II A-LL	80 - 94	-	-	-	-	-	-	-	-	6 - 20	0 - 5
		CEM II B-LL	65 - 79	-	-	-	-	-	-	-	-	21 - 35	0 - 5
	Portland-composite cement[c]	CEM II A-M	80 - 94	←----				6 - 20				----→	0 - 5
		CEM II B-M	65 - 79	←----				21 - 35				----→	0 - 5
CEM III	Blastfurnace cement	CEM III A	35 - 64	36 - 65	-	-	-	-	-	-	-	-	0 - 5
		CEM III B	20 - 34	66 - 80	-	-	-	-	-	-	-	-	0 - 5
		CEM III C	5 - 19	81 - 95	-	-	-	-	-	-	-	-	0 - 5
CEM IV	Pozzolanic cement[c]	CEM IV A	65 - 89	-	←----		11 - 35		----→	-	-	-	0 - 5
		CEM IV B	45 - 64	-	←----		36 - 55		----→	-	-	-	0 - 5
CEM V	Composite cement[c]	CEM V A	40 - 64	18 - 30	-	←----	18 - 30	----→	-	-	-	-	0 - 5
		CEM V B	20 - 39	31 - 50	-	←----	31 - 50	----→	-	-	-	-	0 - 5

Table 4.10 South Africa Common Cements complying with SANS 50197-1(2000)

AFRISAM		Limpopo	Mpumalanga	Gauteng	Free State	KZN	Eastern Cape	NW Province	Northern Cape
CEM I	52.5N	RHC	RHC	RHC	RHC		RHC	RHC	RHC
CEM II A-M	42.5N	HSC	HSC	HSC	HSC	HSC	HSC	HSC	HSC
CEM II B-L	32.5N				APC		APC		APC
CEM III A	32.5N			EBC					
CEM V A	32.5N	APC	APC	APC	APC			APC	
		APC = All Purpose Cement			HSC = High Strength Cement				
		RHC = Rapid Hard Cement			EBC = Eco Building Cement				
LAFARGE		Limpopo	Mpumalanga	Gauteng	Free State	KZN	Eastern Cape	NW Province	Northern Cape
CEM II A-V	52.5N	RapidCem	RapidCem	RapidCem	RapidCem	RapidCem		RapidCem	RapidCem
CEM II A-V	42.5N					Power crete			
CEM II A-M (V-L)	42.5N	Roadcem	Roadcem	Roadcem	Roadcem	Roadcem		Roadcem	Roadcem
CEM II B-M (V-S)	32.5N					Build crete			
CEM IV A-V	32.5R	Build crete	Build crete	Build crete	Build crete	Build crete	Build crete	Build crete	Build crete

Table 4.11 Chemical properties of cement (Lafarge and AFRISAM Data Sheet, 2012)

Chemical Properties			
	Lafarge	Afrisam	Requirements (EN 197)
SO_3	2.30%	2.30%	≤3.5% m/m
Cl	0.02%	0.04%	≤0.10% m/m



SECTION B3500: **STABILISATION**

B3502 **MATERIALS**

(a) Chemical stabilising agents

Delete sub-clauses (ii) Ordinary Portland cement and (iii) Portland blast-furnace cement and replace with the following:

"Cement shall comply with the relevant requirements of SANS 50197-1:2000. The use of strength classes greater than 32,5 shall not be permitted.

On this contract CEM II 32,5 and CEM II 32,5 A-L shall be used for stabilisation purposes."

Figure 12 Project specifications for chemical stabilisation with cement

4.6 Classified Material

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).

The material supplied for stabilisation purposes in this study is a classified G5 crushed granite. Good quality base and subbase material for road construction is becoming increasingly scarce. Granite is one of the more abundant natural road building and one of the most important materials for construction of high quality pavement layers in roads in South Africa as it associated with the acid crystalline group of rocks. Granite is a common type of felsic intrusive igneous rock that essentially contains feldspar, quartz, hornblende and mica. Quartz's hardness, lack of chemical reactivity and near lack of cleavage give granite a significant amount of desirable durability properties that is required for road pavement construction. Granite is marked by the underlying rock upon which sedimentary and other continental rocks rest. Granite 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 13. Weathering effects in granite manifest mainly in the replacement of the feldspar components by clay minerals, chiefly illite and/or kaolinite (Fultons, 2009).

The G5 classified granite "crushed" was subjected to tests shown in Table 4.12. The table is taken directly from Table 3402/1 in the COLTO standards, which is the requirements for soil types G4 to G6 materials (COLTO, 1998). The additional test includes:

1. Ethylene Glycol (EG), which is discussed in point 5.3.5.4 of this thesis,
2. Extension of the plastic index test, which requires material passing the 0.075 micron sieve and dictates an mixing time of 20 minutes instead of the 10 minutes as stated in the TMH1 test method (Journal of SAICE) of the results are shown in Table 4.13.

The grading envelope is also one of the most important factors in the soil classification process and the envelope specifications as shown in Figure 14 is also specified according to Table 4.13.

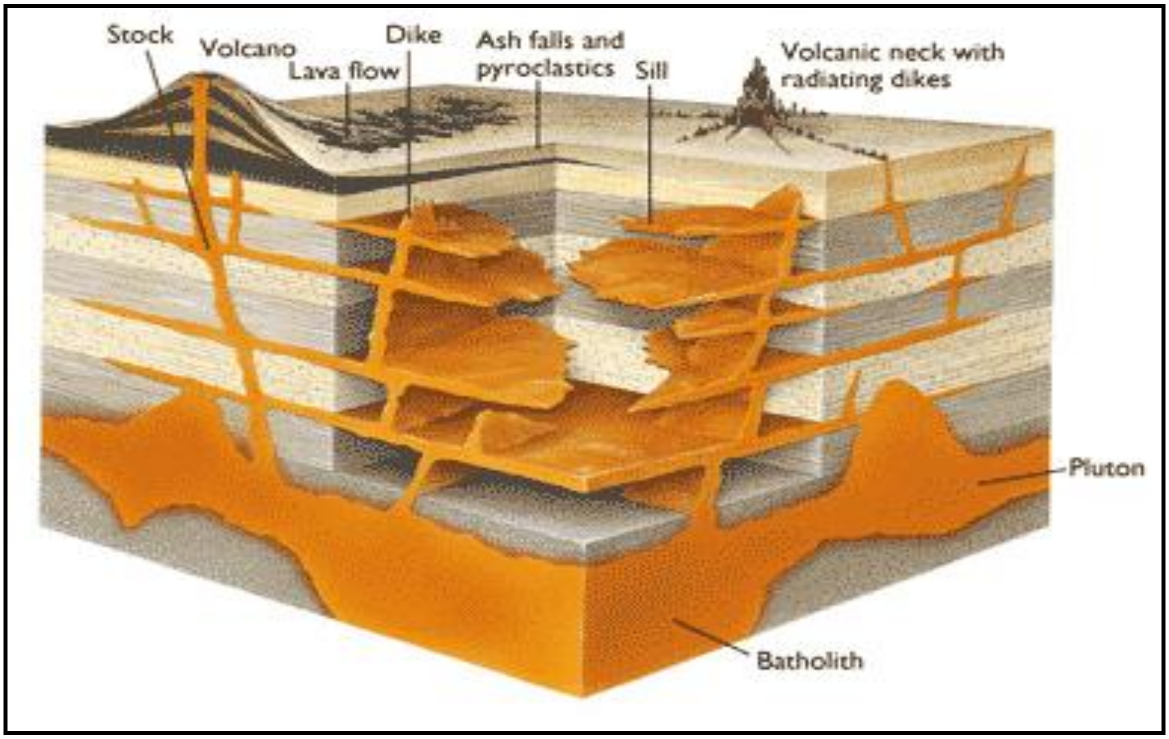


Figure 13 Example of Dykes and Sill

Table 4.12: Requirements for types G5 materials (COLTO, 1998)

Property		Type of Material G5
Description of Material		Natural Gravel, or natural gravel and boulders which may require crushing, or crushed rock
Additional Fines		May contain approved natural fines not obtained from parent rock
Nominal Maximum Size		(i) Uncrushed material : 63mm (ii) Crushed material: 53mm before compaction
Fractured Faces		All alluvial and colluvial material shall be crushed so that at least 50% by mass of the fraction retained on the 4.75mm sieve shall have at least one fractured face
Grading	Aperture size (mm)	The percentage by mass passing the 2.0mm sieve shall not be less than 20% nor more than 70%
	53	
	37.5	
	26.5	
	19	
	13.2	
	4.75	
	2	
	0.425	
	0.075	
Grading Modulus (GM)		$2.5 \geq GM \geq 1.5$
Atterburg Limits for Natural Material (-0.425mm Fraction)		(a) All materials except calcrete: LL shall not exceed 30, PI shall not exceed 10, LS shall not exceed 5%
Strength (CBR)		CBR at 95% of modified AASHTO density shall not be less than 45%
Swell (Maximum)		Swell at 100% of modified AASHTO density shall not exceed 0.5%

Table 4.13 Granite Test results versus COLTO specifications table

Property		Type of Material G5	Test Results
Description of Material		Natural Gravel, or natural gravel and boulders which may require crushing, or crushed rock	Granite
Additional Fines		May contain approved natural fines not obtained from parent rock	Mostly Parent Rock
Nominal Maximum Size		(i) Uncrushed material : 63mm (ii) Crushed material: 53mm before compaction	100% Passing the 53mm Sieve
Fractured Faces		All alluvial and colluvial material shall be crushed so that at least 50% by mass of the fraction retained on the 4.75mm sieve shall have at least one fractured face	N/A
Grading	Aperture size (mm)	The percentage by mass passing the 2.0mm sieve shall not be less than 20% nor more than 70%	Results
	53		100
	37.5		92
	26.5		78
	19		67
	13.2		57
	4.75		44
	2		34
	0.425		18
	0.075		6
Grading Modulus (GM)		$2.5 \geq GM \geq 1.5$	2.42
Atterburg Limits for Natural Material (-0.425mm Fraction)		(a) All materials except calcrete: LL shall not exceed 30, PI shall not exceed 10, LS shall not exceed 5%	Non Plastic
Strength (CBR)		CBR at 95% of modified AASHTO density shall not be less than 45%	60%
Swell (Maximum)		Swell at 100% of modified AASHTO density shall not exceed 0.5%	0.00%

GRADING ANALYSIS

SIEVE	Min Spec	Max Spec	G5
63	100	100	
53	100	100	100
37.5	100	100	97
26.5	100	100	82
19	85	95	72
13.2	71	84	64
4.75	42	60	51
2.00	27	45	38
0.425	13	27	18
0.075	5	12	7

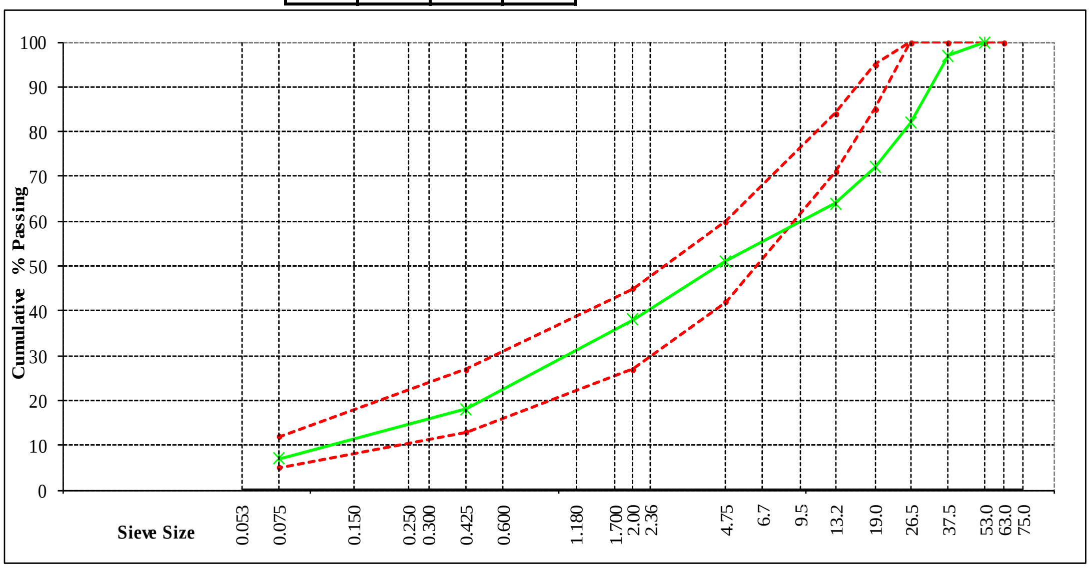


Figure 14: Grading envelope for the G5 classified material

4.7 Discussion

The Fly Ash can be divided into two criteria for key discussion points namely: Chemical and physical properties.

Chemical Properties

The silica (SiO_2) forms stable cementitious compounds in reaction with calcium hydroxide ($Ca(OH_2)$) and with addition of water, the pozzolanic reaction will continue for a considerable period of time. The high percentage of SiO_2 shown in Tables 4.2, 4.5 and 4.7 confirms that all three Fly Ash samples for this study will continue with the reaction process. The lime/silica (CaO/SiO_2) ratio, which is indicative of cementing potential, varies between 0.08 for the DURAPOZZ in table 4.2 and 0.1 for the POZZFILL and Kendal Dump Ash respectively as shown in Table 4.5 and 4.7. All three Fly Ash specimens show a low cementing potential therefore a cementing agent will be required during any stabilisation project. It has been found that the higher the ratio is, the higher the CBR results will be (Tuncer, 2006). 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 Feric 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 4.2, 4.5 and 4.7, it shows that all three Fly Ashes fall in the range of Class F Fly Ash (ASTM C618, 1993).

The LOI is a measurement of unburned coal remaining in the Ash and is critical characteristic of Fly Ash. In concrete, for instance, high carbon levels, type of carbon, the interaction of soluble ions in Fly Ash can result is significant air entrainment problems in fresh concrete, and can affect the durability of concrete. LOI is low on all 3 Fly Ashes as shown in Tables 4.1, 4.2 and 4.3 varied from 0.46 to 0.88 for DURAPOZZ, POZZFILL in Tables 4.4, 4.5 and 4.6 varied from 0.52 to 2.81. Kendal Dump Ash in Tables 4.7 and 4.8 varied from 0.86 to 2.81. All three are well below the required standard of not greater than 5%. (SANS 1491-2, 2005). LOI will not limit strength of hydrated Fly Ash as long as the Fly Ash contains sufficient lime to react with the 3 main ingredients of Fly Ash namely: Fe_2O_3, Al_2O and SiO_2 (FAS) (Conn *et al*, 1997). Class F Fly Ash has very low fCaO content; therefore it will be critical that the LOI is low for the purpose of strength gain over time. 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

SO_3 content must be low to prevent formation of calcium sulphite ($CaCO_3$) that will cause the formation of ettringite. Ettringite increases volume, expansion and cracks can occur (Conn, 1997; Fulton, 2008). fCaO will form free $Ca(OH_2)$ when mixed with water and when in contact with carbon dioxide (CO_2) will form carbonates as shown in the formulae:

$Ca(OH_2) + CO_2 \rightarrow CaCO_3 + H_2O$

Carbonation will thus occur, which means that the cement will revert back to the initial compounds from which it is made. This reaction will cause that the stabilisation process will no longer continue and the preservation of the cementing compounds will cease as the stabilised materials are reverted to un-cemented, granular materials. Netterburg found that carbonation appears to be most rapid at relative humidities of about 50% and minimal at very low and high humidities (Netterberg *et al*, 1984; Concrete Technology, 2013).

fCaO is one of the key components that influences the strength of hydrated ashes. The main components of Fly Ash is the amount of fCaO in combination with FAS that influence the strength of hydrated ashes (Conn *et al*, 1999). The free lime, once hydrated to CaO, would undergo pozzolanic reactions with FAS to form complex hydrates as shown in the following formulae:

$SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.2H_2O2$

$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.Al_2O_3.2H_2O$

$SiO_2 + Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.Al_2O_3.2H_2O$

$Fe_2O_3 + Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.Al_2O_3.Fe_2O_3.2H_2O$

Physical Properties

The fineness for DURAPOZZ is within specified limits of less than 12.5% as shown in Tables 4.1 and 4.3, where the results varied from 9.7% to 11.1%. POZZFILL and Kendal Dump Ash do not make the required specifications as the results varied from 32% to 35.2% in Tables 4.4, 4.6, for POZZFILL and varied from 27.9% to 48.3% in table 4.8 for Kendal Dump Ash. 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 3.350mm to 0,002mm for Kendal ash as seen in Figure 15 and 0.300mm to 0,002mm for both DURAPOZZ and POZZFILL as seen in Figure 15. 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. DURAPOZZ and POZZFILL Fly Ash have most of the particle sizes between 0,020mm sieve and 0,300mm sieve, therefore these will react slowly over time. The Kendal Dump Fly Ash has a variation in particle sizes reading from 81 percent passing the 0,300mm sieve to 21percent passing the 0,020mm sieve. 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 will only contribute 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 17 gives a visual idea of Fly Ash reactivity according to gradation. DURAPOZZ Fly Ash has the highest of passing the 0.020mm sieve of 54 percent followed by POZZFILL Fly Ash with 37 percent passing the 0.020mm sieve and then Kendal Dump Fly Ash with 21 percent. The particles passing the 0.005mm sieve has shown a reverse, as previously stated, as the Kendal Dump Fly Ash has more particles passing the 0.005mm sieve than compared to the DURAPOZZ Fly Ash and POZZFILL Fly Ash. This might be a reason why the Kendal Dump Fly Ash perhaps have a better reaction compared to the processed DURAPOZZ Fly Ash and the POZZFILL Fly Ash. It was also stated that at least 40 percent should pass the 10 micron sieve for more reactive material but this is not the case with Kendal, DURAPOZZ or POZZFILL as seen in Figure 15. 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 3 Fly Ashes in this study have enough pozzolanic material to continue with the slow reactions which will occur continuously over time. Both DURAPOZZ Fly Ash and POZZFILL Fly Ash are fine silty Fly Ashes, which is common of Fly Ash and can be used to improve gradings of coarse granular materials. Kendal is coarse graded but can be of value to weaker material to improve grading thus increasing the strength values of the material. It is critical that the fineness of Fly Ash be within limits stated by ASTM, stabilisation standards will greatly depend on Fly Ash fineness and its particle size distribution. 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 allowable to be retained on the 44µm sieve is not to exceed 34%. It can then be stated that with SANS 1491-2 only DURAPOZZ can be utilised if the required specification is enforced but with AASHTO M295, all 3 Fly Ashes can be utilised for design and construction purposes. Tables 4.3, 4.6 and 4.8 shows the sampling of Fly Ash over a 7 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. Both DURAPOZZ and POZZFILL are consistent with gradation and LOI requirements, due to that both DURAPOZZ and POZZFILL are already processed but the Dump Ash varies with gradation requirement, thanks to it being sampled directly from the disposal landfill sites. This can be overcome by installation of mechanical sieve operations that can sieve out the Fly Ash to a uniform standard so that the percentage retained on the specified sieve is obtained throughout the construction process. The colour of each of the Fly Ash specimens varied from pale grey for

DURAPOZZ, Light grey for POZZFILL to dark Grey for Kendal Dump Ash. The colour depends on its chemical and mineral constituents. Fly Ash is very consistent for each power plant and coal resources. The tan colour is associated with high lime content and dark grey is associated with unburned carbon content.

Fly Ash is composed of various elements as shown in Table 3.1, x-ray spectrometry of the Kendal Dump Ash. One should also take into account the values of Sodium, Magnesium and Calcium, as the combination of these 3 will also contribute to strength gain. As indicated in Figure 16, the values shows that Kendal has a much higher value, which will give the advantage to Kendal Dump Fly Ash for better strengths gain in the early stages of stabilisation.

The 3 Fly Ashes in the this study needs a cementing agent as per information provided in Chapter 4, therefore it is recommended that the Fly Ash conform to the standards set out and discussed in this document, to make sure that proper reaction will take place and that the reaction continues over a period of time.

Classified Material

The Grading envelope as indicated in Figure 14 shows that the material conforms to the G5 specification, as also stated in Table 4.15. The envelope was drawn up using the G4 Classification grading specification to envisage the future use of this type of material as a G5 classified material but with a G4 grading. On most of the road construction projects in South Africa, project specifications do request that the subbase have a minimum standard of a G5 classified material but with a G4 grading specification if the material is crushed. Most of the insitu G5 on the roads do not have to meet the G4 grading material specification but still needs to conform to the G5 classifications. Coarse grained materials can normally carry much heavier loads without deformation than finer materials. In Figure 14, it shows that the material is quite coarsely grained between sieves 63mm micron and 4.75mm micron. The grading modulus for the specific sample was 2.42, which would indicate coarsely grained and relatively good material. The test results shown in Table 4.16 also reveal that the samples do conform to the required classification for a G5 material. The results, when compared to COLTO (1998) classification, shows that if the grading was within the envelope, as shown in Figure 14. This material could be classified as a G4, due to that at 98% of modified AASHTO density, the California Bearing Ratio (CBR) is 90 where in the COLTO specifications it requires at least 80 (COLTO, 1998). This material may in fact, if crushed through the 37,5mm sieve become a G4 classified material. The CBR is an indirect measure of the shear strength on bearing capacity under one load. The swell shows an indication of changes in volume, and due to that the material is non-plastic and coarsely graded.

There are no changes in volume as shown in Table 4.16 as the reading is 0.0%. The atterburg limits measure the plasticity of the soils. This gives a strong indication of the sensitivity of the material to water. The results, shown in Table 4.16, indicate that the material is non-plastic (NP). Ethylene Glycol (EG) is used to check the durability of crystalline rock groups. This shows whether the rock is prone to rapid weathering after exposure to atmosphere. This does occur when rocks contain clay minerals and some of the common rock types in the crystalline group are known for primary minerals in the rock to be altered to the active clay (Jenkins). As stated previously, South Africa has some rapid weathering rock types and the EG test will give an indicator if the material has potential problematic aggregates. The EG test including results is discussed in detail in Chapter 5 of this study.

GRADING ANALYSIS

SIEVE	Kendal	Durapozz	Pozzfill
3.350	100		
2.360	98		
1.180	94		
0.600	90		
0.425	86		
0.300	81	100	100
0.150	64	99	96
0.075	47	96	87
0.060	40	77	68
0.050	36	73	63
0.020	21	54	37
0.005	7	2	2
0.002	1	1	1

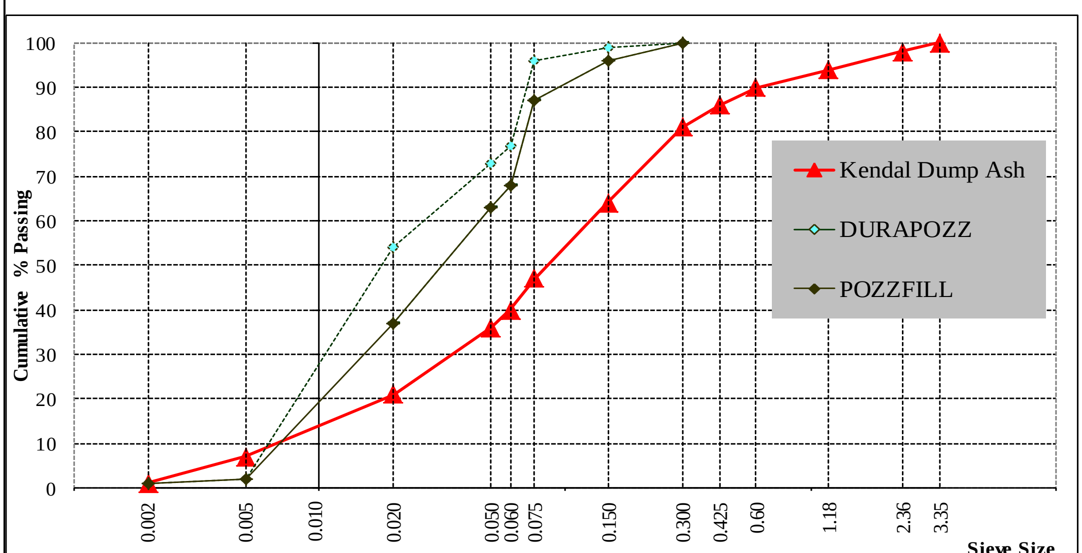


Figure 15: Size distribution curves of Fly Ash

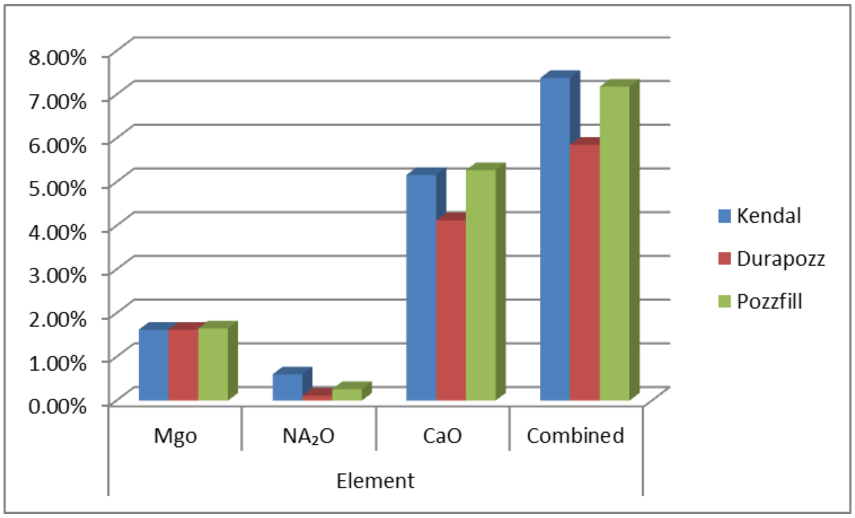


Figure 16: Strength gain elements of Sodium, Magnesium and Calcium

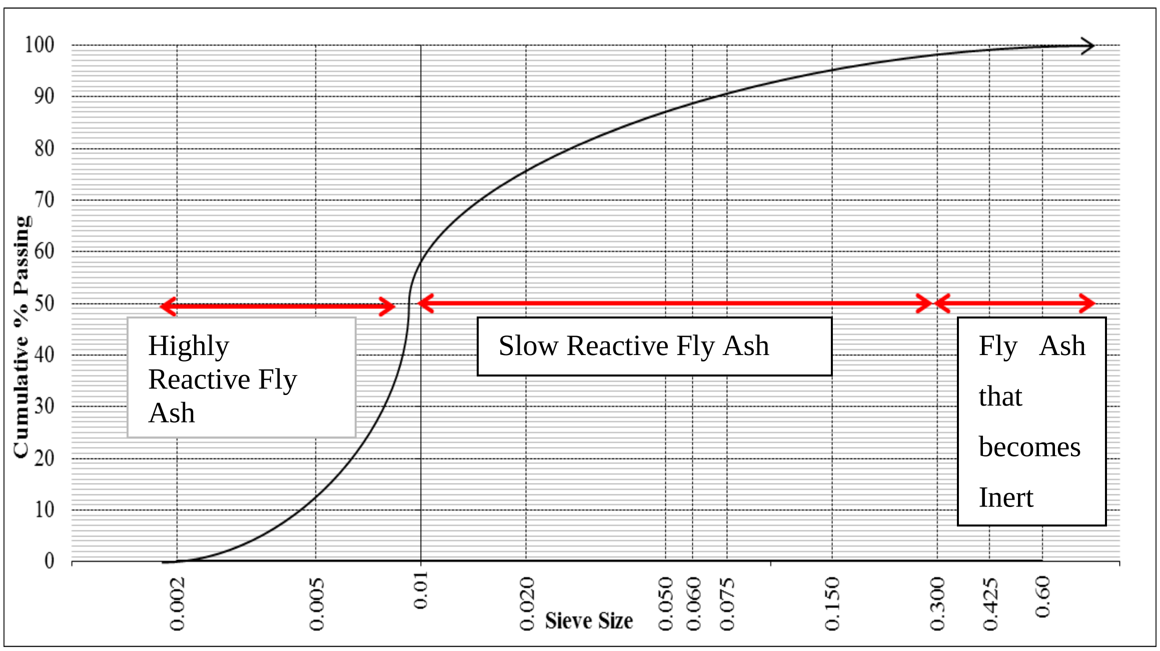


Figure 17: Reactivity of Fly Ash according to Grading

4.8 Summary

Stabiliser selection is a critical path in any stabilisation design process. Each layer must be designed to be:

1. Resistant to shearing
2. Resistant to excessive deflections

3. Resistant to permanent deformation through densification

General guidelines in South Africa is utilised, to obtain desired properties of the soil, for design purposes which can be followed in TRH3, TRH14, COLTO and TRH4. The choice of stabiliser is dependent on the properties of the soil and the purpose for which the pavement will be utilised in the design.

With use of Fly Ash as a suitable stabiliser, is fairly new to South Africa but not new worldwide. In this study, 3 types of Fly Ashes chosen from which two are processed and one is sampled directly from the dump sites, namely: DURAPOZZ, POZZFILL and Dump Ash. To utilise Fly Ash in a stabilisation design process, 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 an additive in the stabilisation process. To date, no actual standards exist in South Africa for the use of Fly Ash as a suitable soil stabiliser, therefore current standards that are being used for cement production needs to be sued and adopted to suit the needs for soil stabilisation evaluation.

With this in mind, three important factors were identified from test results of the Fly Ash:

1. All three Fly Ashes is classified as a Class F
2. The cementing potential is low, therefore the Fly Ash needs a reaction/cementing agent for the proper reactions to occur and continue over time
3. The Fly Ashes have the required pozzolans for reactions to continue for a long period of time after the initial reaction has taken place, in combination with the reaction/cementing agent.

The Fly Ash must be evaluated chemically to the basic steps identified, namely:

1. Classification of the Fly Ash by using results from the XRF analysis.
2. Evaluate the cementing potential
3. Evaluate the pozzolanic reaction time to predict whether the reaction will continue for a long period of time.
4. Determine the Loss Of Ignition (LOI) for strength evaluation
5. Determine of Sulphur (SO_3) content for the formation of ettringite
6. Determine the amount of free lime (fCaO) for activation of carbonation
7. Analyse total amount of Sodium (NA_2O), Magnesium (MgO) and Calcium (CaO), which contributes to higher strengths.

On the physical aspect of the Fly Ash, it is critical that the fineness is less than 45% retained on the 0.045mm sieve as a coarse Fly Ash could lead to less reactive Fly Ash. A full gradation is also an important factor as the reactivity can be determined. The gradation can be divided into three areas, namely: percentage above 0,300mm sieve, percentage between 0,300mm sieve and 0,010mm sieve and the percentage below 0,010mm sieve. The percentage above the 0,300mm sieve is non-reactive and the Fly Ash can be evaluated as an extra filler to improve the gradation of the soil. The section between 0,300mm sieve and 0,010mm sieve is an indication that the Fly Ash will slowly react over time, in which the Class F Fly Ash mostly falls. The area beneath the 0,010mm sieve is the initial reaction that take place immediately and which is only applicable to Class C category Fly Ash. All three Fly Ashes gradation fall between the 0,300mm sieve and the 0,010mm sieve which is indicative that slow reaction will take place and over long time, and also indicates the reason for a reaction/cementing agent to start the initial reaction, as seen in Figure 17.

The Fly Ash in this study have colours of pale grey to dark grey, which is indicative of its chemical and mineral constituents and association with unburned carbon content.

Cement is used in this study, seeing as the Fly Ash, classified Class F, needs a reaction/cementing agent and is the best for low active clay mineral to obtain/gain early strength. Two types of cement was used, which is produced by two different manufactures but contain various mineral compositions. These two types are used throughout South Africa for road stabilisation projects and are readily available, and conform to specifications set out by road authorities.

The classified G5 material is a granite origin and is an abundant material in most of the regions in South Africa. The selection of crushed is so that it can be evaluated as a suitable subbase G5 materials with a possible G4 grading, as it is mostly a requirement from some road authorities in South Africa. Durability is the key for all stabilisation projects with this type of material and additional testing needs to be completed over and above the norm to ensure the life span of the designed pavement layer for which it is to be utilised for.

Chapter 5 Stabilisation Methodology

5.1 Introduction

This chapter focuses on tests that are carried out to ensure the required standards are achieved. The main focus will be on the actual basic design process testing, to evaluate whether the material can be stabilised with Fly Ash using a small percentage of cement as a reaction/cementing agent.

5.2 South Africa Test Protocols

South Africa test protocols have been developing over many years. Protocols have been used from all over the world, and adapted to suit the conditions and materials in South Africa. The majority of major roads in South Africa are built to the requirements of the Standard Specifications for Roads and Bridge Works for Road Authorities (COLTO, 1998). Protocols used by the road building industry keeps evolving and is updated due to several factors:

a. Advances in pavement design

b. More sophisticated testing to evaluate engineering properties more accurately

c. Introduction in new design technologies.

Material quality in the top layers of the pavement is of the highest quality and this is to produce the most cost effective flexible road pavement. New innovative designs are encouraged to use material and modify them if necessary to obtain the most cost effective road pavement. The use of recycled products and waste are playing an important role in ways to produce the effective ways for cost effectiveness and to suite the advances in pavement design and new design technologies. New protocols are developed which would encourage the uses of various new designs for an effective greener future.

5.3 Methodology

Lime and cement stabilisation have been modified by modern laboratory and field tests to fulfil a variety of stabilisation requirements. Treatment of soil to improve its strength and deformation resistance is referred to as stabilisation. Strength is expressed in terms of compression, shear, bearing or load deflection value that indicates load-bearing quality. Durability is indicated in terms of resistance to moisture absorption, softening, strength reduction, freezing and thawing, wetting and drying cycles.

Stabilised layers, not only become permanent with age, but its strength increases over time. This has been proved through many research projects which included a study completed in the 1940's at an airport in Langebaan, close to Cape Town. The airport's runway base was stabilised with cement and 40 years later, samples were re-tested and analysed and the results concluded that the strength tests showed no weakening of the material and was still to the specifications required during the construction phase. The general purpose of soil stabilisation is: to increase strength or bearing capacity, minimize soil compressibility, diminish the flow or migration of sub-surface moisture, lessen erosion by surface water, provide a stable working platform for construction, aid mechanical compaction of soils, and reduce expansive property of soils.

Currently, in South Africa, no national standards for composition or utilisation of non-traditional soil stabilisers exist. To be able to use non-traditional soil stabilisers, specific material properties should be identified and tested to determine whether the specified requirements are met. Once the criteria are established, the cost effectiveness of the product should be determined. This study will look at three different types of stabiliser agents and how the combination of each in separate materials can exhibit very different strength versus time characteristics. It is therefore recommended at the design stage that apart from comparisons between short-term curing methods. It should be noted that laboratory conditions do not resemble field conditions and that short-term curing does not represent long-term field curing. At least one sample set must be considered for long term curing of 90 days (SAPEM, 2010).

It is generally accepted in South Africa that materials for treatment with lime or cement should be at least a G6 quality but for the purpose of this study and with the history of project specifications in South Africa, a G5 quality was sourced. The laboratory tests carried out in design stage is to make sure that the type and quantity of stabiliser treatment will be effective and long-lasting. To ensure material suitability and durability for stabilisation, laboratory testing follows the basic design steps shown in Table 5.1.

Table 5.1 Basic design steps for laboratory stabilisation design

Description	**Test Method**
Initial consumption of lime/stabiliser	TMH1, Method A21T
Maximum dry density and optimum moisture content of laboratory mixed cementitously stabilised materials	TMH1, Method A7
UCS (Unconfined compressive strength)	TMH1, Method A14
ITS (Indirect tensile strength)	TMH1, Method A16T
CSIR erosion test	CSIR

5.3.1 Initial Consumption of Lime/Cement (ICL,ICC)

The gravel initial consumption test is carried out to determine what approximate quantity of stabiliser will be required. The samples are prepared with various stabiliser contents where the contents are usually from 0% to 10%. Water is added so that material forms a paste. A pH meter is then used to measure the pH levels of each paste, and each pH level is then plotted against each stabiliser content. The reading that is close to a pH reading of 12.4 and remains stable is taken as the ICL/ICC of that specific material. Experience has shown that plasticity is permanently reduced only if sufficient stabiliser is added to maintain the pH levels above 12.0 so that cementation occurs and is maintained. Sufficient stabiliser must be added to satisfy the initial consumption of lime or cement and maintain the pH of suitably high level for the design life of the structure to ensure that long-term cementation occurs (Ventura, 2003).

The initial test was with the two cement products namely: LAFARGE CEM II 32,5 VA(S-V) and AFRISAM CEM II 32,5 B-M(S-V), to evaluate at what percentage the pH values will stabilise. Figure 18 and Figure 19 shows that both cement products have pH readings of close to 12.4 at 1% cement with readings of 12.59 for LAFARGE and 12.54 for AFRISAM. The cement pH values stabilised between 4% and 5% for both cement products, with stabilised pH readings of 12.97 for AFRISAM and 13.04 for LAFARGE. These readings show that the G5 material under the study has a high demand of cement to satisfy the initial consumption. Due to that, only 1% cement will be used in this study. It can be concluded that a high percentage of Fly Ash will be required to satisfy the demand for required strengths to be achieved. As stated, research has shown that a high percentage of Fly Ash added varies between 10% to about 20% depending on the quality of the Fly Ash.

With this in mind, ICC was completed with the following mixtures:

% Fly Ash: 6, 9, 12, 15, 18, 21 and 24 each mixed with 1% LAFARGE CEM II 32,5 B-M(S-V)

% Fly Ash: 6, 9, 12, 15, 18, 21 and 24 each mixed with 1% AFRISAM CEM II 32,5 VA(S-V)

This will give an indication at what pH levels the material will stabilise to meet the required strength and satisfy the demand. The high percentage is due to the reason that Fly Ash is classified as Class F, which is a poor quality Fly Ash. Figure 20 to Figure 25 shows the ICC results for the mixtures of Fly Ash with 1% of cement. The ICC results indicated that the average pH readings stabilised between 9% and 15% with 1% cement.

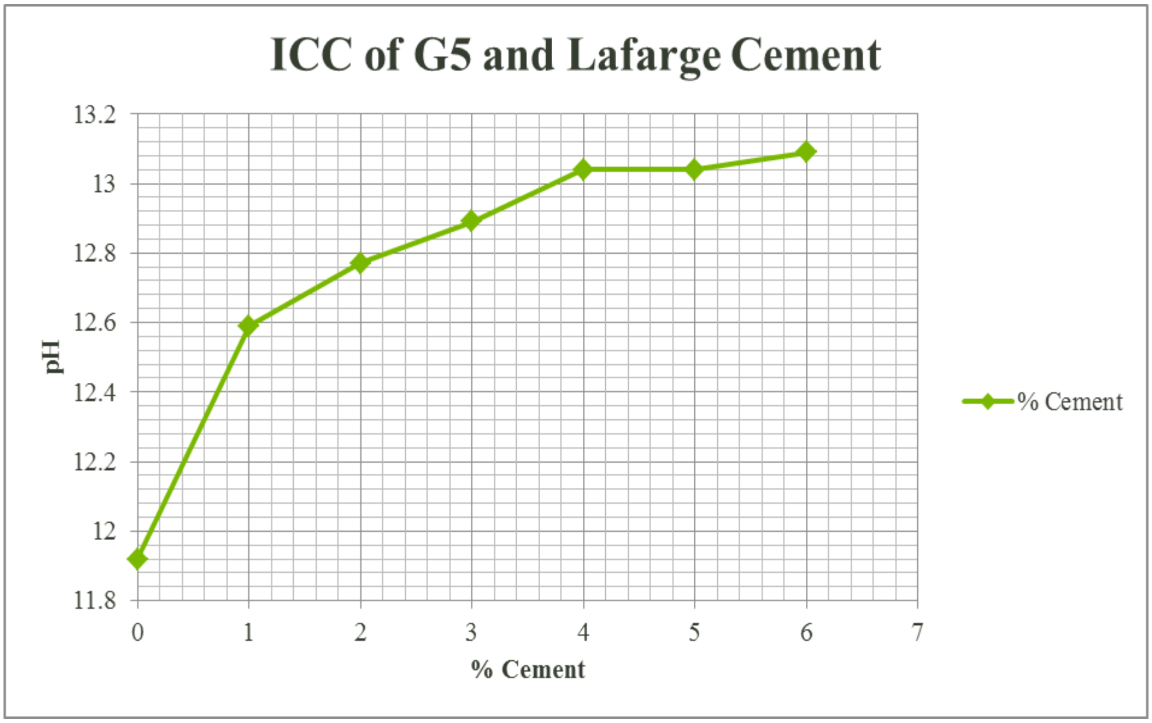


Figure 18 ICC for G5 material with LAFARGE cement

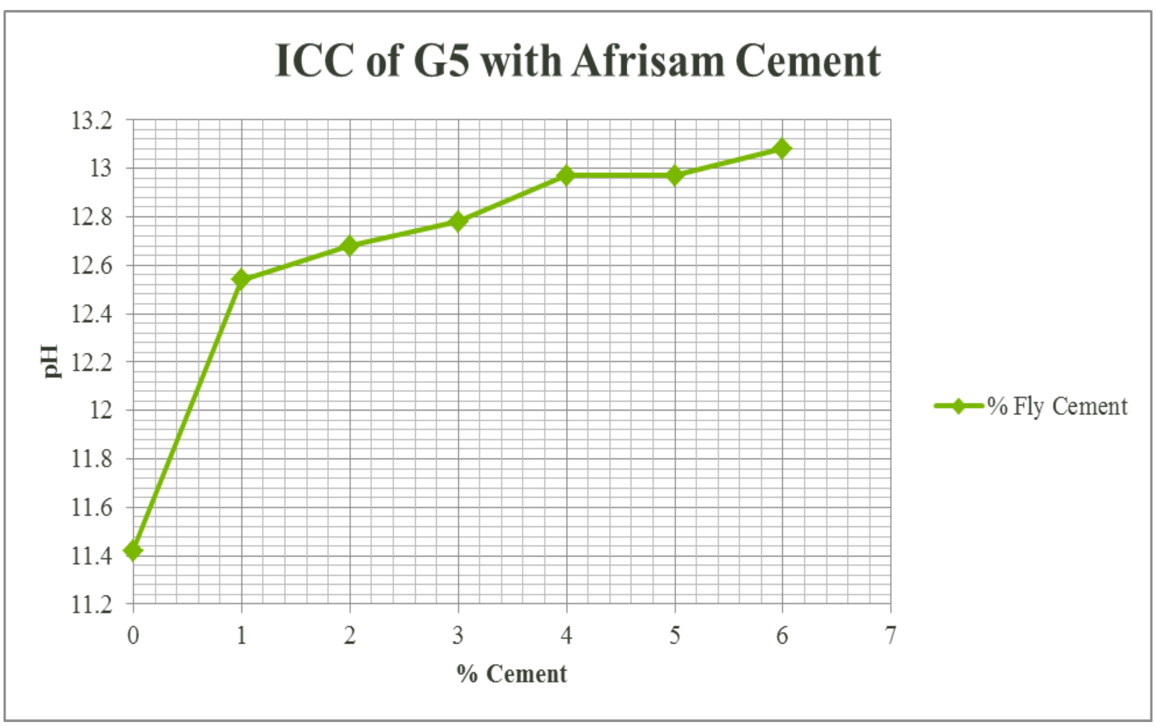


Figure 19 ICC of G5 material with AFRSIAM cement

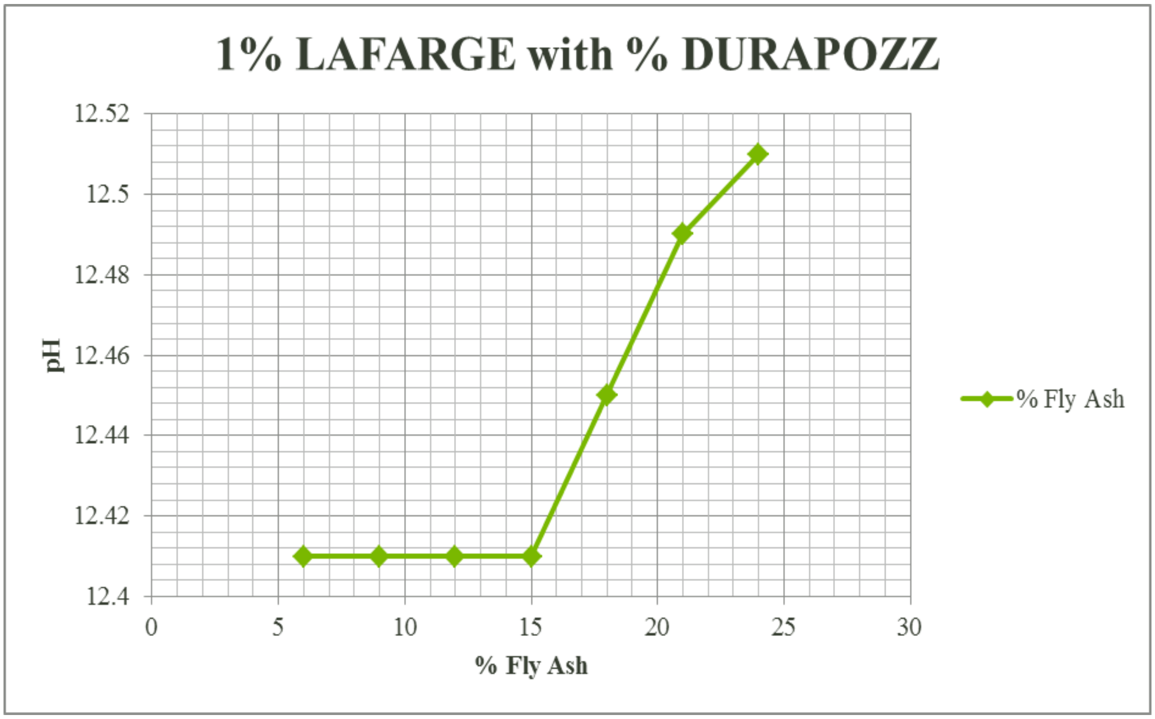


Figure 20 DURAPOZZ Fly Ash percentages mixed with 1% LAFARGE cement and G5 material

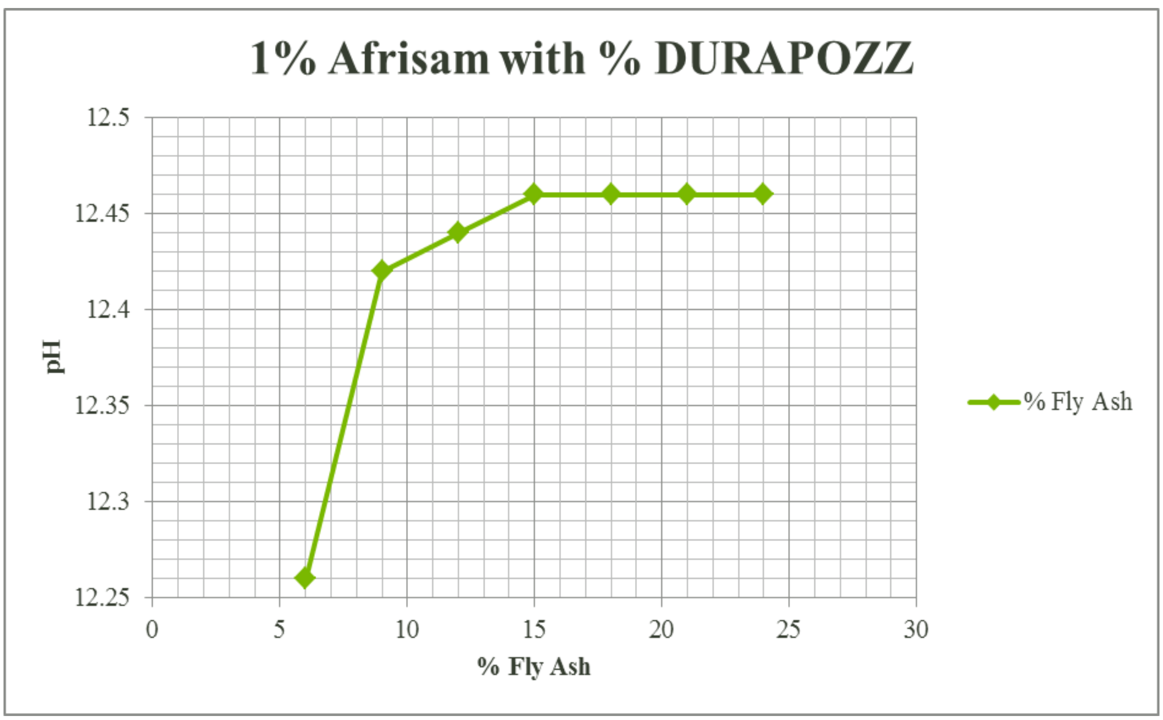


Figure 21 DURAPOZZ Fly Ash percentages mixed with 1% AFRISAM cement and G5 material

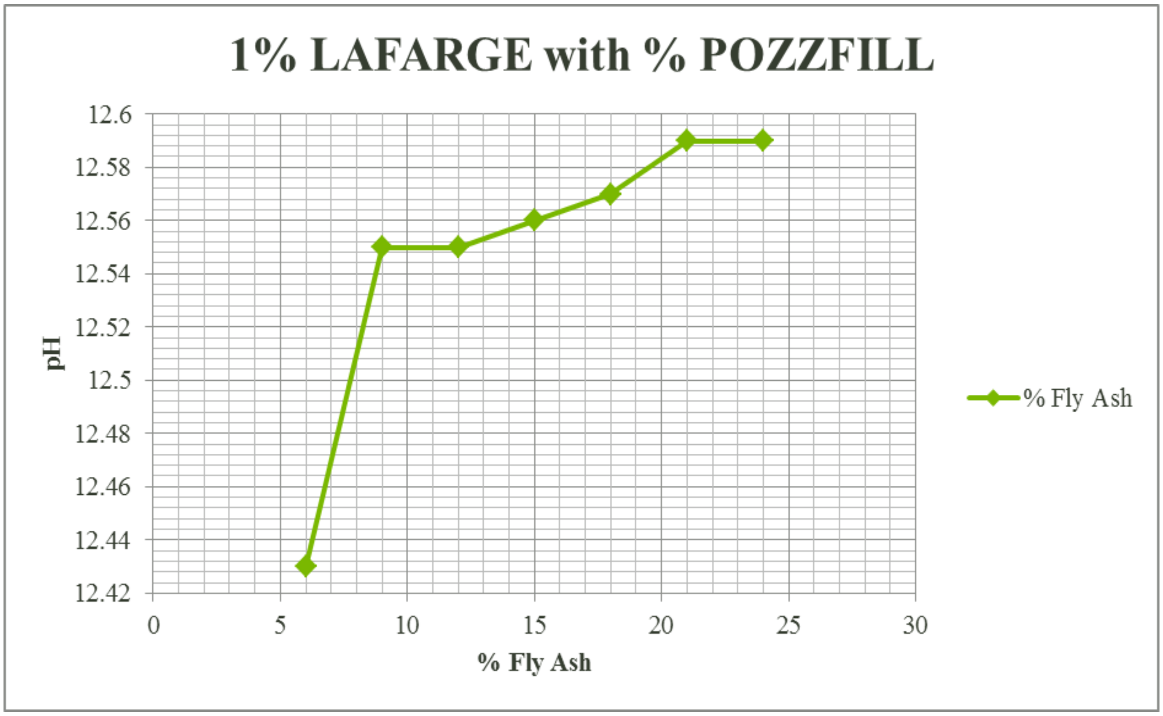


Figure 22 POZZFILL Fly Ash percentages mixed with 1% LAFARGE cement and G5 material

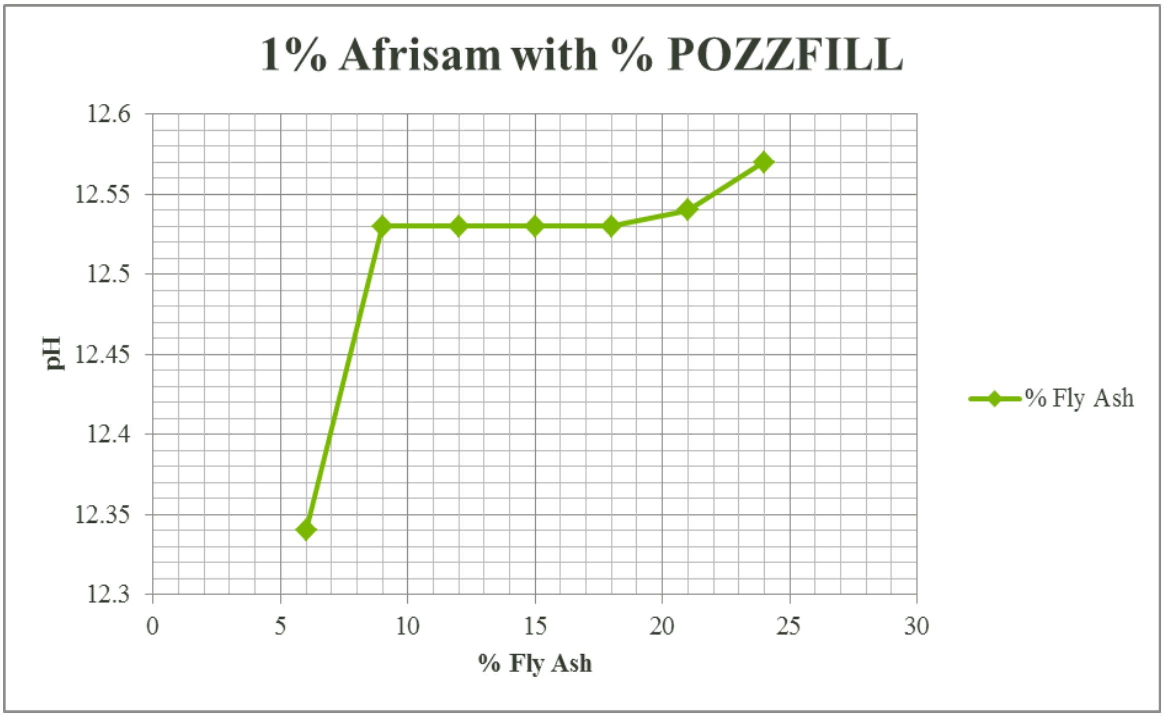


Figure 23 POZZFILL Fly Ash percentages mixed with 1% AFRISAM cement and G5 material

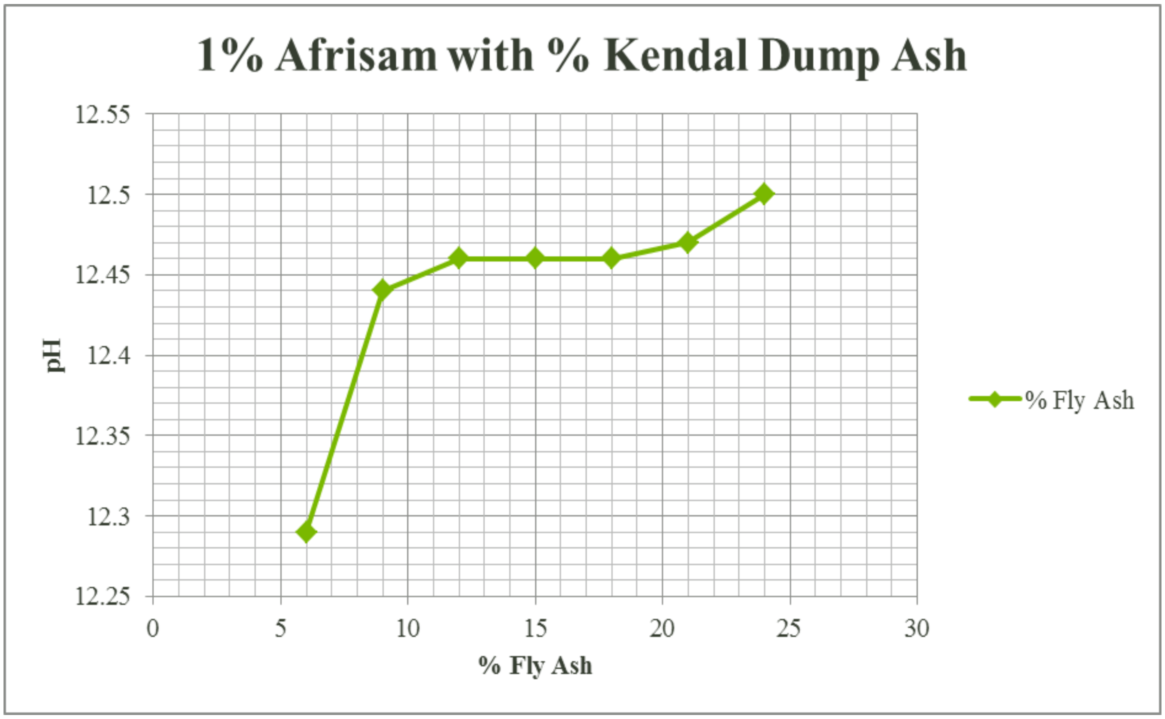


Figure 24 Dump Fly Ash percentages mixed with 1% AFRISAM cement and G5 material

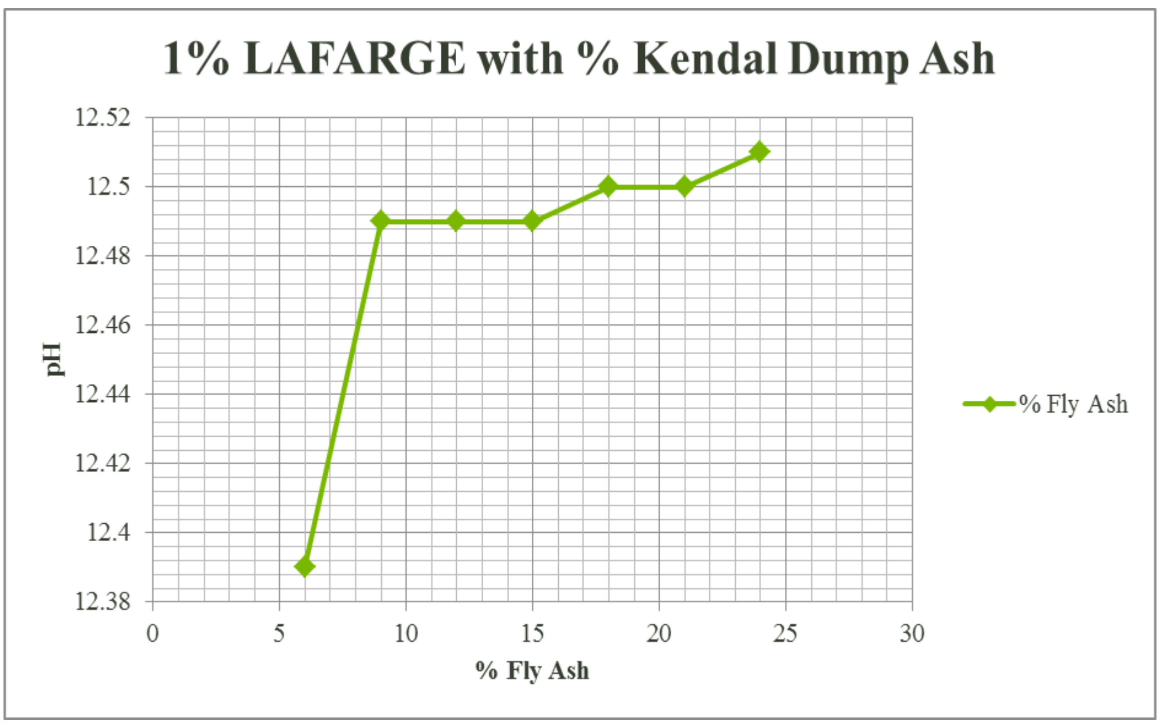


Figure 25 Dump Fly Ash percentages mixed with 1% LAFARGE cement and G5 material

5.3.2 Maximum Dry Density (MDD)

MDD is the dry density value of the material tested, defined by the peak of the laboratory compaction versus moisture content curve using the specified compaction effort (Method A7 – TMH1, 1986). Strength testing and construction quality control is necessary to determine the maximum dry density and optimum moisture content of the material with the design stabiliser. Degree of compaction of soil is measured by its dry unit weight. When water is added, it acts as a softening agent on the soil particles. The soil particles slip on each other and move into a densely packed position. As the moisture increases, so does the dry unit weight of compaction but beyond certain moisture contents, the content tends to reduce the unit weight and this is due to the water that fills up the spaces that would have been occupied by solid particles. With stabilised compaction, the unit weight of soil is lower than the neat unit weight. This is owing to the portion of compactive energy that must be sued to overcome the bonding of the soil particle by cementation and because a portion of cementation is lost. This is illustrated by Figure 26, which is for the non-stabilised G5, Figure 27 shows the average stabilisation curves for G5 mixed with AFRISAM and LAFARGE cement respectively. Figure 28 to Figure 29 shows the average curves for the classified material mixed with the various percentages of Fly Ash from 16% to 22%.

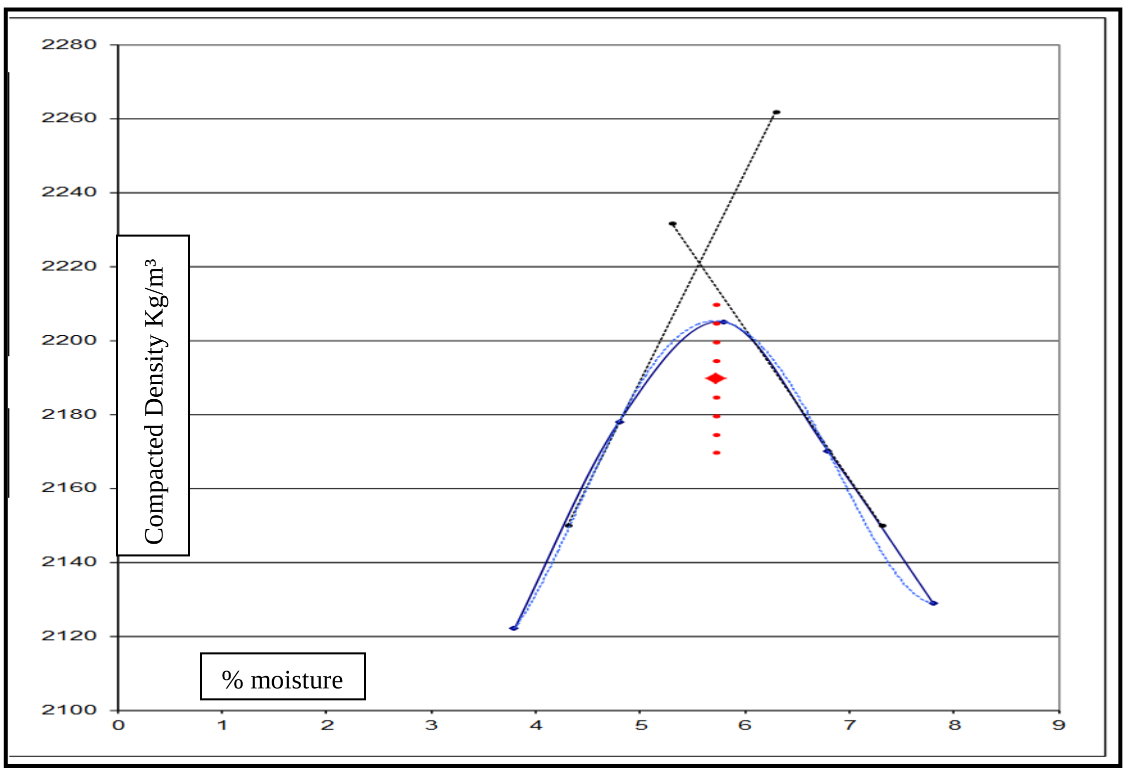


Figure 26 MDD curve for neat G5

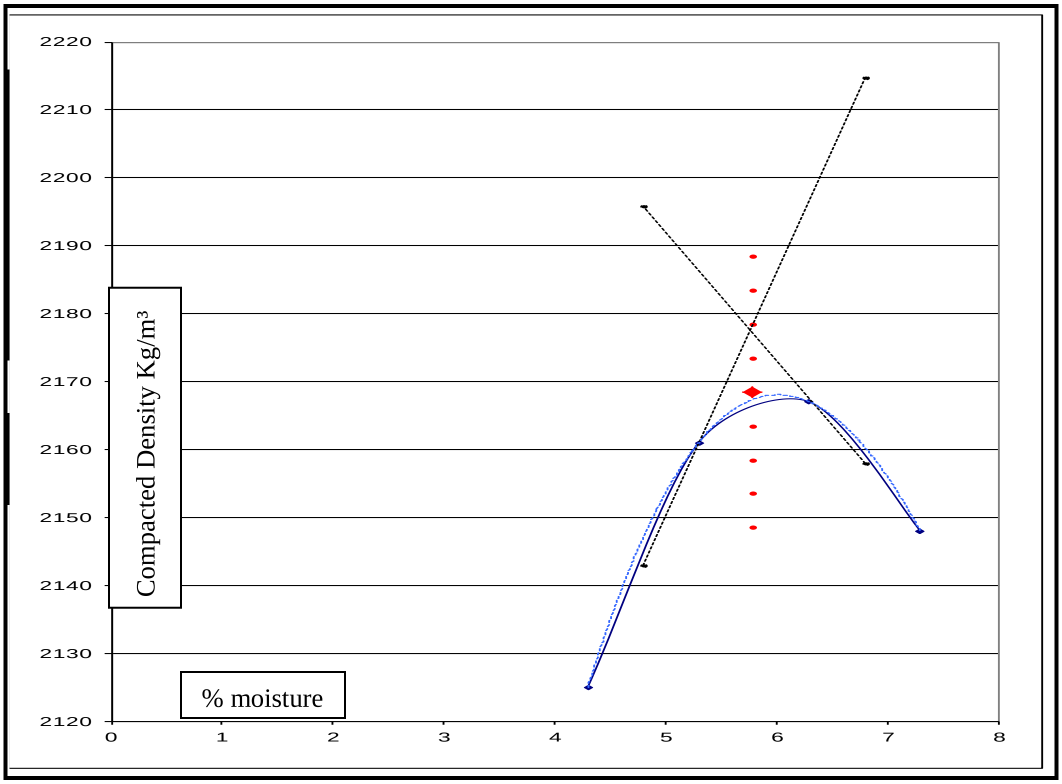


Figure 27 Average MDD curve for the G5 stabilised with cement

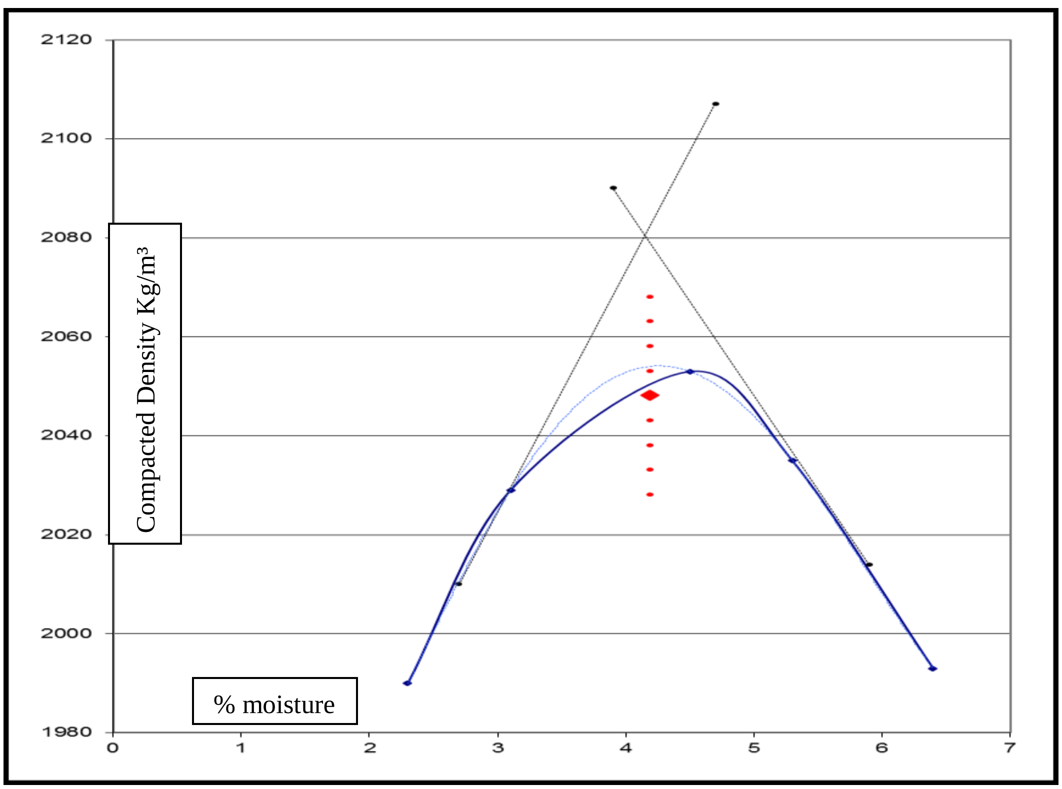


Figure 28 Average MDD curve for the G5 stabilised with 1% cement and 18% Fly Ash

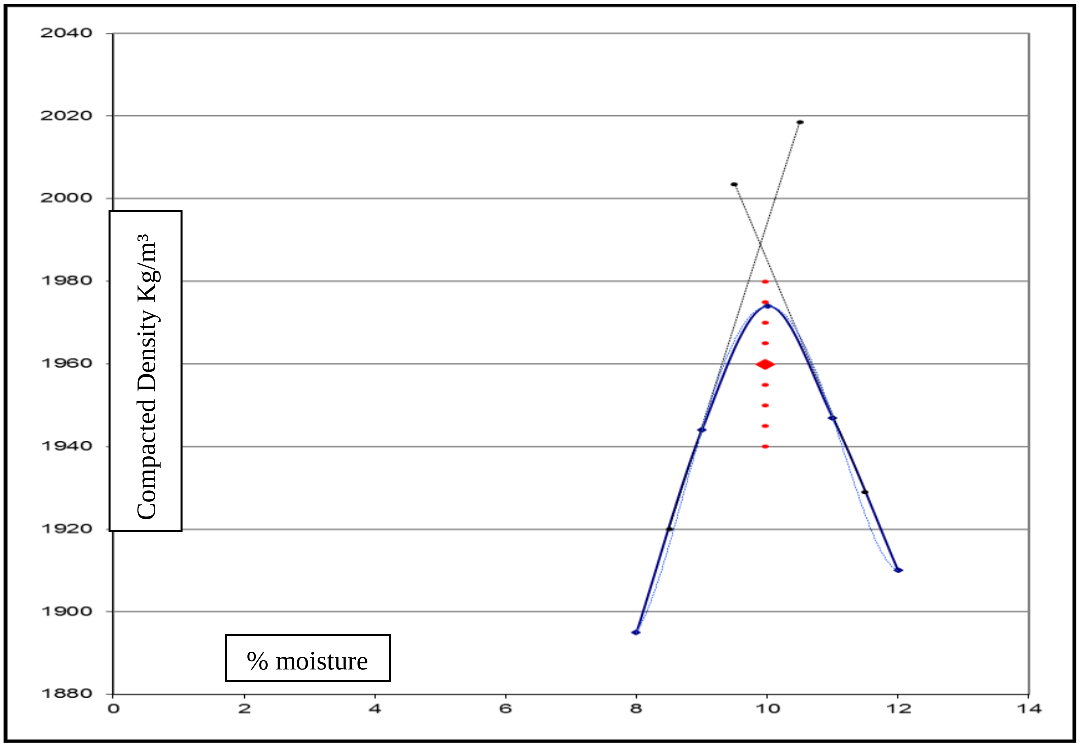


Figure 29 Average MDD curve for the G5 stabilised with 1% cement and 22% Fly Ash

5.3.3 Unconfined Compressive Strength (UCS)

According to the California Test 221, the UCS test is used to measure the shearing resistance of cohesive soils. An axial load is applied using either strain control or stress controlled conditions. The UCS is defined as the maximum unit stress obtained within the first 20% strain (California Test 221, 2000). UCS is carried out as part of the design procedure to establish the appropriate stabilisation agent (Jenkins). In South Africa, the UCS is stress at failure generated by the load required to crush a cylindrical specimen of height 127mm and diameter of 152mm to total failure, at a load application rate of 150kN/min (Method A14 – TMH1, 1986). An initial test was completed where one set of G5 material was stabilised with 1% LAFARGE and another set was stabilised with 1% AFRISAM. The results will thus form the basis to evaluate the impact of which Fly Ash has on the UCS/ITS test results. Table 5.2 show the results of the initial test of the LAFARGE and AFRISAM mixture with G5 material. The ICC/ICL test results have indicated that the material does stabilise at round about 15% but increases again towards 24%. This can be related to the poor quality of the Fly Ash and reaction times. Due to this, the material was tested at various percentages to envisage a percentage that could be used as a standard for the type of classified material and to ensure that the over and above required consumption is met. Summary of the tests at various percentages of Fly Ash and Cement are found in Table 5.3

Table 5.2 UCS results for G5 material stabilised with LAFARGE and AFRISAM

Cement type	**Description**	**%**	**Test**	**Atterberg Limits (TMH1 A2-A4) < 0.425 mm**			**UCS & ITS (TMH1 A14 & A16T)**					
				LL	**PI**	**LS**	**90%**	**93%**	**95%**	**97%**	**98%**	**100%**
Lafarge	G5 Classified Material	1.0	UCS		NP	0.0	496	679	837	1032	1145	1412
Afrisam	G5 Classified Material	1.0	UCS		NP	0.0	551	724	869	1042	1142	1369

Table 5.3: UCS and ITS results for percentage Fly Ash stabilisation: 16%, 18%, 20% & 22%

16% Fly Ash with 1% Cement

	Dump Ash		Pozzfill		Durapozz	
	LAFARGE	AFRISAM	LAFARGE	AFRISAM	LAFARGE	AFRISAM
UCS @100%	1939	1956	3750	3310	2850	2114
ITS @100%	90	98	397	304	403	249
Classification COLTO	**None**	**None**	**C3**	**C3**	**C3**	**C3**
	Suitable for subbase construction					

18% Fly Ash with 1% Cement

	Dump Ash		Pozzfill		Durapozz	
	LAFARGE	AFRISAM	LAFARGE	AFRISAM	LAFARGE	AFRISAM
UCS @100%	2741	1945	3639	3539	2133	2865
ITS @100%	172	149	322	376	318	232
Classification COLTO	**None**	**None**	**C3**	**C3**	**C3**	**C4**
	Suitable for subbase construction					

20% Fly Ash with 1% Cement

	Dump Ash		Pozzfill		Durapozz	
	LAFARGE	AFRISAM	LAFARGE	AFRISAM	LAFARGE	AFRISAM
UCS @100%	1759	1900	3135	3830	2403	2320
ITS @100%	60	81	470	327	205	283
Classification COLTO	**None**	**None**	**C3**	**C3**	**C4**	**C3**
	Suitable for subbase construction					

22% Fly Ash with 1% Cement

	Dump Ash		Pozzfill		Durapozz	
	LAFARGE	AFRISAM	LAFARGE	AFRISAM	LAFARGE	AFRISAM
UCS @100%	1994	1969	2001	2298	1893	1822
ITS @100%	113	203	306	312	228	249
Classification COLTO	**None**	**C4**	**C3**	**C3**	**C4**	**C4**
	Suitable for subbase construction					

The results showed an improvement in the UCS results when compared to the reference samples in Table 5.2. Substantial increase in results is seen with both types of cements, LAFARGE and AFRISAM, mixed in with POZZFILL Fly Ash with results varying from 2001kPa to 3830kPa. A trend can also be seen where the UCS results increase from 16% Fly Ash Mixtures to 18% and then starts to decrease in results from 20% Fly Ash mixtures towards 22%.

5.3.4 Indirect Tensile strength (ITS)

The ITS test has the greatest potential for the evaluation of the tensile properties of highway materials. The ITS is used extensively for evaluating the strength and deformation characteristics of stabilised materials. Research has shown that cohesive or tensile characteristics of subbase significantly affect the performance of the pavement (Hudson *et al*, 1968). The ITS test is carried out in conjunction with the UCS as part of the design procedure to establish the appropriate stabilisation agents. The ITS results of the initial G5 material stabilised with 1% LAFARGE and AFRISAM are shown in Table 5.4, and showed that the material can be classified as a C4. The strengths determined by both UCS and ITS tests will identify the expected classified material as shown in Table 5.5. The classified material is specified according to COLTO Table 3402/5 (COLTO, 1998) and is required for both ITS and UCS results. As discussed in point 5.3.3, the ITS test results are also shown at various percentages due to the fluctuation in ICC/ICL results and is shown in Table 5.3.

Out of the twenty-four samples that were tested, eight samples showed a decline in the ITS results, while the remaining samples showed an improvement. Thirteen of the Fly Ash samples improved the classification of the material from a C4 to a C3, while four samples stayed in the same classification of a C4 and seven fell into the "None" category due to the ITS results being below the specified value of 200kPa for a C4.

Table 5.4 ITS results for G5 material stabilised with LAFARGE and AFRISAM

Cement type	Description	%	Test	Atterberg Limits (TMH1 A2-A4) < 0.425 mm			UCS & ITS (TMH1 A14 & A16T)					
				LL	PI	LS	90%	93%	95%	97%	98%	100%
Lafarge	G5 Classified Material	1.0	ITS		NP	0.0	50	79	406	143	165	223
Afrisam	G5 Classified Material	1.0	ITS		NP	0.0	45	74	103	143	169	235

The results have shown an increase in strength when compared to the reference samples. Being a current practice in the construction field, test samples showing favourable results are selected from the stabilisation mix designs and subjected to further additional testing which is then introduced to ensure conformity to the design life span and that the durability requirements have been satisfied.

Table 5.5 Requirements for chemically stabilised pavement layers

Criteria	C3	C4
Material before Treatment	At Least G6 quality	
Atterberg limits after treatment	PI shall not exceed 6	
Design Strength (Mpa) UCS		
(a) at 100% of modified AASHTO density	minimum: 1,5	minimum: 0,75
	Maximum: 3	maximum: 1,5
(b) at 97% of modified AASHTO density	minimum: 1	minimum: 0,5
	maximum: 2	maximum: 1
Indirect Tensile strength at 100% of modified AASHTO density (kPa)	minimum: 250	minimum: 200

The same standard will be used for further additional testing for the Fly Ash mixes. As stated, the Fly Ash mixtures showed an upward trend between 16% Fly Ash mixtures and 18% Fly Ash mixtures. LAFARGE cement showed a substantial improvement with Fly Ash mixtures mixed in by 16%. AFRISAM, however, showed an improvement at 18% Fly Ash mixture. It is therefore, in the context of this study, to subject additional testing with the following Fly Ash mixtures:

1. 1% LAFARGE mixed with 16% Dump Ash
2. 1% LAFARGE mixed with 16% POZZFILL
3. 1% LAFARGE mixed with 16% DURAPOZZ
4. 1% AFRISAM mixed with 18% Dump Ash
5. 1% AFRISAM mixed with 18% POZZFILL
6. 1% AFRISAM mixed with 18% DURAPOZZ

The reason for the low percentage Fly Ash mixtures is also the consideration of cost in the construction phase. The less the admixture is required, the less the cost will normally be. AFRISAM and LAFARGE have different additives added, which would explain why each one performs better with different percentages of Fly Ash mixtures. Further in-depth study will need to be completed to understand the reaction of each type of cement to each type of the Fly Ashes, and to be able to understand the reasons for the decline in the current ITS values. The in-depth study will thus lead to better understanding of the reactions where new or adjustment to testing methods might be required.

The reference samples will also be subjected to further testing so that comparisons can be made.

5.3.5 Additional Testing

The most important layers in paved roads are the upper layers, which distribute the loads applied by the traffic to avoid overstressing of the weaker materials beneath it. Roads in South Africa are typically designed to provide a service of 20 years, during which time deterioration of materials used in pavement layers should be minimal, i.e., they should be durable. The most widely used crushed aggregates for road pavements in South Africa are those derived from the Basic Crystalline Group, which includes rock types like basalt, dolerite, diabas and gabbo. The Basic Crystalline Group contains no quartz and is comprised of minerals that have the propensity to weather and deteriorate to relatively unstable secondary minerals under appropriate environment conditions. Rapid deterioration of materials is particularly volatile to raised temperatures and moisture conditions of the road which results in the aggregate being weaker and more moisture sensitive to any applied stresses (Paige-Green, 2007). Although the materials used in this study falls part of the Acid Crystalline Group, it must still be considered to evaluate the durability of the materials.

Techniques have been developed for the assessment of their durability and to provide better predictions of the durability of the Basic Crystalline Group materials. These techniques have allowed designers to make more confident selections of rock construction aggregate with associated cost savings (Paige-Green, 2007). The tests conducted for durability are summarised in Table 5.6 showing the type of test and the current specification limits for Basic Crystalline Group materials.

Table 5.6: Durability testing

Test	Reference	Specification	
Wet Dry Durability (WDD)	Method B 8110	Max 20 for C3	Max 30 For C4
Aggregate Crushing Value (ACV)	COLTO table 3602/3	Max 29%	
10% FACT	COLTO table 3602/2	Dry Min 110kN	Wet/Dry relationship min 75%
Durability Mill Index (DMI)	COLTO table 3402/3	Max 125	Max % passing 0.425mm sieve after DMI test 35
Ethylene Glycol Durability Index (EGDI)	HMA, 2001	Subbase - EGDI <20	
		EGDI after 20 days < 1.5 x EGDI after 5 days	

5.3.5.1 Wet/dry brushing test (WDD)

The wet/dry brushing tests (WDD) is performed to ensure the long term durability of stabilised roads, and can be defined as the ability of the material to retain its strength, permeability, dimensional stability and appearance over a prolonged period of service under the conditions for which it is designed. Durability also includes resistance to moisture absorption, strength reduction, wetting and drying (Ventura, 2003). WDD tests are carried out to determine that the quality of stabiliser added is adequate and to ensure long-term durability of the stabilised materials (TMH1, 1986). The WDD test assesses the effect of wetting and drying on the surface of stabilised specimens. The test is carried out by brushing the compacted and cured specimens after each wet/dry cycle by mechanical methods. Material is particularly susceptible to carbonation and deterioration through wetting and drying. The WDD is determined by the calculation of the percentage material loss after 12 cycles. As part of each cycle, the cylindrical specimen is rotated at 60rev/min for 50 cycles. A stationary 2,25Kg brush erodes the specimen surface. Figure 30 shows a typical apparatus for the WDD testing by mechanical means

In many cases, the ICC and ICL have not been satisfied, and while the property of the soil was improved at the time of testing, exposure to carbonation, wetting and drying will result in the agglomeration of the clay in material and reversion to the original soil characteristics (Ventura, 2003).

The results are compared to project specifications, and although not written in COLTO, stabilisation of the material of a classified C3 or C4 are specified as maximum loss for material during the test are 20% for C3 and 30% for C4 as shown in Table 5.8. The results of the WDD are shown in Table 5.7 below:

Table 5.7 Wet Dry Durability results

Wet and Dry Durability Results	
Sample Description	**% Soil Cement loss**
1% LAFARGE + G5	23.7
1% AFRISAM + G5	20.1
1% LAFARGE + 16% DURAPOZZ	32.9
1% LAFARGE + 16% POZZFILL	10.1
1% LAFARGE + 16% DUMP ASH	29.4
1% LAFARGE + 18% DURAPOZZ	10.3
1% LAFARGE + 18% POZZFILL	9.1
1% LAFARGE + 18% DUMP ASH	54

The G5 mixed only with cement, LAFARGE and AFRISAM, showed that material can be used for a specification of a C4 material. The material will be suitable to last for the duration of the design period. LAFARGE mixed with 16% Dump Ash showed a weaker result, but would still be suitable for C4 classified stabilised material. The 16% POZZFILL, however, shows a tremendous improvement of the test results and can be used for a C3 stabilised material with substantial durability properties. The 16% DURAPOZZ fails to meet the maximum requirements of loss of 30% for C4. AFRISAM, on the other hand, showed a reversal of results where DURAPOZZ and POZZFILL showed substantial improvement in durability and can be used for a C3 stabilised material. However, the Dump Ash fails to comply with the maximum C4 loss of 30%.

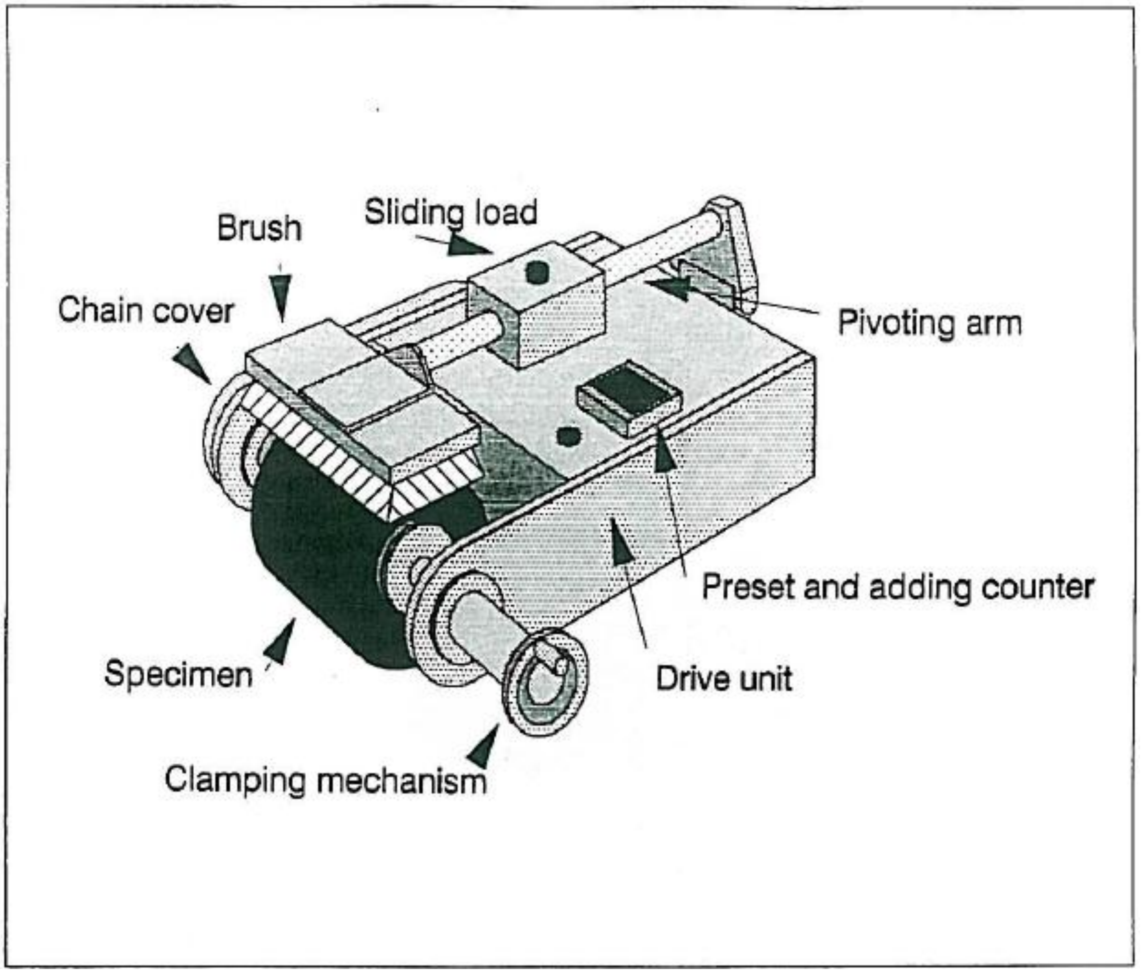


Figure 30 Mechanical WDD apparatus

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

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 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. In addition to the testing, aggregate soaked in Ethylene Glycol for 4 days must also be subjected to the ACV test procedures (TMH1, 1986; SAPEM, 2011; COLTO, 1998). Table 5.8, show the test results of the aggregate and results indicate a satisfactory durability.

Table 5.8 Aggregate durability testing results

Test description	Test method	UOM	G5 Materail
ACV	TMH1 B1	%	26.8
10% FACT Wet/Dry Ratio	TMH1 B2	%	76.7
10% FACT (EG Wet)/Dry Ratio	TMH1 B2	%	82.8
10% FACT (Dry)	TMH1 B2	kN	116
10% FACT (Wet)	TMH1 B2	kN	89
10% FACT (Ethylene Glycol)	TMH1 B2	kN	96

5.3.5.3 Durability Mill Index (DMI)

DMI is a test required by COLTO to determine the durability of G4 classified quality materials. The material is placed in a rotating drum, together with steel balls. The DMI is calculated by the grading of the materials which produces a result to which the materials has disintegrated after a number of required rotations. The DMI test specifically caters for the unusual characteristics of the Basic Crystalline materials. The Plastic Index (PI) should be determined on samples of both the minus 0,425mm fraction and the minus 0,075mm fraction. If Non Plastic (NP) or Slightly Plastic (SP) results are obtained from the material on the minus 0,425mm fraction, the DMI should then be calculated using the PI on the minus 0,075mm Fraction. If the results on the minus 0,075mm fraction are also NP and SP, DMI will be zero. The maximum DMI using PI on either the minus 0,425mm fraction or minus 0,075mm fraction should be 420. If the DMI equals zero, the percentage material passing the 0,425mm fraction for any treatment should not exceed 35 (COLTO, 1998; Paige-Green, 2007). The results found in Table 5.9 show that the material has a satisfactory durability for what is required for the purpose of this study, with crucial points marked in bold.

Table 5.9 Durability Mill Index results

DURABILITY MILL INDEX							
SIEVES (mm)	REFERENCE SAMPLE	B (WATER + BALLS)		$MgSO_4$		GLYCOL	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
37.5	99	99	99	97	98	99	99
26.5	90	94	96	92	93	91	92
19	82	84	89	84	88	82	85
13.2	74	77	85	75	85	75	83
9.5	70	72	83	71	81	69	80
6.7	66	65	81	64	78	63	78
4.75	58	60	79	55	74	58	75
2.00	43	44	70	41	65	40	68
0.425	**19**	**16**	**31**	**14**	**30**	**14**	**27**
0.075	7.2	3	9.9	2.7	11.2	2.6	8.5
LL	30		32		33		33
PI	7		6		8		6
LS	2		2		4		2.5
DMI	**248**						

5.3.5.4 Ethylene Glycol Durability Index (EGDI)

Ethylene Glycol is used to check the durability of the Acid/ Basic Crystalline rock groups. 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 (Jenkins, 2011; Paige-Green, 2007). 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, which indicates the severity of the disintegration to the time classification. This indicates the number of days taken for the most severe disintegration to take place. A modified technique, suggested by Paige-Green, uses 40 pieces of aggregate placed in a fixed position. This technique is to asses each aggregate and its behaviour with time recorded. The inspection should take place after 5, 10 and 20 days. The individual pieces are recorded with the following 3 assessments:

1. Shed of small fragments from edges

2. Fractured into not more than 3 pieces

3. Disintegrated, samples split into more than 3 pieces

The results of the test will indicate possible problematic aggregates that will effect 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 days to determine whether there could be a longer term durability problem. Should the EGDI after 20 days be greater than 1.5 times the EGDI after 5 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 days < 1,5 x mEGDI after 5 days

Results of the samples tested are seen in Table 5.10. Figure 31 shows the condition of the aggregate soaked in ethylene glycol after 20 days.

Table 5.10 EGDI results

Sample	**5 day mEGDI**	**20 day mEGDI**	**1.5 x 5 day mEGDI**
3/5908	0	0	NA

Figure 31 Aggregate after 20 days of ethylene glycol soaking

5.3.5.5 Council for Scientific and Industrial Research (CSIR) Erosion Test

The CSIR erosion test determines the durability of stabilised materials. For erosion to occur in pavement layers; traffic loading, the ingress and movement of water and material susceptible to erosion must be present (Gass *et al*, 1993). Stabilised layers are prone to thermal cracking due to excessive stabiliser content and fatigue cracking under traffic loading owing to low strength and poor support as seen in Figure 32. In any cracking phase of a stabilised layer, the layer is susceptible to ingress of water. The water washes away loose material around the cracked blocks under traffic loading. This process is normally referred to as "*pumping*", which is defined as follows:

"*Pavement pumping is the rapid release of a pressurized soil and water composition from a relatively high to relatively low potential, whereby surface material may be redistributed multi-directionally. Normally, the pressure is released vertically through pavement joints, cracks and edges*" (Gass *et al*, 1993).

The erosions test is to identify the erodible materials so that they can be avoided or correctly modified to prevent erosion failure. Current tests in South Africa are mechanical or manual wet/dry durability test as discussed in 5.3.5.1. The erosion test uses three rectangular specimens, which are submerged in water and covered with a neoprene membrane. A 17.775Kg wheel is cycled 5000 times over the surface of the specimens to erode the surface. The depth of the erosion is measured at 15 locations of the surface of each specimen. An Erosion Index (L) is then calculated, which is the mean of the average depth of erosion for the three specimens. Figure 32 shows a diagram of the apparatus described for the erosion test. Table 5.11, show the specification failure criteria for C3/C4 materials in flexible pavements. Table 5.12 and 5.13 show the results on completion of the CSIR erosion test.

Table 5.11 Failure criteria for C3/C4 materials in flexible pavements

Layer	**Traffic class TRH4 (1985)**	**Traffic class TRH4 (1996)**	**Erosion Index (L) (mm)**
Bases	E0 - E4	ES0.1 - ES30	≤ 1
Sub-bases	E0 - E2	ES0.1 - ES3	≤ 5
Sub-bases	E3 - E4	ES10 - ES30	≤ 3

Table 5.12 Erosion test results for material treated with LAFARGE cement and Fly Ash

Treatment	**Erosion Index**			**Average**
Specimen	**1**	**2**	**3**	
1% Lafarge (Reference)	2.3	2.3	2.3	2.3
1% Lafarge + 16% Durapozz	8.2	6.9	8.3	7.8
1% Afrisam + 16% Pozzfill	7.4	No Reading	10.8	9.1
1% Lafarge + 16% Dump Ash	10.6	10.2	10.8	10.5

Table 5.13 Erosion test results for material treated with AFRISAM cement and Fly Ash

Treatment	Erosion Index			Average
Specimen	**1**	**2**	**3**	
1% Afrisam (Reference)	2.2	2.3	2.1	2.2
1% Afrisam + 16% Durapozz	8.1	8.4	6.4	7.6
1% Afrisam + 16% Pozzfill	8.7	7.7	No Reading	8.2
1% Afrisam + 16% Dump Ash	9	8.3	10.7	9.3

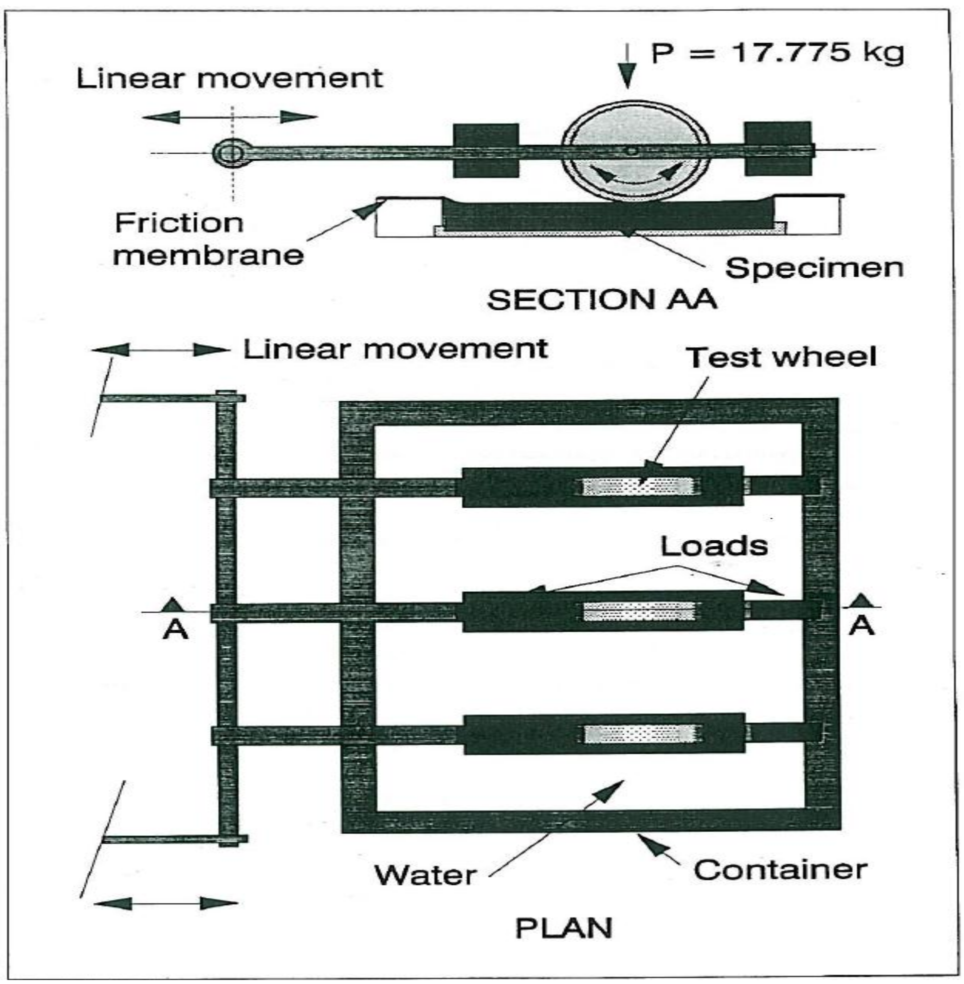


Figure 32 Erosion Test Apparatus (Gass, 1993)

5.3.5.6 Triaxial Testing

Triaxial testing is used to determine the shear properties, resilient modulus and permanent deformation of the material. Triaxial testing is not widely used but it is likely to become a standard test for granular and stabilised materials. The resilient modulus, usually known as stiffness, of a material used in pavement layers provides a good indication of the load spreading capacity of the layer. The strength parameters for a variety of soil types are obtained under drained or undrained conditions. Conventional triaxial tests involve subjecting a cylindrical soil sample to radial stresses and controlled increases in axial stresses or axial displacements. The cylindrical soil specimen is usually at a dimension of 150mm in diameter and at 200mm in height. The specimen is vertically enclosed in a rubber membrane. Samples of cohesive soils are often prepared directly from the saturated compacted samples. The sample is placed in a pressure chamber between two rigid ends. The axial strain/stress of the sample is controlled through movement of the vertical axis. Volume change of a sample is measured by the measuring of the exact volume of the moving water surrounding the sample.

Granular layers are analysed and determined by the shear stress state of the middle layer as illustrated in Figure 33 (SAPEM, 2010). The analysis calculates the safety factor of the material to deformation by using the shear strength parameters in terms of the use of the Mohr-Coulomb model by reading the cohesion and friction angles. Granular materials exhibit deformation due to densification and gradual sheer under repeated loading. The safety factor concept developed from the Mohr-Coulomb theory represents the ratio of the material shear strength divided by the applied stress causing shear.

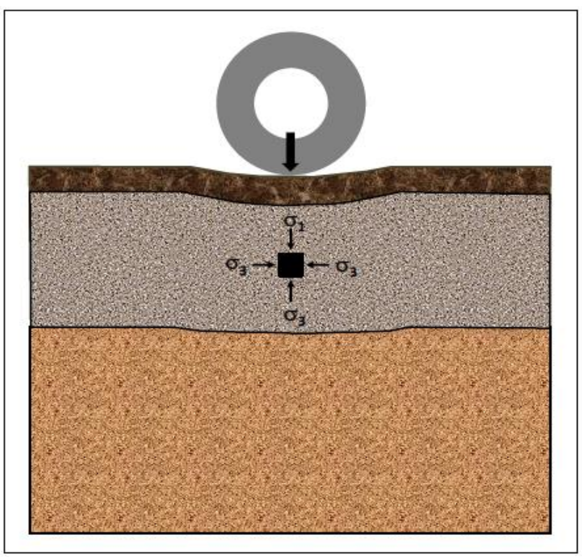


Figure 33 Critical Parameters and Location for Granular Layers (SAPEM, 2010)

The safety factor (F) against shear failure is defined by:

$$(1)\quad F = \frac{\sigma_3[K(\tan^2(45+\phi/2)-1]+2\ K\ C\ \tan(45+\phi/2)}{(\sigma_1-\sigma_3)}$$

Or

$$(2)\quad F = \frac{\sigma_3\ \phi_{term} + C_{term}}{(\sigma_1-\sigma_3)}$$

Where σ_1 and σ_3 = major and minor principle stresses acting at a point in the granular layer

C = cohesion

ϕ = angle of internal friction

K = constant = 0.65 for saturated conditions

0.8 for moderate conditions

0.95 for normal moisture conditions

Safety factors smaller than 1 imply that the shear stress exceeds the shear strength and that rapid shear failure will occur for the static load case. Under real life dynamic loading, the shear stress will only exceed the shear strength for a very short time and shear failure will not occur under one load application, but shear deformation will rapidly accumulate under a number of load repetitions. If the safety factor is larger than 1, deformation will accumulate gradually with increasing load applications. In both instances the mode of failure will, however, be the deformation of the granular layer and the rate of deformation is controlled by the magnitude of the safety factor against shear failure. The safety factor or the major and minor principle stresses are referred to as the critical parameters for the granular layers, for the purpose of this study. The major and minor principle stresses and hence the safety factors are usually calculated at the mid-depth of granular layers. Suggested values of the C and ö-terms for granular materials are given in Table 5.14 (Theyse *et al*, 2000). The transfer functions, relating to the safety factor in equation (2), relates to the number of load applications that can be sustained at that safety factor level and is given by Equations (3) to (6) for different service level requirements and the results are shown in Tables 5.17.1, 5.17.2 and 5.17.3

(3) $N = 10^{(2.605122F\quad 3.480098)}$ for category A roads

(4) $N = 10^{(2.605122F + 3.707667)}$ for category B roads

(5) $N = 10^{(2.605122F + 3.983324)}$ for category C roads

(6) $N = 10^{(2.605122F + 4.510819)}$ for category D roads

Table 5.14 Suggested values of the C and ö-terms for granular materials

Material Class	Moisture Condition					
	Dry		Moderate		Wet	
	ϕ term	C_{term}	ϕ term	C_{term}	ϕ term	C_{term}
G1	8.61	392	7.03	282	5.44	171
G2	7.06	303	5.76	221	4.46	139
G3	6.22	261	5.08	188	3.93	115
G4	5.50	223	4.40	160	3.47	109
G5	3.60	143	3.30	115	3.17	83
G6	2.88	103	2.32	84	1.76	64
EG4	4.02	140	3.50	120	3.12	100
EG5	3.37	120	2.80	100	2.06	80
EG6	1.63	100	1.50	80	1.40	60

Note: EG material class is broken down cemented materials

EG4: G5/G6 material

EG5: G7/G8 material

EG6: G9/G10 material

The material in this study is a stabilised G5 material therefore the calculations will be taken from the range, as indicated in Table 5.14, EG4. All moisture conditions will be taken into consideration as to indicate in what conditions the material will have a safety factor above 1. Once the material shows a reliable safety factor above 1, it can be concluded that the material will be safe to use and can be used in all types of moisture conditions.

The results using equation (1) for the triaxials are summarised in the following tables:

5.15.1 where K = 0.65

5.15.2 where K = 0.8

5.15.3 where K = 0.95

Table 5.15.1 – K = 0.65

Material Description	б1	б3	ϕ	C	K	F1
G5 Untreated	1049	226	37.8	47.3	0.65	0.7177
G5 + 1% AFRISAM	2918	905	55.2	152.7	0.65	2.998
G5 + 1% LAFARGE	2803	905	54.2	153.9	0.65	2.987
G5 + 1% LAFARGE + 16% DURAPOZZ	2181	849	48.3	171.9	0.65	2.88
G5 + 1% LAFARGE + 16% POZZFILL	2407	792	51.3	143.6	0.65	2.595
G5 + 1% LAFARGE + 16% Dump Ash	1653	566	42.6	52.9	0.65	1.562
G5 + 1% AFRISAM + 18% DURAPOZZ	1162	736	22.8	252.5	0.65	2.581
G5 + 1% AFRISAM + 18% POZZFILL	1388	794	32.4	226.8	0.65	2.91
G5 + 1% AFRISAM + 18% Dump Ash	1615	792	38.2	200.5	0.65	2.68

Table 5.15.2 – K = 0.8

Material Description	б1	б3	ϕ	C	K	F1
G5 Untreated	1049	226	37.8	47.3	0.8	0.883
G5 + 1% AFRISAM	2918	905	55.2	152.7	0.8	3.69
G5 + 1% LAFARGE	2803	905	54.2	153.9	0.8	3.677
G5 + 1% LAFARGE + 16% DURAPOZZ	2181	849	48.3	171.9	0.8	3.547
G5 + 1% LAFARGE + 16% POZZFILL	2407	792	51.3	143.6	0.8	3.194
G5 + 1% LAFARGE + 16% Dump Ash	1653	566	42.6	52.9	0.8	1.922
G5 + 1% AFRISAM + 18% DURAPOZZ	1162	736	22.8	252.5	0.8	3.176
G5 + 1% AFRISAM + 18% POZZFILL	1388	794	32.4	226.8	0.8	3.58
G5 + 1% AFRISAM + 18% Dump Ash	1615	792	38.2	200.5	0.8	3.298

Table 5.15.3 – K = 0.95

Material Description	б1	б3	ϕ	C	K	F1
G5 Untreated	1049	226	37.8	47.3	0.95	1.049
G5 + 1% AFRISAM	2918	905	55.2	152.7	0.95	4.382
G5 + 1% LAFARGE	2803	905	54.2	153.9	0.95	4.366
G5 + 1% LAFARGE + 16% DURAPOZZ	2181	849	48.3	171.9	0.95	4.213
G5 + 1% LAFARGE + 16% POZZFILL	2407	792	51.3	143.6	0.95	3.793
G5 + 1% LAFARGE + 16% Dump Ash	1653	566	42.6	52.9	0.95	2.283
G5 + 1% AFRISAM + 18% DURAPOZZ	1162	736	22.8	252.5	0.95	3.771
G5 + 1% AFRISAM + 18% POZZFILL	1388	794	32.4	226.8	0.95	4.251
G5 + 1% AFRISAM + 18% Dump Ash	1615	792	38.2	200.5	0.95	3.916

The following results using equation (2) is summarised in the following tables:

Table 5.16.1 – Dry Moisture Condition

Table 5.16.2 – Moderate Moisture Conditon

Table 5.16.3 – Wet Moisture condition

Table 5.16.1 – Dry Moisture Condition

Material Description	б1	б3	ϕterm	Cterm	F2
G5 Untreated	1049	226	3.6	143	1.162
G5 + 1% AFRISAM	2918	905	4.02	140	1.877
G5 + 1% LAFARGE	2803	905	4.02	140	1.991
G5 + 1% LAFARGE + 16% DURAPOZZ	2181	849	4.02	140	2.667
G5 + 1% LAFARGE + 16% POZZFILL	2407	792	4.02	140	2.058
G5 + 1% LAFARGE + 16% Dump Ash	1653	566	4.02	140	2.222
G5 + 1% AFRISAM + 18% DURAPOZZ	1162	736	4.02	140	7.274
G5 + 1% AFRISAM + 18% POZZFILL	1388	794	4.02	140	5.609
G5 + 1% AFRISAM + 18% Dump Ash	1615	792	4.02	140	4.039

Table 5.16.2 Moderate Moisture condition

Material Description	σ1	σ3	Φterm	Cterm	F2
G5 Untreated	1049	226	3.3	115	1.046
G5 + 1% AFRISAM	2918	905	3.5	120	1.633
G5 + 1% LAFARGE	2803	905	3.5	120	1.732
G5 + 1% LAFARGE + 16% DURAPOZZ	2181	849	3.5	120	2.321
G5 + 1% LAFARGE + 16% POZZFILL	2407	792	3.5	120	1.791
G5 + 1% LAFARGE + 16% Dump Ash	1653	566	3.5	120	1.933
G5 + 1% AFRISAM + 18% DURAPOZZ	1162	736	3.5	120	6.329
G5 + 1% AFRISAM + 18% POZZFILL	1388	794	3.5	120	4.880
G5 + 1% AFRISAM + 18% Dump Ash	1615	792	3.5	120	3.514

Table 5.16.3Wet Moisture Condition

Material Description	σ1	σ3	Φterm	Cterm	F2
G5 Untreated	1049	226	3.17	83	0.971
G5 + 1% AFRISAM	2918	905	3.12	100	1.452
G5 + 1% LAFARGE	2803	905	3.12	100	1.540
G5 + 1% LAFARGE + 16% DURAPOZZ	2181	849	3.12	100	2.064
G5 + 1% LAFARGE + 16% POZZFILL	2407	792	3.12	100	1.592
G5 + 1% LAFARGE + 16% Dump Ash	1653	566	3.12	100	1.717
G5 + 1% AFRISAM + 18% DURAPOZZ	1162	736	3.12	100	5.625
G5 + 1% AFRISAM + 18% POZZFILL	1388	794	3.12	100	4.339
G5 + 1% AFRISAM + 18% Dump Ash	1615	792	3.12	100	3.124

Table 5.17.1 Number of load applications in Dry Conditions

Material Description	N - Road Category			
	A	B	C	D
G5 Untreated	3221937.3	5441092.2	10264625	34581043
G5 + 1% AFRISAM	234165255	395449886	746016538	2.513E+09
G5 + 1% LAFARGE	463204902	782243830	1.476E+09	4.972E+09
G5 + 1% LAFARGE + 16% DURAPOZZ	2.685E+10	4.535E+10	8.555E+10	2.882E+11
G5 + 1% LAFARGE + 16% POZZFILL	694565647	1.173E+09	2.213E+09	7.455E+09
G5 + 1% LAFARGE + 16% Dump Ash	1.856E+09	3.135E+09	5.915E+09	1.993E+10
G5 + 1% AFRISAM + 18% DURAPOZZ	2.69E+22	4.543E+22	8.57E+22	2.887E+23
G5 + 1% AFRISAM + 18% POZZFILL	1.238E+18	2.091E+18	3.945E+18	1.329E+19
G5 + 1% AFRISAM + 18% Dump Ash	1.003E+14	1.694E+14	3.196E+14	1.077E+15

Table 5.17.2 Number of load applications in Moderate Conditions

Material Description	N - Road Category			
	A	B	C	D
G5 Untreated	1602773	2706705.6	5106202.3	17202558
G5 + 1% AFRISAM	54276638	91660441	172917497	582550984
G5 + 1% LAFARGE	98263992	165944707	313054827	1.055E+09
G5 + 1% LAFARGE + 16% DURAPOZZ	3.361E+09	5.676E+09	1.071E+10	3.607E+10
G5 + 1% LAFARGE + 16% POZZFILL	139675881	235879621	444987099	1.499E+09
G5 + 1% LAFARGE + 16% Dump Ash	327634031	553296604	1.044E+09	3.516E+09
G5 + 1% AFRISAM + 18% DURAPOZZ	9.268E+19	1.565E+20	2.953E+20	9.947E+20
G5 + 1% AFRISAM + 18% POZZFILL	1.564E+16	2.642E+16	4.984E+16	1.679E+17
G5 + 1% AFRISAM + 18% Dump Ash	4.31E+12	7.278E+12	1.373E+13	4.625E+13

Table 5.17.3 Number of load applications in Wet Conditions

Material Description	N - Road Category			
	A	B	C	D
G5 Untreated	1024660.3	1730409.7	3264419.3	10997676
G5 + 1% AFRISAM	18351523	30991394	58465290	196966836
G5 + 1% LAFARGE	31111376	52539777	99116332	333918301
G5 + 1% LAFARGE + 16% DURAPOZZ	718373122	1.213E+09	2.289E+09	7.71E+09
G5 + 1% LAFARGE + 16% POZZFILL	42402133	71607201	135087045	455101955
G5 + 1% LAFARGE + 16% Dump Ash	89534915	151203355	285245254	960977960
G5 + 1% AFRISAM + 18% DURAPOZZ	1.363E+18	2.301E+18	4.341E+18	1.462E+19
G5 + 1% AFRISAM + 18% POZZFILL	6.072E+14	1.025E+15	1.935E+15	6.517E+15
G5 + 1% AFRISAM + 18% Dump Ash	4.154E+11	7.015E+11	1.323E+12	4.458E+12

5.4 Discussion

Material, as discussed in this study, was subjected to a basic design laboratory design process. The steps taken were to evaluate whether the material can be stabilised with Fly Ash. The process was to ensure that the purpose of soil stabilisation objective is obtainable.

Material for stabilisation design needs to be evaluated according to specifications as set out in fixed standards, as discussed in this study. The design is basically separated into two parts namely:

1. Classification of the material and the durability of the material
2. Stabilisation mix with either cement or lime and durability of the design

Material, according to standard specifications, needs to be a suitable G5/G6 material. The material goes through classification testing and once it conforms to the standards, it needs further testing to obtain suitable durability requirements to ensure that the material will be durable for the pavement design life. The classification of the material is discussed in Chapter 4.6 of this study. Three critical durability parameter testing is carried on untreated G5 material namely:

1. ACV and 10% FACT
2. DMI
3. EGDI

The test results are favourable for the G5 material as it conforms to the specifications for the ACV and 10% FACT. The test was also carried out for material soaked in Ethylene Glycol, which indicates breakdown of the material in medium to long term after exposure to the atmosphere. It is then critical that the G5 material conforms to the set specifications as set out in Table 5.8 for ACV and 10% FACT tests after being soaked in Ethylene Glycol. The material test results, as seen in Table 5.8, for both standard testing and ethylene glycol soaked, show that the material will have long term durability for the use in road construction applications.

The EGDI test has shown that the material has no potential of breaking down when exposed to atmosphere during the life design in road construction applications. Table 5.10 has shown 0 effect of the EGDI test after 5 and 20 days using the modified EGDI technique. The results show that the material can be utilised in road construction applications, either as a subbase or base material.

DMI testing has proven that the material used for the study has satisfied all parameters and is suitable for subbase construction with the main purpose of retaining design life. The crucial points are indicated in Table 5.9. The points are within acceptable tolerances as indicated in Table 5.6. As stated, Ethylene Glycol will indicate breakdown of material after exposure to atmosphere, it was also then important that the material be subjected to ethylene glycol testing during the DMI which also showed favourable tolerances within the limits as shown in Table 5.6. Although the ethylene glycol testing is not specified, the test results after soaked in ethylene glycol must conform to the proper standards set out in Table 5.6.

In order to evaluate whether the Fly Ash will make an impact on stabilisation of pavements, the G5 material was subjected to tests with only 1% cement. The ICC results, Figure 18 and Figure 19, have shown that the material will reach the required pH values of 12,4 at 1%, but when we go back to view the ICC testing procedure in 5.3.1, it states that material must stabilise to satisfy the initial consumption and to ensure long-term cementation. The ICC test results stabilised for both

LAFARGE and AFRISAM products between 4% and 5%. This indicates that the material, although it will reach early strengths, will require additional cement for the long-term cementation and durability for the life design of the pavement. The Fly Ash will then be required to be of a substantial amount that needs to be added to satisfy the initial consumption with the cement and to gain strength in early stages, and for prolonged periods of time. The 3 Fly Ashes in the study stabilised between 9% and 15%, but, with cement alone, the ICC results stabilised between 4% and 5% with pH values of 12,97 and 13,04. It is therefore the aim to reach these pH values of this specific material to be able to evaluate strength gains and long-term durability.

The Fly Ash graphs, Figures 20 to 25, show that the ICC increases from about 15% and continues to rise to 24%. The poor quality Fly Ashes in South Africa need a cementing agent, as stated in this study, and the UCS/ITS results confirm that the 1% cement will add an initial start to the long-term reaction process with acceptable results as shown in Tables 5.2 and 5.4. The initial start have produced results that the material can be classified as a C4, with UCS results 0f 1412kPa (1,4Mpa) and 1369kPa (1.4Mpa) and ITS results of 223kPa and 200kPa for both LAFARGE and AFRISAM cement respectively, which is according to the requirements as per Table 5.5. The additional Fly Ash will then be to satisfy the consumption demand and to ensure long-term cementation during the life span of the pavement layer. Table 5.3 shows the results of the UCS/ITS when Fly Ash is added to the material with cement. All the results have shown an improvement to the UCS, which varied from 1759kPa to 3830kPa when compared to the reference samples. The same can be seen for the ITS, even though the Dump Ash mixtures decreased the ITS values. The reason for this decrease needs to be additionally investigated, physically and chemically, to understand the decrease.

Further additional testing is required to ensure the stabilised material will be adequate for the design life of the pavement. The main aim of durability testing is to ensure that the material durability will last for the duration of its design life and to indicate whether the material will withstand natural forces if the top layers have failed, thus leaving stabilised layers exposed to the natural elements. The additional testing is evaluated by 3 tests, namely;

1. Wet Dry Durability (WDD)
2. CSIR Erosion Test
3. Triaxial Tests

WDD is a specified test and can be found in most contract documents while the CSIR Erosion test is not. Not all materials as seen in the UCS/ITS evaluation were subjected to these additional tests, as already discussed in this study. The materials that have shown more stable results were chosen and were subjected to the additional testing. 8 samples were tested, of which 2 were referenced samples. The referenced samples conformed to C4 classification with % loss of 20.1% and 23.7% respectively. Out of the 6 samples that were mixed with Fly Ash, 2 conformed to C4, 3 conformed to C3 and 1 totally failed the WDD test. The results can thus now be compared to the UCS/ITS in Table 5.5. The comparison can thus show whether the UCS/ITS, that conforms to a C3/C4, will have a durability to last for the duration of the design period. The results indicate that the UCS/ITS classification, according to COLTO in Table 5.6, will have sufficient durability; except for one result, which shows that the material is vulnerable to erosion, although the material was classified as a C3. The material in question is 1% LAFARGE with 16% DURAPOZZ. Various factors need to be investigated to understand the possible problem, and once identified, a re-test should be considered.

CSIR Erosion Tests were also completed on the durability of stabilised materials. The CSIR Erosion Test is not seen as a proper durability test for gravel road testing and is mostly used by researches and designers on asphalt surfacing, seal and concrete overlays. The results do confirm this, seeing as the results do not conform to the required specification as set out in Table 5.11. It can thus be concluded that this test cannot be used for this specific testing purposes, and should be disregarded. However, the values in the Table 5.12 and Table 5.13 can be used as an indication on the performance of the material in this study, and may be adapted to create a new specification for materials stabilised with cement and Fly Ash. Further in-depth study needs to be completed to produce a standard acceptable for the type of stabilisation required if Fly Ash is used.

Triaxial testing was completed to ensure that shear stress does not exceed the shear strength by calculating the safety factor, and to calculate the number of load applications the material can withstand at that specific safety factor. The study took into consideration all moisture conditions to evaluate the safety factor (F). Reference samples were used to compare with the actual test samples for a consideration of a stabilisation project. Tables 5.15.1 to 5.16.3 show the following reference samples:

1. G5 Untreated
2. G5 with 1% LAFARGE cement
3. G5 with 1% AFRISAM cement

Both equations (1) and (2) were considered to evaluate both scenarios in this study. In both equations, the G5 Untreated sample had a safety factor of less than 1 or just over 1. Equation (1) showed that the G5 with 1% cement has shown an improvement and has ensured that shear stresses do not exceed the shear strength. The Fly Ash stabilised material all showed a safety factor above the required 1, but did not actually improve on the results obtained from the G5 with cement only. The dump ash results have shown a decrease in safety factor but will still have a reasonable shear strength. A trend can be seen with the results of the stabilised material with Fly Ash and that is: the results are fairly close to the results obtained from the reference samples: G5 with cement. These can be seen in all moisture conditions as indicated in Table 5.15.1 to Table 5.15.3.

Equation (2) was evaluated by also taking into consideration all moisture conditions. The safety factors showed a tremendous increase over the reference samples as compared to equation (1). The results in both equation (1) and (2) have shown that the material shear strength will be greater than the shear stresses incurred. Although the material will gradually deform, the rate will only be determined by the increasing load applications.

The load applications took into consideration all road categories and under all moisture conditions relating to equation (2) only. The results show that the material will be able to sustain to a large number of load applications at that specific safety factor and is considerably higher when compared to the reference samples. Road categories C&D indicated the most promising results and have tremendous increase in readings above the reference samples.

5.5 Summary

Methodology followed in this chapter was to ensure that basic South African protocols were followed and to indicate a new evolving chapter in possible pavement design. Treatment of the soils is to improve its strength and deformation resistance. Basic design steps were followed in this chapter to evaluate the Fly Ash characteristics in the stabilisation process in order to make it a viable option for a greener future in South African road construction processes. Key points were evaluated namely;

1. Strength in expressed in terms of compression, shear, bearing or load deflection
2. Durability in terms of resistance to moisture absorption, softening, strength reduction, wetting and drying cycles

Three Fly Ashes obtained went through a thorough testing analysis and was mostly completed for short-term curing methods. The study provided results that were not uniform but one can conclude that the poor quality of the Fly Ash is responsible for this. Although short-term curing proved to be affective, it is critical that samples must be considered for long term curing.

Three main tests have shown the effectiveness of the Fly Ash mixtures when compared to specifications and they were:

1. UCS Results
2. ITS Results
3. WDD Results

The results have shown an increase when compared to the reference samples, but also shown that they are durable in all aspects when compared to specifications. However, the results have revealed that the Fly Ash cannot be predicted as with cement alone stabilisation. The results are inclined to show irregular patterns.

A critical comment that can be said is that CSIR Erosion test can be used as an indicative test but with the irregular patterns of the Fly Ash, a new standard needs to be assessed. CSIR Erosion tests limits leave much scope for improvement for the acceptance criteria. It is feasible to assume that these criteria will change as more performance related testing is done. The study was performed for flexible pavements and the base layer is normally used to distribute the traffic load and transmit it to the subbase and subgrade layers. The base is designed to be stronger than the subbase and therefore requires a higher erodibility criterion than the subbase. It is thus more important to specify stricter failure criteria for base layers than for subbase layers. In this context, it can thus be concluded the Erosion test will be best suited and more adaptable for the base layers than for stabilised subbase layers as also shown in the study. The study has shown that Fly Ash and cement stabilised material is a feasible option as it does improve the durability of the subbase layer in flexible pavements and conforms to the required specified WDD testing criteria.

The classified G5 material also needs to conform to durability testing to ensure the future life of the pavement layer for the design period. The durability tests performed were:

1. ACV and 10% FACT
2. Durability Mill Index
3. EGDI

All three tests have shown that the material conforms to strength, durable and is resistant to rapid weathering.

Triaxial tests were completed to calculate the safety factor of the material to deformation. The safety factor concept developed form the Mohr-Coulomb theory represents the ration of shear strength divided by the applied stress causing shear. Safety factor of above 1 was required to ensure deformation of a gradual nature and not a rapid failure in a short time. These were achieved well above the norm when compared to reference samples.

All tests completed in this chapter have concluded that Fly Ash is a viable option to the standard road construction method. The tests have also shown that with various types of Fly Ash available, proper and thorough testing is required. The poor quality of Fly Ash has shown that no uniformity of the results could be seen nor can it be predicted, thus all testing needs to be completed thoroughly, including durability testing. Most of the results conform to the standard testing available for durability and normal design process testing.

Chapter 6 Conclusions and Recommendations

6.1 Introduction

This Chapter summarises the discussions, findings and conclusions of the results obtained in the previous chapters and recommendations.

6.2 Overview

Aims and objectives of this study were to provide a detailed insight into:

1. Developing a more cost effective method in stabilisation techniques using a higher percentage of Fly Ash with only a partial mixture of cement.
2. Prepare basic design steps in analysing the effectiveness of the Fly Ash mixtures.
3. The properties and effectiveness of the Fly Ash/cement mixtures.
4. Fly Ash characterisation and the effects of the chemical reactions.

In order to achieve the aims and objectives, several procedures had to be set out:

1. Selection of the Fly Ash sources and testing for characterisation for adaptation to design procedures for stabilisation.
2. Physical and chemical characterisation to understand the elements, reaction processes and to identify the main components for suitability for stabilisation.
3. The type of cement readily available that attributes to the required specifications for design purposes.
4. Selection of classified material that is commonly found in South Africa which is mostly used for the stabilisation process. The material also had to comply to specifications set out in the necessary documents for materials to be used for stabilisation.
5. Completing an actual design by using the standard steps set out in the prescribed documentation, which is standard practice in South Africa.

6.3 Fly Ash and Environmental Effects

Fly Ash is an abundant mineral found in South Africa, which is highly variable, both physically and chemically. A complete characterisation was made to provide comparative data on the environmental impact of the Fly Ash mixtures. The 3 Fly Ashes chosen for this study was: Kendal Dump Ash, DURAPOZZ and POZZFILL. Kendal Dump Ash was sampled directly from the dump sites while DURAPOZZ and POZZFILL was sourced from the supplier, which are processed Fly Ashes. DURAPOZZ is the highest quality processed ash that conforms to international standards, while POZZFILL only conforms to certain international standards. Both DURAPOZZ and POZZFILL are successfully being utilised for cement production in South Africa. South Africa only produces Class F Fly Ash and is mostly placed in Dumps covering a wide range of areas at an immensely cumulative amount which has become of major concern.

Just one of these concerns is the impact Fly Ash has on the environment by contaminating our groundwater supplies. Basic steps in revealing any contaminants due to stabilisation with Fly Ash have been revealed through leach testing. Numerous leach testing on Fly Ash have revealed that minimum leach minerals occur that will cause concerns on pollution to the environment. Studies have revealed that once the Fly Ash is “entombed” in the pavement layer, therefore, no leaching will take place.

A number of studies that addressed the leaching of Fly Ash residue, and what impact it has on the environment have revealed that when Fly Ash is used in concrete, there is a minimal risk of leaching. Fly Ash, as shown in this study, when used in road stabilisation projects, has proven to leach only trace amounts of elements, which are not harmful to the environment.

Laboratory leaching sample results have indicated that Fly Ash constituents exhibit limited mobility. The study revealed that Fly Ash is an environmental option and has engineering advantages when used properly for soil stabilisation techniques. The stabilised Fly Ash shows a tremendous reduction in leach elements, which is mainly due to the reaction taking place between cement, Fly Ash and soil.

Critical variables include the sample size and particles size distribution, leachant volume and pH, and duration of leachant test. The project objective, type of material, and type of data desired will determine the most appropriate method. 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. Elements in Fly Ash vary from different classes. As shown, common Class F Fly Ash in South Africa has some potentially hazardous material compared with water’s maximum inorganic allowable when not stabilised as indicated in the study. A full comparison must be conducted at the design stage of an intended project, to compare what hazardous materials are leached and at what toxic level it represents.

The Leach results have shown that the material was "*entombed*" and the possibility of leachant releasing agents of a dangerous nature are minimal. The results have shown that it is even safe if the minor leach agents do enter the drinking water tables. The leach tests in this study have shown that the Fly Ash stabilisation is environmental friendly. It also shows that the Fly Ash particles that are normally released are bound within the soil due to chemical reactions, and continue to be bound as long as reactions take place.

6.4 Fly Ash Analysis

The set of standards that were chosen were to evaluate the Fly Ashes and to obtain the suitability from both concrete and soil stabilisation standards. The standards were combined to provide information on specific items to be able to set guideline standards that can be followed for evaluation of Fly Ash for suitability for soil stabilisation. The guideline standards will ensure proper reactions and continuation of the reactions over time. The standards used were:

1. SANS 1491 part 2
2. SANS 50196-1
3. SANS 50197-1 & 2
4. BS3892-1 & 2
5. COLTO
6. TMH1
7. SANRAL Protocol Manual 2
8. Department of transport Manual 5 (1987)

The results of the tests obtained were to determine the following points:

1. Classification of the Fly Ash.
2. Evaluate the cementing potential.
3. Evaluate the pozzolanic reaction time.
4. Determine the LOI.
5. Determine the SO_3.
6. Determine the free lime.
7. Analyse the chemical components which contribute to strength.

As previously indicated, the Fly Ash chosen for this study needs a cementing agent as the Fly Ash in South Africa is classified as a Class F.

6.4.1 Chemical Analysis

All three Fly Ash samples showed high values of SiO_2 which will form stable cementitous compounds with $Ca(OH_2)$, and which will allow pozzolanic reactions to continue for a longer period of time. This is critical as stabilised pavement layers are designed to remain stable for an estimated 20 years. The Fly Ash samples showed a low cementing potential identified by the ratio CaO/SiO_2. This study provided five critical components of the evaluation of the Fly Ash as a suitable stabiliser:

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. SO_3 which will form calcium sulphite known as ettringite, which will expand in volume and create cracks.
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 comes into contact with CO_2, it will form carbonates, which will cause carbonation.
4. XRF Analysis to do identify the components of the Fly Ash.
5. Cementing potential of the Fly Ash.

The chemical composition of the Fly Ashes relate to the mineral chemistry of the parent coal and any additional fuels or additives used in the combustion or post combustion processes must be taken into consideration. The pollution technology used at power generating plants, also affect the chemical composition of Fly Ash.

6.4.2 Physical Analysis

Three main factors are identified in this study:

1. Particle size distribution
2. The Fineness for pozzolanic reactivity
3. Specific Gravity of the studied Fly Ash

The particle size of the Fly Ash is generally similar to that of silt. It is important to note that more than 40% of the Fly Ash must pass the 10 micron sieve as these will contribute to early day strengths. Fines between the 10 micron and 45 micron will continue strength, but at a slower rate, but for a long period of time. It was found that the Fly Ash in this study has most of the Fines between 10 micron and 45 micron sieves. Therefore, a cementing agent will be required for early strength gain. Particles greater than the 45 micron sieve will become inert and will not participate in pozzolanic reactions, but will be able to contribute to the granular modulus of the material. To judge Fly Ash reactivity, you will have to find out what percentages of the particles are below 10 microns. Fineness of the Fly Ash is most closely related to the operating condition of the coal crusher and the grind ability of the coal itself.

The Fly Ash samples in this study are generally heterogeneous consisting of a mixture of glassy particles with various identifiable crystalline phases such as: quartz, mullite and various oxides. The Fly Ashes colour varies from light grey to dark grey. The processed Fly Ash, namely, DURAPOZZ and POZZFILL are light in colour, which is indicative of low carbon content as well as the presence of some lime and calcium. Kendal Dump Ash is dark grey in colour, which gives an indication of high carbon content, but Kendal Dump Ash results have shown that it is actually low in carbon content therefore it is indicative, but then again the actual evaluation needs to be conducted through physical testing. The testing conducted in this study showed that all three Fly Ash samples are of high quality irrespective of colour indicators. The superior reactivity of high calcium Fly Ashes is related to the composition of glass and the presence of reactive crystalline phases.

6.5 Material

Classified material choice was “crushed” granite, which belongs to Acid Crystalline Group. Crushed granite is G5 classified material, as per COLTO standards that are commonly used throughout South Africa for the stabilisation of the subbase. The crushed granite is prone to weathering after exposure to the atmosphere and it is critical to test the crushed granite for durability. A number of specialised testing procedures have been adopted for durability of the Crystalline Rock Group namely:

1. Ethylene Glycol Durability Index (EGDI)
2. Durability Mill Index (DMI)
3. ACV and 10% FACT

The crushed granite have met the expected results and have met the requirements way above the norm, which indicates that the material should be durable for the period for which the pavement is designed for.

The material grading should be as per COLTO specification. The higher the granular modulus the better the quality of the material, the better for the material's ability to carry heavier loads without deformation which is the case that can be found with finer materials. The material was found to be a strong, durable material which test results have shown can be used as a G4 material once the grading has been adjusted to fall within the G4 grading envelope as specified by COLTO.

Cementing agents chosen for this study include two types developed by two different suppliers, specially developed for stabilisation purposes, namely; LAFARGE CEM II 32,5 VA(S-V) and AFRISAM CEM II 32,5 B-M(S-V). These cement types are commonly used in South Africa road construction works. The cement is more effective for soils of low clay content and to gain early strengths as it is critical due to Fly Ash having a low early strength gain but increases in strength continuously over a long period of time. Both cement types have an improved durability and is effective across a wide range of materials.

Erosion test simulates the grinding action of pavements in the presence of water pressure, whereas the durability tests simulate the loss of cementation due to continued wet/dry cycles in a pavement layer. Reference samples were prepared to evaluate whether the Fly Ash stabilised material do make a difference in the material properties. The reference samples were subjected to all testing, including the durability testing. Although the materials have conformed to the required specifications, initial evaluation will be whether the Fly Ash has added more strength and durability to the material. The study has shown that with the basic UCS and ITS test, most of the material stabilised with Fly Ash does improve on the 1% cement alone by changing the classification from a C4 to a C3. The same can be said for the durability of the material, which includes the following tests:

1. WDD
2. Triaxial

Both the tests have shown a substantial increase in resistance to deformation and fatigue and have shown an increase of traffic loading that can be obtained when compared to the reference samples. It is, however, shown that Fly Ash is unpredictable in South Africa. The Fly Ash samples have had a contentious movement when selecting the amount required, satisfying the material demands. The material is of poor quality and can be seen in the ICC test, and no predictions can be made, although an indication can be seen at what percentage the material will most likely stabilise. The most failures found in the tests were the materials mixed with Dump Ash and 1 % cement. This could be that the Ash contains more inert material and unburnt coal aggregates when compared to the processed Fly Ash samples POZZFILL and DURAPOZZ. With an increase of Dump Ash, the inert material will need an increase in cement for the Fly Ash to perform to the required standards as found on the samples containing POZZFILL and DURAPOZZ. A decrease was also seen when the UCS and ITS decreased from 20% Fly Ash mixtures to the 22% Fly Ash mixtures, which could also be related if more cement will be required for reactions to take place.

The CSIR erosion test was completed to see if material with Fly Ash still conforms to the test specifications. The reference samples performed well, but the Fly Ash mixtures all but failed to meet the required specifications. It must be noted that this test is not a standard test and one should use the WDD test, seeing as this test is the preferred test in the current construction industry.

The Fly Ash, in raw form, does show the possibility that it can be used as is but due to the lack of information on each dumpsite it cannot be used without the proper evaluation. If Fly Ash is to be used directly from the dumps, it would be necessary to analyse the material as completed in this study, which will have time related problems envisaged if designed for a main project. The raw Fly Ash will have to be analysed on a continuous basis as it varies from depth and not all areas will have the same properties, due to the amount of unburnt coal and inert material.

Fly Ash cannot be ignored as this has become a valuable product as shown in the study. Fly Ash is readily available and can be used for modification, stabilisation purposes. With time, it can be envisaged that Fly Ash can be used predominately in projects for low volume roads.

The Fly Ash is of a poor quality and all the tests completed are completed as if a construction project is taking place. Most laboratories use rapid method 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 and speed of construction taking place. The testing process of Fly Ash will take time and the method of analysing the material is shown in this study. To better understand Fly Ash, all tests followed in this study needs to be evaluated under long-term duration. This means, samples should be left to cure for longer than 90 days, under controlled and uncontrolled conditions, and then subjected to the same tests. The results will then realistically present the field conditions of the material.

6.6 Conclusion

Fly Ash contribution in soil improvement 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 environmental friendly.
2. The Fly Ash has shown in all the required specified testing that it is a viable option for stabilisation 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 has tremendous potential and ability to enhance pavement properties.
5. Fly Ash 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 stabilisation design process. It can be said that this study has created a new standard for South Africa to follow when it comes to the design of stabilisation of road pavement materials 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 processed Fly Ashes have shown to be the more desired material when compared to the Dump Ash. This has thus a cost implication as this needs to be acquired with cement if it is to be used for the purpose of stabilisation. The Dump Ash was the main aim in this study to show that the material can be used "*as is*" with only the addition of cement for the reactions to occur. The Dump Ash would be a great consideration due to the following conditions:

1. Samples directly from the dump sites, therefore creating an immediate supply
2. If negotiated properly with owners, the material would be free, or at very little cost, when compared to the processed Fly Ashes.
3. The only payment, if the Fly Ash was free, would be the transport and lying of the Fly Ash.

4. Immediate reduction in landfill sites which will be welcomed by the government.

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.

6.7 Recommendation

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. Although the Dump Ash still needs to be studied in depth, it can be said that each individual stockpile needs to be assessed thoroughly by following basic steps as completed in this study. A data record must be established on the characteristics of each dump site found in South Africa for easy access to results and further studies. The Dump Ash has shown that it is unpredictable and it would be recommended that the Dump Ash be used for stabilisation of clay materials creating better working platforms to support the pavement layers above. If the data can be analysed, future references to using Fly Ash directly from dumps for stabilisation can be foreseen. 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 trail 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 reducing greenhouse gases.

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APPENDICES

ICC/ICL Tetsing

pH meter

Kendal Dump Ash

POZZFILL

DURAPOZZ

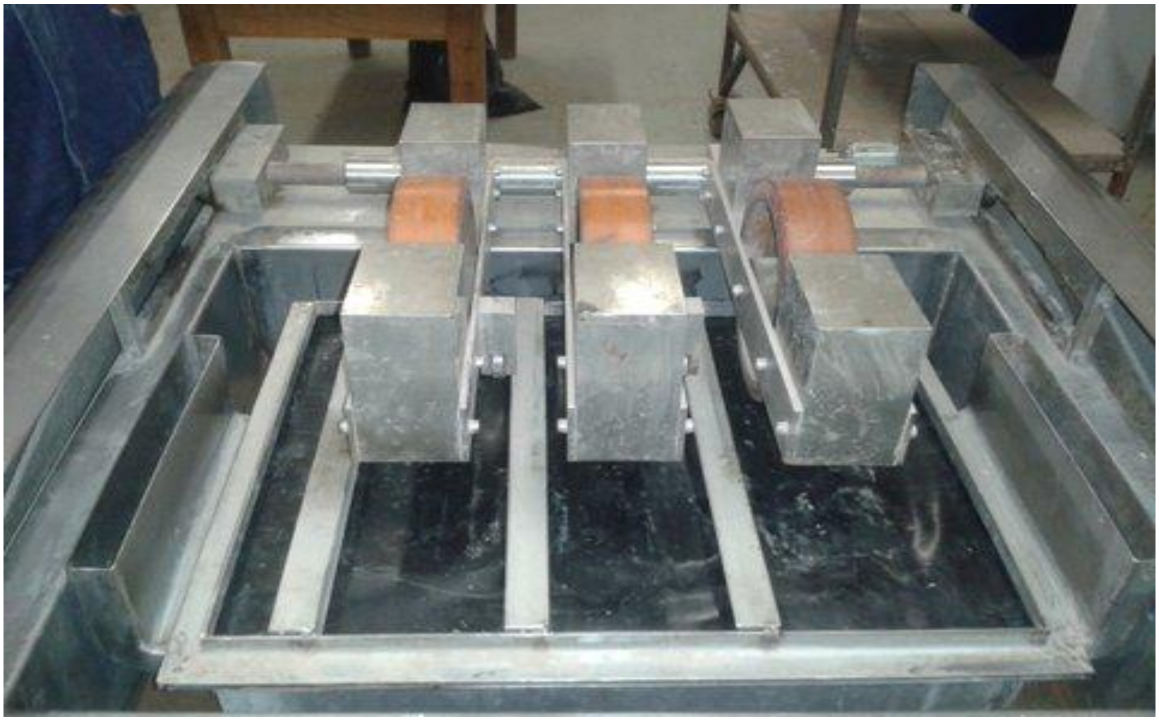
CBR/UCS Test Apparatus

MDD Compactors

Triaxial Testing

Triaxial Samples

WDD Brush Test Apparatus



CSIR Erosion Test Apparatus

CSIR Erosion Test Samples

UCS/ITS compacted briquette

Curing of UCS/ITS samples