UNIVERSITY OF WEST LONDON

December 2017

‘The Utilisation of Fly Ash for Ground Improvement’
A Sustainable Construction of Embankment

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A thesis submitted in partial fulfillment of the requirements of The University of West London for the degree of Doctor of Philosophy

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Abstract

In this work, the effect of Fly Ash (FA) on fine sand and its suitability as a civil engineering material for construction of embankments is investigated. The thesis is concerned with the role of FA content in stabilised soil physical characteristics. The aim of the study presented in this thesis is to examine the suitability of class F FA as a construction material in geotechnical engineering projects. This is achieved through combination of experimental analysis and numerical simulations. Experimental analyses (in accordance with British Standards) were conducted by applying compaction, particle size distribution, bearing capacity tests and resilient modulus, derived from California Bearing Ratio (CBR), while numerical simulation was carried out using finite element and lagrangian finite difference analysis. For the purpose of this thesis, all the samples were tested before and after being treated with four different curing durations, 1 week, 2 weeks, 4 weeks and 8 weeks, and three variations of FA content, 5%, 10% and 15%. The samples were also mixed with 3% of cement as the activator. In this thesis, the research aims and objectives are stated in the introduction chapter, followed by the literature review on FA, soil stabilisation and ground improvement. The research methodology and details about the materials used, are then presented and discussed. The numerical simulations and results are finally presented. FA stabilized samples, with an accurate mixture, were shown to have lower dry densities while producing higher strengths than the sand. Potentially making it an effective material suitable for use in embankment construction and projects alike.

Keywords: Fly Ash; Ground Improvement; Soil Stabilisation.

Acknowledgments

I would like to express my sincere gratitude and thanks to my supervisors, Dr. Susana Lopez-Querol and Dr. Ali B-Jahromi, for leading me through this thesis. Their intellectual guidance and support was crucial for the production of this document. Dr. Querol's broad knowledge in the subject area exposed me to real world challenges that any practitioner would not wish away.

I would also like to thank my family members for their support, selflessness and patience during the long months and years it took me to research and write this thesis. I am profoundly grateful, for without their backing, this process would not have been possible. I like to also thank the people at the Ratcliffe-on-Soar Power Station for providing the fly ash utilised for this research, as it was supplied for free of charge.

Lastly, I would like to acknowledge the input of those who assisted me in one way or the other towards the final realization of the goals of the entire PhD program.

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Abbreviation List

Acronym	**Definition**
ASTM	American Society for Testing and Materials
BA	Bottom Ash
CBR	California Bearing Ratio
C_C	Coefficient of Gradation
CCPs	Coal Combustion By-Products
CCR	Coal Combustion Residues
C_U	Uniformity Coefficient
DEM	Distinct Element Modelling
EA	Environmental Agency
EWC	European Waste Catalogue
FA	Fly Ash
FBC	Fluidised Bed Combustion
FDM	Finite Difference Method
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
FGD	Flue Gas Desulphurization
IEA	International Environmental Agency
LCPD	Large Combustion Plant Directive
MAC	Magaldi Ash Cooler
MDD	Maximum Dry Density
M_R	Resilient Modulus
OMC	Optimum Moisture Content

OPC	Ordinary Portland Cement
PSD	Particle Size Distribution
RE	Rammed Earth
RPM	Asphaltic Recycled Pavement Material
RSG	Road-Surface Gravel
SH	Sodium Hydroxide
SHW	Specifications for Highway Works
SS	Sodium Silicate
STAR	Staged Turbulent Air Reactor
TRRL	Transportation and Road Research Laboratory
UCS	Unconfined Compressive Strength
UKQAA	UK Quality Ash Association
XRD	X-Ray Diffraction

Chapter 1

Introduction

The construction industry is challenged to adopt, adapt and use both old and new materials and methods to provide innovative, economical, and sustainable solutions. Therefore, it can facilitate existing infrastructure rehabilitation and expansion, construction of new infrastructure, environmental restoration and enhancement, safe recovery and utilisation of energy resources, and mitigation of risks from natural disasters. There are currently very low utilisation rates of fly ash (FA) for construction of embankments and highways. Majority of the available data on FA utilisation is also based on clayey soils and minimal research on sandy materials.

This study is concerned with the influence of FA, a coal combustion residue, on stabilised soil. Its effect will be investigated and analysed through a variation of laboratory tests, such as Particle size distribution, Compaction, California bearing ratio (CBR), Resilient Modulus (M_R), as well as computational program analyses for the possible utilisation of FA in geotechnical and geoenvironmental infrastructures.

The aim of the study presented in this thesis is to examine the suitability of class F FA as a construction material in geotechnical engineering projects. An increase in utilisation of FA would lead to a lower rate of disposal, replacement of traditional materials, effectively lowering the CO_2 emissions. The key aim of the study is ultimately to establish the most advantageous FA percentage for both strength and stiffness development of fine sand for embankment projects. The chief objectives of the research are:

- To see how different curing durations affect the soil properties.
- To investigate the influence of FA content on soil performance.
- To distinguish the impact of FA on sand, regarding strength and stiffness.
- To obtain soil parameters from numerical applications for an enhanced methodology.
- To create a more sustainable construction material for projects with fine, sandy and weak soils.
- To reduce the quantity of FA disposal by further utilisation.

The hypothesis for the thesis was derived from an analysis of relevant literature. This study will be based on the working hypothesis that an enhanced soil stabilisation method through utilisation of FA will improve soil's chemical and physical properties (Arioz et al. 2013; Cristelo et al. 2011; Kolias et al. 2005), so that requirements of the specific engineering projects can be met as well as diminishing soil exchange. It is predicted that as the FA content is increased, a higher strength, at optimum conditions, will be achievable. Additionally, it is forecast that the duration of curing will have a positive effect on the physical properties of the treated samples; the longer the duration the higher the obtainable strength. It is also found that cement content, even at low quantities, will play a vital role in the stabilisation process, and subsequently, in the end results.

In the first section of this thesis, a review of previous relevant research is outlined in the literature review. This section covers the background, classification, utilisation, applications, sustainability, health aspects and the storage of FA both in the UK and around the world, continued by ground improvement and soil stabilisation. The literature review is followed by the study methodology, which will be used to answer the research questions. Furthermore, theoretical investigation on the possible use of the developed stabilised soil for embankments is to be concluded through a finite-element and finite difference (Lagrangian formulation) analyses.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a literature review on FA, ground improvement, soil stabilisation and stabilisation procedures.

A significant share of the world's energy needs is met by coal-fired power stations by burning coal as fuel. There are residues generated in these power plants, which are called Coal Combustion Products (CCPs). Coal ash is inclusive of the combustion residues; boiler slag, bottom ash and mainly FA (Feuerborn 2011). In general, most of the CCPs produced are of coal ash. Throughout the past decade, there has been a substantial amount of research on coal combustion products, particularly regarding FA and bottom ash (BA). All around the world, in general, most of the FA produced is disposed of in landfill, causing concerns for environmental agencies.

Sato and Nishimoto (2005, p. 1) believe that 'the decline in demand for cement, the increasing difficulty of finding new landfill sites, the growing generation of coal ash, and the growing social interest in recycling and reuse of natural resources have made it necessary to develop new applications' for utilisation of FA. This study will be focusing on the utilisation of FA only as it has proved to be a more viable soil stabiliser in comparison to bottom ash, due to its finer particle size. FA will be described in depth concerning its background, classification, utilisation, applications, sustainability, health aspects, storage and reprocessing methods.

2.2 Fly Ash

2.2.1 Background

Coal firing for power generation began extensively in the 1920s, since which, millions of tonnes of FA and ash-related by-products have been produced. In the 1930s, FA was firstly used as a constructional material in Willow Creek Dam of America (Pei-wei et al. 2007). Ahmaruzzaman (2010) reported in an article that from the 600 million tonnes of coal ash produced worldwide annually, about 500 million tonnes constituted FA, which accounts for approximately 80% of the total ash produced.

Coal-fired power plants around the world produce nearly 25% of the world's primary energy needs; in other words, 38% of the worldwide electricity is generated from these coal-fired power plants (Barnes and Sear, 2006). In some countries, like Germany, Greece, and the Czech Republic, over half of the electricity generated is from coal fired power stations (World Coal Institute 2002). In the UK, coal combustion accounted for nearly a third of the power generated from March 2014 to February 2015 (Carroll 2015). In the United States, approximately 50% of the electricity consumed is produced by the coal combustion process (Cetin and Aydilek, 2013).

By definition FA has to be derived from the burning of pulverised ground or powdered coal (Dockter and Jagiella, 2005). This process is only possible in boilers where combustion of finely ground fuel is done in a cloud, with combustion temperatures of 1300–1500 °C (Caldas-Vieira et al. 2013). In other words, the definition guarantees that combustion takes place at high temperature, which is high enough to facilitate glass formation in the FA (Caldas-Vieira et al. 2013).

FA consists of inorganic matter that does not burn during the process and is mainly composed of three elements: Iron, Aluminium and Silicon (Barnes and Sear, 2006). Other elements present in FA, at much lower percentage, include; Magnesium, Potassium, Sodium, Titanium and Sulfure (Barnes and Sear, 2006). The concentrations of these minor elements are much higher in FA, than in the parent coal (Yeheyis et al. 2009). These elements are used in establishing the FA type. FA is obtained by electrostatic or mechanical precipitation of dust like particles from the flue gas, and as stated previously, it represents the greatest proportion of the total CCP production (Feuerborn 2011).

Several authors (Pandey and Singh, 2010; Mackiewicz and Ferguson, 2005; Acosta et al. 2003; Kim et al. 2005) report that the origin and nature of the parent coal, conditions and process of combustion, type of emission control devices and methods of storage and handling have a significant effect on the physical, chemical and mineralogical properties of the FA. It is of interest to note that the utilisation of FA in different countries is influenced by specific experience and traditions of that nation (Feuerborn 2011).

Throughout the past decades, FA has been named as a problematic solid waste due to the conventional disposal methods of FA from thermal power plants and factories, as they have contaminated and degraded arable lands all around the world. The subject on ash disposal, product of combustion solid fuels, has been researched since the early 1900s (Jackson et al. 2007). Several studies have been conducted in the 21st century, indicating that chemical, physical and biological properties of the degraded soil can be significantly enhanced by utilising FA as a soil additive (Pandey and Singh, 2010).

2.2.2 Classifications

FA consists of fine, powdery particles predominantly spherical in shape, either solid or hollow and mostly glassy in nature (Ahmaruzzaman 2010). Currently, the American Society for Testing and Materials (ASTM) categorises FA into two groups, Class F and Class C (Nataraja et al. 2007). According to ASTM class F, FA contain at least 70% by weight of Silicon Oxide (SiO_2) + Aluminium Oxide (Al_2O_3) + Iron Oxide (Fe_2O_3) and are typically the product of burning high-rank coals, while Class C FA contain a minimum of 50% by weight of SiO_2 + Al_2O_3 + Fe_2O_3 and a cementitious component, and are usually a product of burning low-rank coals (ASTM 2003, cited in Fox 2005; cited in Kelly 2015; cited in Acosta et al. 2003).

If a bituminous coal, which has low concentrations of calcium compounds, is used, the resulting by-product is, in general, class F FA with no self-cementing properties (Cristelo et al. 2011; Mackiewicz and Ferguson, 2005). Low-calcium FA as a cementitious material has an inherent drawback in that it has a relatively low reactivity (Arjunan et al. 2001a). As a resutls, there is a need for an external agent to accelerate the hydration reactions. The intrinsic reactivity of a FA depends on upon various factors but primarily its chemical and mineralogical composition and fineness (Arjunan et al. 2001a). On the other hand, if a sub-bituminous coal is used, the resulting ash will be classified as type C due to its higher amounts of calcium (Cristelo et al. 2011). This kind of FA has self-cementing properties, which means that, in theory, water is the only additive needed to hydrate this material (Cristelo et al. 2011).

The self-cementing characteristics of FA is determined by its crystalline compounds. The conditions and the processes at which the power plant operates, influences the level of crystallinity, and consequently determining the hydration characteristics of specific FA sources (Mackiewicz and Ferguson, 2005). Additionally, when FA particles are cooled rapidly, the FA produced has a noncrystalline (glassy) or amorphous structure. Meanwhile, when the particles are cooled at a slower rate, the FA produced has a more crystalline structure (Mackiewicz and Ferguson, 2005).

The chief difference between Class F and Class C FA is in calcium content and its three main elements, which as stated previously, are Silicon, Aluminium and Iron content in the ash. In Class F FA, the total calcium typically ranges from 1% to 12% (usually less than 5%), mostly in the form of calcium hydroxide, calcium sulphate and glassy components, in combination with silica and alumina (Ahmaruzzaman 2010; Cristelo et al. 2011). In contrast, Class C FA may have a calcium oxide content as high as 30-40% (Ahmaruzzaman 2010). Furthermore, another difference between Class F and Class C is that the amount of alkalis (combined sodium and potassium), and sulphates are higher in Class C FA than in Class F FA (Ahmaruzzaman 2010).

2.2.3 Utilisation

In order to meet the growing needs of all the sectors, mainly energy and construction, the demand for raw materials has led to earth's natural resources getting closer to being depleted, the demands are now beginning to be met by much deeper mining (Pradhan et al. 2014). FA ranks as the planet's fifth largest raw material resource (Ahmaruzzaman 2010) and can be used as an alternative to conventional materials in the construction of geotechnical and geoenvironmental infrastructures. It is estimated that the remaining worldwide coal reserves will last at least two centuries (World Coal Institute 2002) and in some locations, low-cost surface mining techniques are used to produce high-quality coal, which tends to be exported to various countries. Consequently, coal will remain a major by-product and 'it will also find growing application within the expanding economies of developing countries such as China and India' (Barnes and Sear, 2006, p. 2).

The utilisation of high quantities of coal ashes and related by-products is unfortunately limited due to institutional, economical, technical and legal restrictions. The utilisation of coal combustion products in Europe are being influenced by political decisions and environmental legislation. Currently, the most significant political decisions force increased clean coal technologies for high effective combustion and CO_2 reduction (Feuerborn 2011; Caldas-Vieira and Feuerborn, 2013).

By avoiding mining or quarrying for natural-occurring resources, and using coal combustion products as a replacement, sustainable and environmental benefits can be achieved. Energy demand and emissions into the atmosphere can also be reduced by utilising CCPs (Barnes and Sear, 2006). The CCPs utilisation is well established in some European countries, based on long-term experience and technical as well as environmental benefits. CCPs are mainly being utilised in the building material industry, civil engineering, road construction and for construction work in underground coal mining (Feuerborn 2011). Direct utilisation of CCPs in construction projects requiring large amounts of materials, like highway embankment construction, not only offers a promising solution to the disposal problem currently being faced, but also an economic alternative to the use of conventional materials (Kim et al. 2005). In some European countries, due to FA environmental, economical and sustainability gains, the utilisation is higher than the production. Also, the utilisation of FA throughout Europe is influenced by specific experience and traditions of each country (Feuerborn 2011).

In the UK, coal-fired power stations have produced on average 5-7 million tonnes of FA each year over the past 10 years (Jones et al. 2015). In Figure 1 the development of FA production in the UK from 1999 to 2013 is shown. The total amount increased from 4.45 million tonnes in 1999 to 7.0 million tonnes in 2003 and then decreased to 4.5 million tonnes in 2009. This reduction is believed to be due to the recession in 2008. It can also be seen that, from 1999 to 2003, landfill rates were higher than the utilisation rate; however, from 2003 onwards it was lower than the utilisation rate. In 2010, 36% of the total FA produced was sent to landfill; this increased to 48% in 2012, while the utilisation amount remained at around 3.2 million tonnes, and then in 2013, the rate of landfill dropped to 38%.

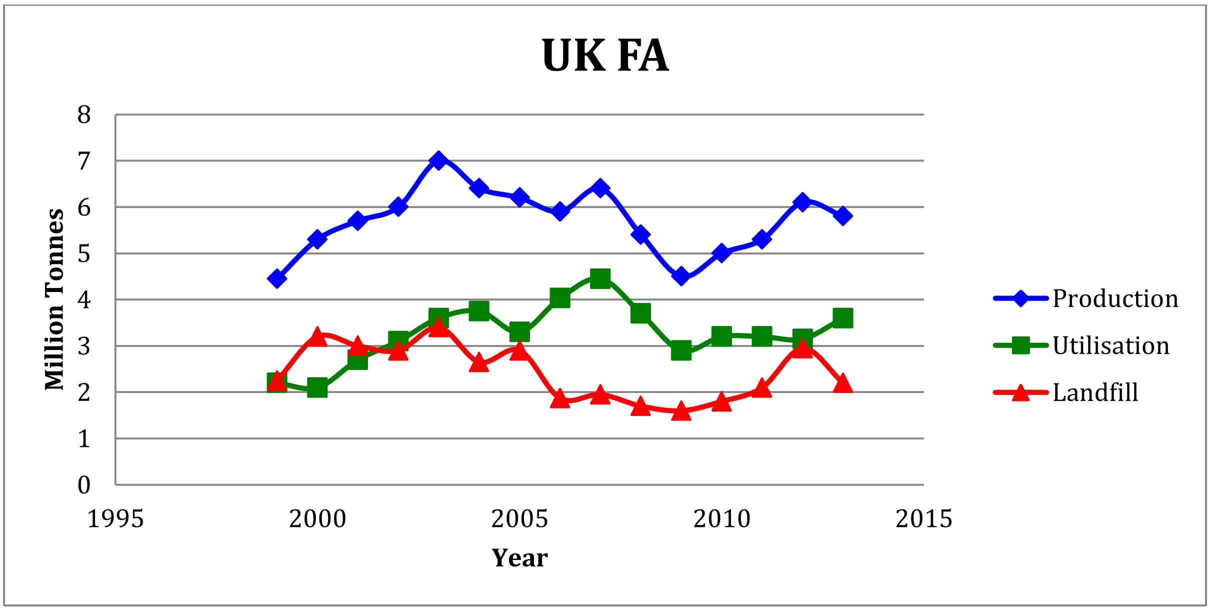


Figure 1: UK FA production, utilisation, and landfill values
Source: After (Carroll 2015; UKQAA 2016)

Most of the FA that is produced is disposed of as landfill. The relative utilisation and production of FA differ noticeably from country to country, as shown in Figure 2. The disposal of FA at this scale has caused major environmental concerns. Ahmaruzzaman (2010) believes that the disposal of FA will soon be too costly if not banned. This can be seen in Netherlands, where all the FA is utilised or exported since landfill is prohibited (Eijk et al. 2011). It is another important issue of Clean Coal Technology to avoid the disposal of the minerals produced in power plants and to use them as valuable sources (Caldas-Vieira and Feuerborn, 2013). Kolias et al. (2005) report that there may be some issues associated with high quantities of FA being used. Some of these problems may be cost of transport, high demand for water and any practical problems that may occur during mixing and spreading of large quantities of FA. In respect to environmental issues, FA utilisation can cause environmental risks to air, suface water and ground water (Nawaz 2013). When used in large quantities, FA can contaminate air by dispersion if not conditioned adequately or transported in an uncontrolled fashion. Additionally, the environmental impacts are potentially increased if the power station with the suitable FA is located extremely far from the site. During a survey, utilities were asked to summarise their key challenges on FA utilisation. The following were their responses (Rokoff et al. 2013):

- Inconsistency in monthly sales;
- Highs and lows of the construction industry and the economy;
- Reliability of end users;
- Distance to end users and markets;
- Air pollution control technology;
- Negative public image;
- Trying to grow utilisation in an environment of increasing regulations.

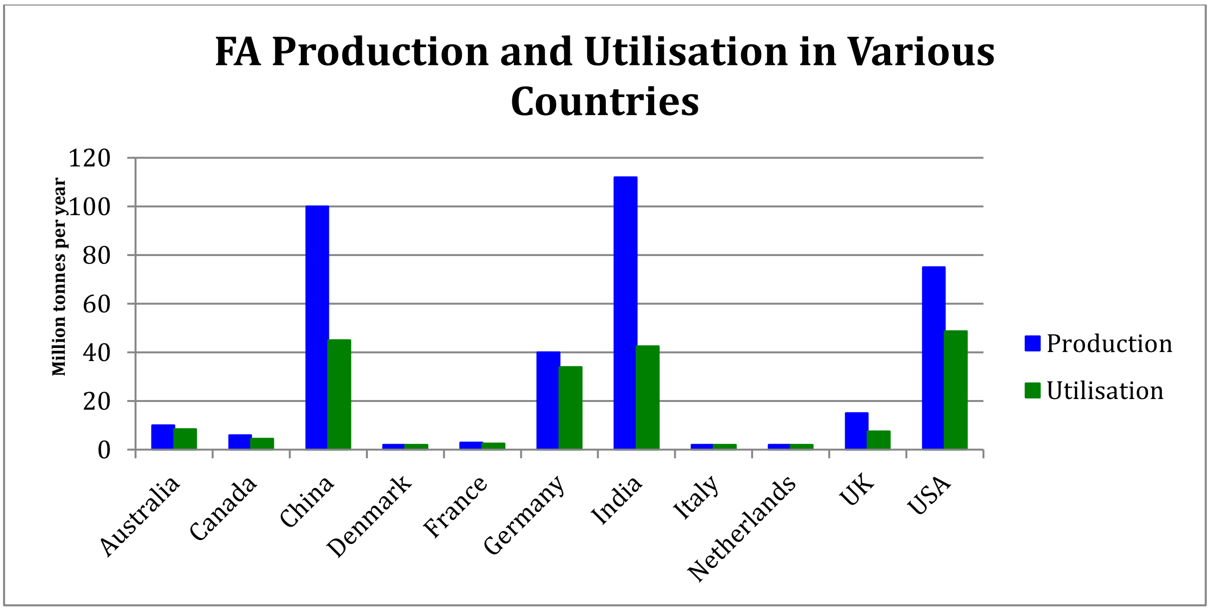


Figure 2: Worldwide FA production, utilisation
Source: After (Pandey and Singh, 2010)

According to Pflughoeft-Hassett and Hassett (2001), there are several institutional barriers to increased ash utilisation:

- Lack of familiarity with potential ash uses.
- Lack of data on environmental and health effects.
- Restrictive or prohibitive specifications.
- The belief that FA quality and quantity are not consistent.
- Lack of FA specifications for non-cementitious applications, resulting in substitution in their applications of the most restrictive specifications for use of FA in cement and concrete.
- The belief that raw materials are more readily available and more cost-effective.
- Actions by environmental agencies that normally support beneficial ash use in principle but that frustrate the actual implantation by restrictive regulations.
- Lack of guidelines on beneficial use.

However, there are many reasons to raise the utilisation of FA. Some of these reasons are stated below (Ahmaruzzaman 2010):

- Minimizing disposal costs.
- Less area is reserved for disposal, thus enabling other uses of the land and decreasing disposal-permitting requirements.
- There may be financial returns from the sale of the by-product or at least an offset of the processing and disposal costs.
- The by-products can replace some scarce or expensive natural resources.

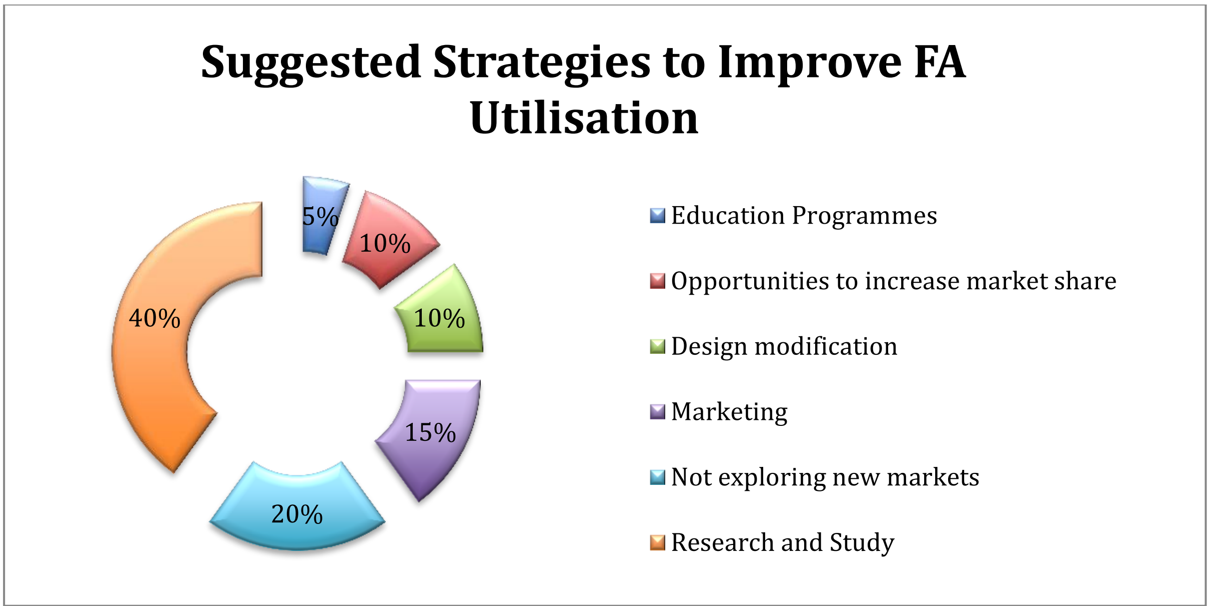


Figure 3: Suggested strategies for further FA utilisation
Source: After (Rokoff et al. 2013)

Lack of awareness on the advantages of CCP-based products among end-users is limiting new initiatives and market potential. There should be an integrated approach by the coordination of technologists, architects and manufacturers for the production of superior quality of CCP-based products to meet consumer acceptability and increased marketability. In addition, in association with scientists, policy makers and CCP generators, awareness of the quality parameters and beneficial effects of CCP-based building materials and their utility should be made clear to the general public for mass consumption and effective utilisation (Asokan et al. 2005). When a group of power plants took part in a survey, a list of strategies was produced on how the utilisation of FA can be improved from their perspective (Rokoff et al. 2013). These strategies are presented in Figure 3.

2.2.4 Applications

Coal combustion products are mainly utilised in the building material industry, civil engineering, road construction, underground coal mining construction and for recultivation and restoration purposes in open cast mines (Feuerborn 2011; Berg and Feuerborn, 2005; Sato and Nishimoto, 2005). FA has a broad range of applications within the construction industry (Figure 4).

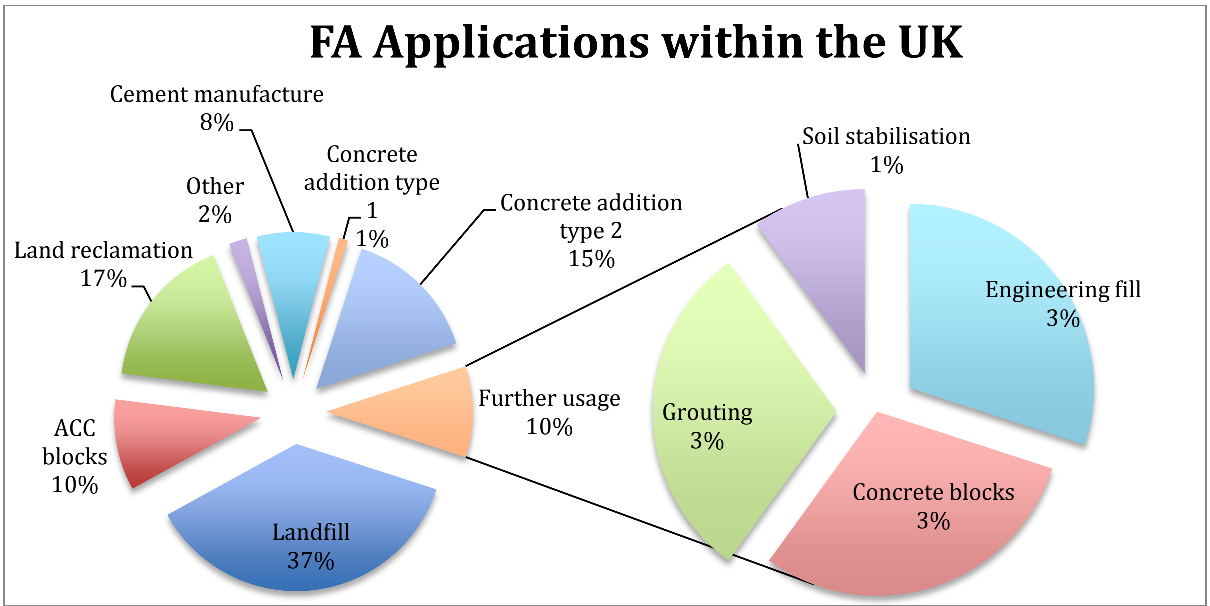


Figure 4: Various FA applications within the UK
Source: After (Carroll 2015)

The use of FA as a partial replacement for Portland cement in concrete is widespread and considerable volumes are used. The development of new construction materials and elements is another way to utilise FA in the civil engineering applications. These materials can include cement, prefab panels, bricks and new binding materials in pavements (Goyal 2010). Some of the main civil engineering applications include highways construction, embankments, and enhancement of foundation. The high cost of road aggregates has created an opportunity to make significant savings through the utilisation of FA in pavement construction. FA has also been utilised as an aggregate filler, in highway construction, soil stabilisation, coarse subgrade material and as a mineral filler for bituminous concrete (Ahmaruzzaman 2010). Some of the advanced applications of FA are (Pandey and Singh, 2010):

- Seepage control through various hydraulic structures.
- As an effective low-cost adsorbent for the removal of heavy metal ions from municipal solid waste leachate.
- Additives for the immobilization of industrial and water treatment wastes.
- The elimination of mercury and lead ions from waste water.

For the production of blended cement, FA is also used, and a gradual increase in demand is observed (Caldas-Vieira and Feuerborn, 2013). Several researchers (Mehta 1986; Manz 1986) proved even from past decades that high carbon FA could replace Portland cement, even if the specifications and proposal revision of standards are not met.

In a study, reported by Pei-wei et al. (2007), utilisation of 50% FA in a concrete dam lead to a reduction of 33% and 40% in shrinkage and expansive strain, respectively, in comparison to samples without treatment (Pei-wei et al. 2007). FA is used worldwide, and its premium application is like cement in concrete. It provides significant technical benefits to concrete, including improved consistency, lower heat of hydration, strength and durability performance (Jones et al. 2006). Also, as a low-cost by-product, FA can reduce the overall unit cost of concrete production (Jones et al. 2006).

The European Standard EN 450 was first published in 1994. It refers to siliceous FA, only. Siliceous FA is defined by a content of reactive CaO of less than 10% by mass. It is believed to be similar to class F FA according to ASTM C 618 (Berg and Feuerborn, 2005). Utilisation of FA, as a partial or full replacement of cement in concrete, may be compromised by the addition of air pollution control chemicals, such as activated carbon and high solubility chemicals such as sodium-based sorbents, and may require different handling (Baldrey et al. 2015).

Since the application as concrete addition constitutes the highest added value for FA, the European Standard EN450 'Fly Ash for Concrete' is of high importantance for the marketing of FA (Berg and Feuerborn, 2005). The standard was published first in 1994 and then revised in the early 21st century (Feuerborn 2011). The revised version of EN450 1994 is in two parts: EN 450-1 deals with specifications, conformity criteria and definitions, and the new section EN 450-2 deals with the conformity evaluation of FA for concrete (Caldas-Vieira et al. 2013; Berg and Feuerborn, 2005).

EN 450-1 deals with siliceous FA, which is collected in a dry state, or which is processed by e.g. classification, sieving, drying, selection, blending, carbon reduction and/or grinding (Feuerborn 2011; Caldas-Vieira et al. 2013).

Recently, it has been shown that FA might improve the compressive strength of bricks and make them more resistant to frost. These FA bricks can weigh nearly 30% less than conventional clay-fired bricks (Reidelbach 1970, cited in Ahmaruzzaman, 2010). In 2010, about 14 million tonnes of FA were utilised for production purposes in underground mining and in the construction industry. Most of the FA produced was utilised as a concrete addition in road construction and as raw material for cement clinker production (Caldas-Vieira and Feuerborn, 2013). Stockpile ash could be a large complementary source but requires a suitable process route to be developed (Carroll 2015). In order to utilise FA on a vast scale, civil engineering applications should be the main focus as soil improvement is mostly required for these applications.

2.2.5 Fly Ash Around the World

According to Gutmann et al. (2014), thermally powered coal plants are the biggest global contributors of greenhouse gas emissions. It has been reported that coal fired plants are responsible for over 70% of greenhouse gas emissions in the energy sector, while producing about 40% of the world’s energy (Gutmann et al. 2014). In a report from the International Energy Agency (IEA 2015) regarding global CCP production from 1972 to 2013 (Figure 5), it can be seen that there has been a rapid growth in the 21st century. The IEA (2015) suggests that this was mainly due to the vast production growth in China.

Due to the relatively low price of coal compared to gas, coal will remain a major by-product, and as stated earlier by Barnes and Sear (2006), FA application is expected to expand for developing countries like China and India. These countries are also the major producers of CCPs in the world (Asokan et al. 2005). The world average utilisation of coal by-products is 16% (Suryawanshi et al. 2012), and in developed countries, which have higher quality CCPs, the utilisation rate is over 33% (Asokan et al. 2005). This section shows the utilisation and applications of FA in Europe and in some countries: Australia, Canada, China, India, Japan, South Africa, Russia and the USA.

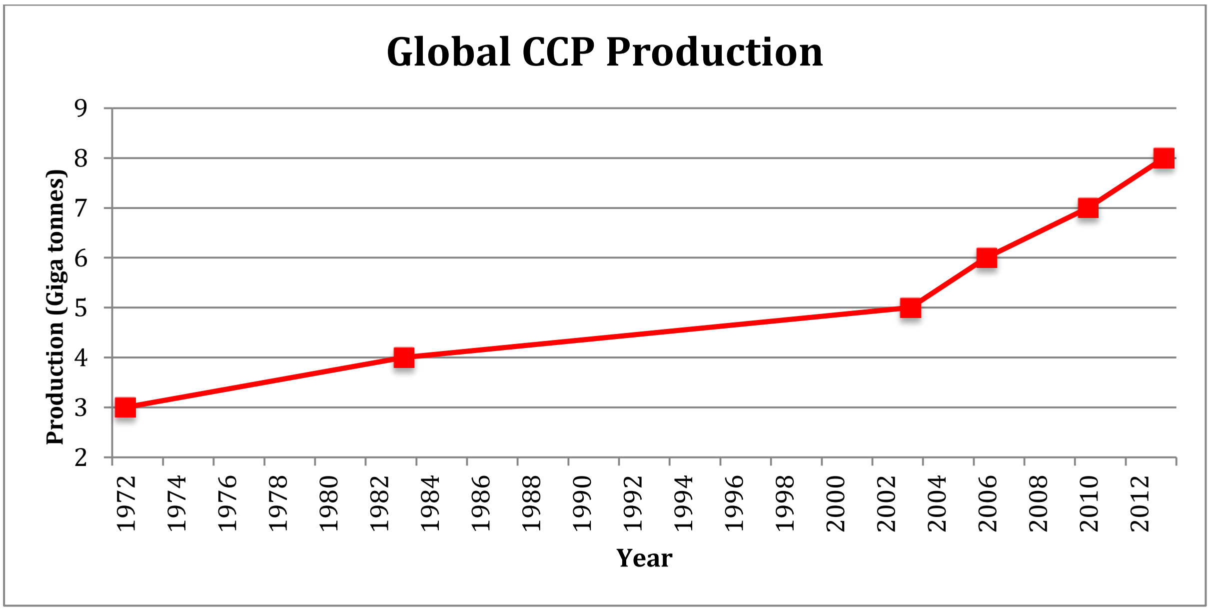


Figure 5: Global coal combustion by-products
Source: After (IEA 2015)

Japan

In Japan, about 90% of the total coal ash generated is FA (Ishikawa 2007). In 2003, 82% of the total CCPs produced was utilised in Japan (Asokan et al. 2005). This figure was reported to have increased to over 96% according to a more recent study (Park 2014). About 16% of the total power generation in Japan is from coal-fired plants (Ishikawa 2007). The use of FA as an admixture for concrete is considered the most effective application (Ishikawa 2007). It can be seen from Figure 6 that from 1994 to 2004 the amounts of FA produced and utilised increased year by year and the amount of FA being landfilled decreased only gradually, with its lowest being in 2004 (Ishikawa 2007).

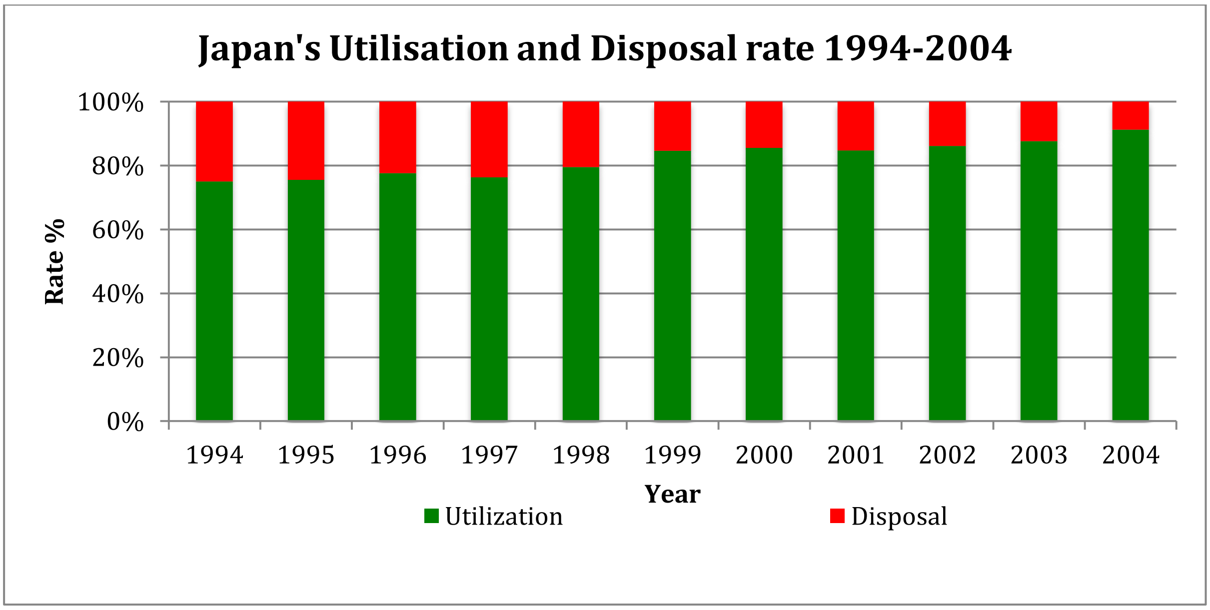


Figure 6: FA utilisation and disposal rates in Japan from 1994 to 2004
Source: After (Ishikawa 2007)

Russia

Between the years 2000-2005 the utilisation of FA in Russia from thermally powered power stations contributed about 18-20% of the annual output (Putilov and Putilova, 2005), one of the lowest utilisation rates around the world. In fact, from the year 1990 to 2005, about 85 % of ashes were disposed of in storage, causing environmental contamination (Putilov and Putilova, 2005). The procedure of discarding was performed through hydraulic ash disposal systems, which also has some disadvantages, some of which are mentioned below (Putilov and Putilova, 2005):

- Negative influence on air (ash disposal dusting) and water (pollution of underground and superficial waters).
- Mineralogical and chemical soil content change.
- Failures of ash disposal.
- Worsening of consumers ash properties.

Figure 7 shows the trend of coal ash production, utilisation and disposal rates in Russia from 1990 to 2005. It can be seen the rate of disposal is really high, between 79% to 89% throughout the 15-year period. The production has dramatically lowered from 1990, over halved in year 2002. Despite the disposal rates following the production trend, it can clearly be seen that the utilisation rates, not only have they dropped, but they have seen an increase. In year 1995, only 5.9% of the coal ash was utilised, whereas the same figure in year 2005 reached over 17%. Even though, the disposal rates are immensely high, the utilisation rates are in the right direction.

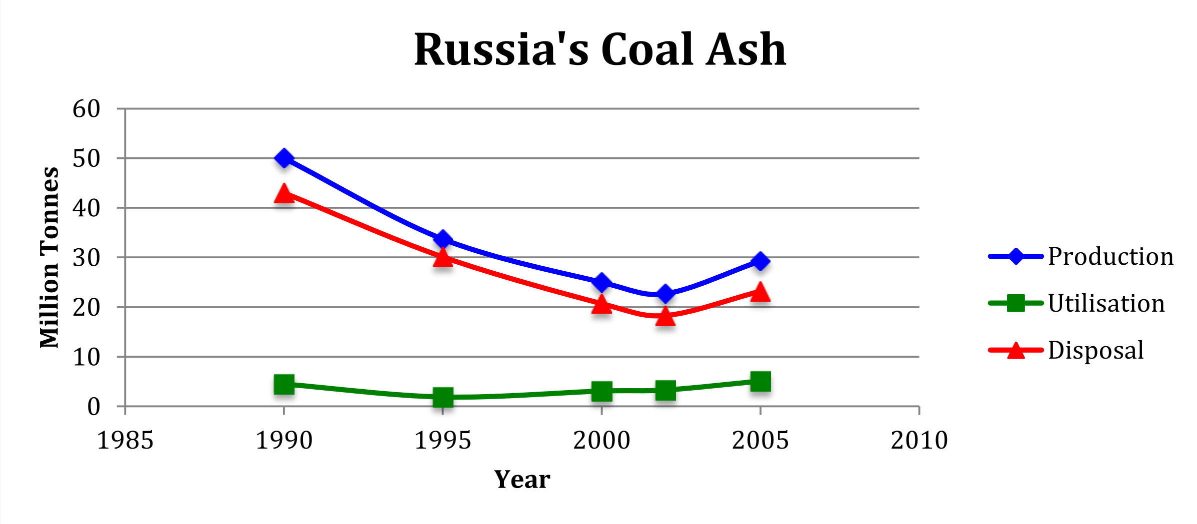


Figure 7: Russia's coal ash production, utilisation and disposal rates from 1990 to 2005
Source: After (Putilov and Putilova, 2005)

China

China has been the world's highest coal producer since 1985 (IEA 2015). As stated earlier, China has been the main cause of the rapid growth of coal production in the 21st century. Since the year 2000, its coal production has increased by about 177%, while the rest of the world's production has increased by about 78% (IEA 2015). In 2006, coal-fired power plants constituted about 80% of the electricity generated in China (Lan and Yuansheng, 2007). In a more recent report by Tang et al. (2013), it was reported that about 69% of the primary energy of China was produced from coal, which is over 200% of the average in the rest of the world. It is also believed that this figure is unlikely to be changed in the near future as other natural resources like gas and crude oil are scarce (Tang et al. 2013). Figure 8 shows the utilisation and production rates of FA in China from 2005 to 2012. It can be seen that FA utilisation has increased with higher productions throughout the past decade.

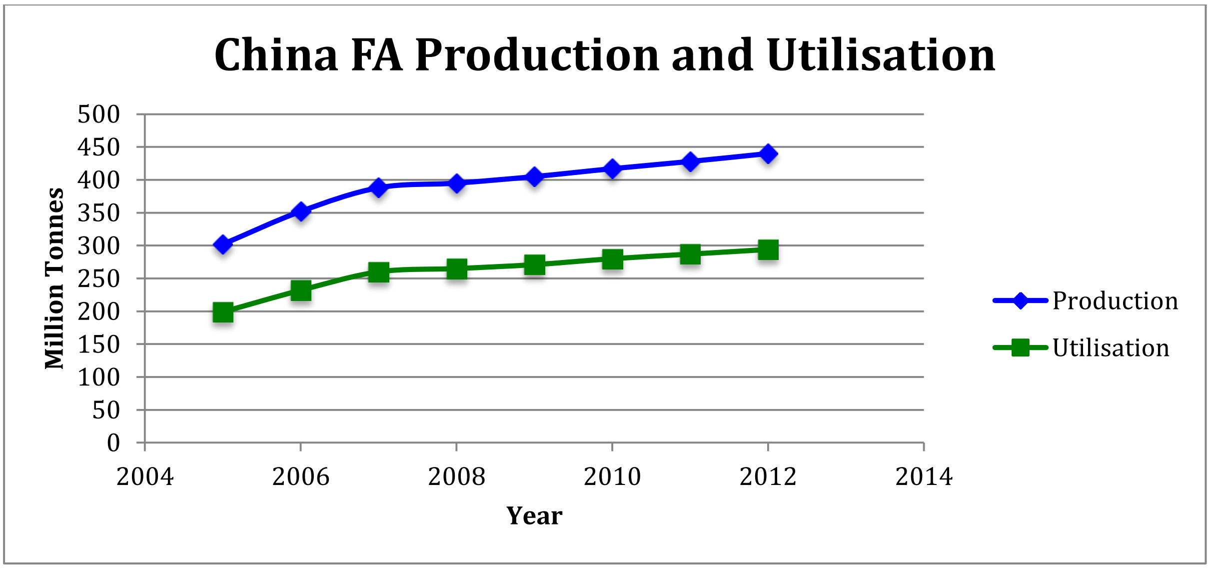


Figure 8: China's FA production and utilisation from 2005 to 2012
Source: After (Harris 2014)

China is also believed to be the highest producer of cement globally, and it has been utilising FA as a supplementary material in the production of cement and concrete for a long time (Lan and Yuansheng, 2007). In China, it has become the norm in concrete production that half is Portland cement, a quarter is FA and the remaining quarter is slag (Lan and Yuansheng, 2007). FA utilisation in China cement's industry accounts for around 38% of the total FA produced annually, about 26% in the masonry industry, and nearly 20% in the fields of road building, backfilling of pile well, soil improvement (Tang et al. 2013). Due to the vast production of CCPs in China, it is very challenging and almost an impossibility for the total FA to be completely utilised. It has to be stored in ash ponds or in open lands, which inevitably releases fine ash into the atmosphere (Tang et al. 2013). Tang et al. (2013) report that the Chinese Government has valued FA utilisation and given the industry priority.

India

In 2005, it was reported that around three quarters of India's power was generated from coal-fired power stations, and again in 2014, this figure was reported to be around 64% (Asokan et al. 2005; Pradhan et al. 2014). In 1992, only 4.7% of CCPs produced were utilised, compared to 27% in 2004 as can be seen in Figure 9 (Asokan et al. 2005). This utilisation of 27% was utilised in the industry of bricks, timber substitute products, cement, as a pozzolana in lime, concrete, as a stabiliser in soil stabilisation, road base embankment, land reclamation, agriculture and consolidation of ground (Asokan et al. 2005).

Figure 9 shows the rapid growth of CCPs production from the 20th century to the 21st. The production rate was increased by 614% from the year 1992 to 2004. According to Asokan et al. (2005), it is expected that the CCPs utilisation rate will increase to 60% by the year 2020. That is an ambitious, yet a very necessary target for the second producer of CCPs in the world. It should be pointed out that 22.5% of FA generated in India is utilised in cement production, and that 19% of the total cement generated in India is FA-cement (Asokan et al. 2005). Additionally, around 56% of FA used, is in the construction industry (Rajak et al. 2016). In India, only about 10% of the produced FA is utilised, which is even below the global average FA usage (Suryawanshi et al. 2012). It is estimated that about 150 million tonnes of FA are being produced from various thermal power plants annually in India (Belani and Pitroda, 2013). That means over 130 million tonnes of FA remain unutilised, which is a major concern for the environment and the future of India.

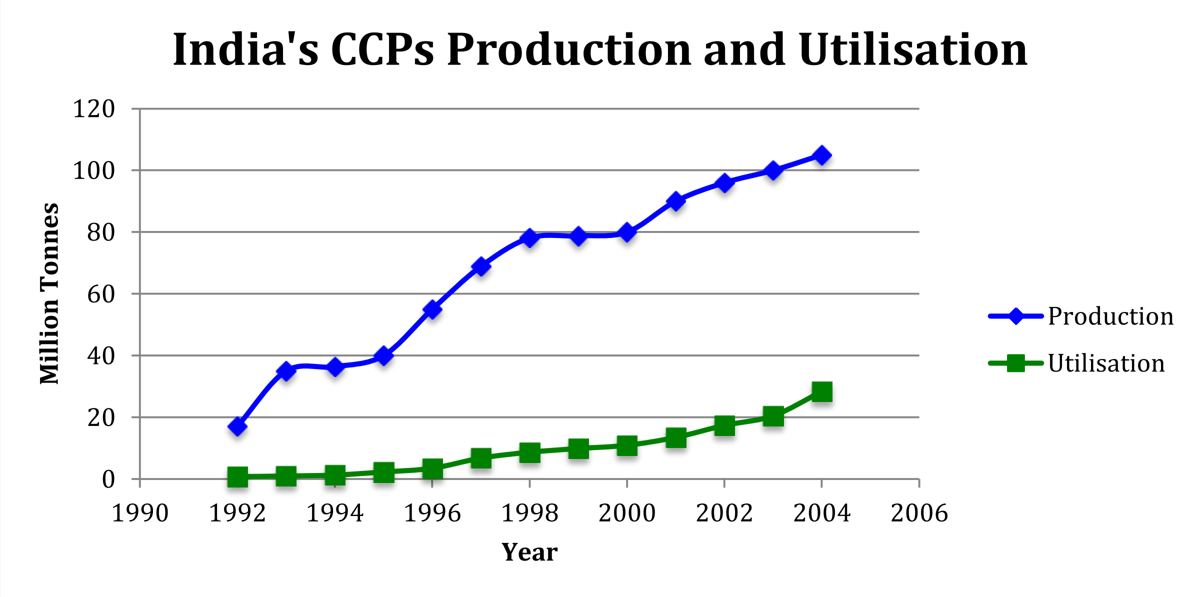


Figure 9: India's CCPs production and utilisation from 1992 to 2004
Source: After (Asokan 2005)

Several authors (Dewangan et al. 2016; Rajak et al. 2016), have recently reported that the Indian Ministry of Environment and Forest has made it compulsory for the construction of roads, compaction of low lying areas, embankments and reclamation projects that are within a radius of 100 km of coal-fired power plants, to utilise FA. This new incentive from the Indian government would certainly be of high support for higher FA utilisation rates in the future.

USA

In 2005, Asokan et al. (2005) reported that over 50% of US electricity was generated from burning coal in thermally coal-powered plants. In the US, the rate of CCP utilisation in 1991 was about 31%, in 2001 it was 33.4% and in 2002 it was 35.4% (Heidrich 2003; Asokan et al. 2005). In a more recent study, it was reported that in 2011, only about 38% of FA produced was utilised, while nearly 62% of generated

FA was disposed of (Sebastian et al. 2013). This rate of disposal, for one of the major producers of FA in the world, is highly alarming.

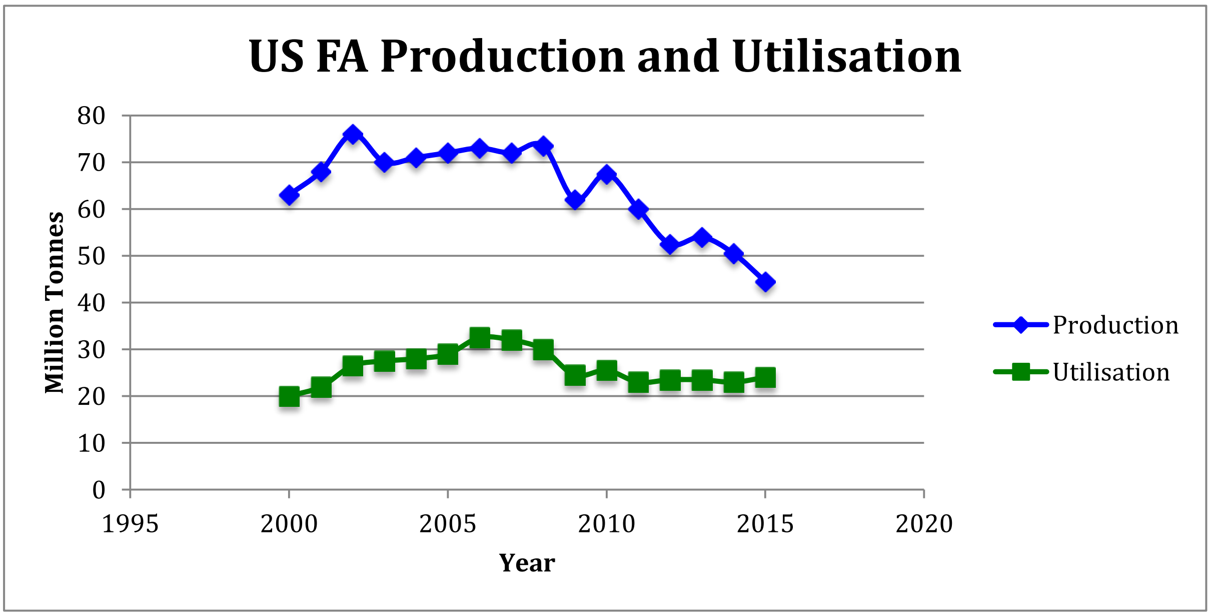


Figure 10: US's FA production and utilisation from 2000 to 2015
Source: After (American Coal Ash Association (ACAA) 2015)

FA can be utilised for a variety of applications within the American construction industry. Figure 10 illustrates the production and utilisation rates of FA in the US from year 2000 to 2015. The production of FA can clearly be seen was decreased post 2008 recession. However, the utilisation rates was maintained over 20 million tonnes, increasing the utilised percentage from 40% in 2009 to about 54% in 2015.

Australia

Australia is the fourth largest coal producer in the world (IEA 2015). In Australia, the rate of CCP utilisation in 1991 was about 9%, and in 2002 a major rise was seen with a utilisation rate of 32% (Heidrich 2003). According to Heidrich (2003), the majority of the FA produced can be classified as class F. About 85% of the FA utilised, is for the enhancement of concrete properties and various building materials, and is utilised to good effect as road base binders and asphalt filler. The same author suggests that Australian FA has the mechanical properties of medium-dense sand and that its compacted mass is about 60% of that of dense sand (Heidrich 2003). Henceforth, this FA has proven to be an excellent construction material for the building of embankments over soft soils and backfilling retaining walls due to the following (Heidrich 2003):

- High internal angle of friction.
- Low unit mass.
- Low compressibility.
- Reduced settlement when used as fill material.
- Ease of compaction.

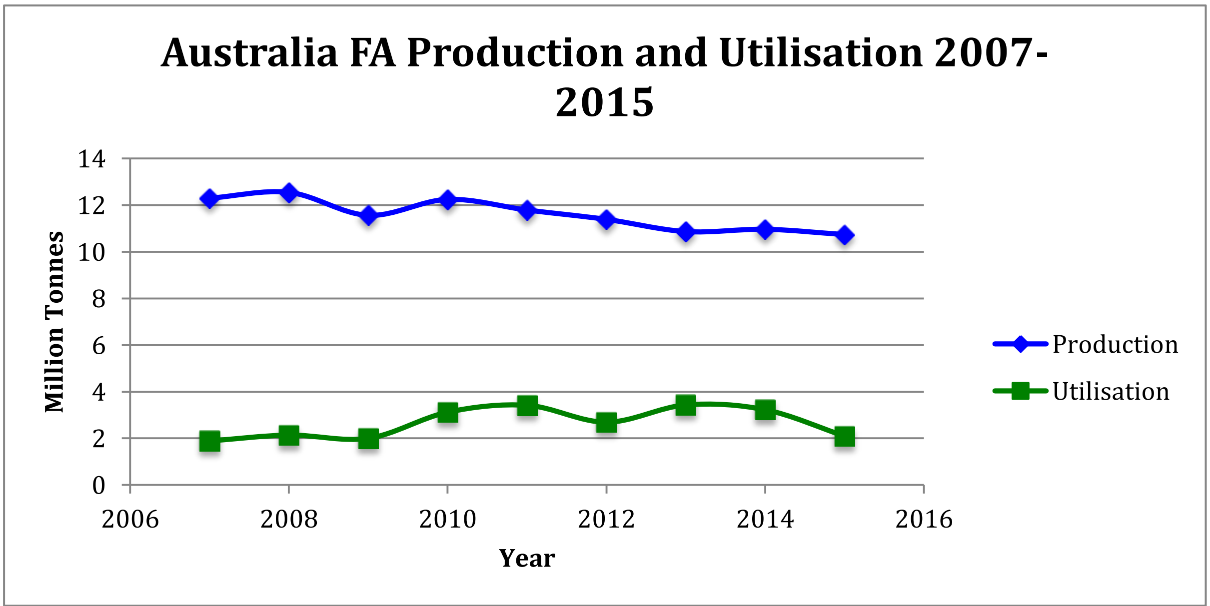


Figure 11: Australia's FA production and utilisation from 2007 to 2015
Source: After (Ash Development Association of Australia (ADAA) 2007; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015)

Figure 11 shows the production and utilisation of FA in Australia from 2007 to 2015. It can be seen that the production of FA has gradually decreased over the years. This is partially due to the closure of some coal-fired power stations. The utilisation rate in 2007 was about 15.4%, with approximately 1.9 million tonnes. It can be seen that the FA used in Australia has been fluctuating over the past years, reaching maximum utilisaiton rate in 2013 with 31.6% and was reduced to 19.5% in year 2015.

Canada

In Canada, the coal-fired power plants were responsible for about 48% of the electricity generated in 1999 and this figure decreased to only around 16% by 2011 (Weir 2013). These coal-fired power plants use over 90% of the total Canadian coal resources (Yeheyis et al. 2009).

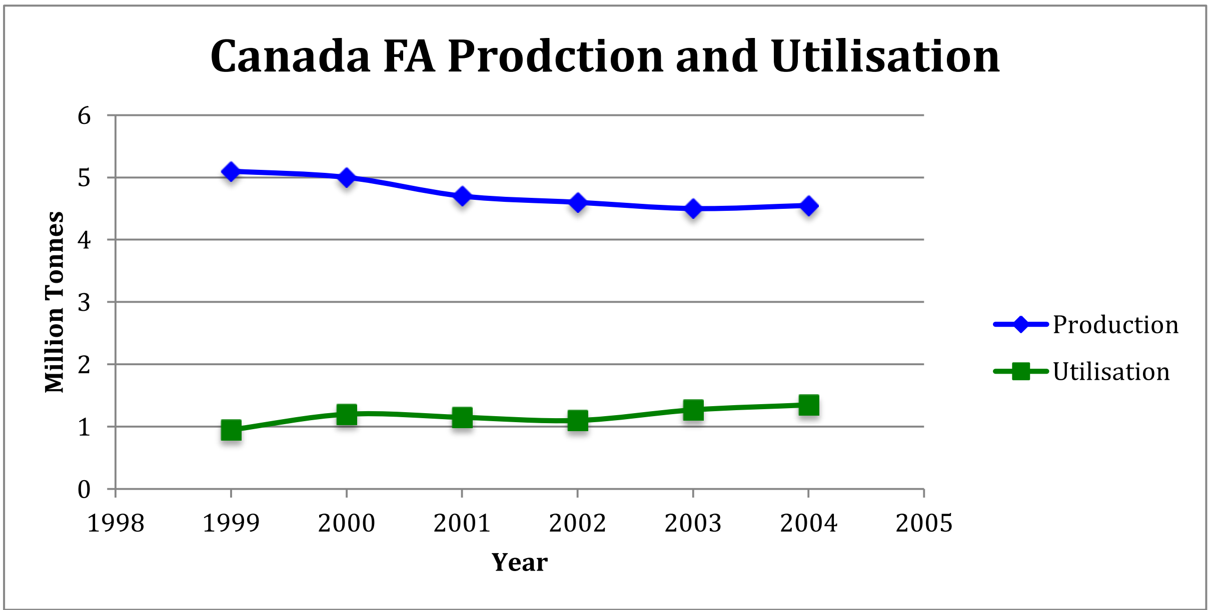


Figure 12: Canda's FA production and utilisation from 1999 to 2004
Source: After (Yeheyis et al. 2009)

The addition of FA as a partial replacement for Portland cement in concrete is widespread and considerable volumes are used. Observing Canada's FA utilisation (Figure 12), over two-thirds of FA produced is disposed of or stored. This is one of the highest disposal rates around the world, while the remainder is mostly used in concrete and cement production. FA utilisation for embankments and highways, which this study is focused on, is only 0.3% of the total FA produced in Canada.

South Africa

For around 30 years, the stabilisation of pavements has been practised widely in South Africa. However, until recently it has been confined to subgrade layers or for rehabilitation and maintenance of existing aggregate layers (Okonta and Ojuri, 2014). The amount of FA in South Africa is about twice of that of cement (Kruger and Krueger, 2005). This significant difference has led to FA being researched and examined much more widely than before, so that innovative applications and higher utilisation rates may be achieved. In South Africa, a FA with a carbon content of below 1% and 90% content of below 45 μm (SABS 1491-2) has become the norm in the industry (Kruger and Krueger, 2005). According to Kruger and Krueger (2005), the SABS 1491-2 FA has the following properties:

- Lower quantity of water required for concrete production
- Lower shrinkage
- Improved density
- Easier placing

It is reported that cement production in South Africa consists of 15 to 35% of SABS 1491-2 FA (Kruger and Krueger, 2005). The innovation in FA utilisation and applications in South Africa has consequently created a growth in FA utilisation, from 20 thousand tonnes/annum in the early 1980s to over 1650 thousand tonnes/annum by 2004 (Kruger and Krueger, 2005).

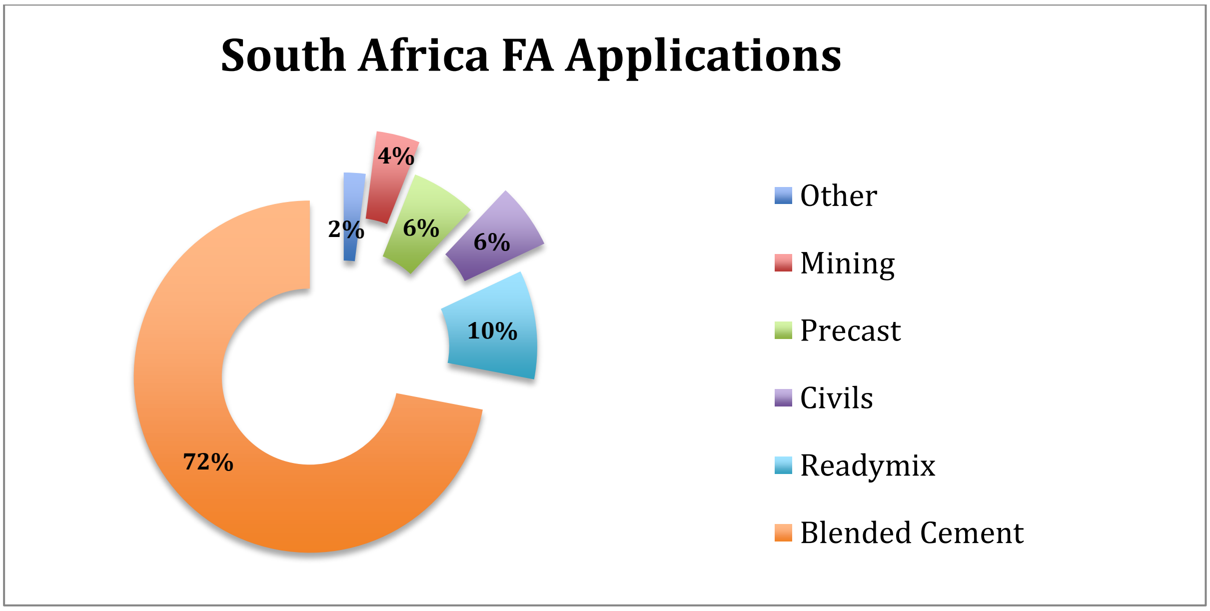


Figure 13: Various FA applications within South Africa
Source: After (Kruger 2015)

Figure 13 demonstrates the different applications that FA is utilised in the South African market. It can clearly be observed that nearly three quarters of the utilisation is in cement industry, and only 12% in the construction industry, with 6% in civil enginering projects and the other 6% in form of precast.The first roller-compacted arch-gravity dam in the world, the Knellpoort Dam, was constructed with an extensive utilisation of FA (Kruger and Krueger, 2005). Kruger and Krueger (2005) also report that there is substantial export of South African FA to the Middle East for projects like the Jumeirah Beach Resort Complex, the height of which is greater than that of the Eiffel Tower.

European Union

Europe has long claimed leadership on tackling climate change (Gutmann et al. 2014). Figure 14 illustrates the utilisation and disposal of CCPs in Europe (EU-15) in the years 2003 and 2008. It can be seen that the utilisation of CCPs in 2008 for the construction industry increased by nearly 2% in comparison to 2003. Despite this increase in utilisation, there were less (6.4%) CCPs stocked, while the disposal rate nearly doubled over the five-year period.

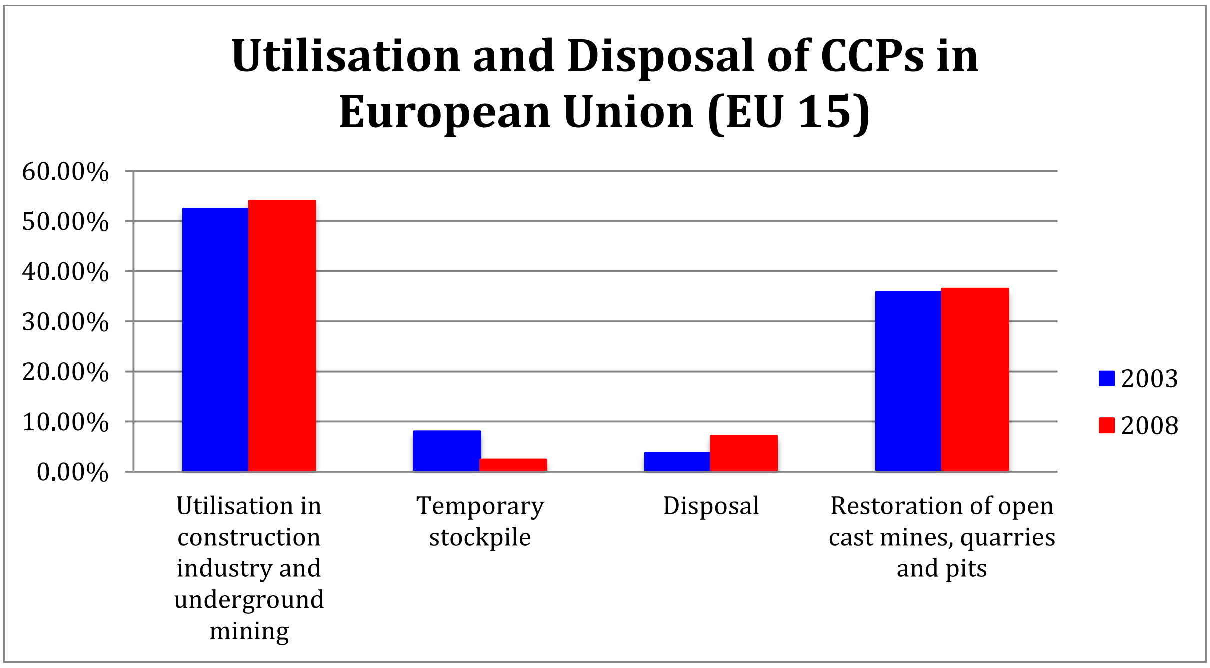


Figure 14: Utilisation and disposal of CCPs in EU-15
Source: After (Feuerborn 2011; Berg and Feuerborn 2005)

The EU-15 comprises the following nations: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, the United Kingdom (OECD 2005). Germany ranks first in the utilisation of coal to produce electricity in Europe, while the UK comes third in total coal consumption for power after Poland (Gutmann et al. 2014). According to Park (2014), Germany, the Netherlands and France had a utilisation rate of over 90% of their produced CCPs during the late 1980s and early 1990s.

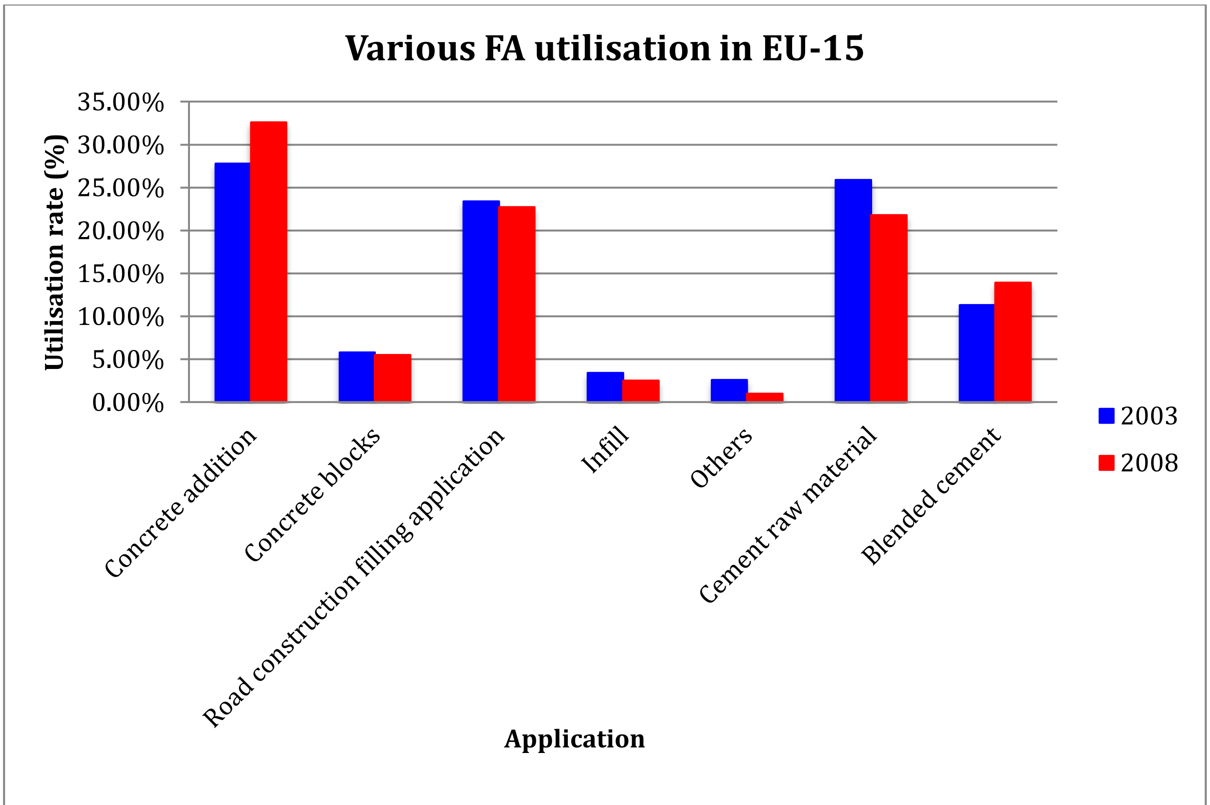


Figure 15: FA applications within the EU-15
Source: After (Feuerborn 2011; Berg and Feuerborn 2005)

Figure 15 presents the applications of FA within the EU-15 in 2003 and 2008. It can be seen that only FA as a concrete addition and its use in blended cement, had an increase in its utilisation. However, a reduction is noted for the remaining applications, like road construction and infill applications.

2.2.6 Sustainability of Fly Ash

The increasing demand for electricity has rendered coal-fired power stations indispensable for many countries. This has resulted in growing amounts of stockpiled FA, inevitably causing environmental problems (Lav and Lav, 2014). The cost of disposal has also been increasing due to high safety standards and lack of available space near municipal areas (Baykal et al. 2004). Beneficial use of waste materials decreases the need for large disposal areas and provides a low-cost mineral resource for construction. To evaluate the engineering performance of these materials and find new applications, characterising their geotechnical properties is a critical task (Baykal et al. 2004).

Sustainable construction products are being sought by specifiers and customers around the world. This well-established trend is mainly driven by market demand and government initiatives. The energy and steam production by coal and subsequently CCPs production is influenced by political decisions and respective legislation (Caldas-Vieira and Feuerborn, 2013). The major issue is the hazard to the quality of underground water and the atmosphere, which can potentially lead to risking the health of people and can inevitably cause a serious economic and environmental burden (Pei-wei et al. 2007).

The environmental limitations of Ordinary Portland Cement (OPC) are related to the high levels of CO_2 released during its production, estimated at 7% of the total anthropogenic CO_2 (Escalante-Garcia et al. 2009), while the chemical vulnerability of OPC is the special concern when dealing with its use in structural foundations or soil improvement, due to the attack by sulphates in the ground or in chemical wastes (Tomlinson 2001). A prime environmental benefit of using FA is a reduction in the amount of Portland cement used (Carroll 2015). According to CalStar (cited in Baldrey et al. 2015), an innovative building products company that incorporates recycled material such as FA, ‘Traditional masonry products use clay or Portland cement and require firing in kilns at thousands of degrees. Our innovative technology and manufacturing processes use 81% less energy, emit 84% less $CO_{2,}$ and utilise up to 37% post-industrial recycled material’ (Baldrey et al. 2015, p. 7).

During the 1990s, the European Waste Framework Directive defined CCPs as waste (Berg and Feuerborn, 2005). At the time, the case was unclear for FA, as there was no processing taking place in the stations and also the recovery phase was the last operation.That meant the material had to be handled, collected, transported and stored as waste (Berg and Feuerborn, 2005). For a concrete producer, this meant they used waste to produce concrete, meaning the ready mixed plant became a waste handling facility. Because of this, the concrete producer may have faced obstacles utilising FA, as it would have damaged their image in the industry (Berg and Feuerborn, 2005).

As the European Commission is aiming at increasing recycling and the utilisation of ‘secondary raw materials’, for materials like FA, the definition would be reconsidered as being no longer a waste (Berg and Feuerborn, 2005). In January 2001, the European Commission adopted a decision in order to come to a harmonised list of hazardous and non-hazardous waste, the European Waste Catalogue (EWC) (Eijk et al. 2011). The EWC includes an annex with a list of about 800 wastes. The different types of waste on the list are fully defined by the six-digit code for the waste. Any waste considered as a hazardous waste obtains a code that is marked with an asterisk (*) (Eijk et al. 2011). According to the European Waste Catalogue, coal combustion ashes are no longer classified as hazardous waste. Additionally, according to the European REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation, coal ashes have been registered as a substance without any hazard classification (Eijk et al. 2011). In the EWC, ashes produced at 100% coal firing power stations are defined as non-hazardous waste (Eijk et al. 2011). Furthermore, the US Department of Energy (Pflughoeft-Hassett and Hassett, 2001) conducted a thorough study that concluded that if utilised in a suitable manner, FA would not be a hazard to the environment when used for soil stabilisation. FA concrete is recognised as a more durable and a more sustainable building material by many architects and engineers (Sebastian et al. 2013). According to Sebastian et al. (2013) structures built with FA concrete last longer, henceforth fewer resources will be depleted in the future.

Engineers are deemed to be responsible for the protection of the environment by reducing the extraction of raw materials used in construction, resulting in the minimization of embodied CO_2 (Jones et al. 2009). By their utilisation they help to save natural resources and to reduce energy demand and greenhouse gas emissions to the atmosphere from mining (Berg and Feuerborn, 2005), and it also improves the sustainability of construction materials (Carroll 2015).

The representatives of 37 industrial countries came to an agreement on the 11 December, 1997 to reduce greenhouse emissions to an average of 5% against 1990 levels over the five-year period 2008-2012 (Caldas-Vieira and Feuerborn, 2013). This agreement is famously known as the Kyoto Protocol, which came into force in 2005 (Kyoto Protocol 2008, cited in Caldas-Vieira and Feuerborn, 2013). Coal-fired power plants have a significant impact on the enviroment. Emissions from these industrial installations have consequently been subject to an EU-wide legislation (Caldas-Vieira and Feuerborn, 2013).

In few countries, the use of nuclear power has been seen as the solution to reach the reduction goals (Caldas-Vieira and Feuerborn, 2013). However, after the Fukushima accident, some countries such as Germany decided to withdraw nuclear power production (Caldas-Vieira and Feuerborn, 2013). All coal-fired power stations built after 1987 had to comply with the emission limits in the Large Combustion Plant Directive (LCPD). According to Caldas-Vieira and Feuerborn, (2013) the power plants in operation before 1987 were labeled as 'existing plants'. Existing facilities could either comply with the LCPD by installing emission reduction equipment like Flue Gas Desulphurization (FGD) or 'opt-out' of the Directive (Caldas-Vieira and Feuerborn, 2013). An existing plant that chose to 'opt-out' must have closed by the end of 2015 (Caldas-Vieira and Feuerborn, 2013). The members of the European Union must prepare to meet the ever increasing energy demands while also meeting the targets set for greenhouse emissions (Caldas-Vieira and Feuerborn, 2013). The energy plan for each country would be different as it depends mainly on the country coal reserves, traditions, and the experiences. In some countries, national mining was completely stopped to reach national CO_2 reduction targets (Caldas-Vieira and

Feuerborn, 2013). In Belgium the last mine was shut down in 1992, while Germany, from having 150 mines in the 1950s, now only has 8 left, which are subject to closure by 2018 (Caldas-Vieira and Feuerborn, 2013).

It is tough for 'governments tasked with obtaining a value for money for taxpayers to award contracts incorporating high cost but sustainable construction, and difficult for contractors to win projects based on sustainable principles when clients award work based on the lowest bids' (Mitchell and Kelly, 2013, p. 127). FA utilisation can help to reduce materials used as well as the carbon footprint. Other benefits include: treatment of polluted soils, preventing and mitigating natural disasters, development of brownfield sites and restoration and maintenance of existing structures and industrial recycling and treating of waste (Mitchell and Kelly, 2013). There are some environmental advantages of using FA as a soil stabiliser (Mitchell and Kelly, 2013):

- Use of a zero-cost raw material.
- Conservation of natural resources; soil, water, coal, and lime.
- Elimination of waste.
- Minimization of global warming.

Less reliance will be placed on fossil fuels such as coal, with an emphasis on renewable sources such as wind, tidal and solar energy, perhaps augmented by new nuclear power stations (Carroll 2015). In addition, the increased use of wind energy may impact the operation conditions of coal stations, and therefore the quality of the coal combustion products of these power plants (Caldas-Vieira and Feuerborn, 2013). FA has low embodied CO_2 and low energy associated with its production, which would decrease the embodied energy and carbon footprint of concrete made with a substantial replacement of Portland cement by FA as compared with conventional concrete (Carroll 2015). Portland cement typically has 913 kg CO_2 e / tonne associated with its manufacture but the comparable figure for FA is only 4 kg CO_2 e / tonne (Carroll, 2015). In 2003, Beeghly (2003) reported that, for a pavement stabilising project, the costs were about $3.50/sq.yd, which in comparison to the regular method of removal and replacement was around $20/sq.yd, producing significant savings. The stabilisation process also had an effect on the pavement granular base thickness from 15 to 7 inches (Beeghly 2003). A reduction in the thickness can also contribute to further savings.

Furthermore, the delivered price of FA in comparison to lime, cement or ground granulated furnace slag, it is at less than 10%, creating the possibility to utilise high FA additions and still show significant overall cost savings (UKQAA 2011d). As an example, if 8% FA was mixed with 4% cement for stabilisation, from a mechanical point of view, it would be equivalent to the soil being stabilised with 8% cement (UKQAA 2011d). In order to reduce the environmental pollution caused by FA and promote its comprehensive utilisation, governments should organise experts and offer significant funding to investigate it (Pei-wei et al. 2007).

Moreover, utilising materials that are already produced results in less energy and emissions in total highway construction, resulting in a 'Green Highway' ('A generic term for a highway that is produced with minimum or even no harm to the environment in terms of protection of natural materials and reduction of greenhouse gas emissions') (Lav and Lav, 2014, p. 11). Hence, FA has the potential of replacing traditional road building materials when circumstances permit. The reuse of waste materials, such as FA, in highway construction, has a significant potential to minimise the amount of disposed waste materials (Baykal et al. 2004; Cetin and Aydilek, 2013). Due to the volumes of material involved in the construction of roads, railways and airports, utilising FA has a profound impact from the environmental point of view on the surroundings (Celauro et al. 2012a). The beneficial reuse of FA in embankment construction not only helps ease one of the most pressing environmental problems, that is disposal of wastes, but may also result in (Cetin and Aydilek, 2013):

- Reducing solid waste disposal costs incurred by industry.
- Reducing landfill requirements.
- Minimizing damage to natural resources caused by excavating earthen materials for construction.
- Obtaining added value from waste materials.
- Conserving production energy.
- Providing sustainable construction.
- Providing economic growth.

2.2.7 Health Characteristics

People living near coal-fired power stations and their employees, as well as those involved in the shipment and processing of coal FA, can be exposed to coal FA. Ash quality is of great consequence for the following three items (Meij and Winkel, 2001):

- The technical quality.
- The environmental quality.
- The health and safety quality.

A lot of research has been done into the health implications of working with FA (Meij and Winkel, 2001; Eijk et al. 2011). Data from experiments and tests show that normal levels of exposure (i.e. exposures of below the limit for nuisance inhalable substances) are unlikely to have any major health implications (Meij and Winkel, 2001). According to Meij and Winkel (2001), the results of epidemiological research support this conclusion.

The most important route for exposure to FA is inhalation. People involved in the processing and production of FA can be exposed via this route (Meij and Winkel, 2001). Most of the exposed radiation would be external, as internal radiation associated with the inhalation of FA is believed to be negligible (Meij and Winkel, 2001). Measurements show that, under normal operating conditions, concentrations of inhalable FA for employees of power plants vary between 0.1 and 7 milligrams per cubic metre, and concentrations of respirable FA linked with such exposure are believed to range between 0.1 and 2.3 milligrams per cubic metre (Meij and Winkel, 2001).

Incomplete combustion of fossil fuels can lead to the production of hydrocarbons and ‘some of the hydrogen atoms in these hydrocarbons can be replaced by atoms of chlorine, fluorine or bromine to form substances called dioxins’ (Meij and Winkel, 2001, p. 6). There are reportedly 210 different types of dioxin, of which a ‘congeneric’ group of seventeen, the so-called ‘dirty seventeen’, are toxic (Meij and Winkel, 2001; Eijk et al. 2011). According to Meij and Winkel (2001), results show that for people living near coal-fired power stations and their employees, the levels of exposure to dioxins caused by the airborne dispersal of FA and flue gases emissions are low. It has also been found that exposure is negligible in relation to the background dioxin burden (Meij and Winkel, 2001; Eijk et al. 2011).

Large-scale combustion of fossil fuels, as in power stations, in general, results in very low levels of dioxins. This is mainly because combustion in modern coal-fired power stations is virtually complete (Eijk et al. 2011). The daily intake as a result of this exposure is negligible in relation to WHO guidelines and to the background daily dioxin intake, which mainly is associated with the consumption of food (Eijk et al. 2011; Meij and Winkel, 2001).

Quartz

Substantial exposure to quartz can lead to ‘black lung’. (Eijk et al. 2011; Meij and Winkel, 2001). It has recently become known that quartz is a human carcinogen at concentrations above a certain threshold (Meij and Winkel, 2001). Since quartz is found in coal and FA, it is suggested that the concentrations in which it is present must be known and also it must be determined whether its presence can cause fibrosis or cancer (Meij and Winkel, 2001; Eijk et al. 2011). Nevertheless, it should be pointed out that these effects are what one would expect from any particulate material (nuisance dust); they are not unique to FA and are definitely not caused by the presence of quartz in FA (Meij and Winkel, 2001). According to Meij and Winkel (2001), quartz loses its fibrogenic characteristics when heated to temperatures of more than 1200 °C. As stated previously, in section 2.2.1, FA by definition must be produced with combustion temperatures of 1300-1500 °C. In other words, all FA particles undergo heating more than this level, eliminating the risk of exposure to quartz.

Radioactive Aspects

Meij and Winkel (2001, p. 6) state that the earth's crust contains 'natural radionuclides, which are naturally radioactive substances present since the formation of the earth', and that they have high longevity and also are in existence constantly. The same authors report that a certain amount of radioactive radiation naturally occurs, also known as background radiation, due to radioactive substances being present throughout the earth's crust. Substances extracted from the earth's crust, including sand, clay, flint, marble, granite and coal, also contain radioactive material (Meij and Winkel, 2001). The use of such substances in construction can result in the concentration of radiation so that levels exceed natural background radiation levels (Meij and Winkel, 2001). According to Meij and Winkel (2001), radioactive materials remain in the ash post incineration of coal, which creates a higher concentration of radioactivity per unit weight in comparison to the parent coal. Furthermore, Meij and Winkel (2001) state that the occupational radiation exposure limit is '1 mSv per year'. If an employee working at a power plant spent all the working hours (around 1800 hours annually) within 25 meters of a FA store, he would be exposed to 0.016 mSv of radiation per year. In other words, one's exposure to FA radiation is negligible. According to Asokan et al. (2005), the radioactivity level of Indian CCPs and pond ash is almost similar to that of normal soil.

Meij and Winkel (2001, p. 3), indicate that there is no reason to regard FA 'as a harmful dust as opposed to a nuisance dust', and that as long as requirements of nuisance dust are met, there is no increased health risk. The concentrations of some of the trace elements may be higher in different types of FA than in natural resources or products utilised for certain uses. To avoid any negative impact on the environment or human health, regulations have been developed for different uses of industrial by-products at a national level in the European Member States (Feuerborn 2011).

2.2.8 Storage and Reprocessing for Further Utilisation

The reuse of waste begins with the development of new technologies for ways to use waste. Accoding to Park (2014, p. 1816), 'technology governs the life cycle of materials with regard to how they are mined, manufactured, used and discarded'. Most applications of coal FA, like concrete, structural fill, and waste stabilisation, utilise fresh FA received directly from coal-fired power stations. However, according to Yeheyis et al. (2009), if the current rate of utilisation carries on, the demand for fresh coal FA for various applications will be increased and utilisation of coal FA disposed in landfills will invariably have to be considered. Taking no action for waste incurs costs on society and the environment, because when FA is landfilled or released back to nature, it will increase the anthropogenic disturbance (Park 2014). The alternative way, recycling and reuse of waste, requires the development of appropriate technologies that make reuse possible (Park 2014). The innovation process for re-use of discarded materials requires skills that are sometimes more creative than the original production process (Park 2014).

Significant amounts of FA are held in ash fields and lagoons throughout the United Kingdom (Carroll 2015). The reactions of FA in contact with water are complex and significant chemical and physical changes occur within conditioned ash deposited in ash fields for periods of months to several years (Carroll 2015). Disposal of coal combustion residuals (CCR) for many plants will change from sluiced wet ash handling and wet surface impoundments to dry landfills as a result of both state regulations and the recently enacted CCR disposal regulation (Baldrey et al. 2015). The forthcoming conversion from wet to dry FA handling and disposal may be an industry opportunity to reevaluate the entire solid waste handling process (Baldrey et al. 2015).

Due to variation in energy needs throughout the year, most FA is produced in the winter; however, it is mainly utilised in the summer. This creates a logistical challenge since EN 450 FA is stored and delivered dry and there is a finite volume of silo storage available (Carroll 2015). Concrete domes have proven to be economically viable and environmentally friendly storage vessels, especially for large quantities of FA (Hunter 2003). All around the world, concrete domes are being used for bulk storage, as they are efficient and economical for storing large quantities of materials, with capacities in the range of 15,000 to 100,000 tonnes (Hunter 2003). Some of the main reasons, suggested by Hunter (2003), for selection of concrete domes being selected over traditional storage methods include the following:

- Keep products dry even in hurricanes.
- Eliminate condensation and dripping.
- Prevent fugitive dust emissions.
- A waterproof exterior membrane keeps out rain and snow.
- Materials can be maintained for long periods of time in the same condition and quality at which they were put into storage.
- Large quantities of materials can be stored in relatively small spaces.
- Simpler than is needed to fill a silo or a flat storage warehouse.
- Concrete does not burn, does not oxidise and it is not eaten by insects.
- Rapid construction (regardless of the weather).
- Concrete domes are cost competitive.

Approximately 50% of the FA generated in the UK has to be stored wet in stockpiles or lagoons and currently there is still in excess of 50 million tonnes of material that has been treated (conditioned) with water for storage purposes around the UK (Jones et al. 2015). FA can be conditioned by mixing with a controlled amount of water (8 to 15% moisture content) and discharged into tipper trucks. Conditioned ash is the required form for many geotechnical applications such as engineering fill (Carroll 2015; Jones et al. 2015). For large fill contracts a specific stockpile of conditioned ash is often built up over the winter months to ensure uninterrupted delivery during the spring and summer (Carroll 2015).

The storage of unused FA is a major problem worldwide and regulatory authorities are increasingly resistant to permitting new facilities. This has created pressure on the extraction of FA for reutilisation in an appropriate manner or space will run out (Jones et al. 2015). Transforming landfills from a major cost to society into a resource recovery opportunity has received little attention (Jones et al. 2012). Most landfills lack detailed registration, requiring exploration of the content (Jones et al. 2012). An inventory of the ash fields and landfill sites across the mainland UK is under development, which would lead to an estimation of the total amount of usable FA (Carroll, 2015). As stated earlier, the disposal of FA will soon be too costly if not banned (Ahmaruzzaman 2010; Baykal et al. 2004). The UK government announced that it would increase the rates of landfill tax in line with inflation (HMRC 2016). Table 1 shows the landfill tax rates from 1996 to 2018. It can clearly be seen that the landfill tax has been increasing year by year. In some years, like 2000-2003, the tax was increased by just one British Pound. Whereas, from 2007 onwards, the rate has been increasing substantially, over 30% increase in some years. It was also announced that it will not fall below £80 per tonne until at least April 2020 (HMRC 2016). The rise in the landfill tax rate would help in reducing the disposal problems of FA and increase the reutilisation of landfilled FA.

Landfill mining can be a very good method of reutilisation of stored and discarded FA. Krook et al. (2012, p. 513) define landfill mining as ‘a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground’. Landfill mining had its genuine start only in the 1990s and in most cases it was limited to the extraction of methane and the partial recovery of valuable metals and/or land reclamation (Jones et al. 2012).

Table 1: UK landfill tax rate
Source: After (HRMC 2016)

Rates per tonne (£)	From
7.00	01.10.1996
10.00	01.04.1999
11.00	01.04.2000
12.00	01.04.2001
13.00	01.04.2002
14.00	01.04.2003
15.00	01.04.2004
18.00	01.04.2005
21.00	01.04.2006
24.00	01.04.2007
32.00	01.04.2008
40.00	01.04.2009
48.00	01.04.2010
56.00	01.04.2011
64.00	01.04.2012
72.00	01.04.2013
80.00	01.04.2014
82.60	01.04.2015
84.40	01.04.2016
86.10	01.04.2017
88.95	01.04.2018

Landfills are the future mines for materials, including FA, and new technologies and innovations should be the way forward for effective and efficient utilisation. This will aid lower emissions induced by production and extraction of traditional materials, further land re-use and also higher economical statuses. As stated earlier, the UK ash fields may contain up to 50 million tonnes of stockpiled ash and this is a large potential source of raw material for use in construction products (Carroll 2015). Transforming stockpile ash into EN 450 FA through a variety of processing methods can improve the utilisation of FA and consequently reduce the impact on the environment. Some of these processing methods include (Feuerborn 2011; Carroll 2015; Caldas-Vieira et al. 2013):

- Blending and sieving.
- Thermal beneficiation.
- Hydraulic processing.
- Drying.
- Electrostatic beneficiation.
- Grinding and milling.

An innovative form of FA beneficiation, the operation of a proprietary staged turbulent air reactor (STAR) facility, can divert large volumes of unprocessed FA from landfills by thermally processing landfilled FA into a low-carbon, mineral admixture product (Sebastian et al. 2013). The stations with STAR facility are capable of processing 360,000 tonnes of FA annually. Using this unutilised FA will reduce the amount of other natural resources used in construction. Furthermore, since structures built with FA concrete last longer, fewer resources will be depleted in the future (Sebastian et al. 2013). In order to reutilise FA in ponds, with the aim of closure of these ponds, the dewatering of FA is found to be necessary to provide construction equipment access and to reduce the water content to facilitate handling/hauling. However, dewatering is challenging because of its relatively low hydraulic conductivity (Seymour et al. 2013). Several dewatering methods are proposed by Seymour et al. (2013):

1. Construction of a series of shallow (1 to 3 m deep) trenches to drain the upper levels of the FA.
2. Mixing of wet FA in place with dry materials such as mine spoil or excavated bedrock.
3. Draining of FA through double handling by excavating wet ash and stockpiling it to allow it to drain to facilitate subsequent hauling and placement.

It has been well established that the finer the FA, the more effective it becomes in terms of geo-engineering benefits (Dhir et al. 1986, cited in Jones et al. 2006). Jones et al. (2006) studied the material characteristics of ultrafine FA. The ultrafine FA had much improved material characteristics when compared to coarser FA in terms of morphology, mineralogy, and chemical composition. The mineralogical and chemical properties of FA not only influence the engineering properties but also the environmental impacts that may arise through its utilisation (Yeheyis et al. 2009). Traces of toxic elements from FA can potentially impact the environment. Authors, Rivera et al. (2015), studied the chemical compositions and speciation of FA and revealed that the mineralogy of the FA matrix and the chemical speciation of the trace elements can be influential in controlling the toxic trace elements against environmental impacts.

In a study by Yeheyis et al. (2009), the effects of weathering and ageing on the disposed coal FA were studied in comparison with the fresh FA from the same site to find out whether disposed coal FA from landfill has suitable engineering and environmental properties needed for various applications. It was found that there was no significant difference in the elemental composition between the fresh and disposed FA; however, the physical, mineralogical and micro-structural characterization results revealed significant differences (Yeheyis et al. 2009). The authors concluded that despite the chemical and mineralogical transformations and slight variations in chemical compositions of disposed FA, both fresh and disposed materials have favorable engineering properties that make them suitable for reutilisation (Yeheyis et al. 2009).

There are power stations that use low-emission production methods, which results in FA with coarser physical characteristics and high residual carbon contents, which often leads to a negative effect on its performance in concrete (Jones et al. 2006). As a result, many ash producers are utilising post-production processing of FA to remove the carbonaceous and clay residue materials and/or refine the particle size. One processing method which has the potential to achieve this is cyclonic separation (Jones et al. 2006).

Kochert et al. (2009) studied a method of transforming BA to FA by using the Magaldi Ash Cooler (MAC) system. This system operates by extracting and cooling the BA, where it is mixed with the designated new patch of coal, then milled and reintroduced into the furnace (Kochert et al. 2009). The MAC system is a proven technology with more than 100 installations worldwide (Kochert et al. 2009). It is also reported by Kochert et al. (2009) that the conversion of BA to FA not only does not have an adverse impact on FA properties, but it can, in fact, increase the FA's overall quality of the FA. Additionally, the total FA production of the plant is increased. The conversions through the MAC system can include the following benefits:

- Zero water usage, reliability.
- Low maintenance.
- The possibility to sell bottom ash with FA to the cement industry.

In a study by Jones et al. (2015), the authors established an innovative technology, in which stockpiled FA can be successfully be up-sized into foamed concrete and processing to produce a synthetic sand suitable for use in mortar or concrete. It was also concluded that the physical properties of the raw material does not affect its potential for recycling (Jones et al. 2015). The resulting 'silt sand' is then exposed to CO_2 to enhance its strength and graded to a specific particle size distribution and assessed for mechanical performance (Jones et al. 2015).

High carbon content in the coal tends to limit applicability. Consequently, a variety of techniques began to be developed in order to reduce the carbon content significantly. These techniques include 'carbon burn-out in an fluidised bed combustion (FBC), electrostatic separation, froth floatation, pneumatic transport separation, and triboelectric separation' (Ruppel 2002, cited in Barnes and Sear, 2006, p. 10). The electrostatic separator is capable of processing the majority of FA range, and is also able to reduce the carbon content from 30% to 2%, which is below the standard for use in concrete (Barnes and Sear, 2006). By the process of thermal beneficiation, which removes carbon and ammonia, coal FA becomes marketable as a pozzolan for the concrete industry (Fox 2005). The effect of these thermal treatments on the FA pozzolanic activity may vary with ash composition (Fox 2005).

Investment in infrastructure and storage facilities to support established markets can lead to the success of the marketers. In a survey, 82% of the utilities reported that having an integrated operation (ability to manage loading, transport and use under one company) was important (Rokoff et al. 2013).

2.3 Ground Improvement

Ground improvement can be defined ‘as the introduction of materials or energy to soils to affect a change in performance of the ground such that it performs more reliably and can be incorporated into the design process’ (Essler 2012, p. 911). In general, ground improvement methods are used all around the world for better stability and load-bearing capacity of soil to enable the construction of projects with very long design lives such as embankments, bridges and retaining walls (Cofra 2005). It generally involves the enhancement of ground properties, principally by a strengthening or stiffening process and compaction or densification mechanisms, to achieve a specific geotechnical performance (Serridge and Slocombe, 2012). The design life can be in the range of 40-100 years. The long-term performance must be extrapolated from short-term laboratory tests, which is a source of uncertainty (Mitchell and Kelly, 2013). In the recent past, the use of ground improvement has increased significantly, down to more construction sites being located in areas of poor-quality ground, contaminated sites, tailings deposits and for redevelopment of existing sites or other uncontrolled fills that have the need to mitigate failure risks from natural disasters (earthquakes, floods, slope instability) (Mitchell and Kelly, 2013). It is suggested that on average, in the UK, the ground treatment market is approximately from ten to twenty million pounds per year (Essler 2012). The main aims of ground improvement are to (Shukla 2015):

- Increase strength and stiffness of soil.
- Decrease compressibility and volumetric change.
- Regulate permeability according to requirement.
- Decrease soil liquefaction susceptibility.
- Increase durability.

Infrastructure projects such as highways, railways, airports and harbours cover large areas of land, at times over tens of kilometers. At most times, projects like railways or highways encounter problematic soils. Construction in increasingly urban environments means that sites with poor soil conditions and even landfills are being utilised for various structures and facilities. This construction activity on poor soil leads to the necessity for ground improvement prior to the start of construction (Raju 2010). Springman et al. (2014) state that constructing embankments on soft ground with reference to modern codes and standards of practice is challenging without ground improvement. Additionally, the design of buildings and infrastructure on soft ground requires a realistic representation of the ground conditions and clear calculation procedures to help the design engineer to fulfill the verification required by the design codes (Springman et al. 2014).

The selection of a suitable method of ground improvement and optimization of its design and construction to meet specific project needs requires extensive background knowledge of available ground treatment technologies and careful evaluation of some factors. These factors are: understanding the procedures of different methods, the use of appropriate design procedures, utilisation of several selection criteria, implementation of the right techniques for quality assurance and control, and consideration of all relevant costs and environmental factors (Mitchell and Kelly, 2013). In most geotechnical and infrastructure projects, the design requirements of the construction site cannot be met without the use of ground improvement techniques. Choosing a site for ground improvement has a few design criteria that should be considered (Makusa 2012):

- Design load and function of the structure.
- Type of foundation to be used.
- Bearing capacity of subsoil.

Makusa (2012) states that key criteria in site selection is the bearing capacity of the soil, and if in any circumstances the bearing capacity proves to be poor, one of the following routes is chosen:

- Change the design to suit site condition.
- Remove and replace the in situ soil.
- Abandon the site.
- Modifying soil properties to meet specific design requirements.

The correct identification of the soil and its properties is a vital step in site selection and the ideal selection of the type of ground improvement technique (Essler 2012). There are several forms of ground improvement, including many traditional ones and some innovative methods. Essler (2012) lists the following as the major forms of ground improvement:

- Void filling.
- Grouting.
- Compaction (dynamic and vibro) and stone columns.
- Soil mixing.

There has been a renewed interest in rammed earth (RE) construction worldwide, due in part to the rising cost of traditional building materials and increased awareness of energy-efficient materials (Dockter et al. 1999). The soil utilised in rammed earth construction must fall within a certain range of properties in order to perform well.

Some of the advantages of ground improvement is to reduce the high cost of building and maintaining the waste-disposal facilities, while increasing the supply of construction material from the waste (Porbaha and Hanzawa, 2001). Construction of embankments is of high importance due to the large amount of virgin materials required in their construction. The beneficial use of FA for embankment construction is one of the promising solutions to reduce the disposal problem (Santos et al. 2011).

FA has been utilised as an engineering fill material in the UK for over 50 years, with the first recorded utilisation for this purpose dating back to 1952 (UKQAA 2007; Fox and Coombs, 2009). Its use was not covered by any legislation other than that employed to ensure safe and appropriate handling and placement (Fox and Coombs, 2009). According to UKQAA (2007) since that time, the 1950s, there have never been any major environmental incidents. However, the association recommends that care must be taken to ensure that the environment is protected and suggests applicable guidance can be found in the 'Environmental Code of Practice for Fill'.

Utilising FA in concrete road construction can result in less depletion of natural resources like stone, metal and soil. It will also save cement, which is the most expensive ingredient in concrete (Suryawanshi et al. 2012; Belani and Pitroda, 2013). About 10% to 30% of cement and 5% to 15% of sand in concrete can be replaced if FA were to be utilised, which can lead to lower production and construction costs without comprising the strength (Suryawanshi et al. 2012). It has been found that FA cement concrete does not gain appreciable strength in the initial 7-14 days. However, the results for conventional concrete and FA concrete after 28 are nearly same (Suryawanshi et al. 2012). Beneficial use of FA in construction projects requiring large material volumes, such as for highway embankment construction, offers an attractive alternative to disposal because substantial economic savings can be attained by the reduction of ash disposal costs and the conservation of natural resources and lands used for landfills (Kim et al. 2005; Suryawanshi et al. 2012; Belani and Pitroda, 2013). Furthermore, other benefits of FA usage in concrete for road construction include improved texture, workability and impermeability, lower water evaporation, reduced leaching effect of Portland cement and the reduction and/or elimination of bleeding (Suryawanshi et al. 2012; Han 1993). There are several potential benefits and few harmful effects of FA application in soil for ground improvement (Pandey and Singh, 2010):

Beneficial effects:

- Improves soil texture.
- Reduces bulk density of soil.
- Improves water-holding capacity.
- Increases soil buffering capacity.
- Reduces crust formation.
- Reduces the consumption of soil ameliorants.

Harmful effects:

- Lower bioavailability of several nutrients down to high pH.
- High salinity.
- High content of phytotoxic elements.

According to Santos et al. (2011, p. 1) ‘an embankment refers to a volume of earthen material that is placed and compacted for the purpose of raising the grade of a roadway above the level of the existing surrounding ground surface’. Kim et al. (2005) established that high volume of FA mixtures, with appropriate design and construction methods, could be suitable for use in highway embankments. Several researchers report that the FA-soil mixtures could deliver similar compressibility and strength to most soils used as fill materials in highway embankments while having the advantage of lower dry densities (Kim et al. 2005; Santos et al. 2011). It has also been found that the compressibility of compacted BA and FA mixture, from a mechanical point of view, are similar to that of conventional compacted sand when utilised for highway embankment purposes (Kim et al. 2005).

There are several geotechnical properties of FA that are important in embankment constructuion, such as its moisture-density relationship, particle size distribution, permeability, and strength (Santos et al. 2011). Han (1993) states that moisture control is a key factor for successful construction. An envelope of cohesive soil is required for the FA embankment to serve as an erosion control device and to provide for vegetation support (Han 1993).

There are a number of advantages in utilising FA as a fill material over naturally occurring materials. FA is beneficial for the following reasons (UKQAA 2007):

- Lightweight in comparison to most materials, which leads to savings in material, transport costs and reduces settlement in underlying soils.
- When properly compacted, FA settles less than 1% during the construction period with no long-term settlement.
- The self-hardening properties of some FAs offer considerable strength advantages over natural clay and granular materials.
- It can exceed the design strength immediately after compaction.
- The immediate strength of FA means simple shallow trenches have a reduced need for shoring.
- With proper profiling, FA fill can be trafficked in all weathers.

According to UKQAA (2007) there are three types of FA available for utilisation as a fill material:

1. Conditioned ash: FA taken directly from the silos at the power station to

which a controlled amount of water is added to assist in handling, dust prevention and compaction on site.

2. Stockpiled ash: Previously conditioned FA that has been stockpiled prior to use.
3. Lagoon Ash: FA that has been slurried and pumped to storage lagoons. It is then allowed to settle and drain before delivery. Lagoon ash can be somewhat more variable in particle size distribution than conditioned ash.

UKQAA (2007) states that FA embankments should invariably be covered using different techniques, either with furher construction, a layer of top-soil or by hydro-seeding. If topsoil is used, a minimum thickness of 100mm is recommended, though up to 500mm of soil may prove necessary in some environmentally sensitive areas (UKQAA 2007).

Furthermore, Belani and Pitroda (2013) believe that with adequate knowledge of the performance of FA based road pavements, a much higher demand can be expected from the road sector to use FA for the construction industry. However, judicious decisions are to be taken by engineers. Appropriate risk assessment and precautions will be required on contaminated sites and to avoid exposure to the atmosphere of chemicals and materials such as asbestos (Serridge and Slocombe 2012). Moreover, Fox and Coombs (2009) state that an exemption to the regulations has to be sought from the environmental agency before FA (or any waste) can be utilised as an engineering fill in construction.

Belani and Pitroda (2013) examined the replacement of cement in concrete, only partial replacement, with FA class F for the development of sustainable low cost rural roads. The authors concluded that there is a significant scope for the eco-efficient utilisation of FA (class F) for sustainable development of road networks (Belani and Pitroda, 2013). It was found that FA has excellent geotechnical and pozzolanic properties, making it highly suitable for all types of construction, including roads, embankments and reclamation of low-lying areas (Belani and Pitroda, 2013). According to Belani and Pitroda (2013), it is believed that construction materials based on FA are gaining in popularity in the industry, due to their durability, and because they are economical, eco-friendly, easy to use and of consistent quality. The same authors concluded that FA (class F) utilisation in concrete could lead to a greener concrete and be a promising addition in construction of low cost rural roads (Belani and Pitroda, 2013). In another study by Han (1993), where waste materials were examined for utilisation in highway construction, the author reported that when working with class C FA, more precautions must be taken as the mixture usually tends to set more quickly than a mixture using a Class F FA, the set time of which varies from several hours to several days (Han 1993). According to the UK Quality Ash Association (UKQAA 2011c), a mixture of FA and cement behaves like cement, quick setting and hardening with little laying flexibility during construction, while a mixture of FA and lime is slow setting and slow hardening, which as a result produces better flexibility during construction. UKQAA (2007) recommends the following for utilisation of FA:

- FA should be delivered in sheeted vehicles to prevent moisture loss and environmental problems.
- The FA should be spread in loose layers not exceeding 225mm thick.

- If water is to be added, this should be sprayed uniformly over the surface before compaction. Back tining may be used to encourage an even distribution throughout the full depth of the layer.
- If FA is stockpiled on site, care must be taken to prevent drying out.
- If the surface becomes wet due to heavy rain, the surface should be allowed to dry out, or if necessary the top 150mm can be removed and replaced. The removed material may be reused when it has dried out sufficiently.

Kim et al. (2005) state that the permeability of compacted ash mixtures decreased as the FA content increased. The authors mention that the cause of this reduction is due to the increasing specific surface with increasingly fines content, which generates more resistance to water flow through voids between particles (Kim et al. 2005). 'Permeability is the measure of the rate at which a fluid passes through a material' (Santos et al. 2011, p. 4). According to UKQAA (2007), FA can be considered comparatively impermeable. Low permeability can eliminate leaching of soluble material from the mass of the compacted material (UKQAA 2007). The permeability of FA is dependable on the size of the grains, the degree at which is compacted and its pozzolanic activity (Pandian 2004). Santos et al. (2011) state that as FA mostly consists of spherical shaped particles, these particles have the capability to be packed densely during compaction, minimizing the seepage of water and lowering the permeability for an FA embankment. According to Manceau et al. (2012), when considering the performance of new build embankments, other factors that should be considered, apart from the stability of the embankment slope include:

- Failure of the embankment foundation.
- Settlement of the foundation material.
- Self-settlement of the embankment fill.

The potential failure of embankment foundation by failure surfaces passing below the level of the embankment fill should be determined as part of the overall assessment of the stability of the embankment slopes. This failure mechanism is unlikely to occur where the embankment is underlain by granular material or over consolidated clay (Manceau et al. 2012).

The Environment Agency (EA) deems that FA is a waste and that it is covered by the waste regulations, and the European Waste Catalogue considers FA to be a non-hazardous waste (Fox and Coombs, 2009). Environmental issues resulting from ground improvement can either be due to polluting the ground with the cement or chemicals used or equally as a result of changes to the local ground water hydrogeology. When considering ground improvement design it is therefore important to review these potential effects (Essler 2012). In a study by Erbe et al. (1999), from the water quality data gathered, it was found that utilising FA (class F in particular) for highway embankments can adequately protect ground water quality, and that the leachate from the FA has no discernable impact on ground water quality. Erbe et al. (1999) suggest that previous studies at highway embankment and structural fill sites constructed with CCPs indicate environmental impacts to ground water are localised and naturally attenuate over relatively short distances from the ash fill. However, the same authors state that despite these studies, potential users, regulators and the public tend to express concerns that utilisation of coal combustion products would lead to the contamination or degradation of ground water quality, which consquently disrupts extensive usage in highway construction and other structural fill applications (Erbe et al. 1999).

According to Mitchell and Kelly (2013) ground improvement can play a vital role in the future of geo-engineering as it can help in achieving a lower quantity of traditional materials used, mitigation and/or even prevention of natural disasters, lower carbon footprint, remediation of polluted soils, development of brownfield sites, maintenance and rehabilitation of existing structures and also treatment and recycling industrial wastes. Nevertheless, challenges exist in providing cost-effective sustainable ground improvement under current economic conditions (Mitchell and Kelly, 2013). Essler (2012) suggests that for sands and gravel grounds all forms of ground improvement are possible with adequate laboratory testing of representative samples. Furthermore, the characteristics of FA are changing as coal-fired power plants respond to increasingly stringent air pollution regulations (Baldrey et al. 2015), this would lead to further investigation and laboratory tests being required for the analysis of changed FA characteristics. The following section gives a few factors to consider for selecting the appropriate ground improvement technique (Raju 2010):

- Suitability of the method.
- Technical compliance.
- Availability of QA/QC methods.
- Availability of material.
- Time.
- Cost.

- Convenience.
- Protection of the environment.

2.4 Soil Stabilisation

Soil modification and soil stabilisation are different methods of ground improvemnt. Soil modification causes improvements such as drying and swells reduction while soil stabilisation consists of long-term strengths for desired freeze-thaw protection (Beeghly 2003). According to O'Flaherty and Hughes (2016), the term 'modification' is used to describe the use of a chemical to improve the properties of a soil without causing much increase to its elastic modulus or tensile strength, while the term 'stabilisation' is used to describe the utilisation of a chemical to achieve a soil stabilised layer with significant strength and stiffness (O'Flaherty and Hughes, 2016). Through the process of stabilisation, the leachability and movements of toxic metals are potentially reduced (Asokan et al. 2005). Stabilisation of soils is 'an economical way to strengthen the earth for building purposes and to diminish the number of soil exchanges' (Kukko 2000, cited in Hossain 2010, p. 173). Furthermore, soil remediation through stabilisation can be an effective means of treating the lead-contaminated soils by significantly reducing the mobility and solubility of lead in the soils (Yin et al. 2006).

Many local highway authorities do not have accessible premium quality aggregate sources and have adopted stabilisation and modification for road construction using locally produced aggregates (Okonta and Ojuri, 2014). For the purpose of this research, examining the suitability of FA stabilisation for embankment construction, improvements on strengths and stiffness are expected, henceforth the form of soil stabilisation and not modification will be dealt with in this study.

There are three primary forms of stabilisation, namely mechanical, chemical and bitumen stabilisation. Mechanical stabilisation involves the compaction and, usually, the blending of two or more soils to improve the gradation, thus reducing the plasticity and improving the bearing capacity (O'Flaherty and Hughes, 2016). The alteration of the physical nature of soil particles can be achieved through the physical process by either compaction, induced vibration, or by incorporating other physical properties like nailing and barriers (Makusa 2012). Chemical stabilisation uses chemical binders, usually lime and/or cement in a process of soil stabilisation to improve the granular properties and/or cementation of soil to create a rigid-type bound material (O'Flaherty and Hughes, 2016). Bitumen stabilisation is a process that is used with cold soil or aggregate to produce a flexible-type bound material by admixing bitumen via either bitumen emulsion or foamed bitumen technology (O'Flaherty and Hughes, 2016).

Through chemical technique, 'stabilisation can be done using chemical and emulsions since they work as compaction aids, binders, water repellents and as well as modifying the soil behaviour' (Graves et al. 1988, cited in Zaliha et al. 2013, p. 259). The chemical reaction of soil particles and chemical additives creates a strong bond between the soil grains, resulting in a stronger, more durable and a better quality soil in comparison to an untreated soil.

One of the major methods used to solve the problems caused by weak soils is soil stabilisation by mixing with a cementitious binder. The most two common binders are lime and cement. In the case of lime, as the chemical additive, the reactions are mainly pozzolanic and with cement, they are hydraulic. A hydraulic reaction needs only water to react and increase in strength while a pozzolanic reaction requires water and a pozzolanic material like soil (Janz and Johansson, 2002). According to several authors (Pacheco et al. 2012; Criardo et al. 2007), alkaline-activated materials are, in general, better performing than cement from a mechanical point of view and show increased durability and stability. The stabilisation is achieved by the soil particles being glued more chemically than physically. Pavement engineers have long recognised the long-term benefits of improved durability and strength of pavement subgrade soil by inducing a cementitious binder throughout reconstruction or new construction (Beeghly 2003).

Dealing with weak soil is one of the most major challenges in the construction industry (Cristelo et al. 2013; Senol et al. 2006). This situation can occur in road and highway construction (Fauzi et al. 2010; Senol et al. 2006) or in geotechnical engineering. It is vital to find methods of soil improvement techniques so that demands can be met. The techniques of stabilised road pavement construction, whether it is with cement, lime or other binders, are in general divided into two main groups (NRRDA 2016):

1. Mix-in-place stabilisation.
2. Plant-mix stabilisation.

Stabilisation of soil with cement is commonly used as a pavement base for construction of roads, residential streets, parking areas and airports (NRRDA 2016). A thin bituminous surface is usually placed on the soil-cement to complete the pavement. The National Rural Roads Development Agency of India (NRRDA 2016) states the following as factors affecting stabilisation of soil with cement:

- Type of soil.
- Quantity of cement.
- Quantity of water.
- Mixing, compaction and curing.
- Admixtures with the cement.

The same agency has listed the following as advantages and disadvantages of soil-cement stabilisation (NRRDA 2016):

<u>Advantages</u>

- High availability.
- High durability.
- Soil-cement is considered relatively weather resistant and strong.
- Very suitable for granular soils with sufficient fines as it requires least amount of cement.
- Reduction swelling characteristics.

<u>Disadvantages</u>

- Possibility of cracks formation.

- Requires more labour.
- Sufficient quantity of water for hydration of cement and creating a workable mixture.

FA is commonly blended with cement for geotechnical soil stabilisation. As FA is a by-product, it is much cheaper than cement. Hence, the more the cement can be replaced by FA for satisfactory soil stabilisation, the more economical the operation becomes (Kogbara et al. 2013). The use of FA reduces cement content, construction risk and costs (UKQAA 2011b). Soils treated with FA are an alternative to soil cement for use as base, sub-base or capping (UKQAA 2011b; 2011d). It is constructed by mixing FA with lime or cement to site arisings, generally, using mix-in-place construction (UKQAA 2011b; 2011d).

Modern rammed earth (RE) construction frequently uses stabilisers to enhance engineering performance and durability. Dockter et al. (1999) established that coal combustion FA has excellent potential for use in constructuon of RE as a low cost method when compared to cement and other stabilisers due to its pozzolanic properties. The purpose of soil stabilisation is not only to enhance the compressive strength of the soft soil (Bergado et al. 1996; Prabakar et al. 2004; Kogbara et al. 2013) but also to improve the shear strength, filter, drainage system (Parabakar et al. 2004), permeability, soil resistance to the weathering process and traffic usage (ASTM 1992, cited in Zaliha et al. 2013; Kogbara et al. 2013) to meet specific engineering projects requirements (Kolias et al. 2005).

FA may disperse at the point of being mixed into the soil. The solution to this problem is that the coal ash is conditioned by adding a small amount of water before mixing is tested for the reduction of dispersion (Sato and Nishimoto, 2005). Veelen and Visser (2007) suggest that a stabiliser can also be a dust palliative when used for strengthening the unpaved road surface. Moreover, Sato and Nishimoto (2005) suggest that the hydration required for mixing any coal ash with solidifying materials for enhancement of the strength can affect the achieved strength and the necessary hydration should be thoroughly investigated. In soil stabilisation applications, it is the CaO contained in the FA that is being exploited for its potential engineering use (Dockter and Jagiella, 2005). Thus, there is usually a minimum level of CaO associated with FA being used in this application. There are several forms of what could be considered soil stabilisation, such as cement-treated base, subgrade stabilisation, subbase stabilisation, and base (Dockter and Jagiella, 2005).

There are two design methods available in current practice for pavement construction: empirical methods and mechanistic-empirical methods. Empirical methods are based on experience gained in practice and from observation of the performance of existing or specially constructed roads under different traffic conditions (Hilmi-Lav et al. 2005). One of the first empirical methods was the CBR (California Bearing Ratio) method developed in the 1930s by Hveem and associates. However, the most well-known example of the empirical design method is the 1972 version of the American Association of Highway Officials pavement design guide developed in connection with the AASHTO (American Association of State Highway and Transportation Officials) road test (Hilmi-Lav et al. 2005). Empirical design techniques are restricted to the range of pavement materials and traffic loads defined in the procedure (Hilmi-Lav et al. 2005). The CBR values are used in the pavement design, the higher the CBR achieved, the lower the overall thickness of the pavement. When a new material or different traffic loads outside the range are considered, the empirical methods become insufficient. As a result of this, mechanistic-empirical methods take their place (Hilmi-Lav et al. 2005). In mechanistic-empirical methods, the first step is to assume the pavement structure and load configuration.

Pavement structure consists of many layers of different materials, but for the general design procedure, the structure is simplified to three separate layers. Such simplification is preferred by many researchers for analysing various pavements (Hilmi-Lav et al. 2005). The top layer consists of the asphaltic concrete, the middle layer can be the stabilised material, and the bottom layer is considered as the subgrade. Cement stabilised materials can be utilised for improvement of subgrade soil and are ideally suitable for well-graded aggregates with a sufficient amount of fines so that it can fill the available voids space efficiently and float the coarse aggregate particles (NRRDA 2016). According to NRRDA (2016), it is recommended from an economic point of view that the method mix in-place construction can be used for subgrade improvement and only granular materials and silty cohesive materials should be used. The same agency suggests that clayey materials would be more effectively stabilised with lime (NRRDA 2016). Asokan et al. (2005) suggest that a mixture of local soil and CCPs and stabilisation with 3–5% lime would provide a good sub-base. After studying the reutilisation of pond FA, the researchers found it a very useful material for the replacement of soil for the making of embankments (Asokan et al. 2005). It was also found that adding CCPs to the cement concrete mix allowed up to 50% of sand to be replaced by CCPs for use in road construction (Asokan et al. 2005).

For subgrade applications, FA can be utilised for stabilisation of a soft soil so that a more stable working platform for highway construction equipment that is strong and stiff is obtained. Moreover, in base applications, FA could be utilised to improve the stiffness of the base course material as well as enhancing the structural capacity of the pavement (Li et al. 2009). Misra et al. (2009) recommend the following criteria and methods for the stabilisation with FA:

- The designated area should have all vegetation and any other unsuitable soil or material like organic soils, debris, etc.
- The area should also be bladed to ensure uniform distribution of FA.
- The subgrade should be firm and have enough stability to support the construction equipment to enable in-place FA treatment.
- Spreading equipment must uniformly distribute the FA without excessive loss and in such manner as to reduce dispersion of FA so that it does not become air-borne.
- The scattering of FA by wind must be minimised and the use of FA on windy days should be avoided.
- Compaction shall commence immediately after the completion of mixing and grading.
- Compaction shall consist of two or more passes with a vibratory pad-foot roller and it shall be completed within two hours.
- In order to accomplish this, the area to be stabilised should be divided into

segments that permit mixing and compaction within this time frame.

- Any section that is too wet, too dry, or insufficiently treated, must be improved.
- Loosening the affected areas, adding or removing material as required, and reshaping and re-compacting by sprinkling and rolling to meet the requirements may accomplish the improvement.
- After the road base has been compacted, the surface must be shaped to the required line, grade, cross-slope and cross section.
- Moisture may be added to the surface at this time to facilitate curing.
- The final surface of the stabilised material must be rolled with an approved steel-wheeled roller.
- The compacted surface must be smooth, free of cracks, ridges, and loose material.
- Water should be sprinkled to facilitate curing and prevent dehydration until such time as the pavement is placed.

It is quite well established that one of the major reasons pavement structures fail is seepage of water. It would not be possible to have road closures whenever there is a rainstorm so that it may dry out sufficiently before it can be used again (Veelen and Visser, 2007). FA stabilisation of the soil subgrade materials can provide a more stable working platform that is not affected as much by moisture and construction traffic (Mackiewicz and Ferguson, 2005). Sato and Nishimoto (2005) report that coal derived ash in the form of powder and granulated coal ash has almost no cohesion. Therefore, in embankments made from these materials, it is vital to take measures against slope failure caused by rain or embankment collapse caused by an earthquake (Sato and Nishimoto, 2005). Subgrade soil stabilisation can save millions of dollars when compared to the conventional method of cutting out and replacing the unstable subgrade soil. The stabilisation of the subgrade in a pavement design can lead to a reduction in the overall thickness of pavement layers (Beeghly 2003). In an investigated case by Beeghly (2003), 5 inches of bituminous base course and 2 inches of the granular crushed stone base were eliminated through stabilisation. The same author reported that stabilisation with a mixture of class F FA and lime could be potentially engineered for long-term performance when it is utilised for low cohesive silty soil or for reclaiming full depth asphalt (Beeghly 2003). Makusa (2012) believes that FA-soil stabilisation has the following limitations:

- Soil to be stabilised shall have less moisture content; therefore, dewatering may be required.
- FA-soil mixture cured below zero and then soaked in water is highly susceptible to slaking and strength loss.
- Sulfur contents can form expansive minerals in FA-soil mixture, which reduces the long-term strength and durability.

It is usual for limitations to be placed upon the total period of time permitted for the construction of a stabilised layer and/or separately for mixing and compaction (Paige-Green and Netterberg, 2004). UKQAA (2011b) has set out specifications describing the requirements for the constituents, composition and performance of soils treated with FA, which are:

- During construction and prior to, overlaying with at least 300mm of pavement.

- The temperature of stabilised FA shall not fall below 5 °C.
- Stabilised FA shall be made from soil, FA and either lime or cement.
- Subject to a minimum total of 8% by dry mass and unless otherwise agreed by the engineer, the minimum proportions by dry mass of constituents shall be as follows:
    - Lime or cement 2% (3% if 5% FA is used).
    - Dry FA 5% (6% if 2% lime or cement is used).
- At final compaction of the stabilised layer, the moisture content for granular and cohesive mixtures shall be not less than 90% of the optimal moisture content.
- Final compaction shall be completed within 2 hours of the mixing-in of cement for FA-cement treatment and for FA-lime treatment, within 6 hours of the addition of lime or FA.
- On completion of compaction, the surface of the layer shall be well closed, free from movement under compaction plant, and free from ridges, cracks, loose material, segregated areas, pot holes, ruts and other defects.
- Immediately on completion of final compaction, the surface of the layer can be sealed with bitumen emulsion.
- Construction plant and other traffic shall not run on the layer other than to enable construction of the overlying layer.

According to Sato and Nishimoto (2005), one of the concerns of utilising FA in soil stabilisation is that coal ash-based materials are strongly alkaline. Therefore, greening is difficult when planting is done directly on earth structures made from these materials. However, Sato and Nishimoto (2005) suggest a countermeasure to this problem, which is to use earth cover that incorporates additional soil. Moreover, one of the major problems that arises with the use of stabilised materials in road pavement layers is cracking (NRRDA 2016). There are many factors that contribute to the cracking and crack spacing of stabilised pavement layers. Some of these are listed below (NRRDA 2016):

- Tensile strength of the stabilised material.
- Shrinkage characteristics.
- Volume changes resulting from temperature or moisture variations.
- The subgrade restraint.
- Stiffness and creep of the stabilised material.
- External loadings such as those caused by traffic.

It is suggested by the NRRDA (2016) that cement stabilisation is often performed for stabilising sandy and other low plasticity soils, and that cement interaction with the silt and clay fractions can reduce their water requirement (NRRDA 2016). FA possesses no plasticity (Bose 2012) and is in general frictional materials (Kim et al. 2005). According to UKQAA (2011d), FA is highly suitable for the treatment of sites with slightly plastic or silty constituents, for which often cement stabilisation has been the solution. Nevertheless, because of cement's rapid set, cement has construction limitations for soil treatment. Veelen and Visser (2007) suggest that the following soil properties require alteration to prevent the defects on roads:

- Strength to increase stability and bearing capacity.
- Volume stability to control swelling/ shrinkage.
- Durability to increase resistance to erosion either from weather or traffic.

- Reduction in permeability.

In a study by Bose (2012), the plasticity index of clay-FA mixes decreased with the higher FA content. Thus, the addition of FA made expansive soil less plastic and increased its workability by colloidal reaction and changing its grain size. It was also found that swelling pressure decreased drastically and shrinkage limit increased with the addition of FA (Bose 2012). In an article, Hossain (2010, p. 182) states that soils with a 'liquid limit less than 40% and plasticity index within the range 22-25% are also most suitable for stabilisation'. However, the same author concluded that soils do not have to meet the two conditions, and may still be suitable for stabilisation (Hossain 2010). It is therefore important to investigate the suitability of soil to be stabilised using different types and combinations of stabilisers and soil types.

The traditional method of dealing with the construction of roadways over weak or soft ground issue, is to replace the soft soil with stronger material, such as crushed rocks. As it is expensive to replace the soft soil, highway agencies suggest stabilised soil as an alternative (Hossain 2010). This can potentially result in savings, with a reduction of 10% to 20% in overall cost (Ahmaruzzaman 2010). It is of interest to note that FA is available free of charge at most power plants, and hence, there are only transportation costs and laying and rolling costs to be considered. Furthermore, FA has good potential for use in geotechnical applications for the following reasons (Bose 2012):

- Relatively low unit weight, making it well suited for placement over soft or low bearing strength soils.
- Low specific gravity.

- Freely draining nature.
- Ease of compaction.
- Insensitivity to changes in moisture content.
- Good frictional properties.

For a given degree of compaction, it is suggested that maximum dry density is lower for stabilised soil than that of soil not stabilised (Makusa 2012). Also, the optimum moisture content increases with increasing binders. This is believed to be the case due the heat generated when the binders begin their chemical reactions. Hydration process for soils stabilised with cement and FA occurs instantly when the cement and water come into contact (Makusa 2012). Additionally, some authors (Santos et al. 2011; Paige-Green and Netterberg, 2004; Acosta et al. 2003; Kim et al. 2005) also concluded a similar behaviour, where the optimum moisture content (OMC) was increased and the maximum dry density (MDD) decreased with the addition of stabilisers. Adequate water content is of high importance in stabilised materials, not only for the occurance of the hydration process but also for effective compaction (Makusa 2012). It has been reported that for cement to be completely hydrated, it would require about one fifth of its weight (Makusa 2012). On the other hand, quicklime takes up about 32% of its own weight of water from the surroundings (Makusa 2012). Inadequate water content can potentially cause binders to compete with soils to gain these amounts of moisture.

Li et al. (2009) investigated FA (class C) stabilisation of soft clay soil, asphaltic recycled pavement material (RPM) and road-surface gravel (RSG) to create working platforms or a stabilised base course for construction of flexible and rigid pavements. The authors reported that the stabilisation improved the stiffness as well as the strength of the materials significantly. In a recent report, a CBR of 2 to 10 times of the material alone after 7days of curing, and a resilient modulus (M_R) of up to two times higher, after 14 days of curing was achieved (Li et al. 2009). The NRRDA (2016) suggests that when a proportion of 2-3% cement content is utilised for soil treatment (without specifiying the soil type) an improved CBR value of more than 25 can be obtained, which can advantageously be used as sub-base/base for rural roads. Li et al. (2009) state that in the three cases investigated, Wisconsin, Minnesota, and Kansas, utilisation of FA for stabilisation achieved substantial success in regards to an improved pavement structure and also a sustainable construction. It should be pointed out that the construction methods in all three cases were similar (Li et al. 2009):

- FA was spread uniformly on the surface of the subgrade, RPM, or RSG using truck-mounted lay-down equipment.
- Then, it was mixed in using a road reclaimer.
- Water was added during mixing using a water truck, whenever required.
- The mixture was compacted within 1 to 2 hours of blending using a tamping foot compactor.
- This was followed by a vibratory steel drum compactor.

Misra et al. (2009) propose that class C FA may be utilised to stabilise reclaimed asphalt base, for low traffic volume roads, to construct a high quality road base. The materials often used in the conventional construction of these types of roads are very diverse and inconsistent. In general, it is quite common for these roads to go without any maintenance at all or very little maintenance, due to budgetary limitations (Misra et al. 2005). For utilisation of FA in the stabilisation of a reclaimed asphalt base, a comprehensive construction methodology, FA content and optimum moisture content are of high importance (Misra et al. 2005). Additionally, as Santos et al. (2011) state, the unit weight of FA-soil mixture is an important factor as it influences the strength, compressibility, and permeability. The same authors report that the unit weight of the compacted mixtures depends on:

- The method of energy application.
- The amount of energy applied.
- The grain size distribution.
- The plasticity characteristics.
- The moisture content at compaction.

In one study, Toraldo et al. (2013) investigated the utilisation of BA stabilisation for use in road pavement. It was found that when BA was mixed with cement (up to 4% content), the results did not meet the required standards for road construction; however, when the cement content was raised to 5%, it proved to be suitable for the purpose. The authors concluded that a BA content of 10% and 5% cement could be used in road construction as the properties fulfilled the technical guidelines as well as meeting the acceptable leaching behaviour (Toraldo et al. 2013). In another study, Bose (2012) investigated soil stabilisation with FA (contents of 0 to 90%), and it was established that the UCS increases at 20% FA -80% clay mix and then decreases, with further addition of FA. Bose (2012) implies that the quantity of FA up to optimum content can induce a pozzolanic reaction and that cemented materials can effciently contribute to shear strength increase, while the additional quantity of FA acts as unbounded silt particles, which have neither appreciable friction nor cohesion, causing a decrease in strength.

Moreover, in the study by Li et al. (2009), the authors concluded that materials stabilised with FA had significantly higher CBR and M_R than the pavement materials, and suggested that stabilisation with FA should be beneficial in terms of increasing pavement capacity and service life. Bose (2012) established that the optimum FA content for improving the shear strength of the treated soils under the presented conditions is 20%. Han (1993) proposed that a typical stabilised soil mixture would contain 80 % ground materials, 16 % FA and 4 percent cement. Moreover, according to UKQAA (2011d), a much more recent evaluation, for coarse-grained soils and as a starter, 5% FA followed by 3% cement may be appropriate.

FA can be used in variety of ways within highway construction for technical, environmental and cost benefits. UKQAA (2011d) has set the following aims for utilisation of FA in the pavement construction industry:

- To make more extensive use of FA, a by-product from coal-fired power generation plants.
- To reduce the consumption of primary materials for pavement construction.
- To widen the range of pavement construction materials.
- To produce more cost effective and environmentally sustainable pavements.

2.5 Stabilisation Procedures

2.5.1 Activation

Activation is a ‘chemical process that allows the transformation of glassy structures, partially or totally amorphous, into very compact well-cemented composites’ (Palomo et al. 1999, p. 1323). Through this process, the chemical reaction of soil particles and chemical additives creates a strong bond between the soil grains, resulting in a stronger, more durable and a better quality soil in comparison to an untreated soil. There are some common activators, such as lime and cement, and there are some more recent stabilisers such as FA (Class C), blast furnace slag, sodium hydroxide and sodium silicate (Palomo et al. 1999). As extensively mentioned in the previous sections, cement is among one of the first binding agents used since the invention of soil stabilisation technology in the 1960s. The reaction produced by cement is not solely dependent on soil minerals; the vital reaction occurs with the available water or moisture in the soil (Zumrawi 2015). This can be the reason why cement is used to stabilise a broad range of soils. Class C FA also has similar characteristics due to its self-cementing properties (Cristelo et al. 2011). There are different types of cement available in the market: ordinary Portland cement, blast furnace cement, sulfate resistant cement and high alumina cement among others (Makusa 2012). Generally, the choice of activator depends on the type of soil to be treated and desired final strength (Makusa 2012).

Stabilisation with lime as the choice of activator, is commonly performed in geotechnical and environmental projects. Some of the applications include rendering of backfill, highway capping, slope stabilisation and foundation improvements such as in the use of lime pile or lime-stabilised soil columns (Makusa 2012).

Class F FA can be used in the stabilisation process if added with an activator such as lime or cement. It is important to note that the impact of Class F (plus an activator) may differ significantly compare to a Class C stabilised sample. It is highly dependable on the pozzolan content of each ash and the degree of self-cementing property of Class C FA (Little and Nair, 2009). Free lime is the basis for stabilisation of Class C FA, which becomes available at the point of contact with water (Little and Nair, 2009). The level of self-cementing properties of a Class C FA, may vary extensively as it is influenced by the source of the parent coal as well as the methods of combustion. According to Cristelo et al. (2012b), when lime-based binders were compared to cement-based binders, the mechanical strength achieved by cement-based binders was higher and of a better consistency. Similar behaviour was found by authors Aydilek and Arora (2005), where the unconfined compressive strengths of cement-stabilised samples were higher than those of lime-stabilised samples, by a minimum factor of ten. Additionally, a further advantage of using FA and cement together is that it can help in containing the leachate of heavy metals (Kamon et al. 2000). Although the National Rural Roads Development Agency of India states that cement is more difficult to mix intimately with plastic material, pre-treating the soil with approximately 2% lime can alleviate the issue (NRRDA 2016).

In one article, Kaniraj and Havanagi (1999) explain that there is a significant gain in strength (particularly in the case of class F FA) even with a small addition of cement, and the gain depends on the cement content and curing time. In an experimental study (Paige-Green and Netterberg, 2004) consisting of extensive laboratory testing, it was found that a 3% cement content as the choice of activator for purpose of stabilisation proved adequate for strength purpose but had inadequate durability in the long term. The UK Quality Ash Association (UKQAA 2011d) states that the precise additions of activators would depend on the required mechanical strength of the project, which would be subject to extensive laboratory testing.

The selection of the activator is based on plasticity and particle size distribution of the material to be treated (NRRDA 2016). It is also believed that different types of stabilisers and activators would require different durations to reach their maximum strength due to their chemical compositions (Veelen and Visser, 2007). A methodology developed by the U.S., air force, by which an appropriate activator and stabiliser can be selected, is presented in Figure 16 (Little and Nair, 2009). According to Okonta and Ojuri (2014), the actual choice of most appropriate stabilising and the quantity of the agent required are usually based on the 7-day UCS of the stabilised soil.

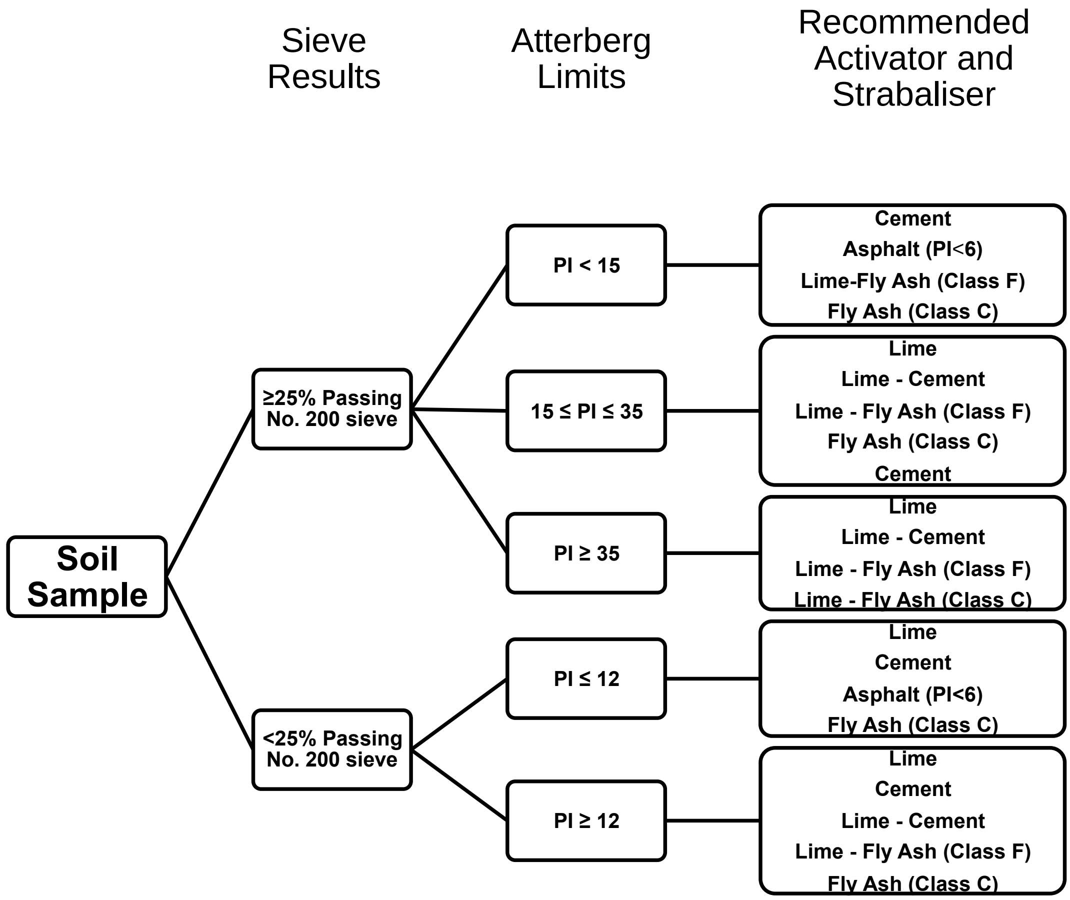


Figure 16: Decision tree of activator and stabiliser selection
Source: After (Little and Nair, 2009)

A systematic study was carried out to identify the most suitable activators that will enhance the reactivity of the class F FA in the early stages of curing (Arjunan et al. 2001a). A mixture of sodium carbonate, sodium hydroxide and calcium hydroxide have proved to produce enhanced strength in stabilised mixutres, where mixutres with sodium carbonate have shown a very low strength activation effect (Arjunan et al. 2001a). Moreover, the study by Arjunan et al. (2001b) showed that utilising low concentrations of sodium hydroxide as an activator for class F FA was highly effective. It is further stated, by the same authors, that the pozzolanic activity of FA can depend on the FA ‘fineness, amorphous matter, chemical and mineralogical composition and the unburned carbon content’ (Arjunan et al. 2001b, p. 1).

It is believed that fine FA produces better strength than the respective activated coarse FA (Arjunan et al. 2001a). Nevertheless, according to Kim et al. (2005) the addition of BA to FA can lead to better well-graded size distribution, allowing for a better compacted material with less void, and ultimately resulting in a higher maximum dry density. It has been known and proven that soil stabilisers and activators can improve the strength of pavement materials; however, it is of high importance to choose the right stabiliser and activator for the specific project (Veelen and Visser, 2007).

It was found that numerous activating agents are suitable for FA stabilisation, i.e. sodium hydroxide, calcium hydroxide, lime and cement. As hydroxide combounds require high level of health and safety for both utilisation and storage, lime and cement were viable choices as activators for the purpose of this research. It was mentioned ealier that cement-based samples achieved mechanical strength higher and of a better consistency when compared to lime-based samples. For the purpose of FA-soil stabilsation, cement was used as the activator in this study.

2.5.2 Curing

Curing is the process of maintaining moisture content and controlling the moisture loss of stabilised materials over a period of time to allow adequate hydration (Okonta and Ojuri, 2014). Appropriate curing is very important for three reasons (AustStab 2012; NRRDA 2016):

- It ensures that sufficient water is retained in the material so that the hydration reactions between the stabiliser, water and the soil can continue.
- It reduces shrinkage.
- It reduces the risk of carbonation.

In a study, by Kaniraj and Havanagi (1999), the samples were closely wrapped in a polyethylene bag and placed above water in a desiccator kept in a room where the temperature (21°C) and the humidity were maintained by the water. In the study developed by Lav and Lav (2014), the samples were also wrapped in plastic bags and cured in a controlled room, with a temperature of 23 °C and 50% humidity. Kamon et al. (2000) also used similar curing methods, where the specimens were sealed and cured under a constant room temperature of 20 °C and a relative humidity of 80%. In order to model samples tested in the laboratory like the field conditions, AustStab (2012), a pavement recycling and stabilisation association, states that for best practice samples are to be sealed in airtight bags and kept at a constant temperature.

Furthermore, in another article, the authors concluded that buried curing resulted in lower strength overall when compared with curing at an ambient temperature and humidity (Cristelo et al. 2011). Meanwhile, Beeghly (2003) had the samples cured at ambient temperatures (22 °C). Celauro et al. (2012b) also cured the samples at this temperature with ± 2 °C tolerance. It is believed that the longer the curing time, the higher the average strength (Palomo et al. 1999).

Palomo et al. (1999) believe that temperature is a reaction accelerator; its effect is so intense that the reaction steps overlap each other. In general terms, if all the factors remain constant, the temperature increases tend to result in a gain of mechanical strength. Paige-Green and Netterberg (2004) investigated the effect of temperature and found that samples compacted at higher temperatures, 40°C and the density had the sharpest decrease, while the maximum density was achieved at 23 °C. It should also be noted, however, that samples compacted at 10 °C achieved a better consistency.

The significant factors affecting the mechanical strengths are always the temperature and the type of the activator (Palomo et al. 1999). It is been found that the effect of higher temperatures was more important than that of the cement type (Paige-Green and Netterberg, 2004). It should be pointed out that different stabilisers need different curing times in order to reach adequate strength (Okonta and Ojuri, 2014). The kind of solution used for the activation of the FA is essential in the development of reactions.

In the field, temperature fluctuates throughtout the day and daily. According to Paige-Green and Netterberg (2004), the pozzolanic reaction is sensitive to changes in temperature. The reactions slow down when temperature are low, which subsequently will lead to lower strength of the stabilised material. In cold regions, it may be advisable to stabilise the soil during the warm season (Makusa 2012). However, in terms of issues faced in hot dry climates, the prevention of moisture loss is very challenging, and the surface should be constantly sprayed and kept damp throughout both day and night (NRRDA 2016). Curing through spraying is significantly more efficient, when a layer of sand with thickness of 30mm to 40mm is spread on top of the layer first (NRRDA 2016). As a result, the number of spraying cycles per day lowers and a considerable amount of water is saved (NRRDA 2016). Prior to spraying, the surface should be swept free of loose material and any damp areas should be free of standing water. The following methods of curing are suggested (NRRDA 2016):

- Covering with impermeable sheeting with joints overlapping at least 300 mm and set to prevent ingress of water.
- Spraying with a bituminous sealing compound.

Alternatively, using crushed ice during compaction, as suggested by Baykal et al. (2004), can overcome the issues of stabilising in cold regions or cold seasons. The same authors had their samples sealed and cured at 21°C for periods of 1, 7, 14, 28 and 90 days. For the purpose of this research, as sugessted by AustStab (2012) and similar curing methods undertaken by Kaniraj and Havanagi (1999), Kamon et al. (2000) and most recently, Lav and Lav (2014), the samples to be tested will be sealed in plastic bags and kept room temperatures for the curing.

2.6 Laboratory Testing

There have been many studies, with different approaches, on the utilisation of FA. The specifications and requirements should be based on a series of laboratory tests for obtaining the optimum moisture content, unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values (Misra et al. 2005). According to NRRDA (2016), the strength of stabilised materials is most commonly evaluated through UCS and CBR tests. The UCS varies with FA content and water content and the CBR values tend to increase with curing time (Santos et al. 2011; UKQAA 2007). In various researches, where FA was utilised for soil stabilisation, there were some common laboratory tests performed, in order to obtain before and after treatment properties, both physical and chemical. Among the most important tests were:

- Particle Size Distribution (Cristelo et al. 2011; 2012b).
- Attersberg's limits (Cristelo et al. 2011, 2012b; Hossain 2010; Kamon et al. 2000; Kolias et al. 2005).
- Compaction test, rammer method (Cristelo et al. 2011; 2012b; Hossain 2010; Kamon et al. 2000; Kaniraj and Havanagi, 1999; Kolias et al. 2005; Jackson et al. 2007).
- California Bearing Capacity (CBR) test (Hossain 2010; Kolias et al. 2005; Jackson et al. 2007; Sato and Nishimoto, 2005; Li et al. 2009).
- Shear Strength (Consoli et al. 2008; Cristelo et al. 2011; Porbaha and Hanzawa, 2001; Sato and Nishimoto, 2005).
- Unconfined Compressive Strength (UCS) (Arioz et al. 2013; Cristelo et al. 2012a; Kamon et al. 2000; Kolias et al. 2005; Sato and Nishimoto, 2005).

- X-Ray diffraction (XRD) Analysis (Arioz et al. 2013; Cristelo et al. 2012a; Kolias et al. 2005).
- Resilient Modulus (M_R) (Li et al. 2009; Aydilek and Arora, 2005).

In a study by Kim et al. (2005), in which both class C and F FA in the United States were examined, typical maximum dry density and optimum moisture content of these FAs where reported (see Table 2). In another study, Acosta et al. (2003) reported the average maximum dry density of FA, 8-7 kN/m^3 and the optimum moisture content of 15-35%.

Table 2: Typical FA maximum dry density and optimum moisture content
Source: After (Kim et al. 2005)

FA	Typical maximum dry	Typical optimum moisture
Class F	11.9-18.7 kN/m^3	13-32%
Class C	13.0-18.7 kN/m^3	11-19%

The UKQAA (2007, p. 4) states that 'the maximum dry density and optimum moisture content should be determined using the 2.5kg rammer as described in BS1377 Part 4'. In practice sufficient compaction can be achieved over a range of moisture contents between 0.8 and 1.2 times the optimum value (UKQAA 2007). The Specifications for Highway Works (SHW 2016) series 600, in the clause for compaction requirements, states that at least 95% of the maximum dry density should be achieved. However, there have been projects where 90% has been accepted (UKQAA 2007). Typical CBR values for inundated ash at zero days are 10-20% (UKQAA 2007). Paige-Green and Netterberg (2004) recommend the following measures for stabilisation purposes:

- Investigations into the relationship between workability and setting times should be carried out.
- Any soil to be used for stabilisation should be tested following the normal material design procedures as well as assessing the temperature and time sensitivity of the density and strength.
- The construction techniques and temperatures should also be simulated as closely as possible.
- The effect of cement, conditioning time and temperature on durability should be assessed.
- Consideration should be given to reducing the strength grade and increasing the setting times for cement-soil stabilisation.

The long-term performance must be extrapolated from short-term laboratory tests, which are a source of uncertainty (Mitchell and Kelly, 2013). Homogeneous mixing is necessary to obtain consistent results in both the lab and the field (Misra et al. 2005). It is suggested that the compactions of samples of FA-soil stabilisation mixtures should be performed two hours after the mixing, so that field compaction delay can be replicated (Santos et al. 2011). Field CBR tests may be used to assess the performance of the road base (Misra et al. 2005). According to Li et al. (2009), field CBR and M_R tests achieved lower values in comparison to laboratory tests. On average, field CBR values were 50-65% lower than the CBR tests performed in the laboratory where FA was used in the mixtures (Li et al. 2009; Bin-Shafique et al. 2004).

Various researchers (Cristelo et al. 2011; Kolias et al. 2005; Aydilek and Arora, 2005; Santos et al. 2011; Cristelo et al. 2012a; Cristelo et al. 2012b; Reyes and Pando, 2007; Sahu 2001; McCarthy et al. 2011) investigated the influence of FA (both class F and C) on ground improvement through stabilisation. The results of these studies are presented on Table 3 and are discussed in-depth further on.

The majority of the soils studied in these studies were found to be in the form of clay, with very few sandy samples. By observing Table 3, it can be seen that an increase in the CBR value was achieved for all the studies, except the case of Sahu (2001). In fact, in this particular paper, the samples of Kalahari sand achieved rather a significant drop in CBR, reducing from 40 to 10% and to 30% when 24% and 8% FA content was utilised. This is believed to be down to the particular characteristics of Kalahari sand. In one of the studies, Aydilek and Arora (2005), the authors stabilised silty sand samples with class F FA with a content of 40%, while choosing lime and cement as activators. At the end of 28 days of curing, the samples stabilised with cement showed a much higher unconfined compressive strength, over twelve times, than that of those achieved by lime activation. As it was stated earlier in the literature, authors Cristelo et al (2012b) had suggested that samples stabilised with cement tend to produce significantly better and more consistent results in comparison to samples stabilised with lime, in terms of mechanical strength.

Moreover, the results of researchers Santos et al. (2011) show that when FA content was raised from 40 to 60%, the improvement was rather insignificant, while when the FA content was raised from 20 to 40%, the strength was almost doubled, from 1.35 MPa to 2.65 MPa. Cristelo et al. (2011) investigated the utilisation of class F for soil improvement. The authors had curing periods as long as a year, where astounding results were achieved, with the sample of 40% FA content attained an unconfined compressive strength of 43 MPa after the 365 days of curing. The same class F FA was cured for 28 and days also, where unconfined compressive strengths of 8 and 17 MPa, respectively, was achieved. It can be said without a doubt, that curing has a direct effect on the results, the higher the curing duration, the higher the strength of the soil. In another study, by Cristelo et al. (2012a), soil stabilisation with both class F and class C was investigates. When comparing the samples of identical FA content (20%), and curing duration (84 days), the samples stabilised with class F ahichved a higher strenght resutls, over three times, than that of samples stabilised with class C FA.

Table 3: Results of soil stabilising by utilisation of FA from nine different

Summary: Experiences of soil stabilization using Fly Ash

	Fly Ash	**Soil**	**Activator (Content)**	**Tests**	**Results: Before Treatment**	**Results: After Treatment**	**Source**
20%	Fly Ash (FA)	Lean Clay	Cement (2%)		20% FA and 91-day curing		Kolias et al. 2005
				OMC	22%	30%	
				CS	0.1 MPa	3.1 MPa	
				CBR	10%	185%	
				MDD	15.9 kN/m^3	13.1 kN/m^3	
20%	Fly Ash (FA)	Lean Clay	Cement (2%)		20% FA and 28-day curing		
				OMC	22%	30%	
				CS	0.1 MPa	1.7 MPa	
				MDD	15.9 kN/m^3	13.1 kN/m^3	
20%	Fly Ash (FA)	Fat Clay	Cement (2%)		20% FA and 91-day curing		
				CS	0.1 MPa	1.75 MPa	
				CBR	10%	110%	
20%	Fly Ash (FA)	Fat Clay	Cement (2%)		20% FA and 28-day curing		
				CS	0.1 MPa	1.25 MPa	
10%	Fly Ash (FA)	Lean Clay	Cement (2%)		10% FA and 91-day curing		
				OMC	22%	26%	
				CS	0.1 MPa	1.9 MPa	
				CBR	10%	140%	
				MDD	15.9 kN/m^3	14.1 kN/m^3	
10%	Fly Ash (FA)	Lean Clay	Cement (2%)		10% FA and 28-day curing		
				OMC	22%	26%	

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

				CS	0.1 MPa	1.1 MPa	
				MDD	15.9 kN/m^3	14.1 kN/m^3	
10%	Fly Ash (FA)	Fat Clay	Cement (2%)		10% FA and 91-day curing		
				CS	0.1 MPa	0.7 MPa	
				CBR	10%	60%	
10%	Fly Ash (FA)	Fat Clay	Cement (2%)		10% FA and 28-day curing		
				CS	0.1 MPa	0.5 MPa	
40%	Fly Ash Class F (FAF)	Silty Sand	Cement (7%)		40% FAF and 28-day curing		Aydilek and Arora, 2005
				MDD		15.46 kN/m^3	
				UCS		5.0 MPa	
40%	Fly Ash Class F (FAF)	Silty Sand	Cement (7%)		40% FAF and 7-day curing		
				MDD		15.46 kN/m^3	
				UCS		3.2 MPa	
				CBR		140%	
40%	Fly Ash Class F (FAF)	Silty Sand	Lime (7%)		40% FAF and 28-day curing		
				MDD		15.36 kN/m^3	
				UCS		0.4 MPa	
40%	Fly Ash Class F (FAF)	Silty Sand	Lime (7%)		40% FAF and 7-day curing		
				MDD		15.36 kN/m^3	

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

				UCS		0.3 MPa	
				CBR		36%	
60%	Fly Ash (FA)	Low Plasticity Clay			60% FA and 28-day curing		Santos et al. 2011
				OMC	14%	28%	
				MDD	17.9 kN/m^3	13.9	
				CS		2.67 MPa	
40%	Fly Ash (FA)	Low Plasticity Clay			40% FA and 28-day curing		
				OMC	14%	25%	
				MDD	17.9 kN/m^3	14.6 kN/m^3	
				CS		2.65 MPa	
20%	Fly Ash (FA)	Low Plasticity Clay			20% FA and 28-day curing		
				OMC	14%	22.5%	
				MDD	17.9 kN/m^3	15.5 kN/m^3	
				CS		1.35 MPa	
20%	Fly Ash Class F (FAF)	Fat clays	SH & SS		20% FAF and 84-day curing		Cristelo et al. 2012a
				UCS		8.6 MPa	
20%	Fly Ash Class F (FAF)	Fat clays	SH & SS		20% FAF and 28-day curing		
				UCS		1.7 MPa	
20%	Fly Ash Class C (FAC)	Fat clays	SH & SS		20% FAC and 84-day curing		
				UCS		3.0 MPa	
20%	Fly Ash Class	Fat clays	SH & SS		20% FAC and 28-day curing		

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

	C (FAC)						
				UCS		1.3 MPa	
10%	Fly Ash Class F (FAF)	Fat clays	SH & SS		10% FAF and 84-day curing		
				UCS		4.2 MPa	
10%	Fly Ash Class F (FAF)	Fat clays	SH & SS		10% FAF and 28-day curing		
				UCS		0.6 MPa	
10%	Fly Ash Class C (FAC)	Fat clays	SH & SS		10% FAC and 84-day curing		
				UCS		2.0 MPa	
10%	Fly Ash Class C (FAC)	Fat clays	SH & SS		10% FAC and 28-day curing		
				UCS		1.1 MPa	
25%	Fly Ash Class F (FAF)	Granitic Residual Soil	SH & SS		25% FAF and 7-day curing		Cristelo et al. 2012b
				UCS		17 MPa	
				MDD	19.2 kN/m^3		
20%	Fly Ash Class C (FAC)	High Plasticity Clay			20% FAC and 40-day curing		Reyes and Pando, 2007
				MDD	12.1 kN/m^3		
				UCS	0.24 Mpa	0.96 MPa	
20%	Fly Ash Class	High Plasticity Clay			20% FAC and 28-day curing		

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

	C (FAC)					
			MDD	$12.1\ kN/m^3$		
			UCS	0.24 Mpa	0.9 MPa	
10%	Fly Ash Class C (FAC)	High Plasticity Clay		10% FAC and 40-day curing		
			MDD	$12.1\ kN/m^3$		
			UCS	0.24 Mpa	0.56 MPa	
10%	Fly Ash Class C (FAC)	High Plasticity Clay		10% FAC and 28-day curing		
			MDD	$12.1\ kN/m^3$		
			UCS	0.24 Mpa	0.45 MPa	
24%	Fly Ash (FA)	Kalahari Sand		24% FA and 7-day curing		Sahu, 2001
			OMC	5%	7%	
			MDD	$17.3\ kN/m^3$	$14.7\ kN/m^3$	
			CBR	40%	10%	
24%	Fly Ash (FA)	Calcrete		24% FA and 7-day curing		
			OMC	15.60%	17%	
			MDD	$17.2\ kN/m^3$	$16.3\ kN/m^3$	
			CBR	40%	90%	
24%	Fly Ash (FA)	Silty Sand		24% FA and 7-day curing		
			OMC	9%	9%	
			MDD	$19.0\ kN/m^3$	$18.2\ kN/m^3$	
			CBR	80%	470%	

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

24%	Fly Ash (FA)	Black Cotton Soil		24% FA and 7-day curing	
			OMC	20%	23.50%
			MDD	15.1 kN/m^3	14.8 kN/m^3
			CBR	0%	25%
24%	Fly Ash (FA)	Low Plasticity Silt		24% FA and 7-day curing	
			OMC	12%	12.30%
			MDD	19.8 kN/m^3	18.9 kN/m^3
			CBR	10%	230%
8%	Fly Ash (FA)	Kalahari Sand		8% FA and 7-day curing	
			OMC	5%	5%
			MDD	17.3 kN/m^3	16.8 kN/m^3
			CBR	40%	30%
8%	Fly Ash (FA)	Calcrete		8% FA and 7-day curing	
			OMC	15.60%	19.90%
			MDD	17.2 kN/m^3	16.4 kN/m^3
			CBR	40%	60%
8%	Fly Ash (FA)	Silty Sand		8% FA and 7-day curing	
			OMC	9%	8.80%
			MDD	19.0 kN/m^3	18.6 kN/m^3
			CBR	80%	315%
8%	Fly Ash (FA)	Black Cotton Soil		8% FA and 7-day curing	
			OMC	20%	22.70%
			MDD	15.1 kN/m^3	15.3 kN/m^3

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

				CBR	0%	5%	
8%	Fly Ash (FA)	Low Plasticity Silt			8% FA and 7-day curing		
				OMC	12%	11.90%	
				MDD	19.8 kN/m^3	19.6 kN/m^3	
				CBR	10%	40%	
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		40% FAF and 365-day curing		Cristelo et al. 2011
				UCS		43 MPa	
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		40% FAF and 90-day curing		
				UCS		17 MPa	
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		40% FAF and 28-day curing		
				UCS		8 MPa	
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		20% FAF and 365-day curing		
				UCS		24 MPa	
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		20% FAF and 90-day curing		
				UCS		5 MPa	
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		20% FAF and 28-day curing		
				UCS		3.5 MPa	

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

24%	Fly Ash -a	Oxford Clay	Lime (3%)		24% FA and 90-day curing		McCarthy et al. 2011
				OMC	25%	26.90%	
				MDD	14.9 kN/m^3	14.3 kN/m^3	
				UCS		1.9 MPa	
24%	Fly Ash -b	Oxford Clay	Lime (3%)		24% FA and 90-day curing		
				OMC	25%	28.10%	
				MDD	14.9 kN/m3	13.7 kN/m3	
				UCS		1.5 MPa	
24%	Fly Ash -a	Oxford Clay	Lime (3%)		24% FA and 28-day curing		
				OMC	25%	26.90%	
				MDD	14.9 kN/m^3	14.3 kN/m^3	
				UCS		1.4 MPa	
24%	Fly Ash -b	Oxford Clay	Lime (3%)		24% FA and 28-day curing		
				OMC	25%	28.10%	
				MDD	14.9 kN/m^3	13.7 kN/m^3	
				UCS		1.2 MPa	
12%	Fly Ash -a	Oxford Clay	Lime (3%)		12% FA and 90-day curing		
				OMC	25%	26.70%	
				MDD	14.9 kN/m^3	14.4 kN/m^3	
				UCS		1.7 MPa	
12%	Fly Ash -b	Oxford Clay	Lime (3%)		12% FA and 90-day curing		
				OMC	25%	27.40%	
				MDD	14.9 KN/m^3	14.0 KN/m^3	
				UCS		1.4 MPa	
12%	Fly Ash -a	Oxford Clay	Lime (3%)		12% FA and 28-day curing		

Table 3 (Cont'd): Results of soil stabilising by utilisation of FA from nine different studies

				OMC	25%	26.70%
				MDD	14.9 KN/m^3	14.4 KN/m^3
				UCS		1.3 MPa
12%	Fly Ash -b	Oxford Clay	Lime (3%)		12% FA and 28-day curing	
				OMC	25%	27.40%
				MDD	14.9 KN/m^3	14.0 KN/m^3
				UCS		1.2 MPa

Legend:

OMC	**Optimum Moisture Content**	UCS	**Unconfined Compressive Strength**	SH	**Sodium Hydroxide**
MDD	**Maximum Dry Density**	CS	**Compressive Strength**	SS	**Sodium Silicate**
CBR	**California Bearing Ratio**				

In overall, in every study, improvements on the physical strength of FA stabilised soil were achieved. By concluding Table 3, it can be said that the most effective stabilisation with FA is utilising class F FA and choosing cement as the activator and finally, the curing duration to be extented as long as viable. Throughout the studies, the choice of activator varied. These include; cement, lime, sodium hydroxide (SH) and sodium silicate (SS). In the studies, Cristelo et al. (2011), Cristelo et al. (2012a) and Cristelo et al. (2012b), the authors used a mixture of SH and SS. Figure 17 is the chart that has been developed from summarizing Table 3. It presents the various possible results of soil stabilisation using FA. It can be clearly seen that further research needs to be carried out on sand, clayey sand in particular, and also on high plasticity silts. The present research is focused on sand only so that the gap of knowledge in FA stabilisation can be fulfilled. In addition, the building sand chosen for this research, was assessable in large quantities without any variation in its physical and chemical properties, producing more reliable and accurate results.

The past experiences obtained by numerous researchers can be briefly summarised into the following:

- The nature and origin of the parent coal has profound effect on the characteristics of FA.
- The percentage of the activator and the curing period effect the strength gain.
- Disposal rates of FA at the global scale are alarming and causing many concerns for the environmental agencies.
- Many methods and techniques are suggested for reutilisation of stored and landfilled FA, as well as proving the suitability of stored and landfilled FA for construction purposes.

- FA radiation is found to be negligible and as long as the requirements of nuisance dust are met, there is no increased health risk.

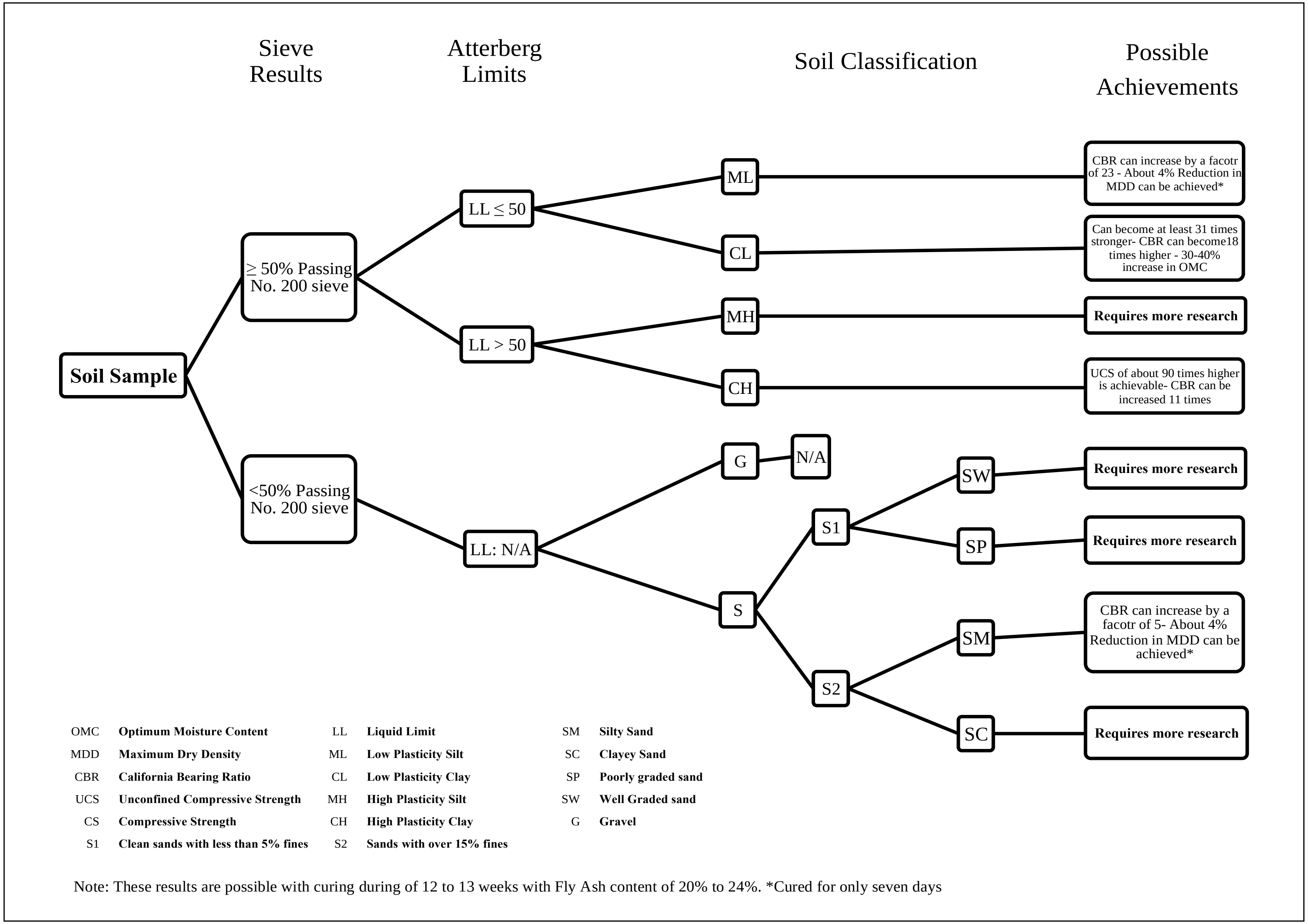


Figure 17: Various possible outcomes of soil stabilisation through FA utilisation

Chapter 3

Research Methodology

3.1 Introduction

For the purpose of this thesis, an applicable methodology was derived through detailed analysis of the previous available literature on the utilisation of FA on the construction of road embankment. The methodology is aimed at satisfying the research objectives obtaining quantitative data, which can be examined through analysis of produced tables, figures and graphs. The analysis for this research was in part from a series of laboratory tests and in part from numerical simulation.

All the different tests were carried out in the concrete laboratory in the University of West London between March 2016 and May 2017. FA and sand bags were also kept in the same laboratory, where all the materials were treated and cured. The FA was kept in the 25kg buckets that were delivered in.

It can be noted that the study of FA utilisation through laboratory tests provided quantitative data to mainly analyse the effect FA has on sandy soils. A comprehensive series of laboratory tests consisting of Particle Size Distribution (PSD), the Standard Compaction Test and the California bearing ratio (CBR) were conducted on untreated soil samples and stabilised samples with different percentage of FA and cement. These tests were tailored for deducing the mechanical properties of the samples. A minimum of three samples from each variation of soil were tested so that reliable results could be attained. Furthermore, there were four different curing durations, 1 week, 2 weeks, 4 weeks and 8 weeks (Kolias et al. 2005; Kamon et al.2000), with three variations of FA content, 5%, 10% and 15% (similar to Cristelo et al. 2012a, 2012b; Toraldo et al. 2013).

The aim of the laboratory tests was to analyse the influence of FA, cement and curing durations on stabilised soil properties. As an activator solution, cement with 3% content was used in this study. The quantity of the cement content was selected as an average based on previous studies (Kolias et al. 2005; Kaniraj and Havanagi, 1999; Toraldo et al. 2013). The proposed tests are described in more detail in the following section. As suggested by Veelen and Visser (2007), an effective laboratory examination of stabilisation of pavement materials, can be achieved by comparing the gain in strength, while utilising different additives (FA and cement) against the virgin material, in this case sand.

All the tests in this study were performed under the optimal conditions of the stabilised material, meaning in its most dense form with optimum water content. Only under these conditions can the best physical properties of any given material be obtained and used within the construction industry. The optimum water content and the maximum dry density of all the proposed varieties of FA-soil mixture were derived through a compaction test (Proctor). Furthermore, these optimal parameters were used to form the samples for CBR testing.

All the laboratory tests proposed for the purpose of this study were performed in accordance with British Standard 1377. This particular standard, 'Methods of test for soils for civil engineering purposes', has several parts; parts 1 (General requirements and sample preparation), 2 (Classification tests) and part 4 (Compaction-related tests) of this standard will be used for guidance on moisture content tests, PSD tests, compaction tests and CBR tests (BSI 1990a, 1990b, 1990c). It should be also noted that for a series of tests on a particular soil, one size mould shall be used consistently (BSI 1990c).

3.2 Temperature and Humidity

In order to keep records of both the temperature and humidity, a pair of temperature humidity data loggers were obtained. The recordings can be exported into a computer using the data logger software provided by the supplier. It is capable of taking a maximum of 16,320 temperature and relative humidity readings with the following accuracy and range:

- Measure temperature range: -40 to 60 °C.
- Temperature accuracy: ±1.0 °C under 0-50 °C.

- Measure humidity range: 10-99 % RH.
- Humidity accuracy: ±4 % under 20-80 %.

3.3 Moisture Content

Moisture content is required as a guide to the classification of natural soils and as a control criterion in recompacted soils and is measured on samples used for most laboratory tests (BSI 1990b). The water content of a material drastically effects material strength; the water content at which the material is strongest is known as the optimum water content. The minimum sample size for moisture content tests, for the oven drying method, and for medium grained is 300g (BSI 1990a). For moisture content, at least two representative specimens for determination of the moisture content, are taken and, hence, an average is derived (BSI 1990a). Ovens should be capable of maintaining the temperature required for the test to within ±2.5 °C (BSI 1990a). The soil is classified dry when no further water can be removed at a temperature not exceeding 110 °C (BSI 1990b). The period required for drying will vary with the type of the soil, the size of the sample and the number of samples in the oven. Note; between 16h to 24h is usually a sufficient length of time for drying most soils (BSI 1990b).

The test for obtaining natural water content was carried out in accordance with British Standard 1377-2 (Classification Tests) using the Oven Drying Method (BSI, 1990b). The material being tested came from bags of building sand, natural moisture content tests were carried out on 4 bags selected at random to establish variations in natural water content. An air drying oven set at between 105 °C and 110 °C was used to dry the sample. The sample was dried in the oven for 24 hours, in accordance with the British Standard method. The samples were weighed before and after drying. The weight difference between the original sample and the weight of the dried sample gave the weight of the water in the sample. From this the natural moisture content percentage of the sample could be calculated. Additionally, the optimum moisture content is determined by this procedure.

The water content calculations (BSI 1990b):

$$\boldsymbol{w = \frac{m2 - m3}{m3 - m1} \times 100}$$ **Equation 1**

where m1 is the mass of the container

m2 is the mass of the container and wet soil

m3 is the mass of the container and dry soil

3.4 Particle Size Distribution (PSD)

This is a standardised system of classification of soil particle size distribution. The particle size distribution tests performed during this thesis were done in accordance with British Standard 1377-2 (Classification Tests) the ‘Dry Sieving Method’ (BSI 1990b). Though this test the characteristics of the soil can be classified and then be identified as either clay, silt, sand or gravel. The ‘Dry Sieving Method’ is mainly used for examining materials with grain size of between 75mm and 0.063mm. The principal method to obtain particle size distribution is to put the soil sample through a set of sieves and record the mass remaining on each sieve. Then a graph is drawn with the particle sizes plotted on the horizontal axis and the percentage of remaining soil from each sieve on the vertical axis. The smallest sieve used is usually a 63 μm sized sieve. For particles smaller than that, the distribution curve must be attained by sedimentation.

Summary of PSD test procedure:

- Select and prepare test specimen.
- Oven dry, cool, weigh.
- Select sieves.
- Pass through sieves.
- Weigh each size fraction.
- Calculate cumulative percentages passing each size.
- Plot grading curve.
- Report results.

The distribution of the grain size in a given soil must be known for a better understanding of the nature of the soil. The grain size distribution of coarse-grained soils (gravelly and/or sandy) is determined by sieve analysis (Das 2014). The grain size distribution can be used to determine some of the soil parameters, including the uniformity coefficient and the coefficient of gradation (Das 2014). The effective size of soil is the diameter through which 10% of the total soil mass is passing and referred to as D10. The uniformity coefficient C_U is defined (Das 2014) as:

$$\boldsymbol{C_U = \frac{D60}{D10}} \qquad \textbf{Equation 2}$$

where D60 is the diameter through which 60% of the total soil mass is passing. The coefficient of gradation C_C is defined as:

$$\boldsymbol{C_C = \frac{D30^2}{D60 \times D10}} \qquad \textbf{Equation 3}$$

where D30 is the diameter through which 30% of the total soil mass is passing (Das 2014).

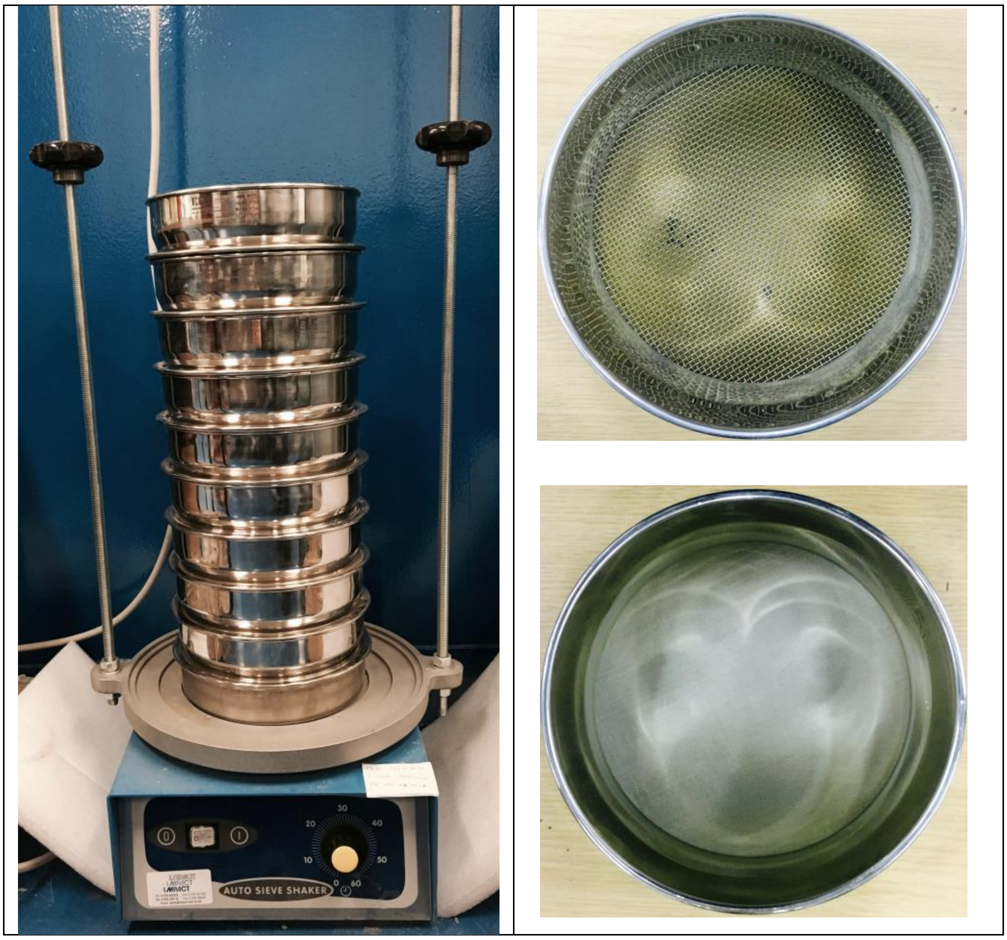


Figure 18: The sieve shaker and test sieves in UWL Concrete Laboratory

The soil is called well-graded soil if the distribution of the grain sizes extends over a large range, which means the value of the uniformity coefficient is high. Uniformity coefficient gives an indication of the spread of the particle sizes present in a soil, and it can range from 1 to 1000. A C_U close to 1 refers to the soil consisting of particles of almost one size, when the soil is defined as uniformly graded. If a soil has an excess of certain particle sizes and a deficiency of other sizes, for example, if C_U < 4, then the soil is called poorly graded soil (Shukla 2014; O'Flaherty and Hughes, 2016).

The sieves used for the purpose of this study consisted of woven-wire square meshes (Figure 18). This Figure, shows the arrangement for the sieving operation where one can see a series of sieves with a sieve shaker. The sieves were arranged in descending order, finishing with a tray to collect particles smaller than 0.63mm. The material that therefore passed through all the sieves into the tray was classified as the fines of the sample as it was smaller than 0.63mm.

The sieve size given on the label identifies the size of the spacing between the wire making up the mesh. At the end of the sieving operation, the mass of the soil retained on each sieve size was weighed, and the cumulative percentage by weight passing was calculated as the results of the sieve analysis (Shukla 2014). Figure 19 shows the outcome of sand grains separation through dry sieving. Therefore only particles smaller than the size given on the sieve passed through that specific sieve onto the next sieve.

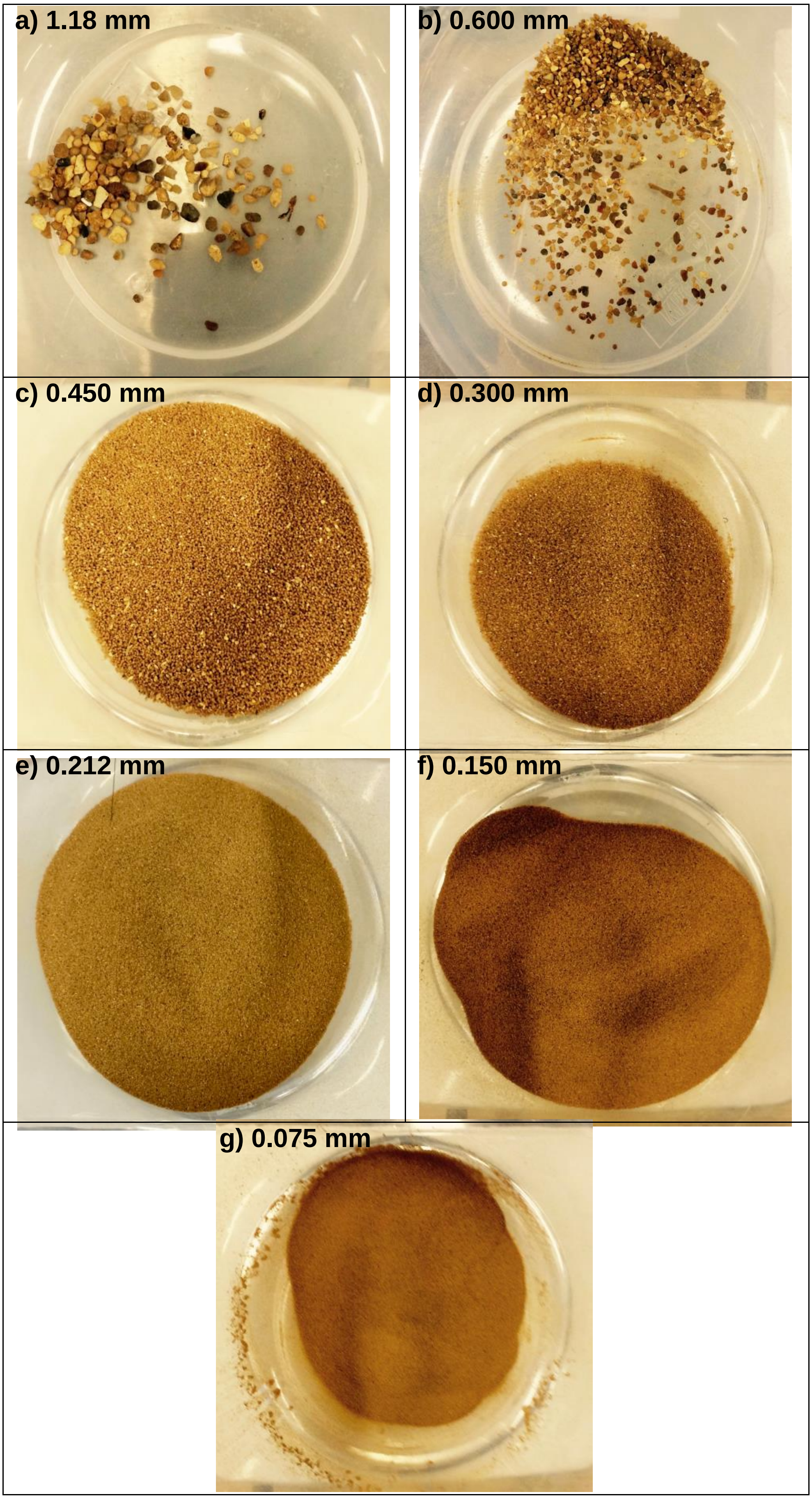


Figure 19: The outcome of sand grains separation through dry sieving

As stated earlier, the results of a PSD test were presented as a plot of the sieve size versus the percentage passing each sieve, with the sieve or particle size on a logarithmic scale and the percentage on an arithmetic scale (O'Flaherty and Hughes, 2016). From the classification graph produced as a result of PSD, the grading and uniformity of the soil sample could be calculated, along with the soil classification using the British soil classification system, which classifies soils with a particle size range of 0.06 mm to 2 mm, as sand (BSI 1990b).

According to O'Flaherty and Hughes (2016), the typical values for the Coefficient of Gradation (C_C) and the Uniformity Coefficient (C_U) in soil classification, for even graded soils is <1 and <6, respectively. Table 4 presents typical C_C and C_U values for different soil gradation.

Table 4: Typical Cu and Cc Values
Source: After (O'Flaherty and Hughes, 2016)

Soil Gradation	**C_U value**	**C_C value**
Multi-graded	>15	1<C_C<3
Medium graded	6-15	<1
Even graded	<6	<1
Gap-graded	Usually high	Any
Well graded	>5	1<C_C<3

There are several requirements set by the British Standard that were adhered to during this study. They include (BSI 1990a; 1990b):

- Mechanical sieve shakers shall hold a nest of test sieves with their lid and receiver secure (in order to prevent loss of any material).

- Their design shall ensure that the test material progresses over the surface of the sieve while it is agitated.
- The minimum shaking period should be 10min.
- Prior to sieving, the soil shall be dried in oven and maintained at a temperature of 105 to 110 °C for a minimum of 24 hours.

3.5 Compaction test (2.5kg rammer)

In order to evaluate the suitability of FA addition to sandy soil through stabilisation, the mixtures had to be tested at optimal conditions. The optimal conditions of any given material are when the material is in its most dense form while constituting optimum water content. The aim of laboratory compaction was to obtain optimum moisture content (OMC) and the maximum dry density (MDD), also known as the compaction parameters, by simulating the field compaction procedures. The compaction test is a test that determines the relationship between dry density and water content from a given energy of compaction. The OMC of soils ranges from 5 to 45% with a typical range of 10% to 20%.

In general, it is specified that mixing of the soil, its compaction, and final shaping should be conducted within one or maximum two hours of initial mixing (Mackiewicz and Ferguson, 2005). Strength and compaction characteristics achieved with no delay define the optimum properties of the FA treated materials. The unit weight of

FA-soil mixture is an important parameter since it controls the strength, compressibility, and permeability. The unit weight of the compacted samples depends on the method and amount of energy applied, the grain size distribution and moisture content at compaction (Santos et al. 2011). According to Mackiewicz and Ferguson (2005), when there is delay in compaction, as normaly happens in field operations, chemical reactions between soil particles and FA particles initiate bonding together, which ultimately will interfere with the material being densified. It has been reported that a delay of one hour after the materials have been mixed can reduce the maximum dry specific weights by 0.6 to 1.6 kN/m^3 (Mackiewicz and Ferguson, 2005). It is believed that the drop in strength caused by the delay is due to the disruption of cementitious bonds and consquently a reduction in the number of intergranualr contacts (Mackiewicz and Ferguson, 2005). An efficient method for evaluating FA stabilisation is to determine the moisture-density, and moisture-strength relationship for the FA treated materials (Mackiewicz and Ferguson, 2005).

In the compaction test, a steel rammer of mass 2.5kg (Light or Standard Proctor Compaction Test) or 4.5kg (Heavy or Modified Proctor Compaction Test) is dropped either manually or automatically from a certain height on the loose soil placed in the cylindrical mould. The soil at a selected moulding water content is compacted in the mould in three layers of equal thickness, with each layer compacted by a specific number of blows. After the compacted material has been removed from the mould, a new air-dried sample of soil is prepared, a higher increment of water is added, and a new compacted sample is prepared using the same standard proctor test procedure (O'Flaherty and Hughes, 2016). The compaction test is performed with at least five different variations, water content, in order to establish a reliable moisture content-dry density compaction curve. For the light compaction method, a standard CBR mould with a diameter of 152mm and height of 127mm is utilised (BSI 1990c). For the purpose of this study, the light compaction was chosen as the suitable method of compaction.

The dry density and the water content corresponding to the peak of the curve are the maximum dry density and the optimum moisture content. The OMC and MDD are reported to the nearest 0.1% and 0.02 kN/m^3, respectively (Shukla 2014). The main factors affecting compaction are water content, compaction effort, soil type and method of compaction (Shukla 2014). The main objectives of compaction include:

1. Increase in strength and stiffness.
2. Decrease in compressibility and volume change.
3. Decrease in permeability.
4. Decrease in liquefaction potential.
5. Increase in durability.

Table 5: Typical values of MDD and OMC of various soil types
Source: After (O'Flaherty and Hughes, 2016)

Type of Soil	MDD (kg/m^3)	OMC (%)
Heavy Clay	1555	28
Silty Clay	1670	21
Sandy Clay	1845	14
Sand	1940	11
Gravel-Sand-Clay	2070	9

Table 5 compares some typical MDD and OMC values obtained from standard tests on various soils. In this Table, it can be seen that the maximum dry density increases and OMC decreases as the soil becomes less plastic and more granular.

The moulds available (diameter of 150mm and height of 150mm) were of different diameter and height to that of the CBR mould specified in the British Standard. As this led to a change in the internal volume of the mould the total number of blows had to be recalculated to ensure the compaction energy was maintained.

The standard size of a CBR mould stated in the British Standard has a diameter of 152mm and a height of 127mm. In order to maintain the compaction energy used for compacting CBR moulds in accordance with British Standard 1377-4 (Compaction-related tests) the number of blows had to be calculated due to the chosen mould having a slightly different size (BSI 1990c). The calculations are shown below:

British Standard CBR mould size:

Diameter (D_{m1})	0.152m
Height (H_{m1})	0.127m
Volume (V_{m1})	$[(D_{m1}/2)^2 \times \pi \times H_{m1}]$

British Standard for standard compaction method:

Steel rammer mass (M_r)	2.5kg
Steel rammer weight (W_r)	2.5 x 9.81= 24.525 N
Dropped height of rammer (H_r)	0.300m
Number of layers (N_l)	3
Number of blows/layer (N_{b1})	62

Compaction energy (E_c) = (W_r x H_r x N_l x N_b)/V_{m1}

= 593830.4138 J/m^3

The number of layers (3) and other parameters of compaction remained the same as the British Standard. The number of blows (N_{b2}) for the same compaction energy was derived for the new mould. The size of the mould chosen for this study:

Diameter (D_{m2})	0.150m
Height (H_{m2})	0.150m
Volume (V_{m2})	$[(D_{m2}/2)^2 \times \pi \times H_{m2}]$

Compaction energy (E_c) = 593830.4138 J/m^3

= (W_r x H_r x N_l x N_{b2})/V_{m2}

Therefore:

$$N_{b2} = (V_{m2} \times E_c)/(W_r \times H_r \times N_l)$$

= 71.3140

It can be concluded that in order to maintain the compaction energy in accordance with British Standard and meeting the requirements for compaction and CBR testing, the samples had to be subject to 72 blows per layer. This meant that each mould was subject to 216 blows in total.

In order to find the optimum values, the light compaction test was carried out in accordance with British Standard 1377-4. Each sample was mixed thoroughly with a different amount of water to give a suitable range of moisture content until a homogeneous mix was obtained. According to the British Standard (BSI 1990c), the range of the moisture content had to be such that at least two values lay either side of the optimum at which the maximum dry density occurred. Each individual compaction test was performed within 20 minutes after the completion of sample mixing. On average it took about 3 hours to complete one compaction test, to perform at least five samples with different water content.

Procedure of compaction in accordance with British Standard 1377-4 (BSI 1990c):

- Weigh the mould to 1 g.
- Measure the internal dimensions.
- Place the mould assembly on a solid base.
- Place a quantity of moist soil in the mould such that when compacted it occupies one-third of the height of the mould.
- Apply 72 blows from the rammer dropped from a height of 300 mm above the soil as controlled by the guide tube.
- Distribute the blows uniformly over the surface and ensure that the rammer falls freely and is not obstructed by soil in the guide tube.
- Repeat twice more.
- Remove the extension, strike off the excess soil and level off the surface of the compacted soil carefully to the top of the mould using a spatula.
- Weigh the soil and mould to 1g.

- Remove the compacted soil from the mould and place it in on the metal tray.
- Take a representative sample of the soil for determination of its moisture content.
- Add a suitable increment of water and mix thoroughly into the soil (The water added to each sample should be such that a range of moisture contents is obtained which includes the optimum moisture content. In general, increments of 1% to 2% are suitable for sandy soils)
- Repeat to give at least five determinations.

The methods and measures stated earlier, section 3.3, for deriving moisture content were also used in determining the optimum moisture content of compaction samples. The procedure was done in accordance with British Standard 1377 part 1 (BSI 1990a):

- At least two representative specimens for determination of the moisture content were taken, and then the average was calculated.
- The drying of soil samples for deriving moisture content were dried by oven drying, an oven maintained at a temperature of 105 to 110 °C.

Compaction calculations in accordance with British Standard 1377 part 4 (BSI 1990c):

$$\boldsymbol{p} = \frac{\boldsymbol{m2} - \boldsymbol{m1}}{\boldsymbol{V}}$$ **Equation 4**

where m1 is the mass of the mould

m2 is the mass of the mould and compacted soil

V is the internal volume of the mould

p is the bulk density

$$p_d = \frac{100 \times p}{100 + w}$$ **Equation 5**

where w is the moisture content of the soil

p_d is the dry density

Figure 20 shows the different stages taken for performing standard proctor compaction tests throughout this thesis. The results of dry density and moisture content were then tabulated and ultimately used to produce a graph with the compaction curve. A minimum of three different compaction curve graphs was produced for each FA-soil and cement-soil mixture so that the most valid and reliable results could be obtained. These conditions were then used to make the samples that were to be tested for the CBR tests. From the average of the compaction results, the amount of water necessary to reach optimal conditions could be evaluated for each variation. Table 6 presents a list of the compaction tests performed in this study.

Table 6: The list of compaction tests with different variations

Code	Variation	Number of Samples
S-0C-0FA	Sand	5
S-3C-0FA	Sand+3% Cement	3
S-5C-0FA	Sand+5% Cement	3
S-3C-5FA	Sand+3% Cement+5% FA	3
S-3C-10FA	Sand+3% Cement+10% FA	3
S-3C-15FA	Sand+3% Cement+15% FA	3

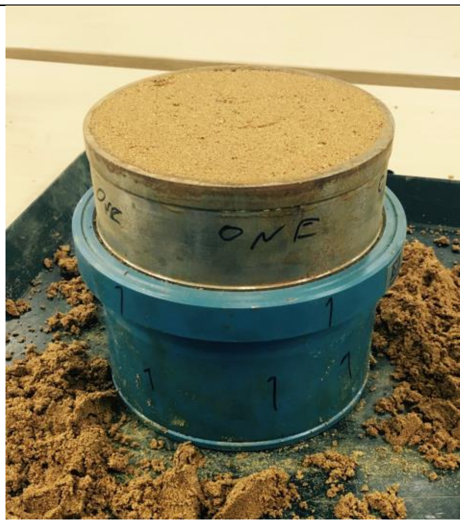
a) **The 2.5 kg rammer used in this study.**	
b) **Post completion of compaction with the extension removed.**	
c) **The excess soil has been stroked off using a spatula.**	

Figure 20: Different stages taken for performing standard proctor compaction tests

d) **The sample demoulded and made ready for taking moisture content samples.**	
e) **Two moisture content samples being taken from the centre of the sample.**	
f) **A collection of moisture samples post oven drying.**	

Figure 20 (Cont'd): Different stages taken for performing standard proctor compaction tests

3.6 Curing

The compacted samples were placed and sealed in plastic bags within five minutes of completion of compaction. For better consistency and assurance of maintaining the moisture content within the samples, all the specimens were bagged in a minimum of two plastic bags as shown in Figure 21. Furthermore, as the laboratory was accessible to other users, subsquently all the samples, after being bagged, were moved into a lockable storage unit to eliminate interference of the samples, and any sort of damage to the plastic bags.

Figure 21: Examples of samples sealed in plastic bags for curing

This method of curing was chosen as it was sugessted by AustStab (2012) and the fact several other authors used this techniqure for similar purposes (Kaniraj and Havanagi, 1999; Kamon et al. 2000; Lav and Lav, 2014).

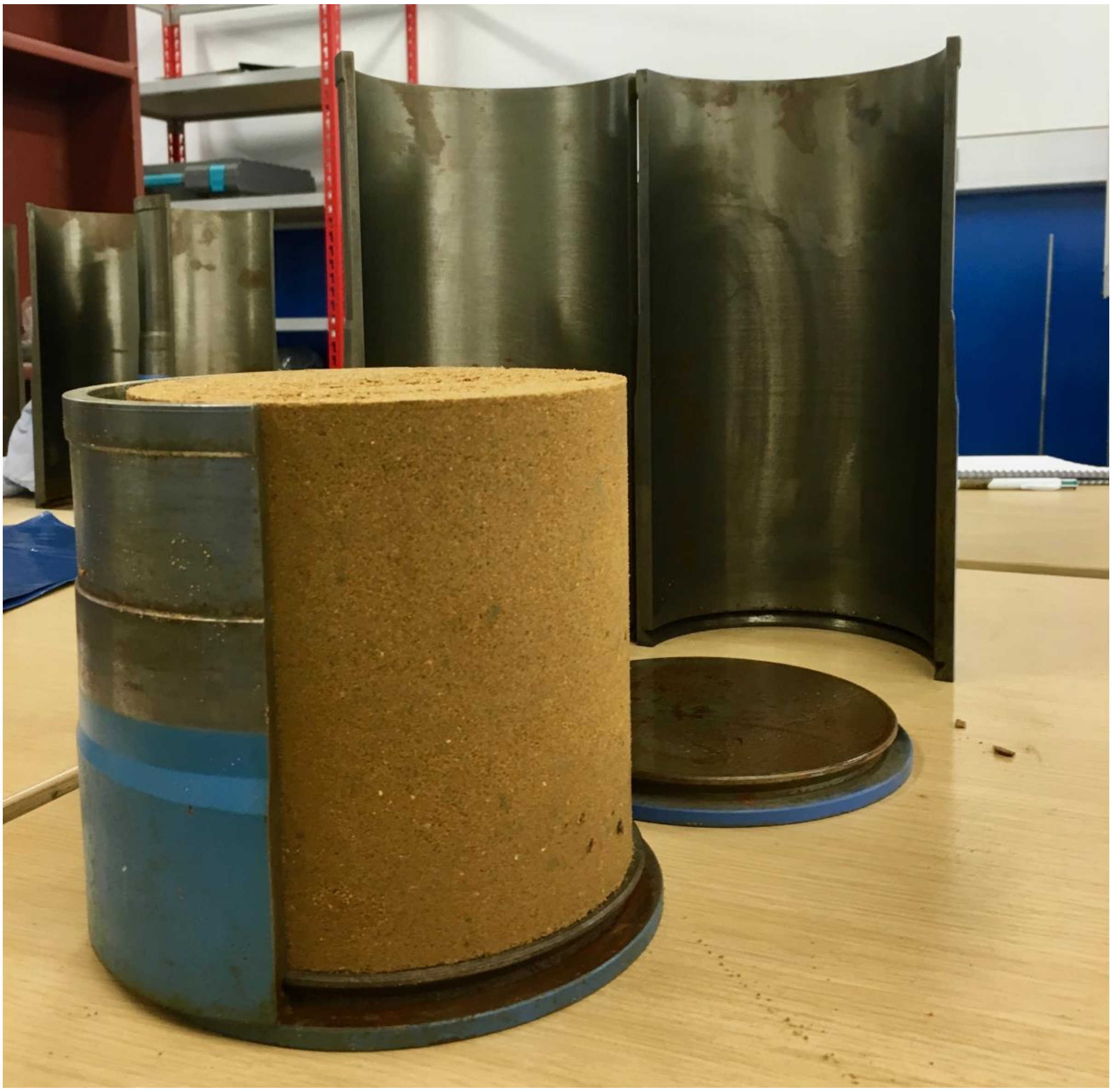


Figure 22: Examples of large (D:15cm and H:30cm) and small (D:15cm and H:15cm) moulds used in this study

At times, where the samples had to be moved from the small moulds to the larger moulds, this process, (opening the bags of the smaller mould, moving the sample from the small to the large mould, rebagging the large mould) was performed within five minutes. Figure 22 shows both the small and the large moulds. During the preliminary tests performed in the early stages, it was learned that the samples must not ever be pushed or pulled into and out of the storage unit as it would subsquently tear the plastic bags and jeopardise the plastic bags' intactness. Any damage, tear or puncture to the bags would have led to the loss of moisture and hence would make the samples invalid and unreliable for testing.

3.7 Bearing Capacity

Putri et al. (2012) state that the California Bearing Ratio (CBR) test is widely used to determine the suitability of a soil as a subgrade or subbase for highway and runway design and construction. Similarly CBR tests have been used to evaluate improvements in stiffness and bearing resistance of soil to be utilised for subgrade construction (Li et al. 2009). The CBR is obtained by measuring the relationship between force and penetration when a cylindrical plunger is made to penetrate the soil at a standard rate. Developed in California before WWII, to this day it forms the basis of the pre-eminent empirical pavement design methodology used in the UK (Rogers 2008). Beeghly (2003) states that CBR is a relative measure (%) compared to crushed stone. As it is not feasible to establish shear strength and stiffness modulus for soil, the CBR test is often used as an index test. While it is not a direct measure of either the shear strength or the stiffness modulus, it is widely used as an indicator due to the level of knowledge and experience with it that has been developed by practitioners (Rogers 2008).

The CBR test rig shown in Figure 23 was used to measure penetration against force in this thesis, with the force used to penetrate the material by 2.5mm and 5mm. These forces were then compared to the forces for a standard material and the CBR value is a percentage of this value. The gauge that measures force acting on the plunger and the gauge that measures the penetration of the plunger can be seen in Figure 23.

Figure 23: The CBR machine in UWL Concrete Laboratory

The CBR tests in this study were performed in accordance with British Standard 1377 part 4 under conditions obtained through the in-depth compaction tests conducted previously. As was stated earlier, the British Standard establishes that for a series of tests on a particular soil, one size mould shall be used consistently (BSI

1990c). The same mould size that was used in the compaction tests was also used throughout the CBR tests. The results of the CBR tests were then be used to make a comparison between stabilised mixtures and sand only, to establish the degree of stabilisation achieved from the addition of cement and FA to the mixture.

CBR test procedure in accordance with British Standard 1377-4 (BSI 1990c):

- Same apparatus and similar procedure as the compaction test.
- Samples are tested at their optimum condition (Derived from compaction test).
- Following compaction, the specimen, still in its mould, is covered with annular surcharge weights. Weighting at 2kg with a diameter of 15cm.
- The force applied and the penetration is measured for every 0.25mm of penetration, up to a maximum of 7.5mm; the required loading is recorded.
- Then a force-penetration curve is plotted and compared against a standard force-penetration curve, with a typical CBR value of 100%.
- The test loads are read off at 2.5mm and 5mm penetrations.
- These loads are expressed as a percentage of the standard forces.
- The highest of the two percentages measured at the 2.5mm and 5mm penetrations is then taken as the CBR value for the soil.

$$\boldsymbol{CBR = \frac{Test\ load}{Standard\ load} \times 100}$$ **Equation 6**

Table 7 presents the different variations tested for CBR testing. The variables in this test were the FA content, cement content and the curing period. As it can be seen samples S-3C-0FA56 and S-3C-15FA56 were cured for 8 weeks, so that the effect of cement only and FA with cement stabilisation could be compared in the long term. All the samples were not cured for this duration, as it would not represent the methods and conditions of tests and results at site. In addition, stabilised soil with cement tends to achieve majority of their strength in the first two weeks with very little growth post two weeks. The number of samples for each variation and mixture is between three to five samples. This is in agreement of previous researches (Cristelo et al. 2012b; Kaniraj and Havanagi, 1999).

Table 7: The list of different samples made for CBR testing

Code	Sample	Curing Period (days)	Number of samples
S-0C-0FA	Sand	0	5
S-3C-0FA7	Sand+3%Cement	7	3
S-3C-0FA14	Sand+3%Cement	14	3
S-3C-0FA28	Sand+3%Cement	28	3
S-3C-0FA56	Sand+3%Cement	56	3
S-5C-0FA7	Sand+5%Cement	7	3
S-5C-0FA14	Sand+5%Cement	14	3
S-5C-0FA28	Sand+5%Cement	28	4
S-3C-5FA7	Sand+3%Cement+5%FA	7	3
S-3C-5FA14	Sand+3%Cement+5%FA	14	4
S-3C-5FA28	Sand+3%Cement+5%FA	28	4
S-3C-10FA7	Sand+3%Cement+10%FA	7	3
S-3C-10FA14	Sand+3%Cement+10%FA	14	3
S-3C-10FA28	Sand+3%Cement+10%FA	28	3
S-3C-15FA7	Sand+3%Cement+15%FA	7	4
S-3C-15FA14	Sand+3%Cement+15%FA	14	3
S-3C-15FA28	Sand+3%Cement+15%FA	28	5
S-3C-15FA56	Sand+3%Cement+15%FA	56	3

3.8 Correlations

3.8.1 Resilient Modulus (M_R)

AASHTO is favoring the resilient modulus dynamic stiffness test for characterizing the strength of pavement material (Beeghly 2003). Resilient Modulus (M_R) is defined as the ratio of the deviatoric stress to the resilient (elastic) strain experienced by the material under repeated load applications (O'Flaherty and Hughes, 2016). Resilient modulus (M_R) is the elastic modulus utilised in mechanistic-empirical pavement analyses and design (Lav and Lav, 2014). The term resilient is used to differentiate the elastic or recoverable response of soil under dynamic load from the plastic or creep component (O'Flaherty and Hughes, 2016). M_R is the fundamental subgrade strength parameter needed as input to any rational or mechanistic pavement design process (O'Flaherty and Hughes, 2016).

Determination of resilient modulus is accomplished through laboratory testing. Buchanan (2007) defines granular material as stress hardening material, meaning minimal deformation occurs under higher applied stress and ultimately resulting in a higher resilient modulus and stiffness.

$$\mathbf{M_R} = \boldsymbol{k_1 \theta^{k_2}} \quad \textbf{kPa} \qquad \textbf{Equation 7}$$

where k_1 and k_2 = regression constants

θ = bulk stress

Regression coefficients, k_1 and k_2, represent the y-intercept and slope, respectively, of a regression line on a log-log plot of resilient modulus versus bulk stress (Buchanan 2007). A number of attempts have been made to relate the modulus to other test parameters, in particular to CBR values. The first correlation was made in the 1960s, which developed the following simplified relationship based on tests of sand subgrades (O'Flaherty and Hughes, 2016). The general function that is proposed by AASHTO design is as follows (Coleri 2007; Buchanan 2007):

$$\mathbf{M_R = 10342.1 \times \mathit{CBR}} \quad \textbf{kpa} \qquad \textbf{Equation 8}$$

This correlation appears to be effective for CBR values less than about 20, which restricts the use of this equation for pavement design (Coleri 2007). Also, there are various other equations used for estimating the resilient modulus based on the CBR results:

U.S Army Crops Engineers (Coleri 2007):

$$\mathbf{M_R = 37293.8(\mathit{CBR}^{0.71})} \quad \textbf{kpa} \qquad \textbf{Equation 9}$$

South African Council on Scientific and Industrial Research (Coleri 2007):

$$\mathbf{M_R = 20684.3(\mathit{CBR}^{0.65})} \quad \textbf{kpa} \qquad \textbf{Equation 10}$$

Transportation and Road Research Laboratory (TRRL) (Coleri 2007; Buchanan 2007):

$$\mathbf{M_R = 17616.1(\mathit{CBR}^{0.64})} \quad \textbf{kpa} \qquad \textbf{Equation 11}$$

M_R is well established to be a key parameter in pavement design. According to Buchanan (2007), with a precise evaluation of M_R the pavement engineers can conduct an accurate assessment of traffic loading in the design of pavement layers. It is important to note that resilient modulus is a stiffness measurement, not the strength of the material. For the purpose of this study, the correlation derived by TRRL was used to evaluate M_R values in correlation with the obtained CBR values. This specific correlation was chosen for this thesis as it is one of the most recent equations used for predicting resilient modulus, and also as it is one of the most common correlation suggested by several authors (Coleri 2007; Buchanan 2007; Sukumaran et al. 2002).

3.8.2 Unconfined Compressive Strength (UCS)

UCS is one of the other important and common factors in design and construction of embankments. For the purpose of this study, CBR values will also be used to correlate UCS values. A correlation between the CBR and UCS was developed by two authors in a study investigating FA-lime mixtures for curing periods of one-week and four-weeks, Equations 12 and 14, respectively (Behera and Mishara, 2012, cited in Purwana and Nikraz, 2014). Using the correlations for these two curing durations, a correlation for curing periods of two weeks was developed (Equation 13). These UCS/CBR correlations are stated below:

7-Days $$\boldsymbol{UCS = \frac{CBR - 14.14}{108.8}}$$ **Mpa** **Equation 12**

14-Days $$UCS = \frac{CBR - 26.63}{82.63}$$ **Mpa** **Equation 13**

28-Days $$UCS = \frac{CBR - 39.13}{56.45}$$ **Mpa** **Equation 14**

3.9 Health and Safety

As both cement and FA were utilised in this study, certain health and safety measures had to be taken into account. FA and cement have very similar requirements in regards to health and safety. A brief summary of some of the possible hazards that may occur by utilising FA is listed in Table 8. Nevertheless, there was also certain protection equipment and clothing, which had to be worn during the utilisation of cement and FA due to their ease of dust nuisance (UKQAA 2011a). These protections are listed below:

- Respirator.
- Dustproof goggles (EN 166).
- Full body plastic cover.
- Impervious and abrasion and alkali resistant gloves (Made of low soluble Cr (VI) containing material).
- Heat resistant gloves for using the oven.

Table 8: Possible hazards for utilisation of FA
Source: After (UKQAA 2011a)

Hazard	Effect	Control Measures
Eye	Eye irritation	If the substance has entered the eyes then irrigate with emergency eye wash solution (if available) or clean water for up to 15 minutes. Obtain medical advice if any pain or redness persists. Goggles are advised to be worn, due to long testing period.
Inhalation	Coughing or nose Irritation	If inhalation of the dust causes irritation of the nose or coughing, remove the patient into fresh air. Keep warm and at rest. Carefully remove any excess dust from nasal passages and rinse mouth with water until clear. If symptoms persist obtain medical advice. Mask is advised to be worn due to long testing period.
Ingestion		There are no known adverse affects. Wash mouth out with water and give water to drink. Do not induce vomiting. It is advised that a mask be worn due to long testing period.
Skin	Skin irritation	Wash contaminated areas of the body with soap and water as soon as is reasonably practical. It is advised that a full body cover be worn due to long testing period.

3.10 Constraints and Limitations

There were 10 larger moulds available in the laboratory, of the exact same diameter but with different heights. At times, throughout the laboratory tests conducted in this study, the samples had to be moved from the small mould and then back to the large one, in order to accommodate the mixture of CBR and compaction tests without causing unnecessary delays. In order to prevent the stabilised samples from adhering to the moulds and aid the demoulding of the samples during curing without deformation of their shape and size, a lubricant, WD-40, was used. An example of where lubricant was not used is shown in Figure 24. It clearly shows that the sample was partially glued to the inner wall of the mould and came off during demoulding.

It was found in the literature that a popular testing for stabilisation of FA was the use of a scanning electron microscope. However, this was not possible for this study as the equipment was not available within the institution. As equipment was unavailable to carry out the sedimentation process, it resulted in materials less than 0.063mm being classified as fines. As the percentage of fines in the sandy material employed in this study was not significant, this limitation is not affecting the conclusions derived from this research.

Figure 24: Example of a sample without use of WD-40

Chapter 4

Materials

4.1 Introduction

In this chapter the materials used for the laboratory tests are defined and discussed. The materials utilised throughout this thesis consist of sand, FA and cement. The results of the particle size distribution tests performed are presented in this chapter and henceforth; the characteristics of the sand and FA are determined. The natural moisture content of the FA and the sand were also established by taking an average of ten samples for each material, using the method mentioned in section 3.3.

4.2 Sand

For the purpose of this study, the sand, ‘soft building sand’, was obtained from Civils & Lintels, a UK supplier of materials for construction purposes. The sand was delivered in polyethylene bags of 25kgs. In total, around 35 bags, 875kgs, of this sand were utilised. Some of this sand was utilised through trial tests and samples that turned out to be void. The remaining sand was utilised to obtain preliminary results, particle size distribution tests, compaction tests and CBR test. The natural water content of the sand slightly differed from bag to bag. In order to obtain an average value of its natural water content, ten different bags were tested and an average value of 10.39% was achieved, as shown in Table 9. The materials were oven dried at temperatures of 105 to 110 °C.

Table 9: Natural water content of sand

Sand Sample	Natural Water Content	Average
1	8.5 %	10.39 %
2	10.0 %	
3	12.07 %	
4	11.78 %	
5	9.0 %	
6	10.2 %	
7	9.33 %	
8	10.81 %	
9	12.18 %	
10	9.98 %	

The characteristics of the sand were obtained through a PSD test. A total of five particle size distribution tests were performed for classification of the sand. The results of the tests are presented below. Figure 25 shows the grading curves. The uniformity coefficient and coefficient of gradation of each sample tested was individually calculated after the derivation of D10, D30 and D60.

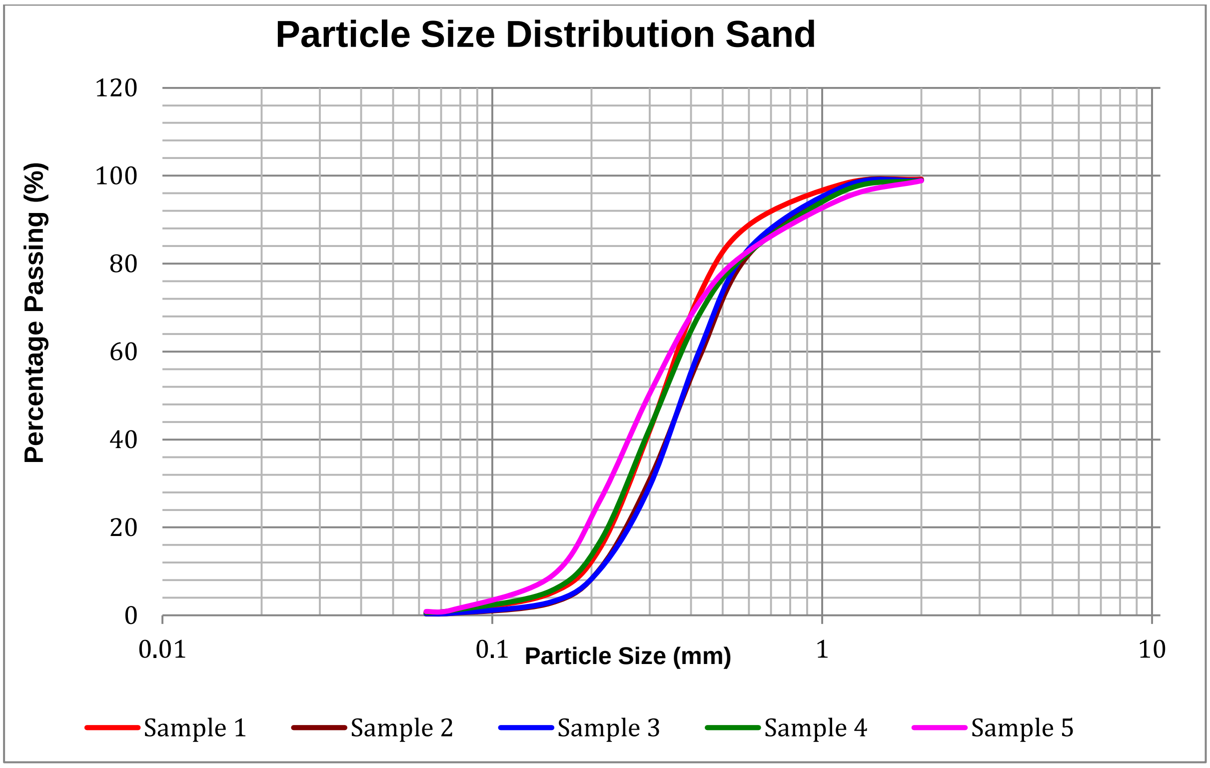


Figure 25: PSD of five samples of sand

The calculations of the uniformity coefficient and coefficient of gradation for all the sand samples are shown below.

Sample 1:

D10= 0.188mm

D30= 0.262mm C_U= 1.93

D60= 0.363mm C_C= 1.006

Sample 2:

D10= 0.210mm

D30= 0.297mm C_U= 2.06

D60= 0.433mm C_C= 0.97

Sample 3:

D10= 0.211mm

D30= 0.303mm C_U= 2.01

D60= 0.424mm C_C= 1.03

Sample 4:

D10= 0.185mm

D30= 0.259mm C_U= 1.97

D60= 0.365mm C_C= 0.99

Sample 5:

D10= 0.158mm

D30= 0.225mm C_U= 2.19

D60= 0.346mm C_C= 0.926

Average Values:

C_U= 2.036

C_C= 0.9844

After the analysis of the PSD for the soil (Figure 25), the coefficients of the sand were evaluated, with a C_U value of about 2 and C_C value of just under 1 (0.98). This classifies the soil as a poorly and/or even graded soil based on the typical C_C and C_U

values presented earlier in the methodology (Table 2). It can also be seen from Figure 25 that the soil classifies as sand according to the British Standard (BSI 1990b) as the majority of the particles size ranged between 0.06 mm and 2 mm.

4.3 Fly Ash

The FA used in this study was obtained from the Ratcliffe-on-Soar power station, located in Nottingham, England. Ratcliffe-on-Soar is known as one of the most efficient coal fired power stations in the UK. This power station uses coal as fuel. With a total generation capacity of 2,000 MW from four identical units, it produces enough electricity to meet the needs of approximately 2 million homes (E.ON 2016a). Each of the four 500 MW generation units is fitted with Flue Gas Desulphurization (FGD) equipment, meaning that around 92% of the sulphur dioxide is safely removed before the flue gases are released into the environment. Additionally, high efficiency high pressure turbines are used in each of the generation units, so that the same amount of electricity will be procuced, using less steam. As there is less water sent to the boiler, less coal will be required for heating, effectively, leading to a reduction in the amount of ash and emissions produced (E.ON 2016e). The station is also fitted with electrostatic precipitators, which remove dust and grit from the fumes with an effiency of around 93% (E.ON 2016b).

As stated earlier in the literature (section 2.2.6), the Large Combustion Plant Directive (LCPD) is a European Union Directive that aims to reduce acidification by controlling the emissions of sulphur dioxide, oxides of nitrogen and dust from a large combustion plant. Large power stations in the UK must comply with the LCPD. Ratcliffe is compliant with the LCPD as it has FGD (E.ON 2016c). The FGD technology enables Ratcliffe to use British coal, which, in general, tends to have a high sulphur content so burning it causes sulphur dioxide to be released (E.ON 2016d).

Table 10: Chemical analysis of FA
Source: After (Omni-Cem 2011)

Property	Quantity (%)
Water soluble chloride	<0.01
Acid soluble sulphates	0.72
Total sulphur	0.37
Calcium oxide	5.67
Magnesia	2.53
Silica	42.69
Ferric oxide	9.19
Alumina	23.09
Potassium oxide	2.27
Sodium oxide	0.72
Titanium dioxide	1.01
Others	11.73

Upon collection from the power plant, the FA was sealed in plastic tubs of 25kgs, and was brought to the UWL's laboratory. The physical and chemical analyses of the FA used in this study are given in Table 10. According to ASTM, class F FA contains at least 70% by weight of Silicon oxide (SiO_2) + Aluminium oxide (Al_2O_3) + Iron oxide (Fe_2O_3) (ASTM 2003, cited in Fox 2005; cited in Kelly 2015). The FA obtained from Ratcliffe power station contains nearly 75% by weight of SiO_2 + Al_2O_3 + Fe_2O_3. This classifies the FA in this research as Class F. Additionally, in order to obtain an average value of its natural water content, ten different tubs were tested and an average value of 12.85% was achieved, as shown in Table 11. The materials were oven dried in temperatures of 105 to 110 °C. In total, eight tubs (200 kg) of FA were utilised throughout this study.

Table 11: Natural water content of FA

FA Sample	Natural Water Content	Average
1	11.2 %	12.85 %
2	13.39 %	
3	16.54 %	
4	14.04 %	
5	9.62 %	
6	15.79 %	
7	10.43 %	
8	11.5 %	
9	13.4 %	
10	12.6 %	

The FA supplied had rather large aggregates. In order to produce more homogeneous samples, the FA was oven dried (105-110 °C) and then sieved through a 2.36mm sieve. After testing, over 30 samples from different tubs, on average about 21% of the FA, were greater than 2.36mm. Figure 26 illustrates the coarse and fine contents on separate.

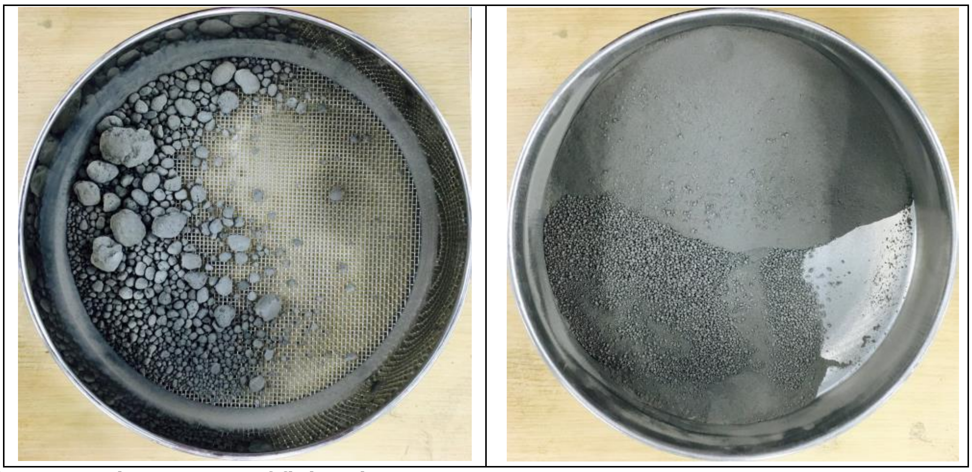


Figure 26: The process of fining the FA

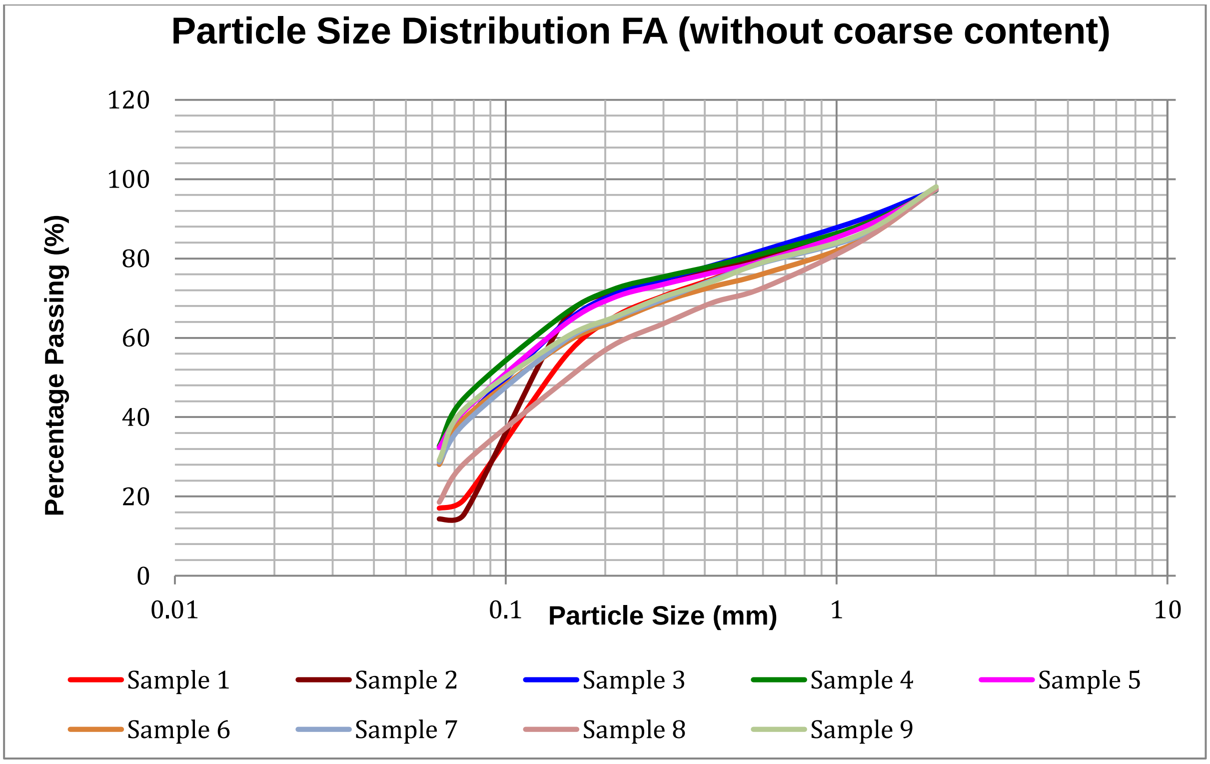


Figure 27: PSD test of sand FA without coarse content

For comparison, the particle size distribution for the FA was performed without coarse content (Figure 27) and with it (Figure 28). Six samples out of the nine samples show very similar trend and fines content. Samples 1, 2 and 6 show different percentage of fines, about half, to the majority of the samples. This variation also occurred when testing FA with coarse content. In these cases, the largest portion of the material was retained in a 0.075 mm sieve, whereas in other cases, the highest portion had passed through the smallest sieve (0.063). The FA has a grain size similar to that of silt and/or clay.

In order to obtain reliable and maintaining the consistency of the results, each new tub of FA that was to be used, a PSD test was performed and only if the results matched the results presented in Figure 27, the tub was used in the research. Note, if only matching the results of the majority, i.e. exclusion of sample 1, 2 and 6.

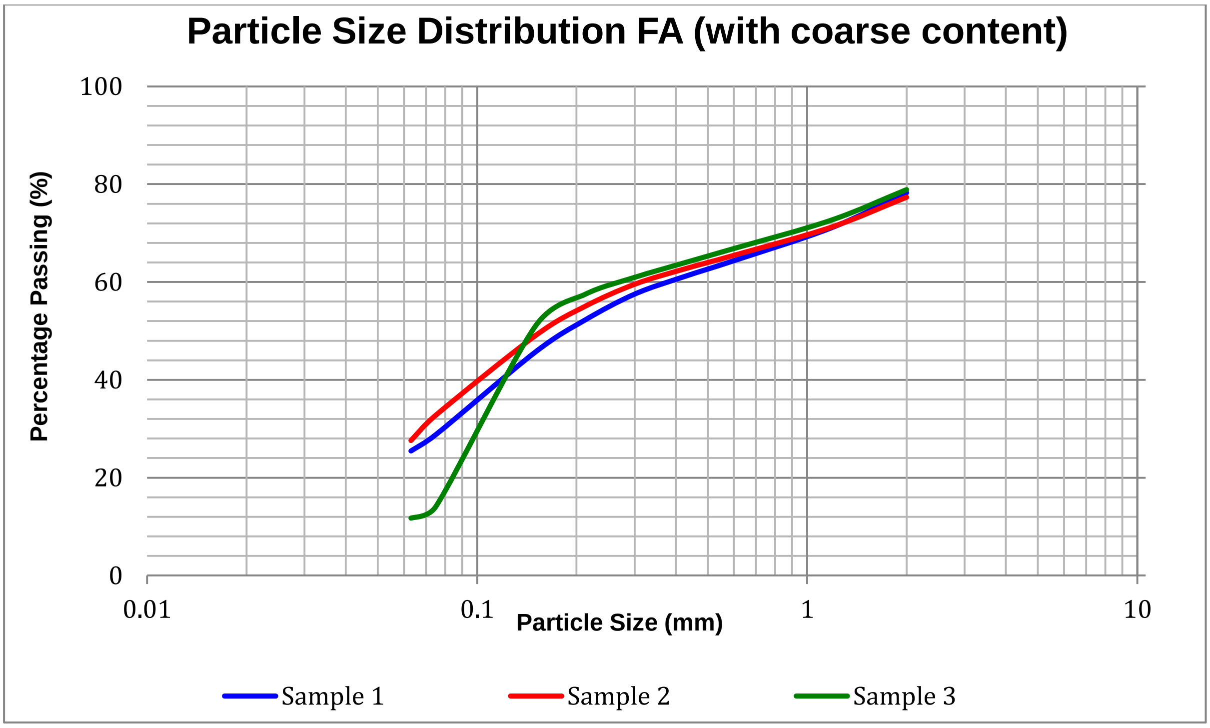


Figure 28: PSD test of sand FA with coarse content

4.4 Cement

Internationally, conventional cement is amongst the most common cementitious soil activators. Factors that ensure its wide usage are that (O'Flaherty and Hughes, 2016):

- Reasonable-quality cement is available in most countries at a relatively low price.
- The use of cement usually requires less care and control that many other activators, such as lime.
- Much technical information is easily available on cement-treated soils.
- Most soils can be stabilised with cement utilisation as an activator if enough is added with the right amount of water, and proper compaction and curing is carried out.

Ordinary Portland Cement is most commonly used for activating soils. On the other hand, rapid-hardening cement is normally avoided, as it does not allow the time required for mixing and compaction in the cement activation process (O'Flaherty and Hughes, 2016). The cement chosen for this study was Ordinary Portland Cement, provided by a UK supplier. The manufacturer provided the following conditions (Lafarage 2012):

- Based on sustainable cement technology.
- Grey in colour.
- Consistent strength meeting all the conformity criteria in BS EN 197-1.
- Manufactured from natural products.

Chapter 5

Results and Discussion on the Experimental Research

5.1 Introduction

In this chapter the experimental results of conducted laboratory tests and the determined correlations of these test results are presented and discussed. In the first part, the average temperature and humidity results obtained from the recording devices are briefly stated. This is followed by the results of compaction tests and CBR tests for all the various samples, with different FA and cement content and different curing periods, tested throughout this research. In the final section of this chapter, the CBR results are converted into resilient modulus and unconfined compressive strength using the correlation formulas presented earlier in the methodology (section 3.8). These results are presented in both tabulated and graphical form and are discussed and analysed.

5.1 Curing Temperature and Humidity

In this section the recorded temperature and humidity values are presented. Figure 29 shows the temperatures throughout the eight months of curing for all the different variations. The CBR tests, along with the curing of the samples took place from August 2016 to May 2017. The temperature and humidity data presented in this section are from this period, with a reading recorded every 30 minutes.

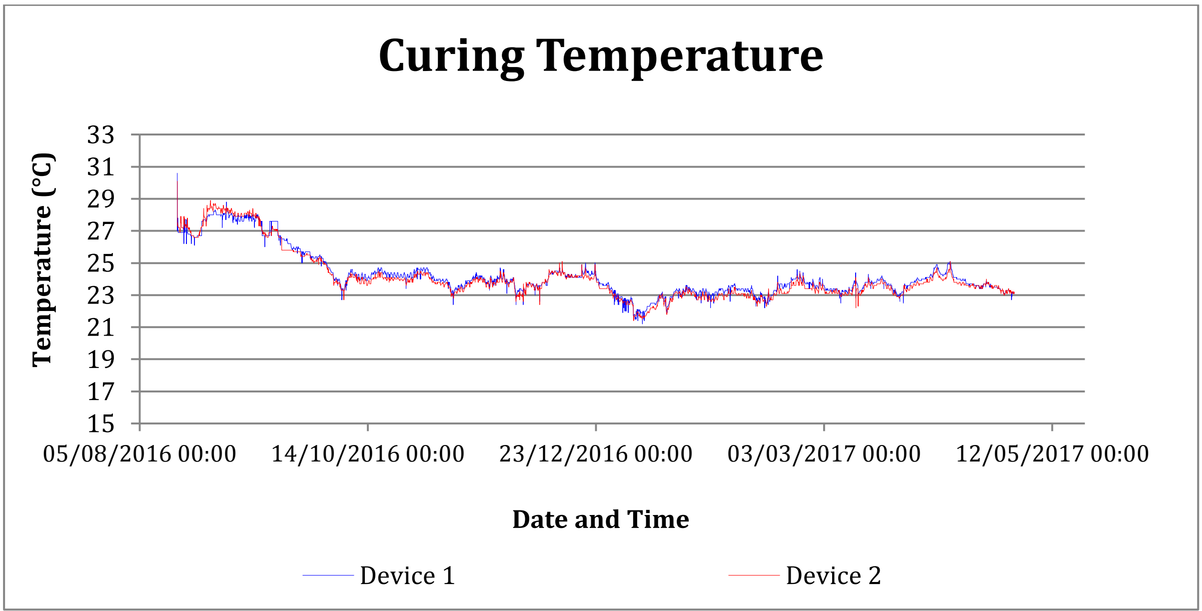


Figure 29: Curing temperatures recorded

The mean, minimum and maximum temperatures for the whole period are presented in Table 12.

Table 12: Temperature values (°C)

	Device 1	Device 2	Average
Mean	24.246	24.096	24.2
Minimum	21.2	21.4	21.3
Maximum	30.6	30.1	30.35

The results of humidity recordings are illustrated in Figure 30. Table 13, developed from this Figure, presents the mean, minimum and maximum humidity values recorded during the eight months of curing for all the different variations.

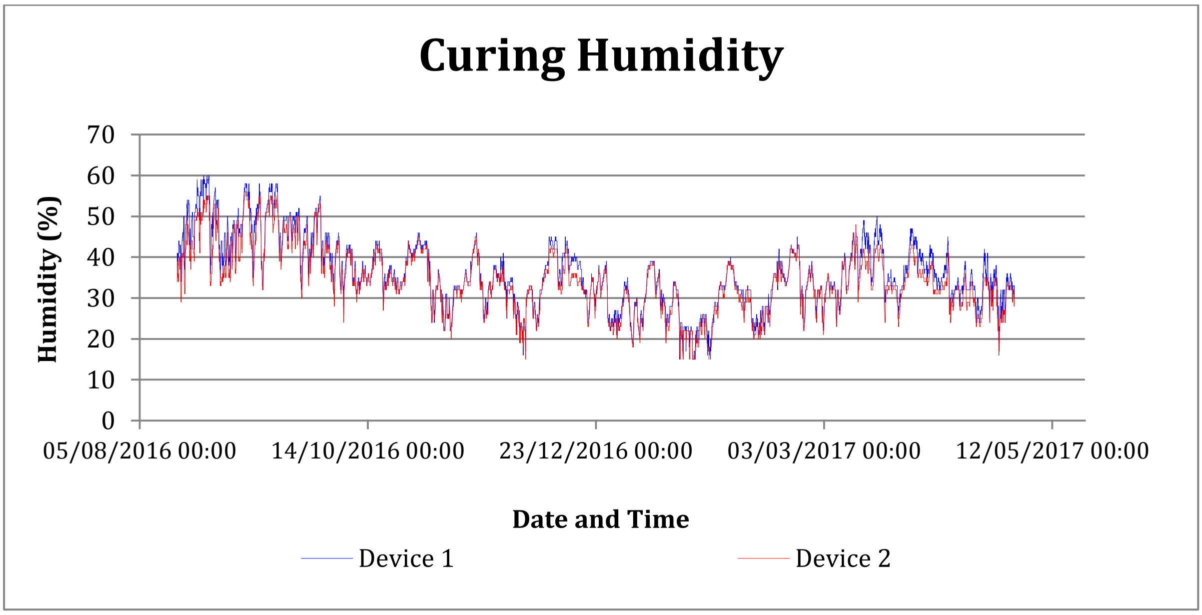


Figure 30: Curing Humidity recorded

Table 13: Humidity values

	Device 1	Device 2	Average
Mean	36.186	34.302	35.2
Minimum	15	15	15
Maximum	60	56	58

In case of both the temperature and humidity readings for both of the devices, the results are mostly of similar values. It can be seen that, after the month of the October, the fluctuation in temperature is insignificant. The humidity was often altered mostly due to the time of the day.

5.3 Compaction

The results of each individual compaction test for sand alone and various variations are given in compaction curve graphs, where the optimum moisture content and maximum dry density of each specimen are determined. The closest compaction curve to that of derived average value was chosen to be plotted in the Figure with all the average compaction curves, so that the effect of cement and FA addition to sand could be compared and analysed. The compaction test results of sand only (S-0C-0FA), 3% cement-sand (S-3C-0FA), 5% cement-sand (S-5C-0FA) and FA-sand mixtures of 5%, 10% and 15% FA content with 3% cement addition (S-3C-5FA, S-3C-10FA and S-3C-15FA) are presented in this section. Table 14 shows the list of the samples that were tested for obtaining the compaction results.

The overall compaction results, after summarising and tabulating the derived average OMC and MDD values of each variation are presented further on. At the end of this section, there is an in-depth discussion of the effects of cement and FA content on maximum dry density and optimum moisture content. In total, there were around 360 individual compactions, including the preliminary tests.

Table 14: Compaction samples tested

Code	Variation	Number of Samples
S-0C-0FA	Sand	5
S-3C-0FA	Sand+3% Cement	3
S-5C-0FA	Sand+5% Cement	3
S-3C-5FA	Sand+3% Cement+5% FA	3
S-3C-10FA	Sand+3% Cement+10% FA	3
S-3C-15FA	Sand+3% Cement+15% FA	3

Figure 31 shows the influence of both FA and cement content had on the maximum dry density of the stabilised samples in comparison to the untreated sand sample (S-0C-0FA). It can seen that 3% cement content had a much more profound effect on the MDD than that of the 5% cement addition. When 3% cement content was used to stabilise the sand, the maximum dry density was increased by almost 50 kg/m^3. This is due to the cement particles filling the voids left in the sand, resulting in a higher density in comparison to sand only (S-0C-0FA). In contrast, when 5% cement content was utilised, the MDD increased by just less than 10 kg/m^3. This is caused by the lower density of the OPC used in comparison to the sand; the higher the percentage of cement being used the lower the overall density of the samples.

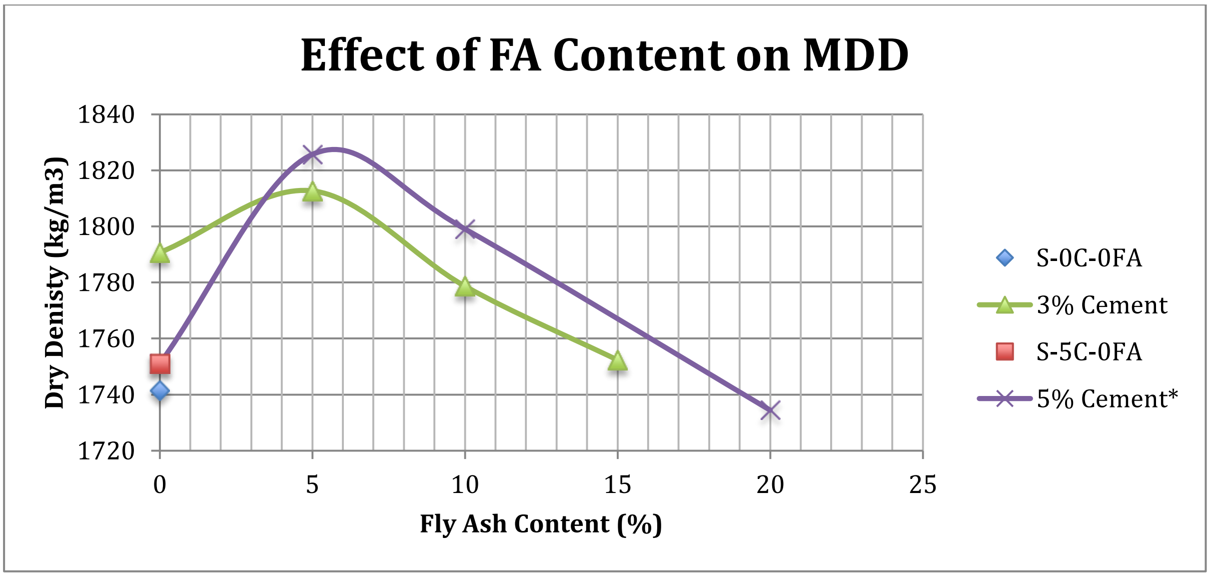


Figure 31: Behaviour of MDD in relevance to cement and FA content
***Results after Wood (2016)**

Furthermore, an increase in the maximum dry density was evident when the sand was mixed with 3% or 5% cement and 5% FA content. The higher MDD is achieved as with addition of FA, the voids, between the sand particles, are filled in during the compaction procedure. However, with further additions of FA, 10% and 15%, the

MDD is seen to decrease from about 1813 kg/m^3 to approximately 1779 and 1752 kg/m^3 respectively. This indicates that after the voids being filled, the further addition of FA act as sand replacement, and with lower density, the overall density of the samples are lowered. A similar behaviour can be observed for the samples mixed with 5% cement and 5, 10 and 20% FA, as reported by Wood (2016), who utilised the same materials. As the figure shows, with further additions of FA, the maximum dry density falls below the S-0C-0FA MDD. This is expected, as numerous authors suggested, because as the percentage of FA was increased, the maximum dry density decreased due to its lower density.

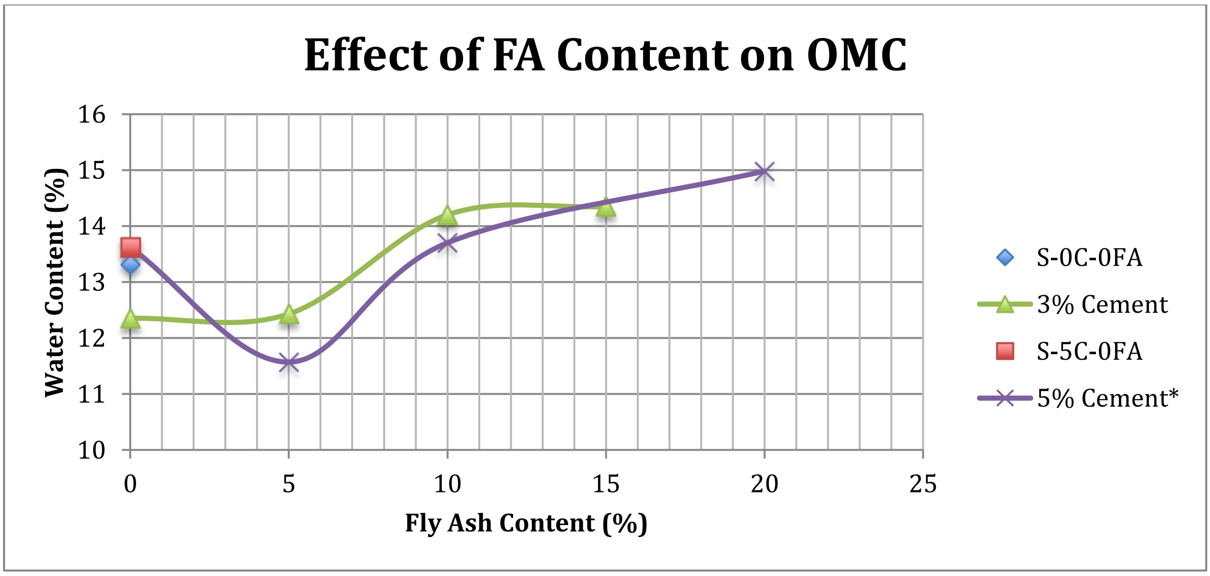


Figure 32: Behaviour of OMC in relevance to cement and FA content
***Results after Wood (2016)**

Moreover, the influence of FA and cement content on the optimum moisture content is presented in Figure 32. Observing this Figure, it can be seen that, with an addition of 3% cement content, the OMC decreased from 13.31% (S-0C-0FA) to 12.35%. The excess heat generated during the chemical process of activation causes this decrease. However, in contrast, an addition of 5% cement increased the OMC by

0.3% (with no addition of FA). Despite the generation of heat mentioned earlier, this rise in the optimum moisture content was due to the fact that a higher percentage of cement requires a higher percentage of water to become activated adequately for optimum conditions. With the introduction of FA into the mixtures, in the case of 3% cement, the OMC was increased in relation to the percentage of FA content. The more FA was utilised the higher the OMC required.

Sand samples mixed with 10% and 15% FA content obtained a higher OMC than the untreated sample (S-0C-0FA), while the rise from the sample of 10% FA content to 15% FA content was not significant. In the case of 5% cement, the optimum moisture content decreased to about 11.6% for 5% FA addition. Then, it was increased by further addition of FA, 13.7 and 15.0% at 10 and 20% FA content, respectively. Similar to the samples treated with 3% cement, in the case of 5% cement, the rise in OMC from 5% FA content to 10% proved to be significant, while from 10% to 20%, despite being doubled up, it proved to be not as significant. Like the MDD, these were the anticipated results, as suggested earlier in the literature and shown in Table 3. The reduction in maximum dry density is due to the fact that FA has a lower density, and is lightweight in comparison to the sand, and the rise in the OMC is attributed to the extra water required for hydration. It can be concluded that both the maximum dry density and the optimum moisture content show significant dependence upon the FA and cement contents.

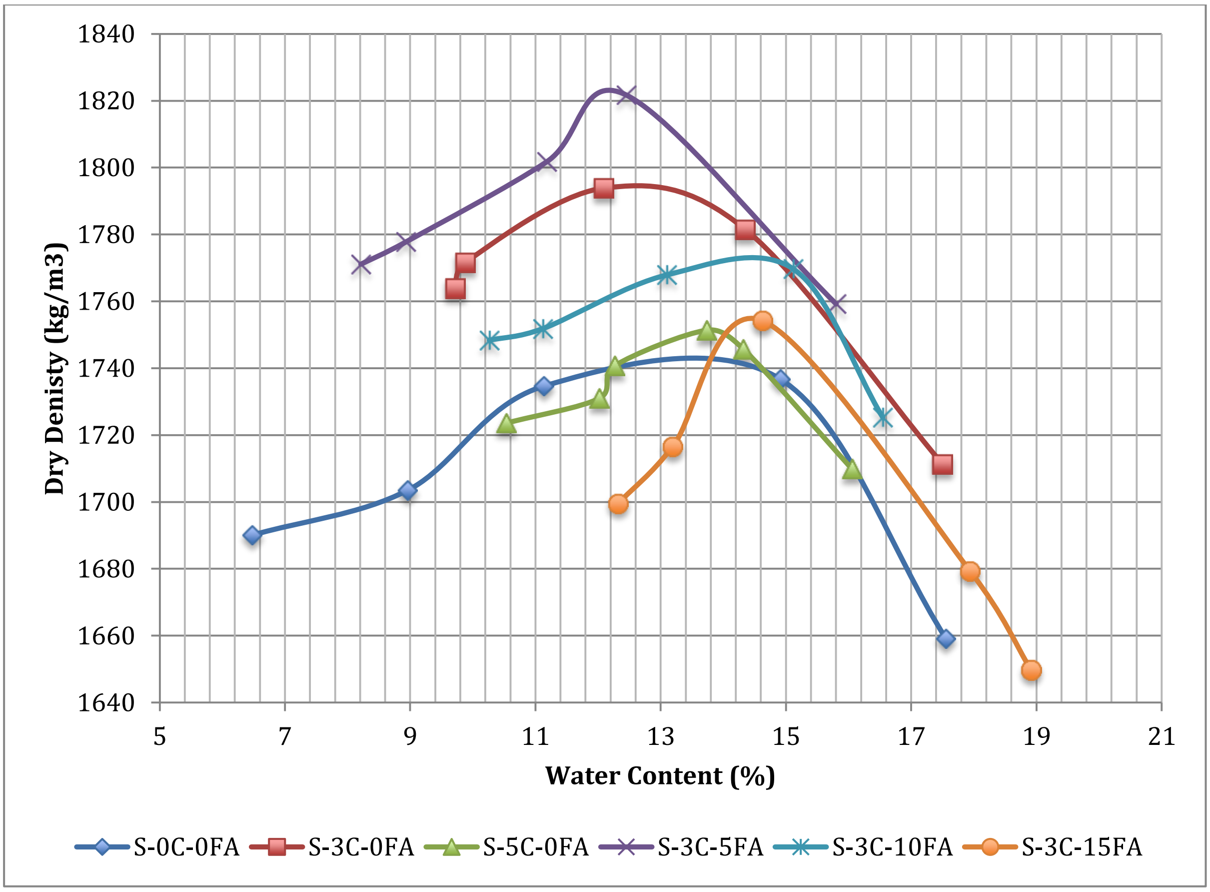


Figure 33: Compaction results of all the different variations tested in this study

The comparison of all the variations tested is illustrated in the compaction curves presented in Figure 33. Comparing the sand only sample (S-0C-0FA) to the 3% cement sample (S-3C-0FA), there is a clear overall upward shift with a light movement to the left of the curves OMC lower. Yet, sample S-5C-0FA is positioned very close to the sand only sample. However, removing samples with 0% FA, i.e. if only S-3C-5FA, S-3C-10FA and S-3C-15FA, were to be observed, it can clearly be seen that the compaction curve shifted to the bottom right as the FA content was increased. If these three samples were isolated, the theory that was evaluated in the literature (Makusa 2012; Santos et al. 2011; Paige-Green and Netterberg, 2004; Acosta et al. 2003; Kim et al. 2005), namely, the higher the FA content, the higher the OMC and the lower the MDD, can be clearly seen. Table 15 shows the average optimum moisture content and maximum dry density of all the different variations tested through laboratory compaction tests, which was developed from the results presented earlier.

Table 15: Average OMC and MDD of all the different variations
***Results after Wood (2016)**

Code	Variation	OMC (%)	MDD (kg/m^3)
S-0C-0FA	Sand	13.31	1741.4
S-3C-0FA	Sand+3% Cement	12.35	1790.67
S-5C-0FA	Sand+5% Cement	13.62	1751
S-5C-5FA*	Sand+5% Cement+5% FA	11.57	1825.67
S-5C-10FA*	Sand+5% Cement+10% FA	13.7	1779.07
S-5C-20FA*	Sand+5% Cement+20% FA	14.98	1734.43
S-3C-5FA	Sand+3% Cement+5% FA	12.43	1812.67
S-3C-10FA	Sand+3% Cement+10% FA	14.2	1778.67
S-3C-15FA	Sand+3% Cement+15% FA	14.35	1752.33

5.4 CBR

Similar to the demonstration of the compaction test results, every individual CBR test of sand and all the other variations are presented in Force/Displacement graphs, where the applied forces at 2.5mm and 5.0mm displacements are determined and converted into CBR values. The highest CBR value of either of these readings, is taken as the CBR value for that specific specimen. A minimum of three CBR tests were performed for each FA-soil and cement-soil mixtures with multiple curing periods. The maximum CBR values of each were averaged to give the CBR value for that variation and the relative curing duration. The sample with the closest CBR value to the derived average CBR was chosen to be plotted in the average Force/Displacement graph with all the various cement-soil and FA-soil mixtures for better comparison and analysis.

Table 16 shows all the different variations with various curing periods, the relative optimum moisture content, the start date and the number of samples for that variation. In total, there were around 70 CBR testings, including the preliminary samples, performed for obtaining the CBR results. The CBR results are followed by in-depth discussions of the effects of cement and FA content on CBR and also the influence curing durations have on CBR.

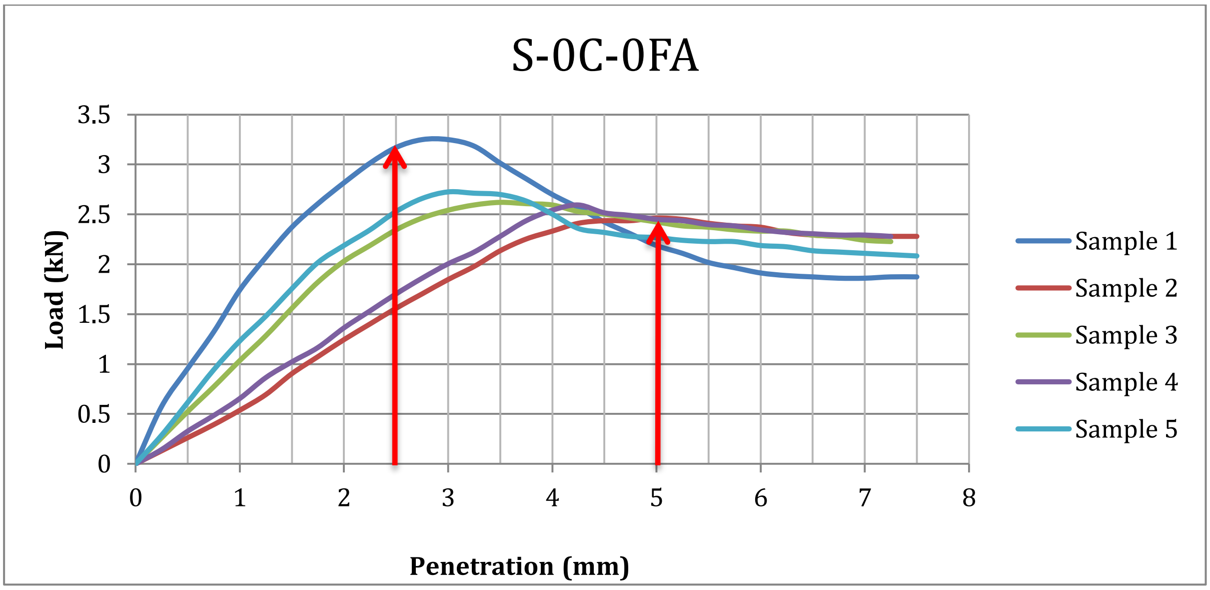


Figure 34: CBR test results for sand (S-0C-0FA)

Table 16: List of all the CBR samples with various curing periods, the relative optimum moisture content, the start date and the number of samples

Code	Sample	OMC (%)	Curing Period (days)	Number of samples	Start date
S-0C-0FA	Sand	13.31	0	5	31/03/2016
S-3C-0FA7	Sand+3%Cement	12.35	7	3	18/08/2016
S-3C-0FA14	Sand+3%Cement	12.35	14	3	25/08/2016
S-3C-0FA28	Sand+3%Cement	12.35	28	3	08/09/2016
S-3C-0FA56	Sand+3%Cement	12.35	56	3	12/03/2017
S-5C-0FA7	Sand+5%Cement	13.62	7	3	13/02/2017
S-5C-0FA14	Sand+5%Cement	13.62	14	3	27/03/2017
S-5C-0FA28	Sand+5%Cement	13.62	28	4	21/04//2017
S-3C-5FA7	Sand+3%Cement+5%FA	12.43	7	3	16/08/2016
S-3C-5FA14	Sand+3%Cement+5%FA	12.43	14	4	31/08/2016
S-3C-5FA28	Sand+3%Cement+5%FA	12.43	28	4	09/09/2016
S-3C-10FA7	Sand+3%Cement+10%FA	14.2	7	3	17/08/2016
S-3C-10FA14	Sand+3%Cement+10%FA	14.2	14	3	26/08/2016
S-3C-10FA28	Sand+3%Cement+10%FA	14.2	28	3	10/09/2016
S-3C-15FA7	Sand+3%Cement+15%FA	14.35	7	4	19/08/2016
S-3C-15FA14	Sand+3%Cement+15%FA	14.35	14	3	27/08/2016
S-3C-15FA28	Sand+3%Cement+15%FA	14.35	28	5	12/09/2016
S-3C-15FA56	Sand+3%Cement+15%FA	14.35	56	3	22/12/2016

Figure 34 shows the CBR results of sand only samples. As the S-0C-0FA results were to be used to establish the effects of any additions of cement and FA, a minimum of 5 samples were tested. These CBR results are tabulated and averaged, as shown in Table 17.

Table 17: Average CBR results for S-0C-0FA

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	3.1702	24.0	2.1877	10.9	24.0	17.2
2	1.5589	11.8	2.4628	12.3	12.3	
3	2.3449	17.8	2.4235	12.1	17.8	
4	1.703	12.9	2.4497	12.2	12.9	
5	2.5283	19.2	2.2663	11.3	19.2	

The lowest and the highest CBR values belong to samples 2 and 1 respectively. By observing Figure 34, it can be seen that sample 3 is the middle sample at 2.5mm displacement and one of the highest peak values at 5.0mm displacement. Additionally, the average CBR value of all the samples is calculated to be 17.2%, which also indicates sample 3 to be the most appropriate representative sample for sand only variation. This sample was then chosen for further analysis throughout the thesis.

Figure 35 shows the CBR results of the samples that were mixed with 3% cement content with different curing periods in comparison to sand only sample (S-0C-0FA). The samples of each variation presented in Figure 35 are the representative samples that were chosen earlier. It can be seen the force applied in all the stabilised samples was at least over two times that of the untreated sample.

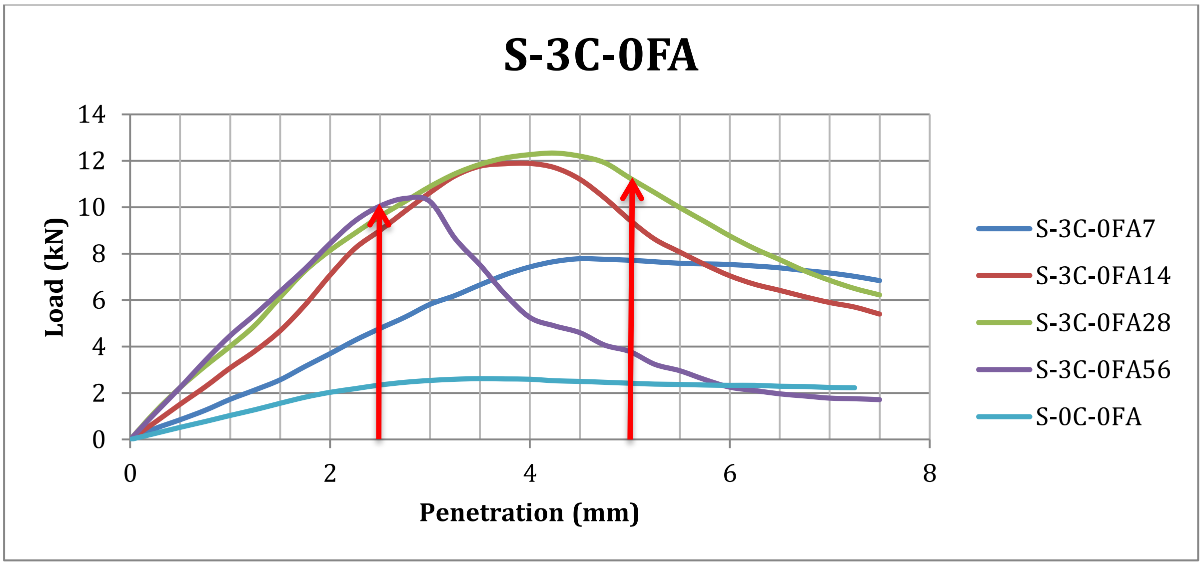


Figure 35: CBR test results for S-3C-0FA, with all curing periods

As was suggested earlier in the literature review, cement stabilised materials obtain most of their strength in the first two weeks. This can also be seen in Figure 35. The samples S-3C-0FA14 and S-3C-0FA28 show insignificant difference in their Force/Displacement curve. Nevertheless, it is clear that by curing, the strength of cement stabilised samples increased by up to about 440% (S-3C-0FA56). As it can be seen from Figure 35, the sample S-3C-0FA56 shows high consistency with the other results up to 3.0mm penetration. This is caused by the long period of curing and the fact that the sample behaves highly brittle after this level of penetration.

The overall CBR test results of 5% cement content, using the chosen samples of each curing period, are presented in Figure 36. The cement stabilised results are plotted against the untreated sample (S-0C-0FA). Figure 36 shows a significant rise in the forces applied during penetration when comparing sand only to stabilised samples. In the case of S-5C-0FA7, the applied force experience at 2.5mm was over five times that of the equivalent of sand only. However, despite the insignificant difference between the treated samples, all of them showed an improvement in strength.

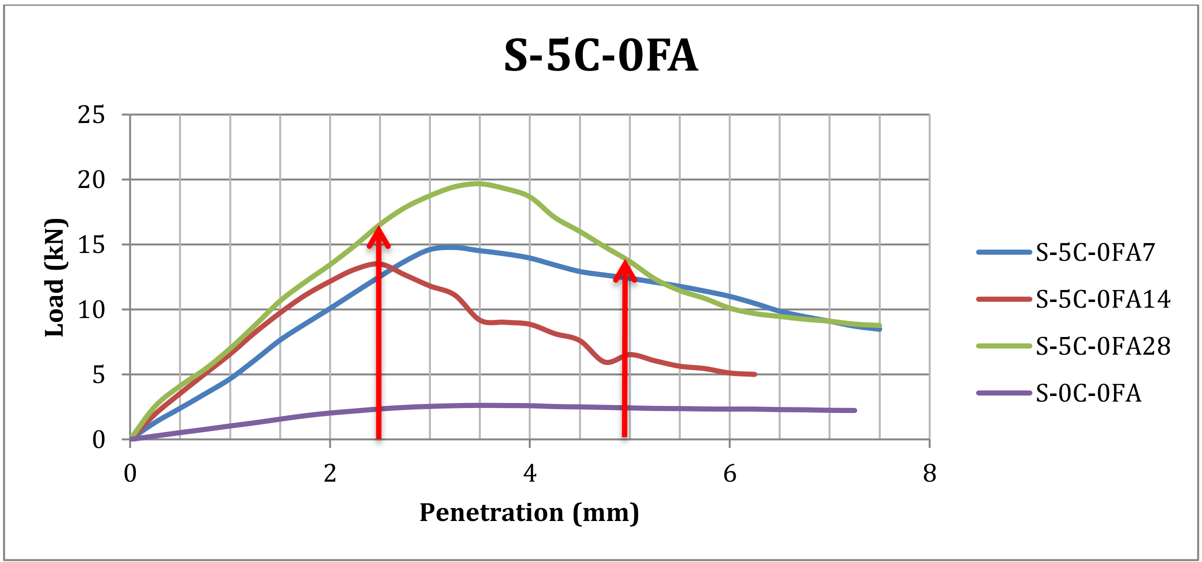


Figure 36: CBR test results for S-5C-0FA, with all curing periods

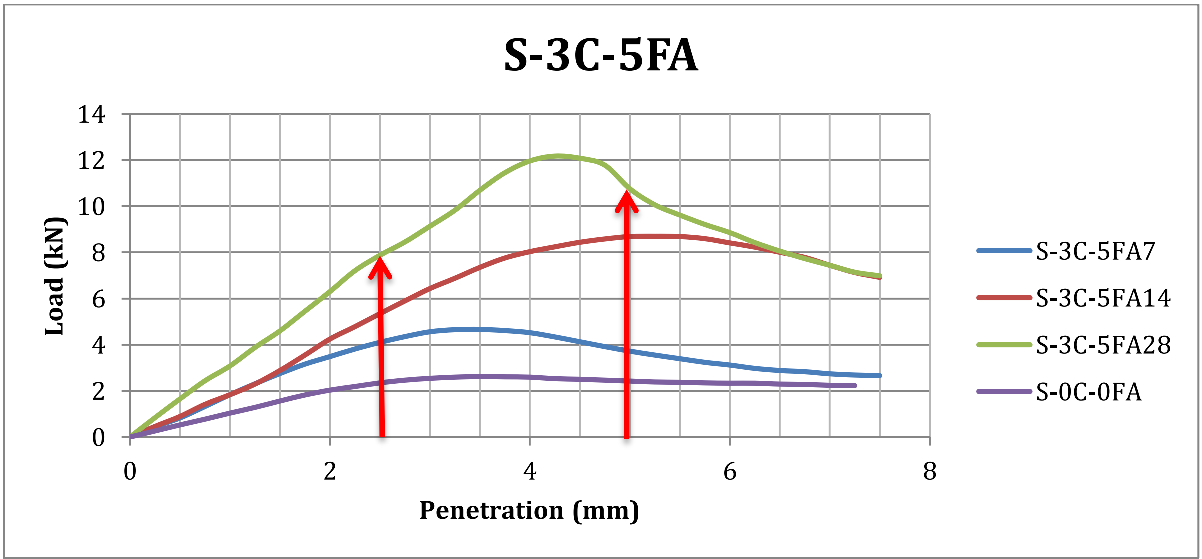


Figure 37: CBR test results for S-3C-5FA, with all curing periods

The samples chosen earlier to represent each variation of 5% FA content samples were used to create Figure 37. They have been plotted against the sand only chosen sample so that a comparison could be made. There is a clear gradual rise in the Force/Displacement curves as the sand was mixed with 5% FA and 3% cement content and curing time increased. Observing the forces applied at 2.5mm, the sample S-3C-5FA7, S-3C-5FA14 and S-3C-5FA28 achieved a rise of about 1.8, 3.0 and 5.5kN respectively. For the sample S-3C-5FA28, that is an increase of approximately 336%.

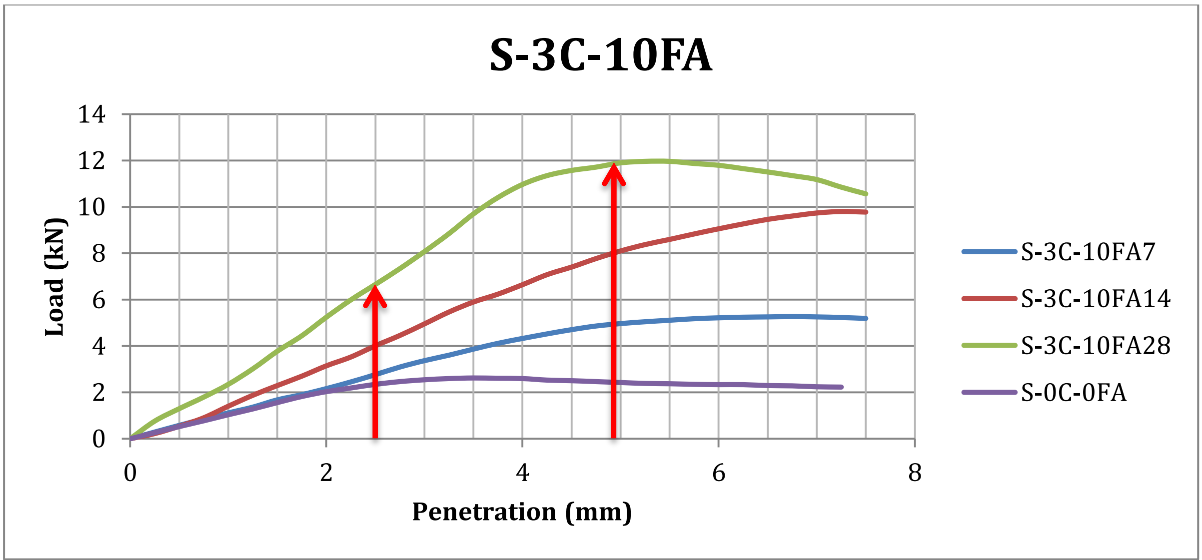


Figure 38: CBR test results for S-3C-10FA, with all curing periods

The CBR results of all the samples with 10% FA and 3% cement content are presented in the Force/Dispalcement graph, Figure 38. The representative samples chosen earlier were used to develop this figure. The sand only sample (S-0C-0FA) was also plotted in the figure for better analysis. Observing the forces applied at 2.5mm displacement, no significant improvement can be seen for samples S-3C-10FA7 and S-3C-10FA14, whereas for the sample S-3C-10FA28, a rise of about 4.3kN can be seen. Nevertheless, the main improvements in the case of 10% FA samples seem to have occurred at 5.0mm displacement, where an improvement range of 204 to 488% was achieved in terms of the applied forces.

Figure 39 presents the CBR results of the final variation tested in this thesis, 15% FA and 3% cement content. Each of the samples plotted in this Figure were the samples chosen to represent that specific variation. It can be seen that, for all the treated samples, the forces sustained at 2.5mm penetration are almost identical to one and another, except the S-3C-15FA56 sample, which obtained the highest CBR (64.1). However, for the other curing periods, one, two and four weeks, observing the forces applied at 5.0mm displacement, major improvements can be seen. The minimum percentage of rise in applied forces (from sand only to sample S-3C-15FA7) is about 278%, an increase of 4.3kN where the maximum percentage was obtained by sample S-3C-15FA28 (at 5.0mm penetration), an increase of 543% or in other words 10.8kN.

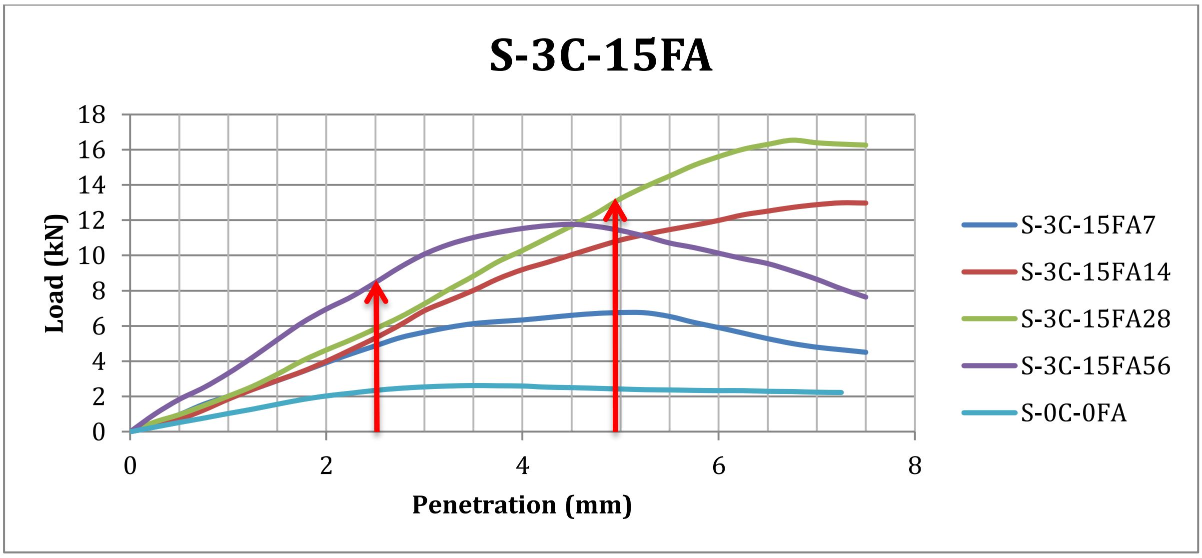


Figure 39: CBR test results for S-3C-15FA with all curing periods

The overall results of CBR tests performed with different FA content, different curing periods and cement content are compared in this section and discussed further. The effects of cement and FA contents and the curing periods are illustrated throughout this section. Figure 40 shows the influence of cement on CBR values. The results demonstrate that in all cases the CBR of both cement contents, 3% and 5% of cement, was significantly higher than that of sand only. Observing the samples cured for only one week, S-3C-0FA7 and S-5C-0FA7, an increase of over two times and five times respectively can be seen. The sand only (S-0C-0FA) achieved a CBR value of just over 17%. The highest gain in strength was achieved by the sample of 5% cement and no FA with a curing period of 28 days, an improvement by a factor of about 7.5. Figure 40 demonstrates that the cement content had a significant impact on the strength of the stabilised materials, whereas the curing duration had a less significant influence for S-3C-0FA samples, after the two weeks period in particular, yet, S-5C-0FA samples continued strength gain till four weeks curing. Sample S-5C-0FA28 achieved a CBR value of 129.2.

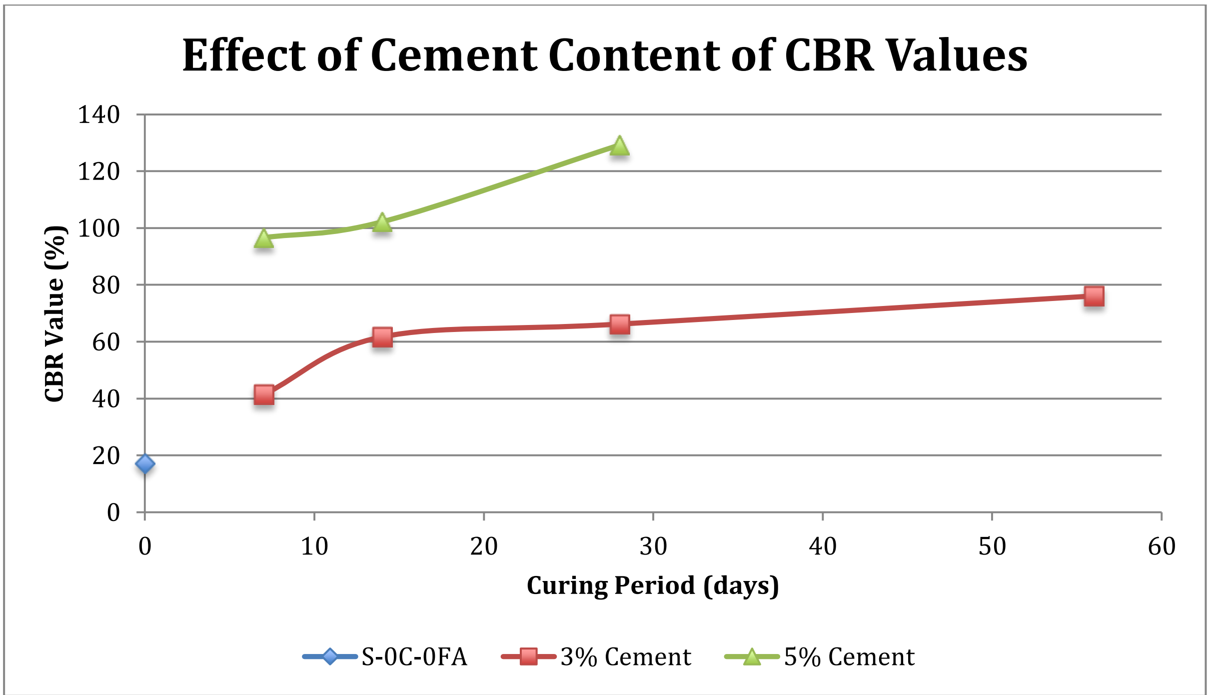


Figure 40: Effect of cement content on CBR values untreated sand and sand + cement (0% FA)

Comparing the samples S-3C-0FA7 and S-5C-0FA7 CBR values, it can be observed that the CBR value increased from 41.4% to 96.6% by the addition of 2% of cement.

In contrast, the addition of 3% cement to sand increased the CBR value by 24.2%. As was found earlier, the samples treated with 5% cement had a very similar optimum water content as well as maximum dry density. Achieving a CBR value of about 562% higher than the sand in just over seven days shows the profound effect cement (OPC) has on this particular sand used for this research. Overall, cement stabilisation has played a vital role in enhancing CBR values.

The effect of FA content on the CBR values is illustrated in Figure 41. The results of 3% cement content samples (with 0% FA) were also included so the influence of FA could be analysed consistently, as all the FA samples stabilised in this thesis included 3% cement for activation purposes, making the FA the only variable. The average CBR value of the untreated sample (S-0C-0FA) is also plotted. For all the different curing periods, it can be seen that there was a reduction in CBR values by adding 5% FA into the mixtures. For samples that were cured for one week, this reduction was observed until the addition of 10% FA. From then onwards, it gradually rose to a value, at 15% FA, very similar to that achieved by 5% FA content. The CBR achieved for samples S-3C-5FA7 and S-3C-15FA7 was 31.8% and 33.3%.

However, in the cases of two-week and four-week curing periods, the samples gained strength not only at 15% FA addition, but also at 10% FA content. In general, if cement only samples (S-3C-0FA series) were to be overlooked, it can be said that the higher the addition of FA the more the CBR value increased. Additionally, all the CBR values obtained were higher than that of 100% sand, with a range of 14.6% to 48.5%. Variants S-3C-0FA and S-3C-15FA were also cured for duration of eight weeks.

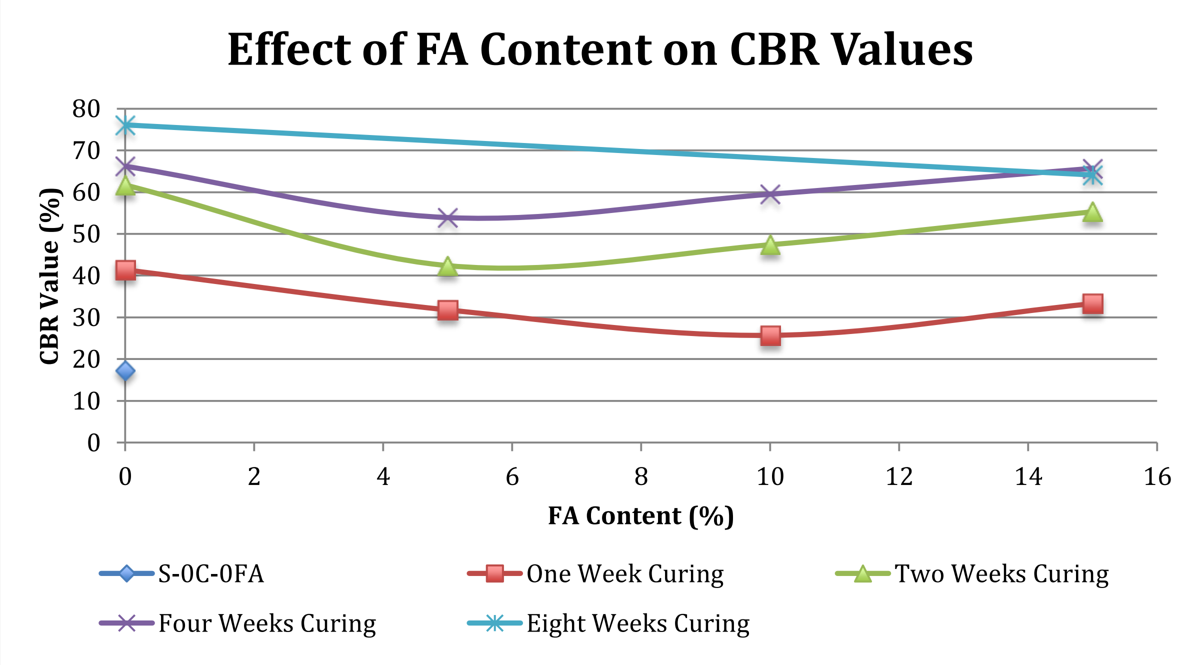


Figure 41: Effect of FA content on CBR values (Activator: 3% cement)

As it can be seen, the CBR values obtained for samples with FA addition, S-3C-15FA56, were lower than the S-3C-0FA56 sample. It was observed earlier, Figure 39, that the S-3C-15FA56 sample showed higher loading capabilities until about 4.5mm penetration, at which point began to fail. With further testing samples it will be possible to obtain a more accurate CBR for this variation (S-3C-15FA56).

Figure 42 demonstrates the effect of the curing period on the CBR values of all the different variations of mixtures tested throughout this research, with the addition of results obtained by Wood (2016), who performed CBR tests on mixtures of 5%, 10% and 20% FA content with 5% cement content as activator. As it was stated earlier in section 5.3, this author used the exact same materials, i.e. the FA, the cement and the sand. Observing Figure 42, it can be seen that the stabilised samples tested with 3% cement as activator (S-3C-0FA, S-3C-5FA, S-3C-10FA and S-3C-15FA) have a similar overall trend. The CBR values increase as the curing duration extends. Nevertheless, it should be pointed out that the CBR values show a slight reduction in CBR gains intensity post 28 days of curing and therefore a low upward gradient can be seen. The purpose of this Figure is to understand the effect the curing period has by maintaining the same value for cement content as activator and FA content, samples which had undergone different curing periods, one, two, four and eight weeks.

The S-3C-0FA series achieved a higher CBR than all of the other variations with the addition of FA (S-3C-5FA, S-3C-10FA and S-3C-15FA) although the CBR value achieved at four weeks time for the sample with 15% FA content was just 0.8% higher than the CBR achieved for the same curing duration for the 3% cement only sample. As the CBR values obtained for eight weeks curing showing the S-3C-15FA56 sample achieving lower CBR than S-3C-0FA56, further tests for these two variants are highly recommended, so that a more true analysis can be obtained.

In general, an improvement in CBR values by longer curing duration can be seen for all the cases. The FA samples with 3% cement content range from a CBR value of 25.7% to 67.9% with a slight upward correlation between all, proving that as curing time is increased so is the strength of the sample.

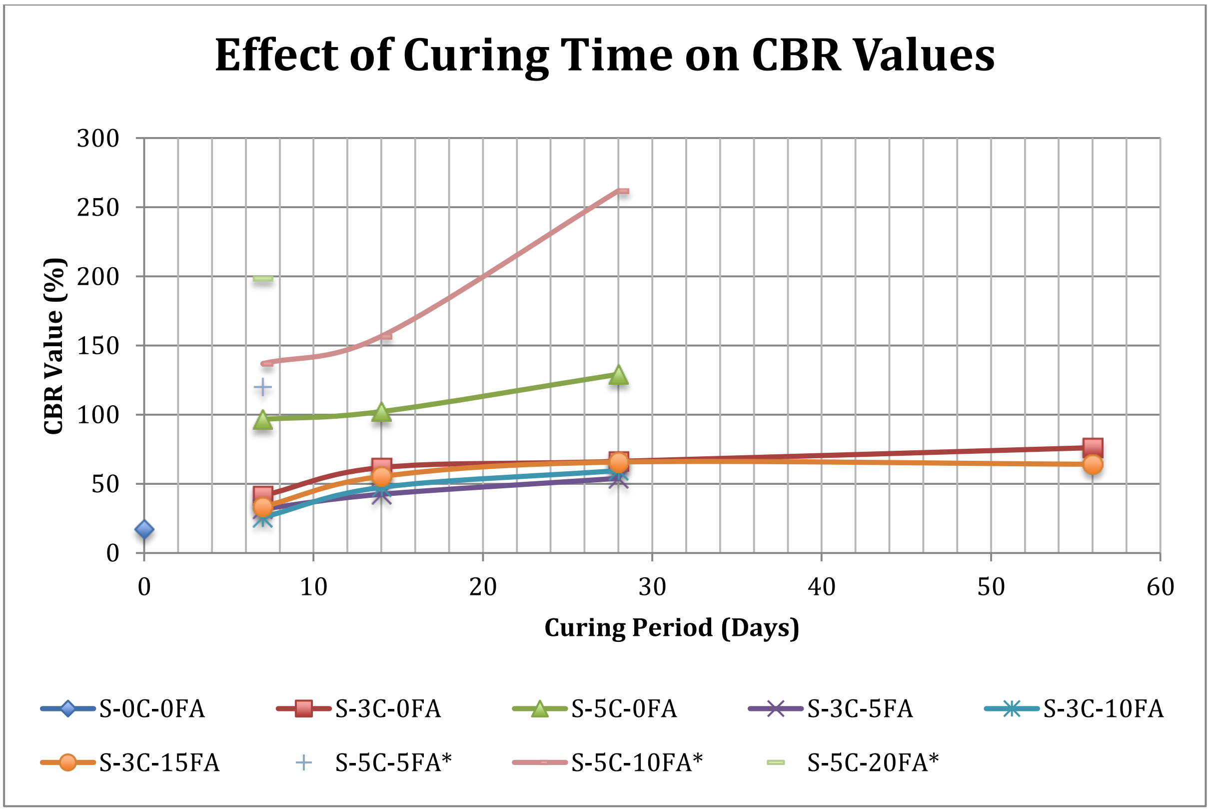


Figure 42: Effect of curing periods on CBR values
***Results after Wood (2016)**

In contrast, observing the samples treated with 5% cement, it can be seen that the S-5C-0FA series curve is positioned below the samples stabilised with FA (S-5C-5FA, S-5C-10FA and S-5C-20FA), unlike the results of the 3% cement samples. Wood (2016) only tested the 10% variation (S-5C-10FA) for different curing periods. The clear upward line of the curve for this variation can be seen in Figure 42, suggesting the possibility of even further improvements with further curing time. The sample which was mixed with 20% FA and 5% cement and cured for seven days, achieved a CBR value of 198.5%, an improvement by a factor of over eleven times. It is astonishing to gain such strength in just over one week. Nonetheless, the 10% FA sample achieved a CBR value of over 260% in four weeks, over fourteen times that of 100% sand, yet another astounding result.

The addition of cement was only for activation reasons, as class F FA was to be utilised for this research. The CBR results seems to prove that an addition of only 3% ordinary Portland cement is rather inadequate and needs to be of higher percentage, as the results of 5% cement content revealed. By just increasing the cement content by 2%, it enhances the results profoundly and also makes the case for FA utilisation. However, for economical reasons, the activation with 3% cement can also be considered appropriate and cheaper than 5%, since the improvement achieved by the treated samples is also significant, although not as strong. A similar behaviour was experienced in a study by Kolias et al. (2005), where samples (5% FA content) that were stabilised with 4% cement showed much more viable results than those samples stabilised with only 2% cement. All the CBR tests performed in this study and the ones performed by Wood (2016) are tabulated in Table 18.

Figure 43 shows the penetration values at peak force obtained in the CBR tests, for samples that were cured for 28 days. The results of this curing period show the most accurate results, as time is sufficient for the potential strength growth. This Figure indicates that as the FA content of the samples is increased the higher the penetration the samples could withhold prior to point of failure. This shows that with added FA, the samples become stiffer.

Table 18: The CBR results of all the variations reported in this thesis
[1] **Results after Wood (2016)**
[2] **Results after Kolias et al. (2005)**

Code	Sample	Curing Period (days)	Average CBR (%)
S-0C-0FA	Sand	0	17.2
S-3C-0FA7	Sand+3%Cement	7	41.4
S-3C-0FA14	Sand+3%Cement	14	61.7
S-3C-0FA28	Sand+3%Cement	28	66.2
S-3C-0FA56	Sand+3%Cement	56	76.1
S-5C-0FA7	Sand+5%Cement	7	96.6
S-5C-0FA14	Sand+5%Cement	14	102.2
S-5C-0FA28	Sand+5%Cement	28	129.2
S-3C-5FA7	Sand+3%Cement+5%FA	7	31.8
S-3C-5FA14	Sand+3%Cement+5%FA	14	42.4
S-3C-5FA28	Sand+3%Cement+5%FA	28	53.9
S-5C-5FA7	Sand+5%Cement+5%FA[1]	7	120.0
S-3C-10FA7	Sand+3%Cement+10%FA	7	25.7
S-3C-10FA14	Sand+3%Cement+10%FA	14	47.4
S-3C-10FA28	Sand+3%Cement+10%FA	28	59.5
S-5C-10FA7	Sand+5%Cement+10%FA[1]	7	136.9
S-5C-10FA14	Sand+5%Cement+10%FA[1]	14	156.7
S-5C-10FA28	Sand+5%Cement+10%FA[1]	28	262.0

Table 18 (Cont'd): The CBR results of all the variations reported in this thesis

S-3C-15FA7	Sand+3%Cement+15%FA	7	33.3
S-3C-15FA14	Sand+3%Cement+15%FA	14	55.3
S-3C-15FA28	Sand+3%Cement+15%FA	28	65.7
S-3C-15FA56	Sand+3%Cement+15%FA	56	64.1
S-5C-20FA7	Sand+5%Cement+20%FA[1]	7	198.5
LC-2C-20FA91	LeanClay+2%Cement+20%FA[2]	91	185
FC-2C-20FA91	FatClay+2%Cement+20%FA[2]	91	110
LC-2C-10FA91	LeanClay+2%Cement+10%FA[2]	91	140
FC-2C-10FA91	FatClay+2%Cement+10%FA[2]	91	60

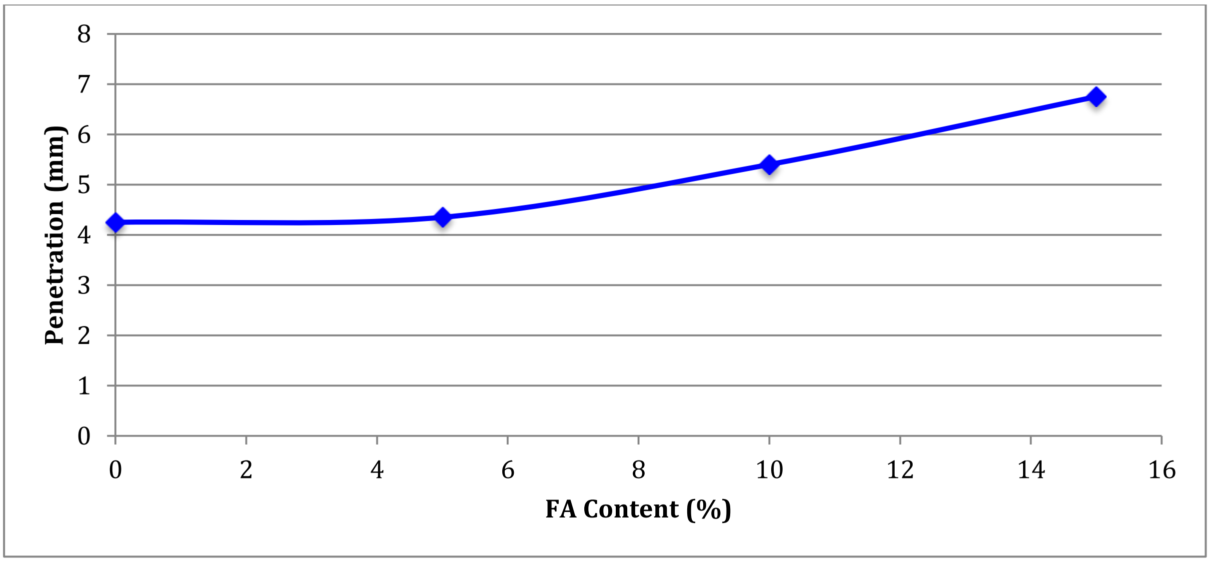


Figure 43: Penetration at peak force for samples cured for 4-weeks

5.5 Correlation and Prediction Results

In this section the results of CBR have been converted into resilient modulus (M_R) and unconfined compressive strength (UCS) values using the correlations stated earlier in the methodology. The results are demonstrated in both tabulated and graphical form, where M_R and UCS values are plotted against FA content. The CBR results performed in this study are all presented in tabulated form, where the figures are comprehensive of the results obtained in this study only.

5.5.1 M_R Correlation Results

In this section, the results of M_R, derived from CBR test results, are reported. Equation 11, from section 3.8.1, was used to derive the M_R values.

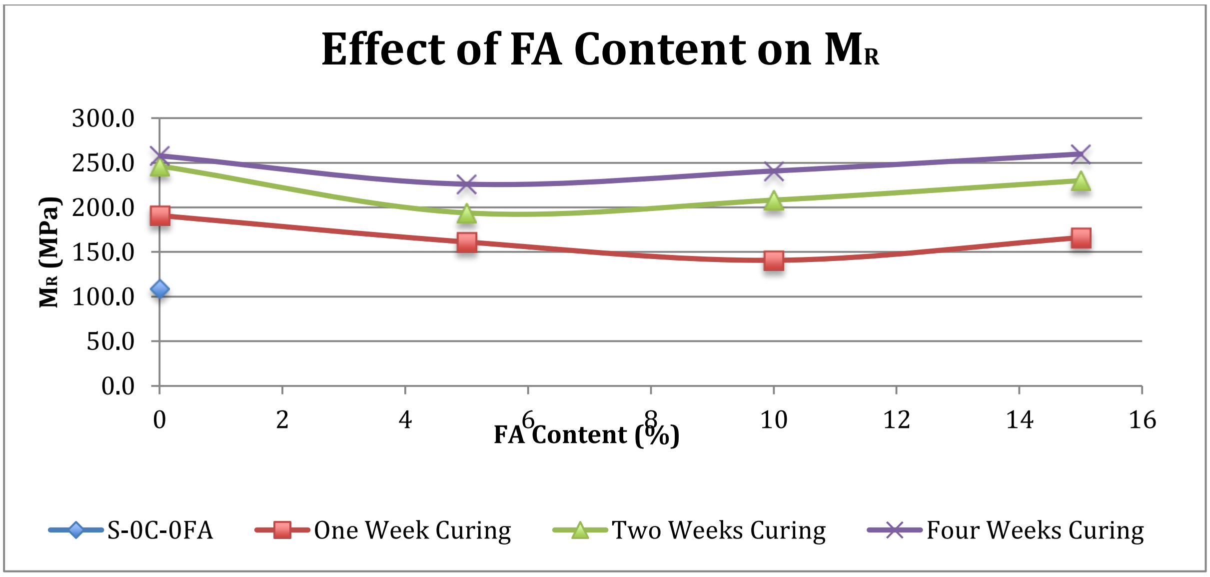


Figure 44: Effect of FA content on Resilient Modulus

Figures 44 illustrates the relationship between FA content and the M_R. It can be seen that, all the different curing periods have produced the same behaviour and are in correlation with each other. Obviously, Figure 44 has similarities of Figure 41. Samples with two-weeks and four-weeks curing periods show an upward trend by further FA addition after 5% FA content. Li et al. (2009) found that the higher the FA content, the higher the M_R. In their study, it was found that stabilising with soil with FA for pavement construction purposes, the M_R was increased by a factor of 2 to 3 times, achieving a mean M_R value of 139 MPa through their laboratory tests (Li et al. 2009). Observing the sample S-3C-15FA28, an increase of 147.7 MPa (236%) can be seen in comparison to untreated sand (S-0C-0FA), indicating similar results to that obtained by authors Li et al. (2009).

Standard for highways in the UK classifies the foundation into four classes in the design guidance for road pavement foundation (IAN 2009):

- Class 1: Specification Series 600 materials.
- Class 2: CBGM A or B, C3/4.

- Class 3: Types 1, 2, 3 or category B sub-base on capping.
- Class 4: CBGM A or B C8/10.

The M_R results evaluated through the CBR tests obtained in the laboratory are in agreement with the long-term in-service surface modulus stated in the highway standard (IAN 2009). All of the M_R results (except samples with curing period of seven days) show the suitability of the samples for Class 1 and 2 foundations, and samples with curing period of two weeks and over are suitable for Class 3 as well. The long-term in-service surface modulus for class 4 foundations is achieved through the series S-5C-10FA and S-5C-20FA.

5.5.2 UCS Correlation Results

In this section, the results of UCS, derived from CBR tests, are reported and discussed. Equations 12-14, from section 3.8.2, were used to derive the UCS values in respective of the curing period. For samples cured for eight-weeks, Equation 14 was used.

Figure 45 presents the relationship between FA content and the UCS. As different equations were used for different curing periods, a slight variation, however similar trend can be seen in comparison to Figures 44 and 41. For all the different curing periods, it can be seen that there was a reduction in UCS values by adding 5% FA into the mixtures. For samples that were cured for one week, this reduction was observed until the addition of 10% FA. From then onwards, it gradually rose to a value, at 15% FA, very similar to that achieved by 5% FA content. It can be seen that with further addition of FA higher strengths can potentially be obtained.

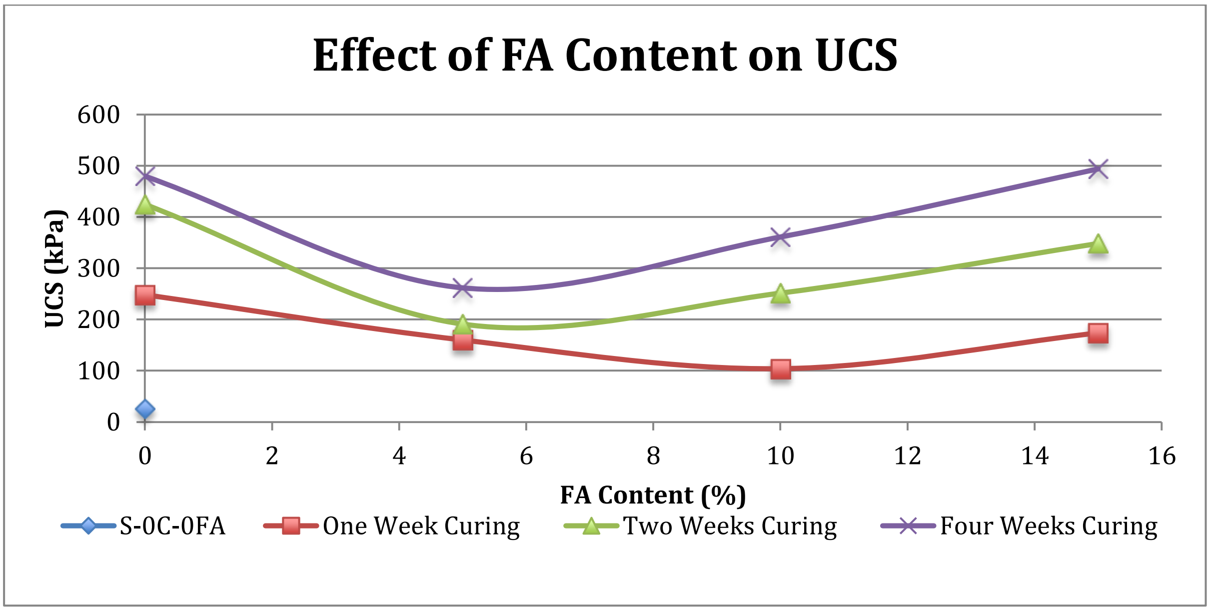


Figure 45: Effect of FA content on UCS

The reduction in strength from no FA content to 5% content is higher. It can be seen that there is very low strength development over the three different curing periods for S-3C-5FA series. The highest UCS value (for 3% cement samples) obtained was for the S-3C-15FA28 sample, with a value of 493.7 kPa, achieving an improvement of over nineteen times compared to the untreated sample. As included earlier in Table 3, the UCS results of several studies, concerning with FA-soil stabilisation were discussed. In most of the cases, the UCS was at least increased by a factor of 4 over a 7-day curing period. Despite the improved UCS values with FA stabilisation, cement-only (3% content) stabilised samples produced even higher UCS values in comparison to samples stabilised with 3% cement. The obtained results for UCS are in agreement with previous experimental researches (Rezagholilou and Nikraz, 2015). The results of M_R and UCS are presented and tabulated in Table 19.

Table 19: Derived M_R and UCS values for all the different samples
***Results after Wood (2016)**

Code	Sample	M_R (MPa)	UCS (kPa)
S-0C-0FA	Sand	108.8	25.7
S-3C-0FA7	Sand+3%Cement	190.9	248.2
S-3C-0FA14	Sand+3%Cement	246.4	424.4
S-3C-0FA28	Sand+3%Cement	257.8	479.5
S-3C-0FA56	Sand+3%Cement	281.8	654.9
S-5C-0FA7	Sand+5%Cement	328.3	755.5
S-5C-0FA14	Sand+5%Cement	340.4	914.6
S-5C-0FA28	Sand+5%Cement	395.5	1595.5
S-3C-5FA7	Sand+3%Cement+5%FA	161.2	159.9
S-3C-5FA14	Sand+3%Cement+5%FA	193.8	190.9
S-3C-5FA28	Sand+3%Cement+5%FA	226.0	261.6
S-5C-5FA7	Sand+5%Cement+5%FA*	377	970.6
S-3C-10FA7	Sand+3%Cement+10%FA	140.7	103.9
S-3C-10FA14	Sand+3%Cement+10%FA	208.2	251.4
S-3C-10FA28	Sand+3%Cement+10%FA	240.8	360.9
S-5C-10FA7	Sand+5%Cement+10%FA*	410.4	1125.9
S-5C-10FA14	Sand+5%Cement+10%FA*	447.5	1574.1
S-5C-10FA28	Sand+5%Cement+10%FA*	621.8	3948.1
S-3C-15FA7	Sand+3%Cement+15%FA	166.1	173.7
S-3C-15FA14	Sand+3%Cement+15%FA	230.0	348.2
S-3C-15FA28	Sand+3%Cement+15%FA	256.5	470.7
S-3C-15FA56	Sand+3%Cement+15%FA	252.5	442.3
S-5C-20FA7	Sand+5%Cement+20%FA*	520.6	1692.1

Chapter 6

Numerical Analysis

6.1 Introduction

In this chapter, finite element and finite difference analysis is used to numerically reproduce the experimental results obtained: the CBR tests, and to assess the effect of FA and cement content, as well as the curing period on Young modulus and the cohesion of the stabilised sand, assuming Mohr Coulomb constitutive model. In the first section of this chapter, the relevant research is presented in the literature review. This is followed by the methodology used in this thesis to perform the numerical analysis. In the end, this numerical chapter is concluded in the results and discussion section, where the results obtained with two commercial codes (PLAXIS and FLAC) are presented and discussed.

6.2 Numerical Literature Review

Numerical models can be defined as mathematical models that can reproduce behaviour over time by using numerical techniques. Numerical methods are used to assess ultimate limit states and deformations. The methods can range in complexity from simple analytical equations through to advanced large strain finite element or distinct element modelling (DEM) (Mitchell and Kelly, 2013). According to Pradhan et al. (2014), numerical modelling can get detailed solutions by applying simple assumptions in a very short amount of time in comparison to alternative methods as they enable higher number of trials in the design and other parameters. Development of finite-element/finite-difference methods has provided geotechnical engineers with powerful tools for design. Until recently, many considered an accuracy of ± 100% on predicted deformations about the best that could be achieved in geotechnical engineering. However, careful selection of parameters and modelling of the site conditions suggests that it is now possible to be more accurate. This can be achieved through simplified stratigraphy and geometry inputs, with the characterisation of the soil determined by constitutive models (Mitchell and Kelly, 2013). It should be noted that although the numerical methods are very powerful, the results are still an approximation of real behaviour (Mitchell and Kelly, 2013).

Finite element analysis (FEA) is the modelling of products and systems in a virtual environment for the purpose of finding and solving potential structural or performance issues. FEA is the practical application of the finite element method (FEM), which is used by scientists and engineers to mathematically model and numerically solve very complex structural and other problems. FEA is the most widely used method of structural analysis, due to developments in computer hardware and software (Cirulis and Wicks, 2015; Mitchell and Kelly, 2013). There are mainly two types of analysis (Lee 2012):

- Linear analysis: When the responses of a system are linearly proportional to the loading, it is called a linear system, and the simulation is known as a linear simulation.
- Nonlinear analysis: When the responses of a system are not linearly proportional to the loading, it is called a nonlinear system, and the simulation is referred to as a nonlinear simulation.

For the purpose of this study, Mohr-Coulomb simulations will be run. In order to have a basic idea of finite element methods it is necessary to divide the entire domain into many small and geometrically simple bodies called elements so that equilibrium equations of each element can be written down, and all the equilibrium equations are then solved simultaneously (Lee 2012). The elements are assumed to be connected by nodes located on the edges and vertices of the elements. FEA can be used in both new or existing projects, so that to a certain extent the design will meet the project sepcification prior to any actual physical commencement. According to Lee (2012), with FEA it is possible to:

- Predict and improve product performance and reliability.
- Reduce physical prototyping and testing.
- Evaluate different designs and materials.
- Optimize designs and reduce material usage.

Most of the steps involved in computer FEA can be automated within FEA software. The analyst's role is to provide the essential input required by the FE software to ensure that the FE model is fit for purpose and to interpret the results (Cirulis and Wicks, 2015). The main steps in FEA in its simple form are (Cirulis and Wicks, 2015):

- Evaluate the element stiffness matrices.
- Assemble the global structure stiffness matrix.
- Apply the boundary conditions.
- Solve the global structure displacements.
- Evaluate the element forces or stresses.
- Provide results.
- Interpret the results, validation, and verification.

Authors Mitchell and Kelly (2013) suggest that it is good practice to test the numerical model against a laboratory test result or a simple well-defined analytical result. FEA can provide a very good prediction of the behaviour of soil structure interaction problems if the different construction stages and the material behaviour are simulated correctly and accurately in the analysis (Maula and Zhang, 2011). The benefits of FEA include its comprehensive ability to model deformations as well as to predict collapse (Maula and Zhang, 2011). For designing and forecasting the mechanical behaviour of geo-engineering projects like embankments, Khan and Abbas (2014) suggest that the two most widely used methods of analysis are finite element and conventional limit equilibirium. The authors state that the advantages of the FEA over the conventional limit equilibrium method are that there is no need for the predetermined failure mode and that a full interaction of the embankment foundation can be simulated (Khan and Abbas, 2014).

There are numerous commercial codes that could be used as numerical simulators. They cover both 3D and 2D simulations. However, reducing a problem to 2D has many advantages over the 3D approach, and it is recommended to be used whenever possible (Lee 2012). These benefits include, simpler to build geometry, better mesh quality and less computing time (Lee 2012), this is only possible to do when the problem is 2D, i.e. plain strain and axisymmetric problems.

The limitation of FEA is that it is not suitable to capture high strains, since the FE mesh gets highly distorted, compromising the convergence of the algorithms (Zienkiewizc et al. 2000). Brinkgreve and Swolfs (2008) examined the limitations of FEA for geotechnical applications. The following limitations are from the conclusion these authors made (Brinkgreve and Swolfs, 2008):

- The position of model boundaries should be chosen in accordance with the type of analysis and the type of soil model.
- Element type, size and local refinement, as well as extended and iso-parametric interface elements are essential to accurately predict bearing capacity in soil-structure interaction problems.
- Simple soil models with direct input of shear strength may be adequate to calculate bearing capacity (ultimate limit state), but more advanced models are required to accurately model deformations (serviceability states).
- It may be necessary to apply limit state criteria to all construction stages and not only the final stage.

The most common material model used in geotechnical calculations that have also been implemented in the softwares is mainly of the Mohr-Coulomb theory (Spetz 2012). Mohr-Coulomb failure criterion is the most widely used material model in soil mechanics. According to Spetz (2012), this mathematical theory ‘was first developed by Charles-Augustin de Coulomb and it was the first material model to take the hydrostatic pressure into account’ (Spetz 2012). The Mohr-Coulomb criterion is an elastic perfect plastic material model and it may in some cases overestimate the soils hydrostatic compressive strength. Spetz (2012) states that when the Mohr-Coulomb model is used, it is important to consider that in the general case the criterion does not consider the hardening or softening behaviour and may therefore not give a credible result for all calculations (Spetz 2012).

In the finite difference method (FDM), every derivative in the set of governing equations is replaced directly by an algebraic expression, which is written in terms of the field variables (e.g. stress or displacement) at discrete points in space; these variables are undefined within elements (FLAC 2016). Explicit methods are best for ill-behaved systems, like nonlinear, large-strain, physical instability (FLAC 2016). They are not efficient for modeling linear, small-strain problems. The incremental displacements are added to the coordinates so that the grid moves and deforms with the material it represents. This is termed a Lagrangian formulation. The constitutive formulation at each step is a small-strain one, but is equivalent to a large-strain formulation over many steps (FLAC 2016). Also, in finite difference method, matrices are never formed, making the method very efficient from the computational effort point of view.

Bartlett (2010) reports that numerical softwares FLAC and PLAXIS are the most commonly used by advanced geotechnical consultants. For the purpose of this study, both of these programs will be used in order to achieve comprehensive analysis against the results obtained from the laboratory tests.

PLAXIS

PLAXIS, short for 'Plasticity Axi-Symmety', is a Dutch based company providing numerical modelling software for construction industry for geotechnics, underground and tunnel construction, hydraulic and offshore engineering, mining and foundation engineering, etc, sectors (PLAXIS 2017). The collaboration between PLAXIS and the academic world began from 1980s and is still currently being continued (PLAXIS 2017).

PLAXIS 2D is a finite element package intended for the two-dimensional analysis of deformation and stability in geotechnical engineering. In PLAXIS 2D the user has two options in how to idealize the real problem at hand, either with plane strain conditions or as an axisymmetric problem. The user interface in PLAXIS 2D consists of three sub programs: Input, Calculations and Output. As the software is purposely created to handle geotechnical engineering problems there are generalised methods in how to set up common geotechnical problems (Spetz 2012). It is equipped with features to deal with various aspects of geotechnical structures and construction processes using robust and theoretically sound computational procedures. Typical PLAXIS applications include, but are not restricted to (PLAXIS 2016):

- Assessing street level displacements during a tunnel construction.
- Consolidation analysis of embankments.
- Soil displacements around an excavation pit.
- Dam stability during different water levels.

FLAC

The first version of FLAC (Fast Lagrangian Analysis of Continua) was released in 1986 (ITASCA 2017). It has been widely used in the hydrogeology, microseismicity and geomechanics sectors since its incorporation (ITASCA 2017). It aims at providing solutions to problems related to rock behaviour processes for the construction industry. FLAC developed by Itasca Consulting Group, USA, by utilising an explicit finite difference formulation, it can be used in complex models where several stages, behaviours and displacements are involved, unlike FEA programs.

FLAC is a 2D finite difference code with lagrangian formulation. It uses an explicit, time-marching method to solve the governing field equations, in which every derivative is replaced by an algebraic expression written in terms of the field variables at discrete points in space; these variables are undefined elsewhere (FLAC 2016; Frydman and Burd, 1997; Bolton and Gui, 1995). FLAC is capable of simulating ‘the behaviour of structures built of soil, rock or other materials that may undergo plastic flow when their yield limits are reached' (FLAC 2016). The explicit, Lagrangian calculation scheme used in FLAC ensures that plastic collapse and flow are modelled very accurately as no matrices are formed; large 2D calculations can be made without excessive memory requirements (FLAC 2016). The medium is divided by the user into a finite difference mesh of quadrilateral elements. Internally, FLAC subdivides each element into two overlayed sets of constant-strain triangular elements (FLAC 2016; Frydman and Burd, 1997). The programme also includes an internal programming option (FISH), which enables the user to define quantities to be calculated and to control the analysis process (Frydman and Burd, 1997). Authors Frydman and Burd (1997) made a comparison of FLAC to one FEA (OXFEM) code and conclude that FLAC is superior in some respects for footing problems. These benefits include efficiency and smoothness of the pressure distribution (Frydman and Burd, 1997).

Cases of Element Test

Jiang et al. (2015) report that as laboratory CBR test can be considerably influenced by laboratory testing conditions and the sample disturbance, it is suggested to use appropriate prediction models to either complement, replace and/or validate the obtained CBR values. The same authors, tested graded crushed rocks and compared to laboratory CBR values to those achieved in the numerical test. It was found the difference between the laboratory and numerical results was about 4.5% on average, and below 7% in all the cases. Furthermore, it was concluded, in the same study, that the effect of poisson's ratio on CBR numerical tests is negligible

(Jiang et al. 2015). In a study by Caicedo and Mendoza (2015) the effect of stiffness and strength parameters on the results of CBR tests was assessed using a elastic-plastic constitutive model, Mohr Coulomb, in the ABAQUS software. It was found that the CBR value depends on the Young modulus and also the strength parameters, i.e. friction and cohesion angle.

In another study by Sukumaran et al. (2002), finite element analysis was employed to determine CBR values and verify the results against those achieved in the field and laboratory. ABAQUS, with elastic-plastic von-Mises model, was the chosen software for the numerical test in this study. Upon plotting the Force/Displacement graph and comparing the numerical results and field results, significant similarities were achieved (Sukumaran et al. 2002). Employing numerical test with similar methods, authors Sukumaran et al. (2004) using 3D finite element modelling can accurately predict the stress-strain behaviour of subgrade soil.

Rashidian et al. (2016) also used the ABAQUS software to predict CBR values. However, the numerical test was modelled with constitutive model Mohr Coulomb. Poorly graded gravels and poorly graded sand were used in their laboratory tests. After comparing the CBR values achieved in the laboratory and by employing the numerical tests, it was found the numerical CBR value for poorly graded gravel samples were on average 7% higher than that of achieved in the laboratory, and about 2% higher for the poorly graded sand samples (Rashidian et al. 2016). Usluogullari and Vipulanandan (2008) used PLAXIS software, Mohr Coulomb model, to validate the laboratory CBR values obtained for stabilised sand, with 3% cement content. The ratio of predicted CBR values obtained through PLAXIS to the CBR values obtained in the laboratory had a range of 0.69 to 1.07 (Usluogullari and Vipulanandan, 2008).

For the purpose of this thesis, numerical software PLAXIS and FLAC will be employed to supplement the CBR values obtained in the laboratory. The aim of the numerical analysis is to access the effect of FA content, cement content and the period of curing has on Young modulus and the cohesion of the stabilised samples, through calibration of the numerical model against the experimental results. The results will be compared in Force/Displacement graphs.

6.3 Numerical Methodology

The aim of the numerical analysis was to calculate the model parameters and to investigate the effects of the different treatment on them.

For the purpose of this study, 2D simulation was used. There are two commertial packages (PLAXIS and FLAC) that were used as numerical simulators. These simulations were examined against the resutls obtained from the CBR tests (similar to Putri et al. 2012). In both of programs, the elastic-plastic Mohr Coulomb consitutive model was used and Youngs modulus, friction angle and the cohesion of the soil were varied individually throughout the simulations to achieve applicapble results (assuming no tension strength and no dilation). The initial Youngs modulus or the Elasticity modulus (E) were predicted by using Equation 15. The correlation between CBR and E, used in this study, was developed by Putri et al. (2012):

$$E = 840.53CBR \text{ (kPa)}, \qquad v = 0.3 \qquad \text{Equation 15}$$

The Poisson's ratio (v) is a property of unsaturated elastic materials and commonly assumed to be in the range of 0.2 to 0.4 (Putri et al. 2012). A Poisson's ratio value of 0.5 is given when the soil is saturated and undrained. For the purpose of this study the value of Poisson's ratio will be assumed constant at 0.3 (normal value for unsaturated granular materials (Putri et al. 2012) for both of the programs, hence the initial E (E_1) being predicted by Equation 15. However, it should be kept in mind that this is only a correlation and not the exact E and these correlated values are only employed as first attempts in the calibration process.

PLAXIS

The Finite Element Analysis (FEA) was created and analysed using the PLAXIS Introductory geo-engineering program. PLAXIS was used to predict the initial elastic behaviour by correlating the initial slope obtained in the CBR Force/Displacement graph. A flowchart was developed constituting all the steps and methods taken in the process of each PLAXIS variation simulation, as presented in Figure 47. The model used in PLAXIS was axisymmetric with 15-Noded option. This particular model and element options were chosen due to the cylindrical shape of the mould. Because of this, the dimensions of the mould input in PLAXIS had half the diameter (D_{m2}) of the modified CBR mould, with the same height (H_{m2}). The maximum dry density values derived from the compaction tests were used as input for the saturated and unsaturated densities in the material section. Table 20 presents the material properties initially used in the PLAXIS modelling.

Table 20: The material properties initially used in the PLAXIS modelling

Material	γ_{unsat} (kN/m^3)	E_1 (kPa)	Cohesion C	Friction Angle	v
S-0C-0FA	17.07	15154.76	20	30	0.3
S-3C-0FA7	17.62	34823.16	30	30	0.3
S-3C-0FA14	17.62	51860.70	40	30	0.3
S-3C-0FA28	17.62	55626.28	50	30	0.3
S-3C-5FA7	17.77	26745.66	60	30	0.3
S-3C-5FA14	17.77	35604.85	70	30	0.3
S-3C-5FA28	17.77	45338.19	80	30	0.3
S-3C-15FA7	17.18	27804.73	100	30	0.3
S-3C-15FA14	17.18	46456.09	100	30	0.3
S-3C-15FA28	17.18	56273.48	100	30	0.3

In PLAXIS, simulations are modelled either with a prescribed load and/or a prescribed displacement. In this thesis, only a prescribed displacement was used for this software. The dimensions of the displacement were derived from the CBR plunger and the maximum depth of displacement, as it was stated earlier in CBR methodology, would be 7.5mm. As axisymmetric modelling was used, half of the plunger diameter (0.025m) was set as the width of the displacement. The prescribed displacement (Displacement$_x$) had to be set to 'Fixed'. In order to specify the uniform prescribed vertical displacement, the value had to be set with a negative value, forcing a downward direction into the mould. In the selection explorer, after assigning the prescribed displacement, the y-displacement ($U_{y,start,ref}$) was set to -0.0075m.

Upon generating the mesh (Figure 46), the 'Fine' option was chosen as the element distribution. As the final results were to be used to produce a Force/Displacement graph, the centre of the mould, or the top left hand corner of the PLAXIS mould (Figure 46) had to be assigned, point A, using the 'Select points for curves' function prior to the commence of the calculations. Once the results were produced and tabulated, both the displacement and the force had to be amended so that it could be placed in the CBR graph for correlation analysis. The forces in PLAXIS were in terms of kN/rad as the axisymmetric modelling was used, and the displacement values were in terms of m, which had to be changed into units of mm. In other words, the forces were multiplied by 2π and the displacements multiplied by 1000.

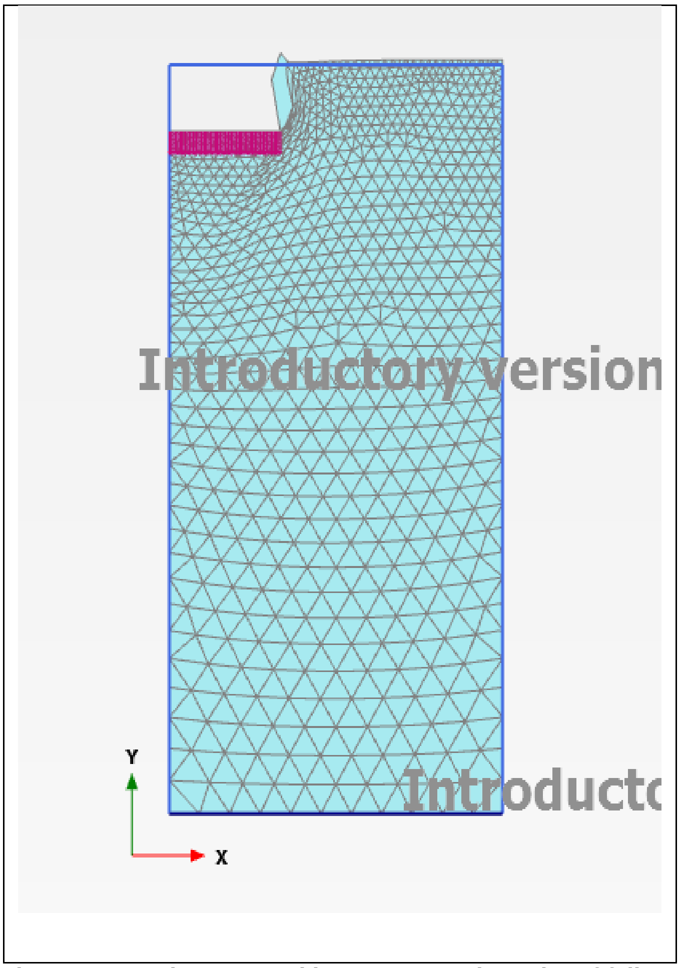


Figure 46: Mesh generated by PLAXIS at the point of failure

FEA through PLAXIS provides a steady plastic flow. The program was only used to obtain the initial slope by mainly altering the Young's modulus. It was not possible to evaluate strength properties using PLAXIS due to the limitations mentioned earlier, hence the requirement of further analysis through FLAC. It should be noted that, the PLAXIS simulations were run again after the completion of FLAC analysis, so that more accurate results could be obtained. The main criterion, throughout the PLAXIS analysis, was for the predicted results and CBR results have the same or the closest value of force at 2.5mm penetration. This point (2.5,F) was made the benchmark in PLAXIS analysis. For all the simulations the values of elasticity and cohesion were slightly changed over time so that the best fit could be found in the Force/Displacement graph.

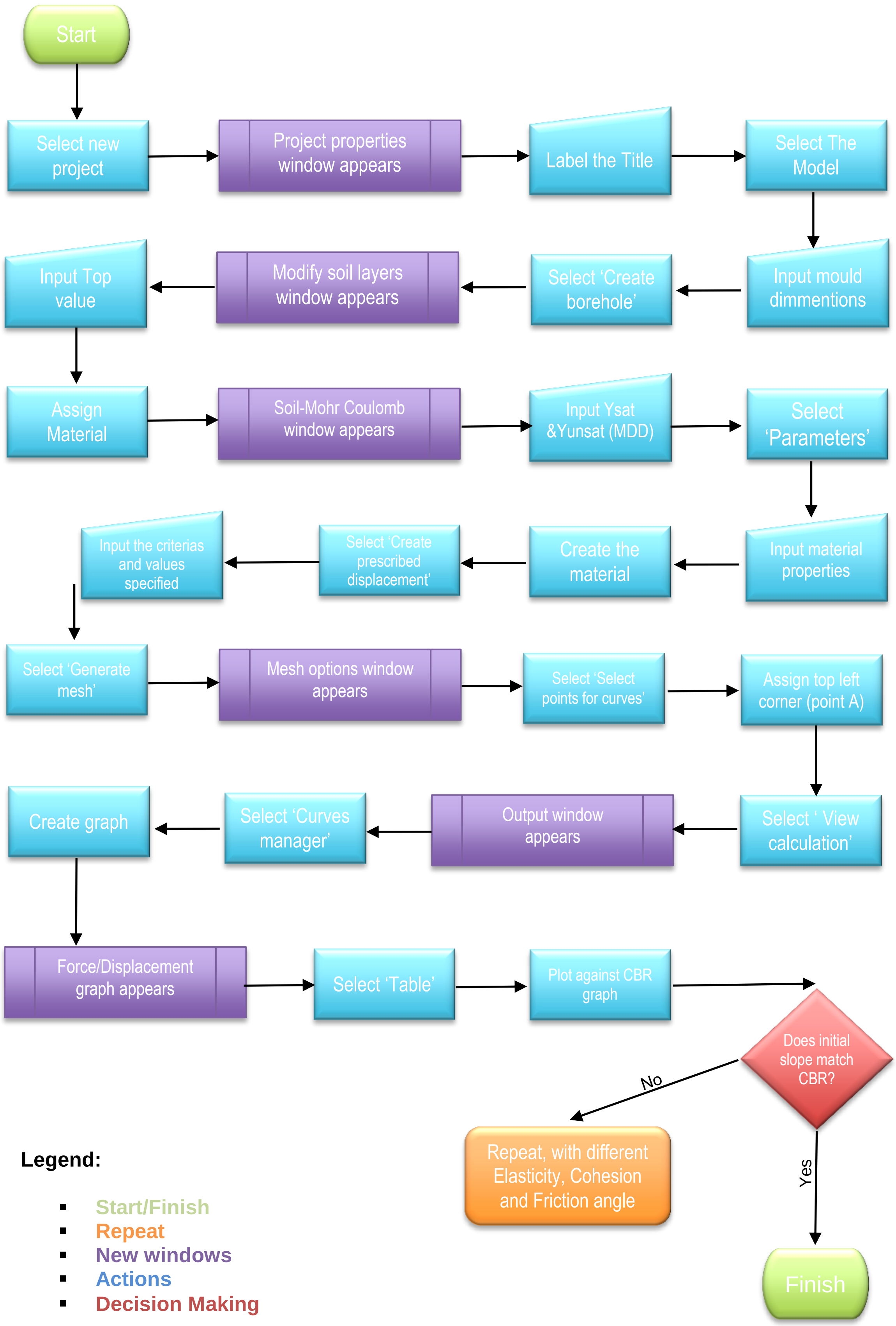


Figure 47: Flowchart illustrating steps for PLAXIS simulation

FLAC

In the present study, the explicit 2D finite difference program FLAC version 8.00 was used to predict the elastic-plastic soil model parameters by correlating the peak force obtained in the CBR Force/Displacement graph.

The predicted behaviour was further used to obtain Shear (G) and Bulk (K) modulus using the following formulae (FLAC 2016). A data file including all the dimensions of mould, plunger, load force, shear force, strain, friction angle, cohesion and the poisson's value was developed for the FLAC simulation. A flowchart has been developed constituting all the steps and methods taken in the process of each FLAC variation simulation (Figure 49).

$$G = E/2/(1-v) \quad \text{Equation 16}$$

$$K = E/3(1-2v) \quad \text{Equation 17}$$

The model used in FLAC, like in PLAXIS, was axisymmetric. This configuration was chosen cause of the cylindrical shape of the CBR mould. The dimensions of the mould input in FLAC were identical of that in PLAXIS, half the diameter (D_{m2}) and the same height (H_{m2}). In FLAC the initial elasticity modulus (E_p) used was the elasticity value derived from the simulations preformed in PLAXIS. Using equations 16 and 17, the shear and bulk modulus were calculated and placed in the data file. Table 21 presents the material properties initially used in FLAC simulation.

Table 21: The material properties initially used in the FLAC modelling (Model: Mohr-Coulomb group)

Material	Unit Weight (kN/m^3)	E_p (kPa)	Bulk (kPa)	Shear (kPa)	Cohesion C (kPa)	Friction angle (degree)
S-0C-0FA	17.07	22,000	18.333	8.462	30	30
S-3C-0FA7	17.62	35,000	29.167	13.462	30	30
S-3C-0FA14	17.62	68,000	56.667	26.153	40	30
S-3C-0FA28	17.62	75,000	62.500	28.846	50	30
S-3C-5FA7	17.77	30,000	25.000	11.538	60	30
S-3C-5FA14	17.77	30,000	25.000	11.538	70	30
S-3C-5FA28	17.77	55,000	45.833	21.154	80	30
S-3C-15FA7	17.18	34,000	28.333	13.077	100	30
S-3C-15FA14	17.18	40,000	33.333	15.385	100	30
S-3C-15FA28	17.18	45,000	37.500	17.308	100	30

In FLAC the simulations were moulded with an applied force because obtaining the reaction against the soil displacement is not automatic with this software. In this study, the applied force was in form of the CBR plunger as can be seen in Figure 48. The dimensions of the plunger were set with a width of 0.025m and a height of 0.08m, which was considered elastic. Table 22 shows the properties used for the creation of the plunger that were coded in the data file.

Table 22: The plunger properties employed in the FLAC modelling (Model: Elastic group)

	Density (kN/m^3)	Bulk (kPa)	Shear (kPa)
Plunger	2000	1.00E+10	1.00E+9

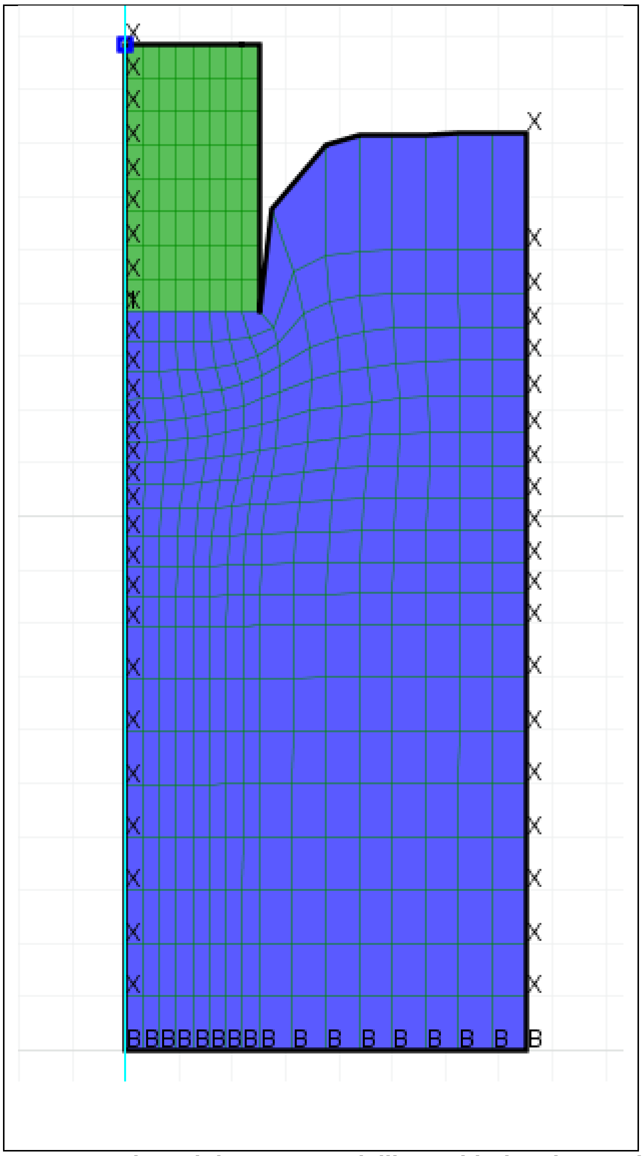


Figure 48: Generated mesh in FLAC modelling, with the plunger (in green)

For each simulation the applied force was changed in order to obtain set of Force/Displacement values so that it could be plotted in the CBR graph. To obtain one curve or line for the Force/Displacement graph, all the parameters; bulk, shear, cohesion, friction angle, dilation and tension, were kept unchanged, while the applied force was gradually increased. The number of cycles in this study was set to 400,000, for which convergence of the solution was found in all cases. The displacement at the end of the cycles, at cycle 400,000, was the value that was used to produce the one point (x-axis), at the specified force (y-axis) for the Force/Displacement graph.

Similarly to the end calculations of PLAXIS, the applied force was in terms of kN/rad and the attained displacement in terms of m. For that reason the applied force values were multiplied by 2π and the displacements by a factor of 1000 so that it could be plotted in the CBR graph. For all the simulations the values of elastic modulus and cohesion were slightly changed over time so that the best fit could be found in the Force/Displacement graph.

The shape of the particles mainly governs the friction angle of any material. We assumed the angle of friction to remain constant at 30 degrees, as with further addition of FA and cement, a better bond is created between the particles and ultimately increasing the cohesion.

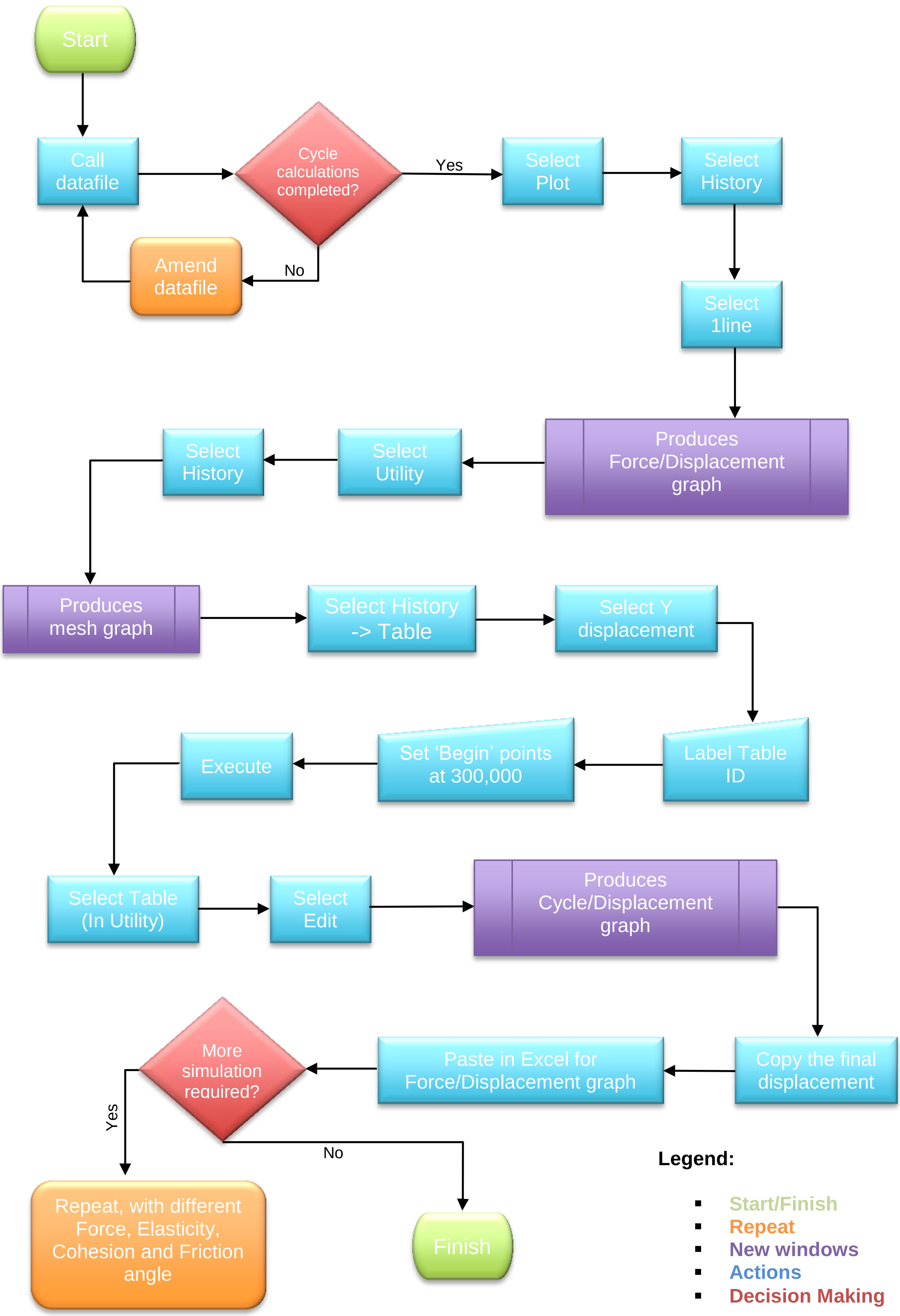


Figure 49: Flowchart illustrating steps for FLAC simulation

6.4 Numerical Results and Discussions

In this section the results obtained from the numerical simulations of both programmes, PLAXIS and FLAC, are presented and discussed. For the purpose of this thesis the following samples were chosen for numerical analysis.

- S-0C-0FA
- S-3C-0FA7
- S-3C-0FA28
- S-3C-5FA7
- S-3C-5FA28
- S-3C-15FA7
- S-3C-15FA28

The purpose of the numerical analysis is not intended to reproduce the whole CBR test, as the softening of the material after the peak values occur when the soil is soft and at a very high strain level, yielding inaccurate results through numerical simulation. Henceforth, in both approaches, FLAC in particular, the focus was put on the initial slope and the peak values obtained through laboratory CBR tests. Each variation is assigned a code with the corresponding friction angle (fi), cohesion (c) elastic modulus (E), measured in degrees, kPa and kPa, respectively.

PLAXIS

For each sample, numerous simulations were run to produce PLAXIS/CBR colorations by achieving similar initial slope. As stated earlier in the methodology section, the calculated E, derived from CBR, was used to make the initial simulations, and then E values and cohesions values were moderately altered so that the closest correlation could be obtained. In this section the results of each of the chosen samples is presented in the Force/Displacement graph. The results achieved by PLAXIS will be used further on to achieve further numerical analysis through FLAC. Figures 50-56 illustrate the PLAXIS results against the CBR results achieved in the laboratory. These Figures show the initial slope obtained for each sample. The load at 2.5mm penetration was the key point in achieving the initial slope by correlating the PLAXIS Force/Displacement curve to that of CBR result.

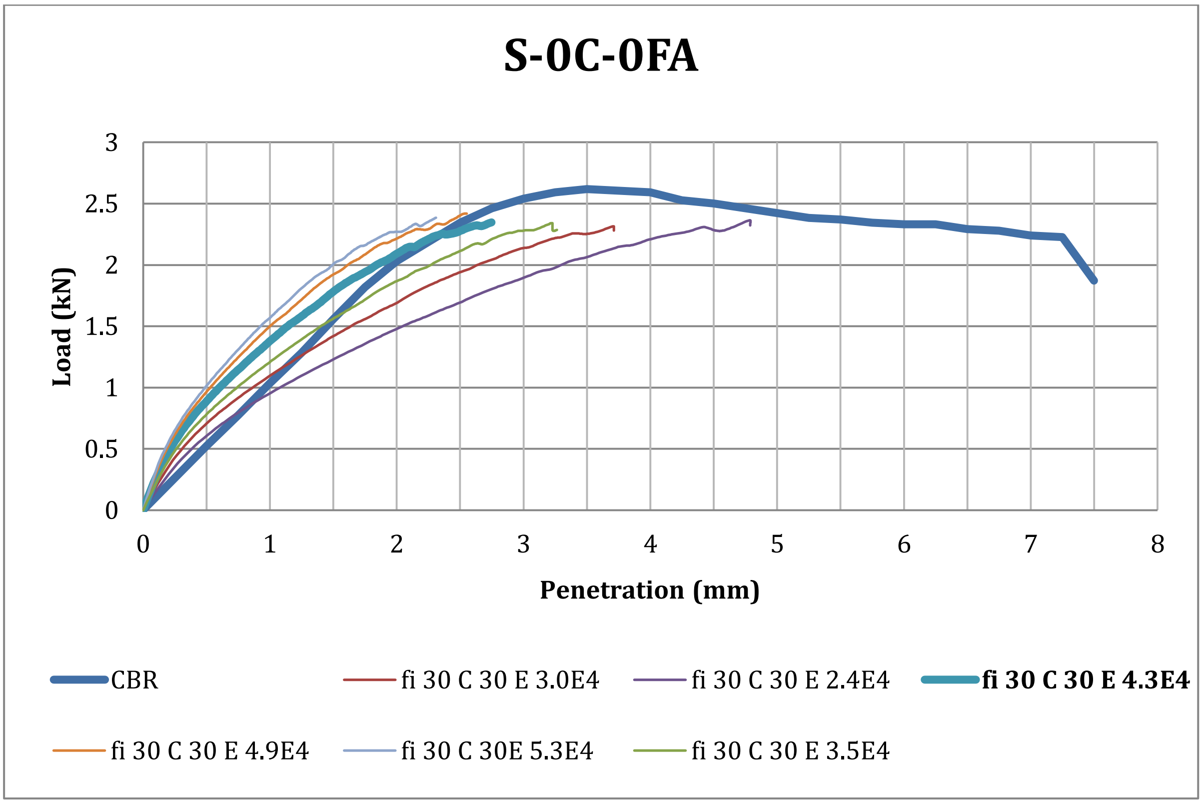


Figure 50: PLAXIS/CBR comparison for sample S-0C-0FA

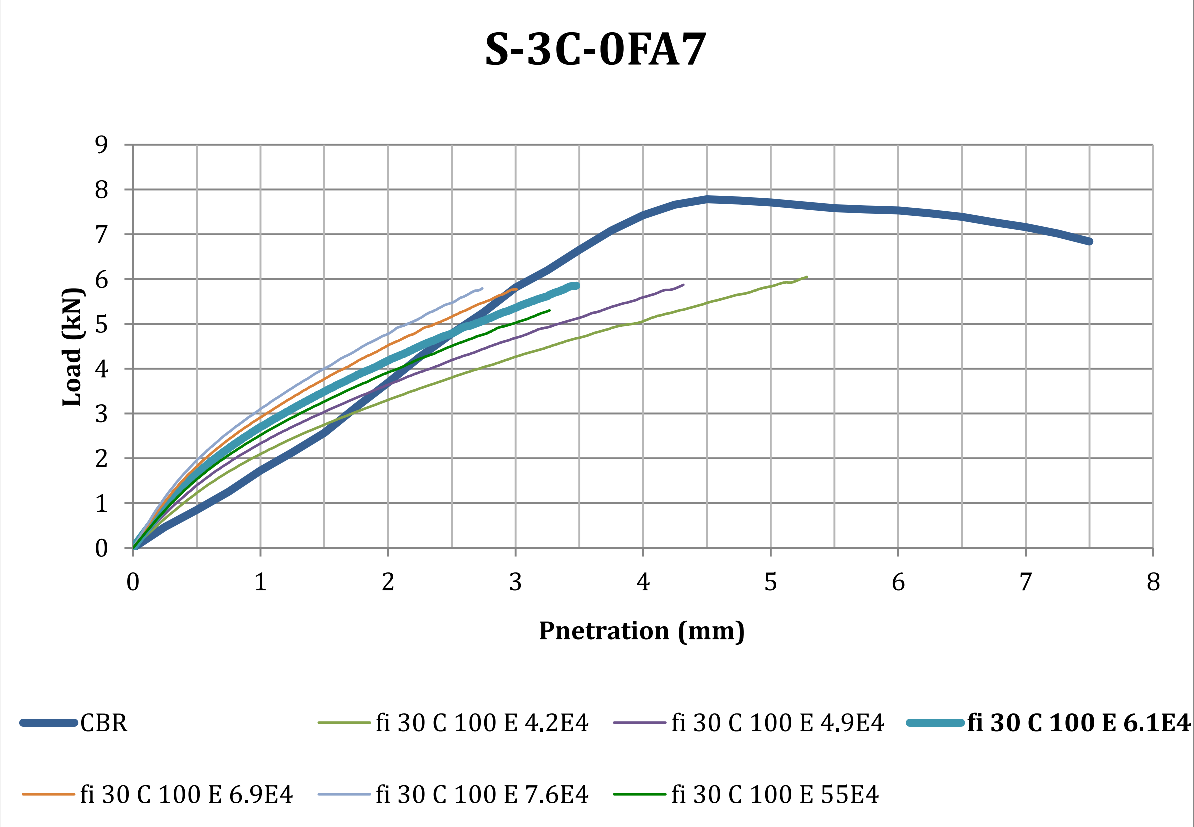


Figure 51: PLAXIS /CBR comparison for sample S-3C-0FA7

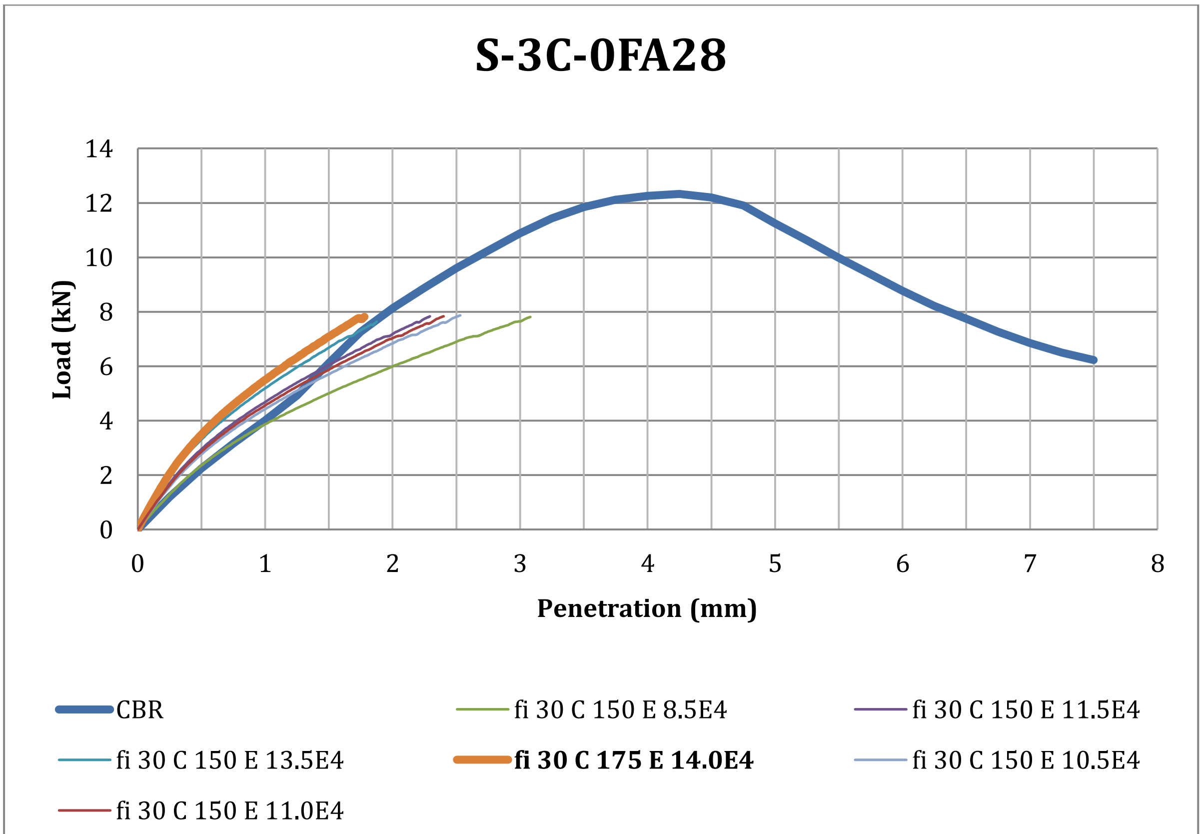


Figure 52: PLAXIS/CBR comparison for sample S-3C-0FA28

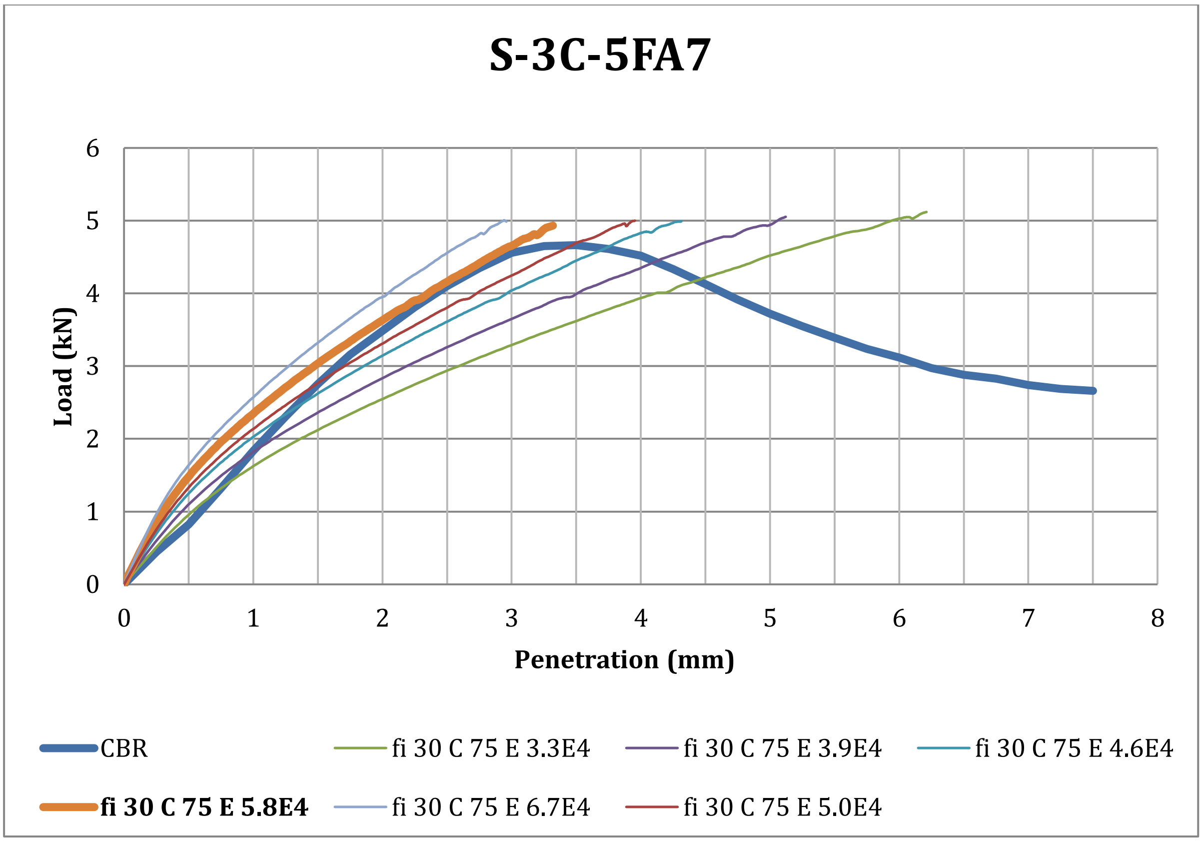


Figure 53: PLAXIS/CBR comparison for sample S-3C-5FA7

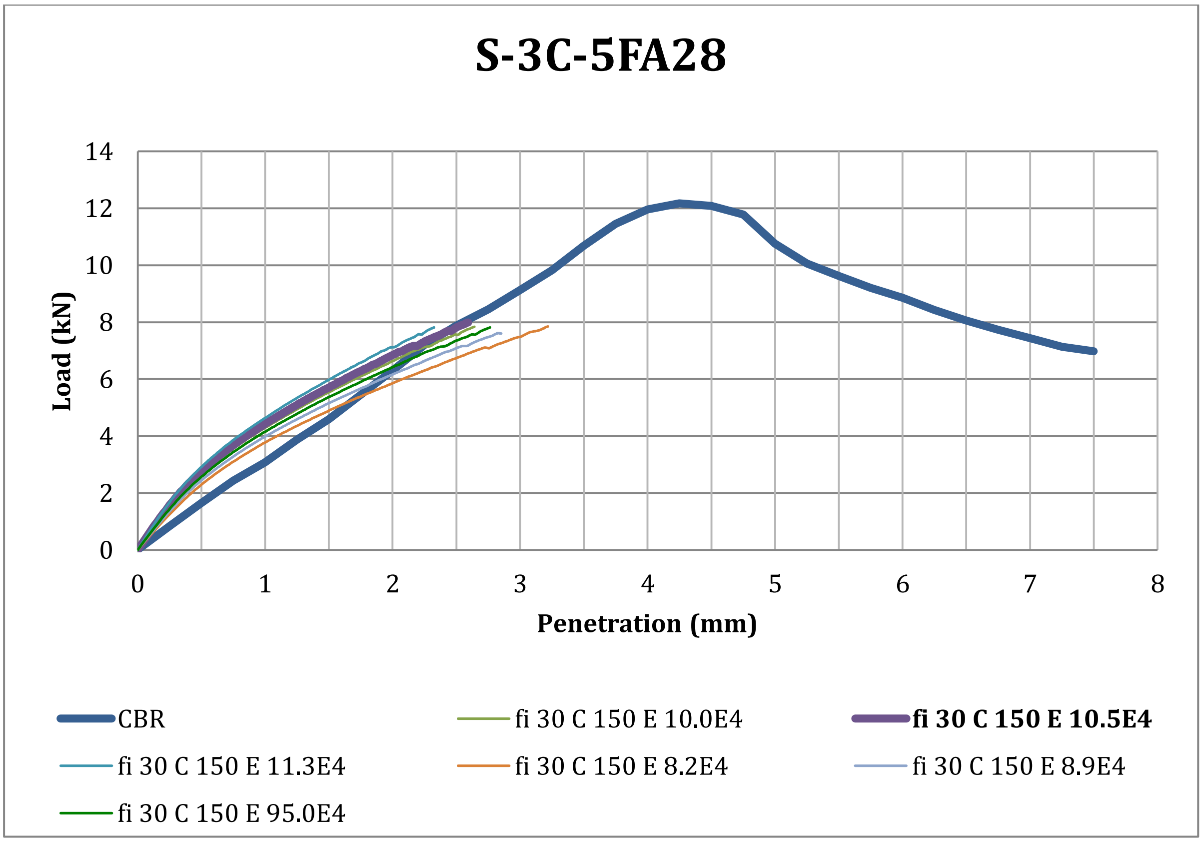


Figure 54: Plaxis/CBR comparison for sample S-3C-5FA28

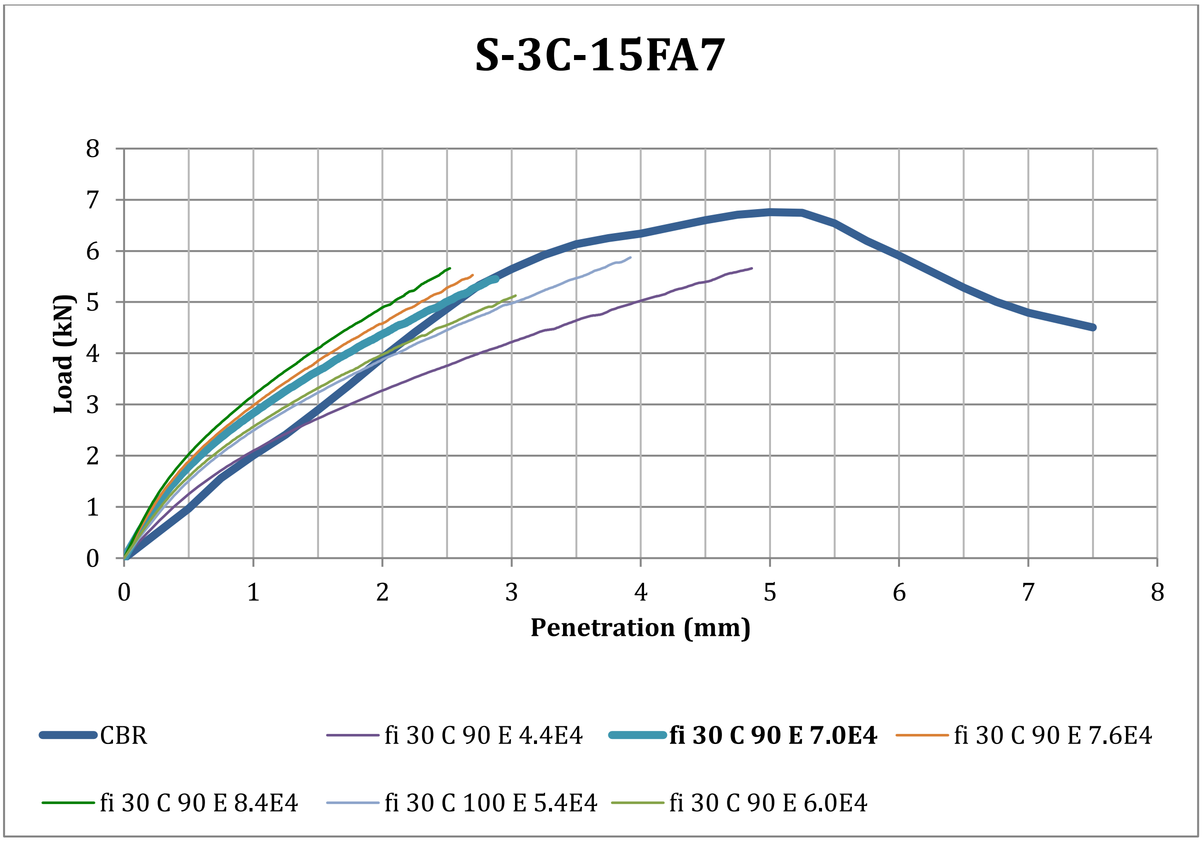


Figure 55: PLAXIS/CBR comparison for sample S-3C-15FA7

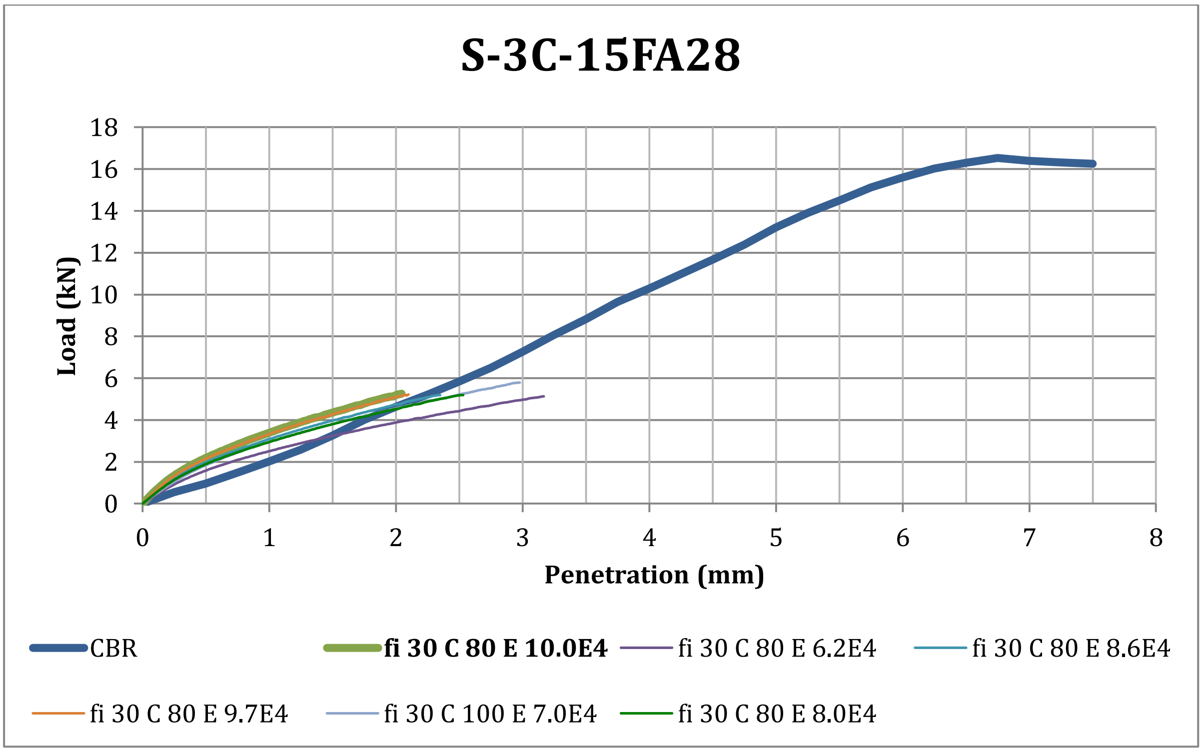


Figure 56: PLAXIS/CBR comparison for sample S-3C-15FA28

Table 23 shows the results of the PLAXIS analysis for all the samples. It shows that the correlations of CBR/E used to predict the Young's modulus (E_1) from the CBR results, proved to be inaccurate. The elasticity values achieved through PLAXIS simulation are significantly higher than E_1 values calculated. It can be seen that on average all the E_p values are about 20000 kN/m^2 higher than the E_1 values, and in case of samples S-3C-0FA28 and S-3C-5FA28, it is approximately two times greater. With the addition cement, 3% by content, the cohesion was multiplied by a factor 3.3 and 5 for samples S-3C-0FA7 and S-3C-0FA28 respectively. Overall, the cohesion was increased for all the samples by a minimum factor of 2.5.

Table 23: PLAXIS/CBR results

Sample	**E_1 (kPa)**	**PLAXIS Elasticity E_p (kPa)**	**Cohesion (kPa)**
S-0C-0FA	15154.76	43000	30
S-3C-0FA7	34823.16	61000	100
S-3C-0FA28	55626.28	140000	175
S-3C-5FA7	26745.66	58000	75
S-3C-5FA28	45338.19	105000	150
S-3C-15FA7	27804.73	70000	90
S-3C-15FA28	56273.48	100000	80

Figure 57 shows the effect of curing on Young's modulus obtained in PLAXIS simulation. In case of all the variants, the elasticity (E) was increased when the curing was increased from one to four weeks. The highest rise can be seen in the case of cement and the lowest for the S-3C-15FA series. Based on these PLAXIS results, the elasticity of samples cured for four weeks with 5% FA addition show a very similar value to that of samples with 15% FA addition. In fact, the S-3C-5FA28 sample achieved a Young's modulus of 105 MPa, 5 MPa higher than S-3C-15FA28.

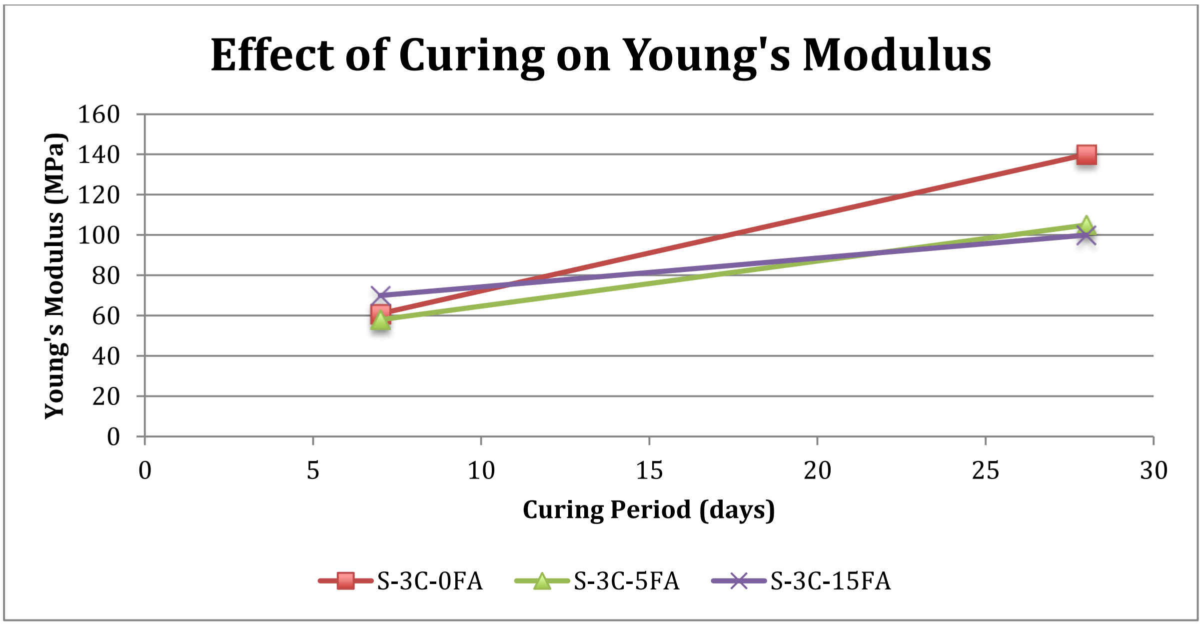


Figure 57: Effect of Curing on Young's Modulus by PLAXIS

FLAC

For the numerical analysis through FLAC, the Young's modulus and cohesion values obtained through PLAXIS were used initially. Thenceforth, multiple series, with different elasticity, cohesion and friction angles, were created for the FLAC analysis performed in this thesis. Each series was run to a maximum loading higher than that of peak CBR results, to the point of failure if possible. Figures 58-64 illustrate the results of FLAC analysis against the CBR results, so that the best-fit line, i.e. similar initial slope and similar peak values, to the CBR results, could be identified and analysed.

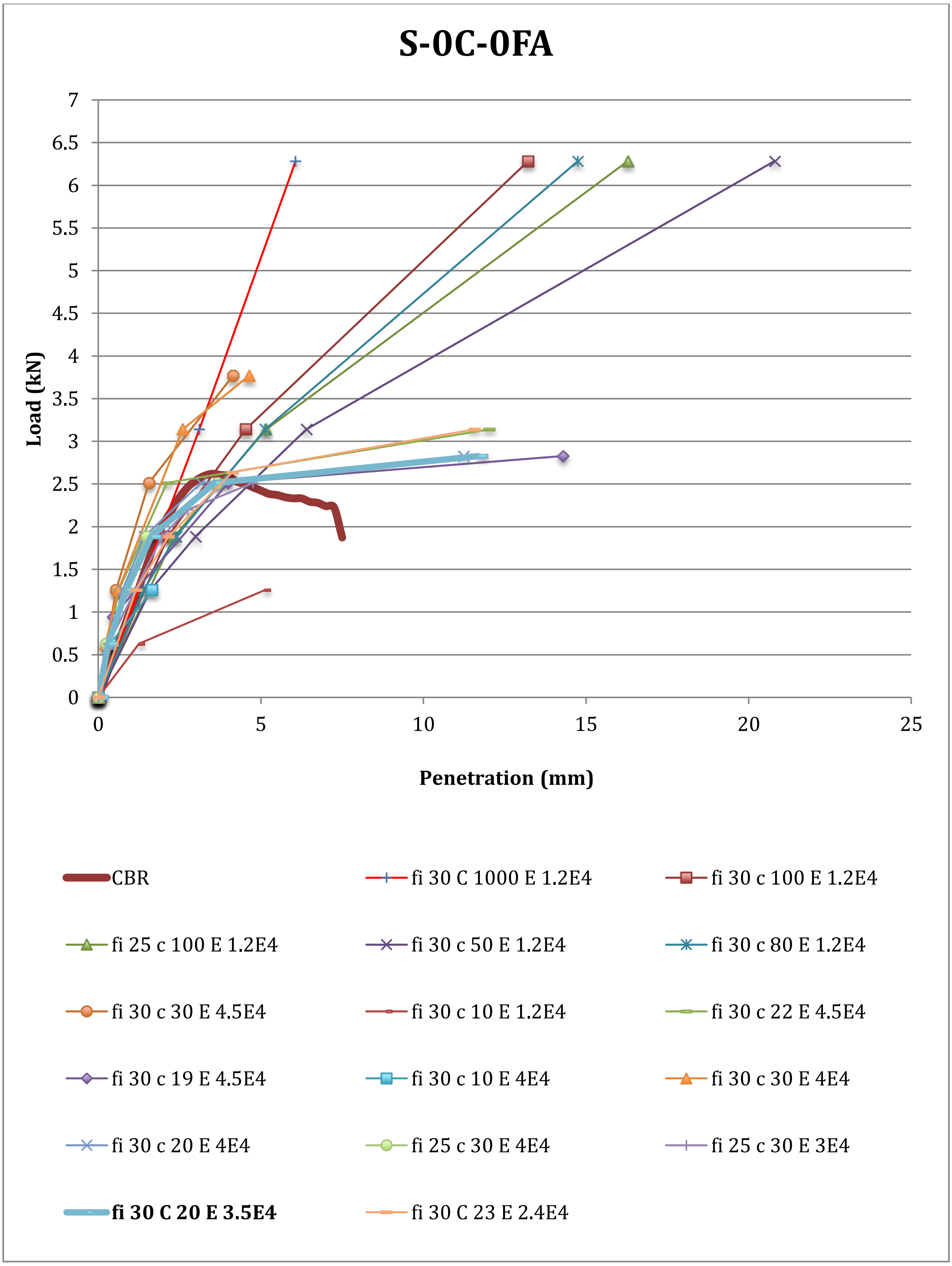


Figure 58: FLAC/CBR comparison for sample S-0C-0FA

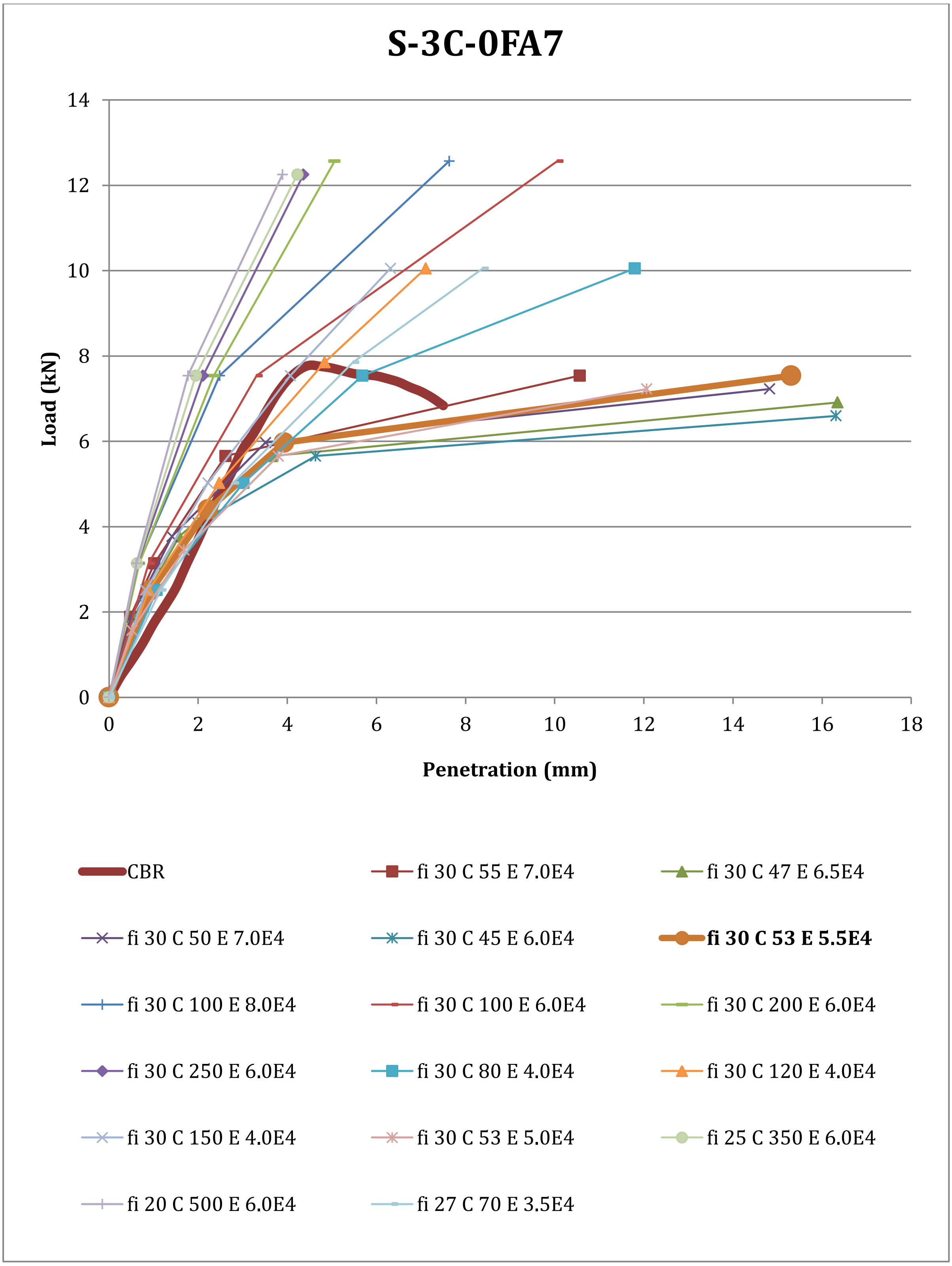


Figure 59: FLAC/CBR comparison for sample S-3C-0FA7

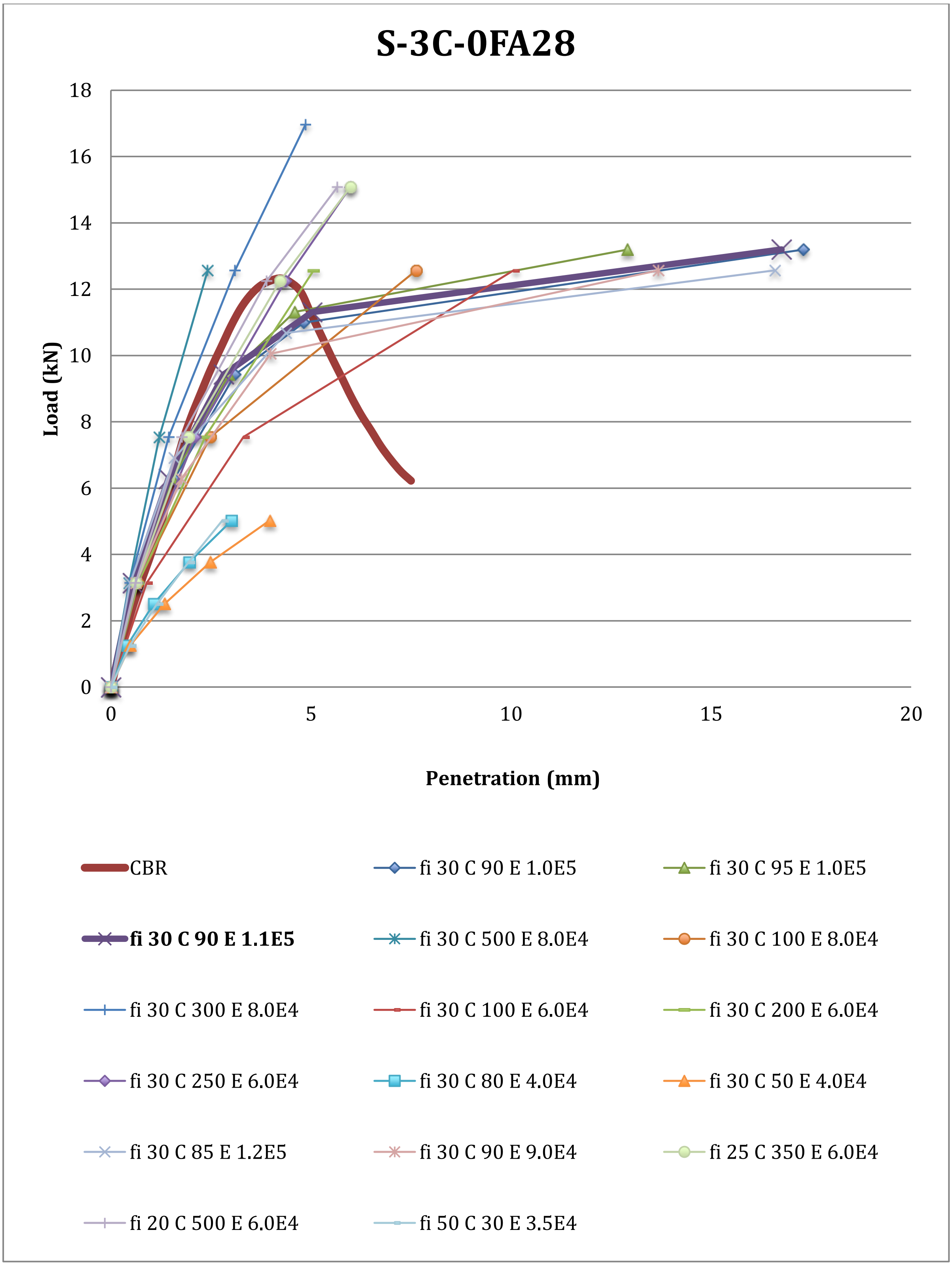


Figure 60: FLAC/CBR comparison for sample S-3C-0FA28

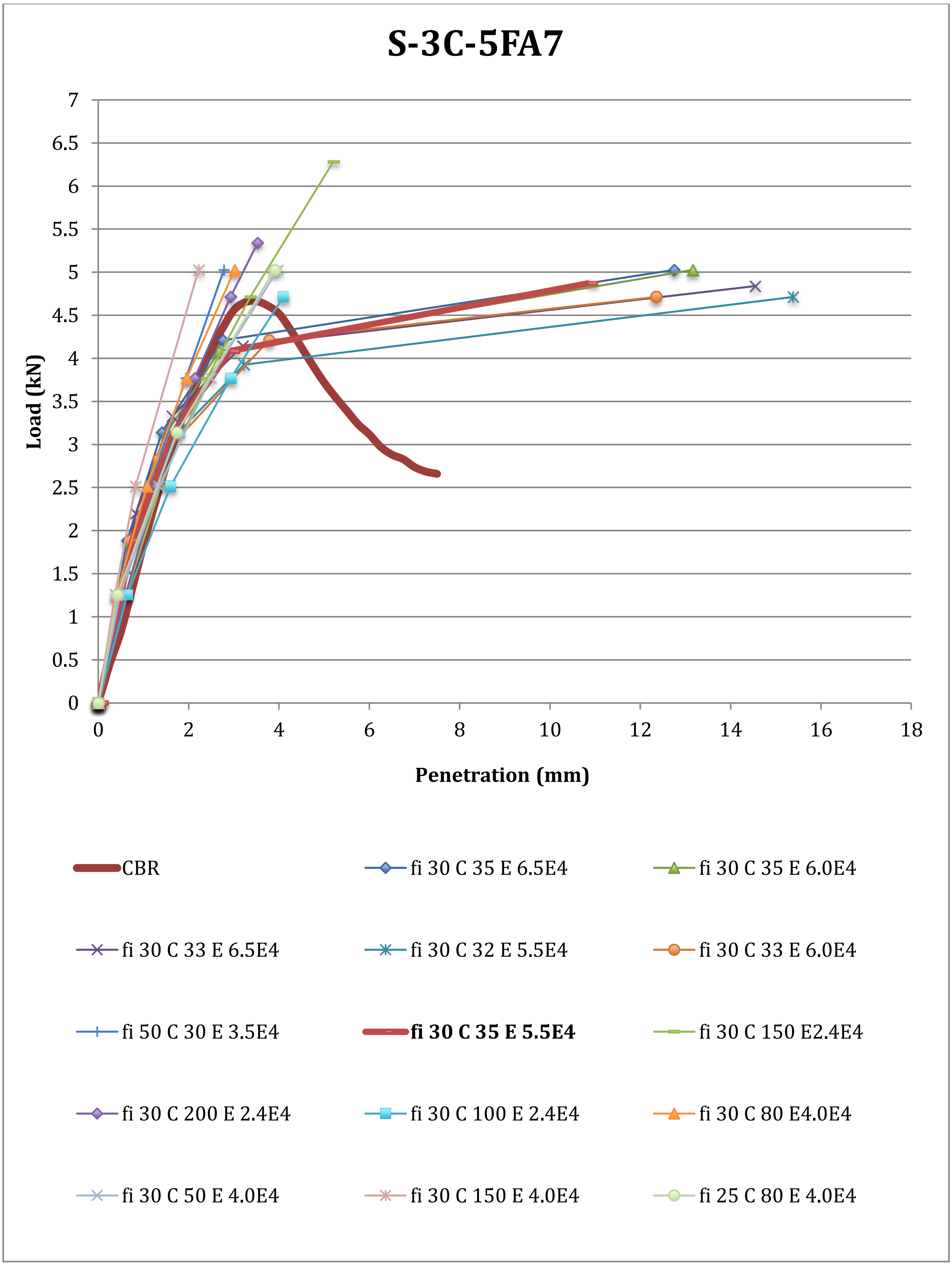


Figure 61: FLAC/CBR comparison for sample S-3C-5FA7

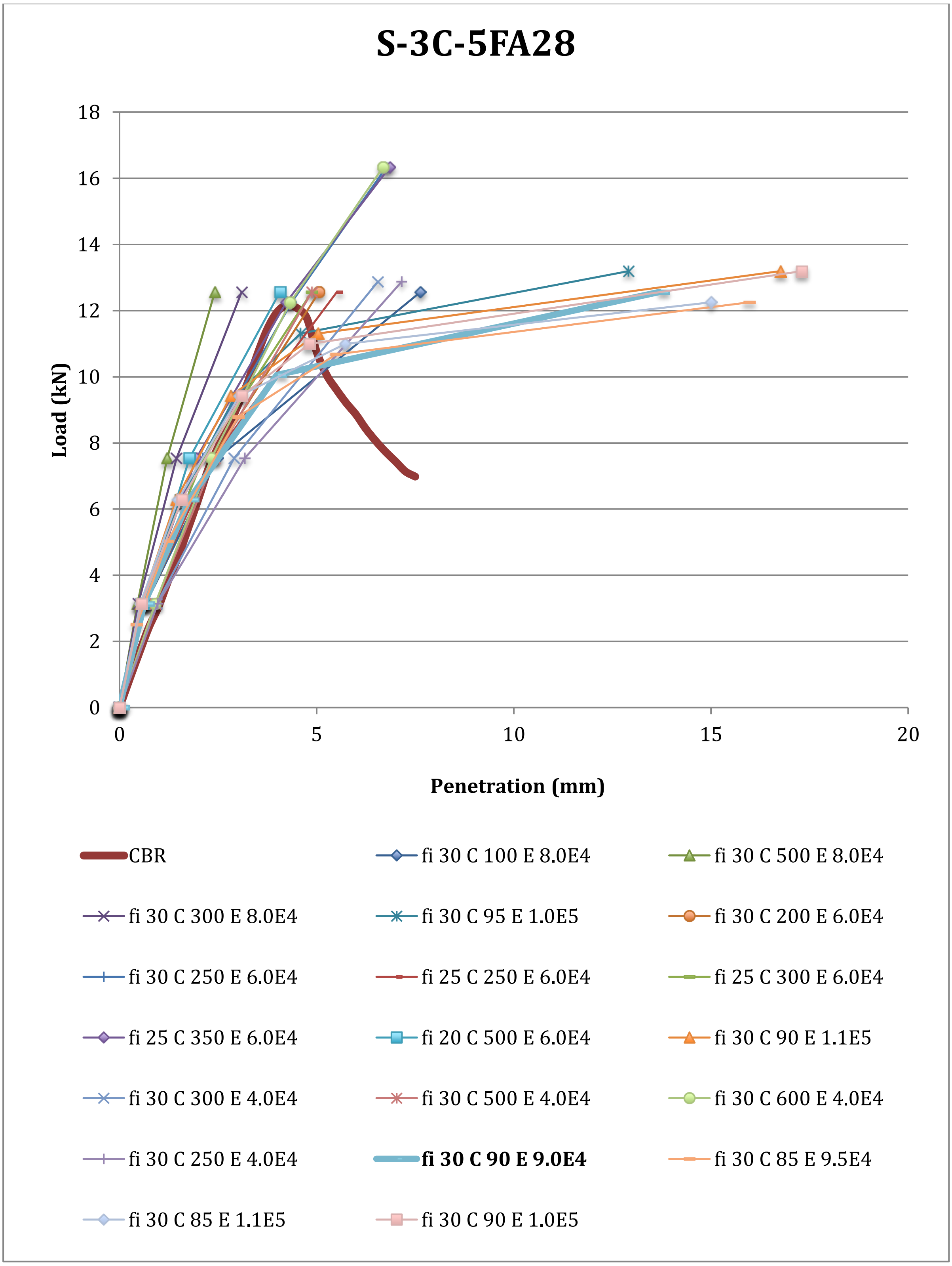


Figure 62: FLAC/CBR comparison for sample S-3C-5FA28

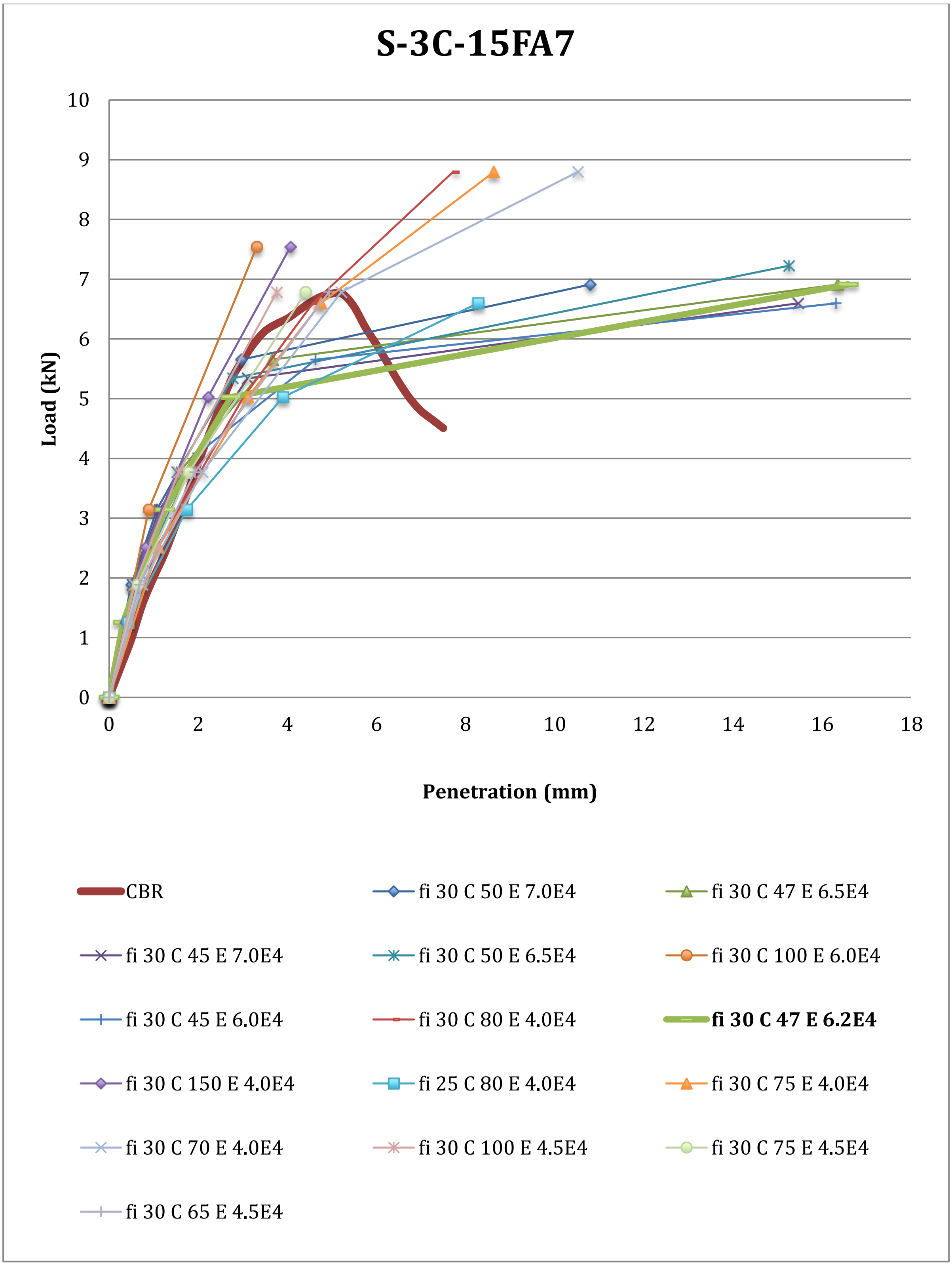


Figure 63: FLAC/CBR comparison for sample S-3C-15FA7

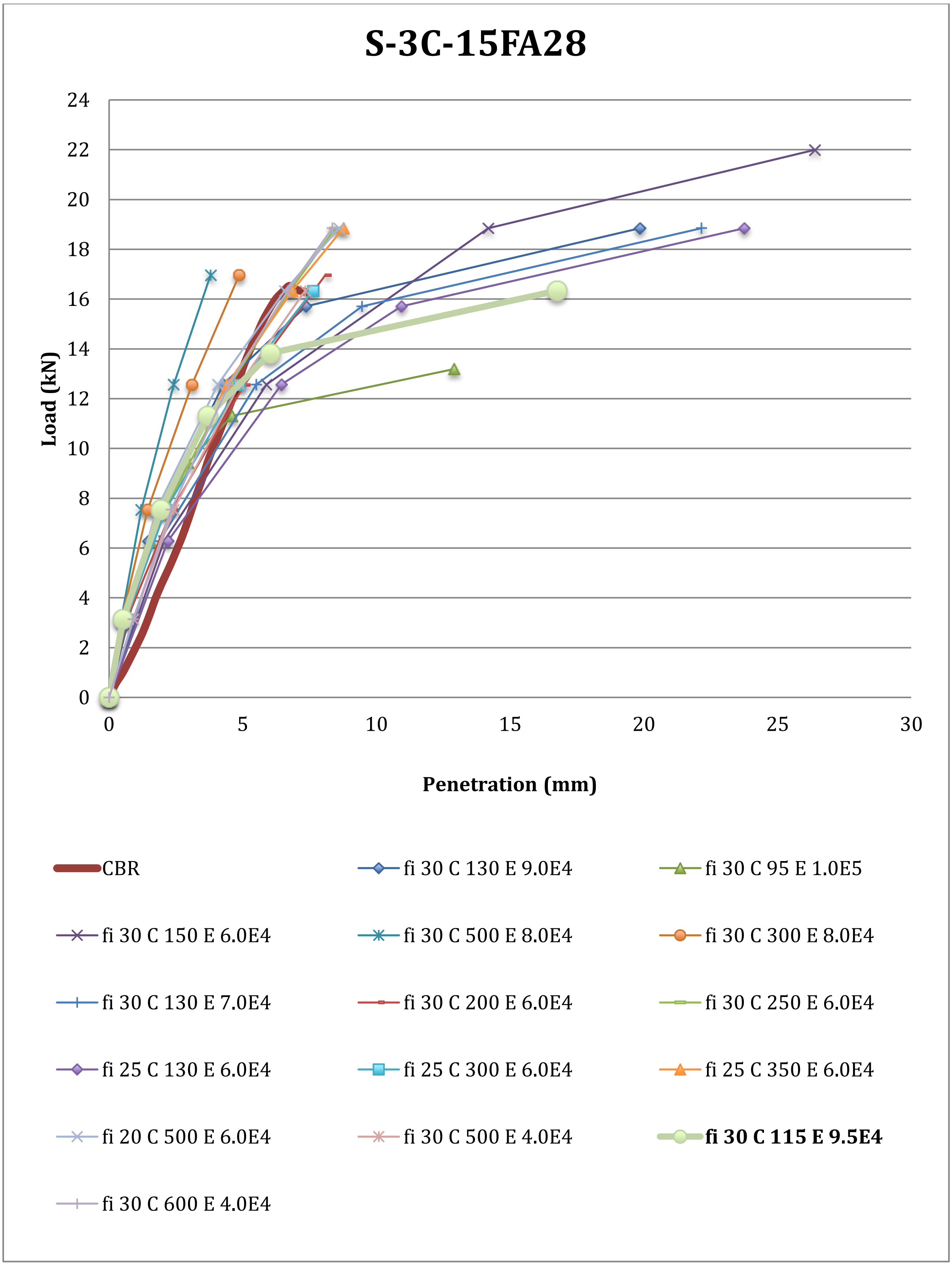


Figure 64: FLAC/CBR comparison for sample S-3C-15FA28

Table 24 shows the results of the FLAC analysis for all the samples. The results presented in Table 24, for each sample, is the result of the series that produced the best-fit, i.e. similar initial slope and similar peak values, to the CBR results. The elasticity values achieved through FLAC are very similar to those achieved through PLAXIS simulation. However the cohesion values are substantially lower in the results obtained through FLAC modelling, as the strain level simulated with FLAC is much higher and closer the failure point. It can be seen that curing period has major impact on the Young's modulus as well as the cohesion. Samples cured for four weeks, all obtained an elasticity of 90 kN/m^2 and over, with cohesion values of at least 90.

Table 24: Results of FLAC analysis

Sample	Elasticity (kPa)	Bulk (kPa)	Shear (kPa)	Cohesion (kPa)
S-0C-0FA	35000	29167	13462	20
S-3C-0FA7	55000	45833	21154	53
S-3C-0FA28	110000	91667	42308	90
S-3C-5FA7	55000	45833	21154	35
S-3C-5FA28	90000	75000	34615	90
S-3C-15FA7	62000	51667	23846	47
S-3C-15FA28	95000	79167	36538	115

Figure 65 illustrates the effect of curing on Young's modulus obtained by FLAC, while Figure 66 shows the effect of curing on the cohesion. The results in Figure 65 are of better consistency than the results obtained earlier with PLAXIS. The Young's modulus of all the variants was increased from one week curing to four weeks. The rate at which it was increased is of similar percentage. It can be seen that the longer the curing period the higher the possible obtainable elastic modulus. The elastic modulus increases as the strength of the samples increases, due to more time being available for the necessary bonds and reactions between the soil particles and the stabilising mix.

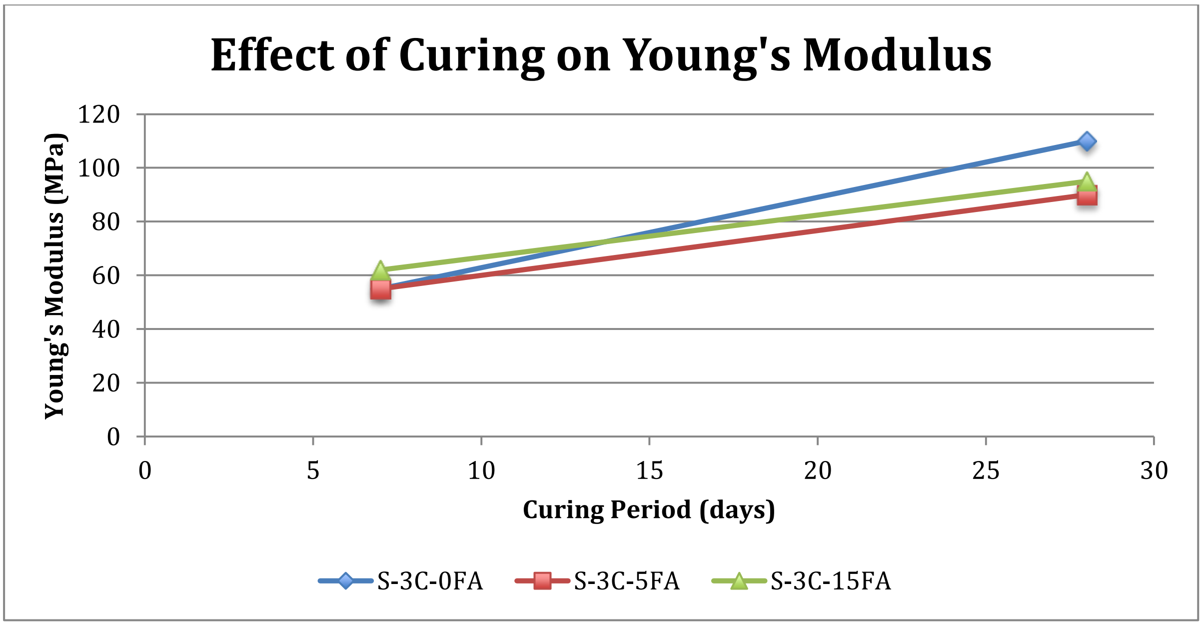


Figure 65: Effect of Curing on Young's Modulus by FLAC

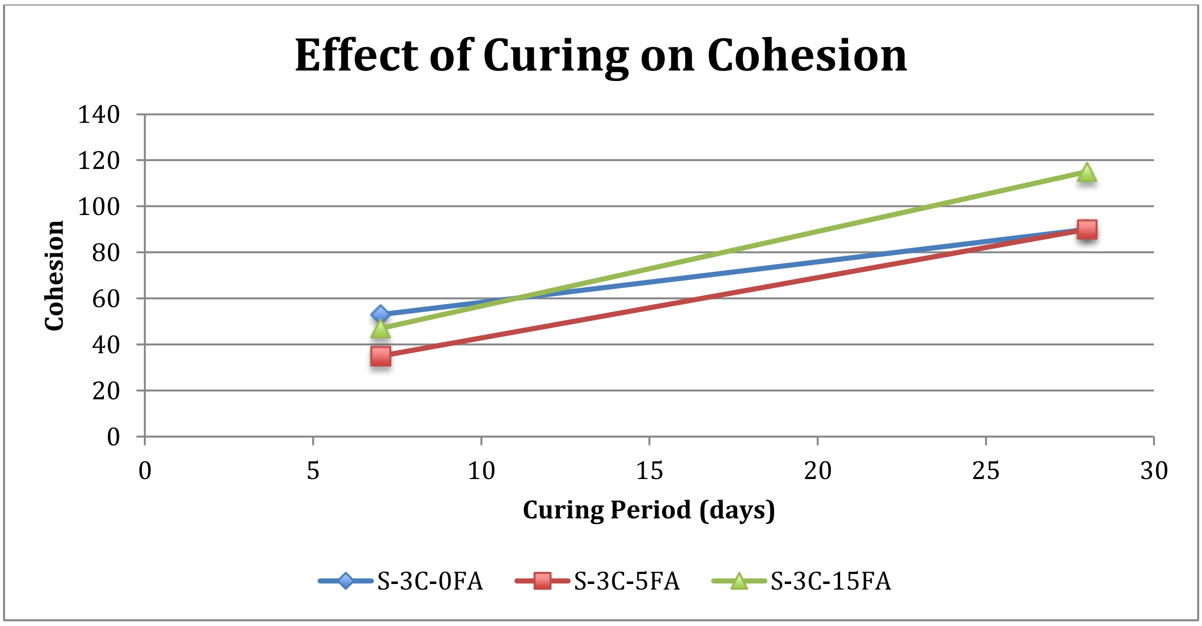


Figure 66: Effect of Curing on Cohesion by FLAC

Comparing the cohesion values at one week and four weeks curing period, it can be seen the cohesion of samples is dependable on the duration of curing. Samples with FA addition, S-3C-5FA and S-3C-15FA, show almost identical cohesion growth and the gradient of the trend. The results presented in Figure 66, shows that the higher the amount of FA, the higher the cohesion.

It has been demonstrated the possibility of the numerical simulations carried out in this study to represent the experimental results obtained in the laboratory. The parameters obtained by calibration could be employed in further numerical simulations of the embankments, with a given geometry, to predict the performance of such geo-structures in site for the different percentage of FA and also different curing durations.

Chapter 7

Conclusions and Future Research Lines

Coal-fired power stations are the source of about 40% of the world's energy production. It is clear that coal by-products (CCPs) production, FA in particular, will continue for the foreseeable future, especially as coal reserves around the world are to last for over 200 years and also because of the fact that CCPs are no longer classified as waste with hazardous characteristics. One of the key issues regarding the low utilisation rates of CCPs is the lack of awareness of its advantages and benefits, which is limiting new initiatives and market potential. There should be an integrated approach through the coordination of technologists, architects and manufacturers for the production of a superior quality of CCPs to meet consumer acceptability and increased marketability. Additionally, their utility should be made clear to the general public for mass consumption and effective utilisation.

Moreover, negative public image, the high number of regulations, limited data on environmental and health effects and low consistency of both quantity and quality of FA have created barriers to its utilisation. New technologies can provide higher rates of utilisation of waste, and recycled materials with larger volumes can decrease the demand for natural mineral resources. As it has been established, most of the FA produced worldwide is disposed of as landfill. Technological innovation can aid in minimizing the need for disposal of large volumes of waste material. The key findings of this research based on the literature review are:

- The origin and nature of the parent coal, conditions of combustion, type of emission control devices and storage and handling methods have a significant effect on the physical, chemical and mineralogical properties of FA.
- The strength gain is highly dependable on the percentage of the activator and the duration of curing.
- Soils stabilised with cement-based binders achieved higher and more consistent results in comparison to lime-based binders, in regards to mechanical strength.
- A combination of FA and cement stabilisation can aid in containing the leachate of heavy metals.
- FA can be delivered at less than a tenth of the price of common binders.
- Soils stabilised with class F FA achieved strengths three times higher than those achieved with class C.
- In terms of geo-engineering benefits, the finer the FA, the more effective the final results.
- Both fresh and landfilled FA are suitable and usable for engineering properties.
- No major environmental incidents have ever been reported for FA utilisation as an engineering fill material (in the UK).

- Permeability decreases as the FA content increases.
- Swelling pressure also decreases with the addition of FA.
- FA utilisation can protect ground water quality sufficiently.
- FA leachate has no perceptible impact on ground water quality.
- The minimum suggested activator content is 2%, and 5% for FA.
- In almost all the cases, the maximum dry density reduces and the optimum moisture content increases as the FA content increases.
- FA can significantly improve the CBR value through stabilisation.
- FA utilisation can be beneficial for environmental motives, i.e. use of a zero-cost raw material, conservation of natural resources such as soil, water, coal, and lime, elimination of waste and minimization of global warming.
- FA radiation is found to be negligible and as long as the requirements of nuisance dust are met, there is no increased health risk.
- Concrete domes were found to be the most economically viable and environmentally friendly FA storage approach.
- Further investigation and research is required on sand, clayey sand in particular, and also on high plasticity silts.
- The most effective mixture for stabilising the particular sand employed in this thesis, was found to be S-5C-10FA28, achieving a UCS of just under 4.0MPa, an improvement by a factor of over 153 times that achieved by 100% untreated sand.
- It is anticipated 20% FA content with 5% cement content and a curing period of four weeks would have achieved even higher unconfined

compressive strength, as after only seven days the UCS achieved was 1.7 MPa.

The following are key findings of the results obtained during this study:

- The ordinary Portland cement used in this research, at 3% content, had a profound influence on the dry density.
- The maximum dry density of the stabilised samples reduced with further addition of FA, because of the lightweight of FA in comparison to sand.
- The optimum moisture content of the stabilised samples increased with further addition of FA, because of the extra water required for hydration.
- Samples with FA contents of 10% and over, in particular of 5% cement content series, achieved results consistent with results in the literature, namely higher optimum moisture content and lower maximum dry density.
- CBR values were profoundly affected by the cement content: achieving a CBR value of about 562% higher than the sand in just over seven days, when 5% cement was used.
- The bearing capacity also increased as the FA content was increased.
- The curing duration had a direct influence on the achieved CBR values: the longer the curing period, the higher the CBR.
- Samples cured and stabilised with FA and 3% cement content all achieved CBR values lower than the samples without FA, except one (S-3C-15FA28).
- For effective curing and achieving CBR values, i.e. high bearing capacity and high strengths, and obtaining strong upward correlations as curing

time expands, 5% cement content was found more suitable than 3% for the sand tested in this research.

- As the FA content of the samples is increased the higher the penetration the samples could withhold prior to point of failure.

The key findings of the numirical anaylsis undertaken are:

- After performing the numerical simulations through both commercial codes, it was found, the longer the curing period the higher the Young's modulus.
- Also, it was found that the cohesion is directly dependent on the FA content, the higher the FA content, the higher the cohesion.
- The correlated results of Modulus of resilient are in agreement of pavement design requirements, hence a suitable material for embankment construction.

FA is the fifth largest raw material resource in the world and its utilisation can be a sustainable business providing cost-effective solutions to pertinent problems. It contributes significantly to the economy as well as resource conservation and fewer CO_2 emissions. A prime environmental benefit of using FA is a reduction in the amount of Portland cement used, as the CO_2 emitted during cement production is nearly 230 times higher than FA. In order to reduce the environmental pollution caused by FA and promote its comprehensive utilisation, governments should organize experts and offer significant funding to investigate it. Reasons to increase FA utilisation include:

- A smaller area is reserved for disposal, thus enabling other uses of the land and decreasing disposal-permitting requirements.
- The by-products can replace some scarce or expensive natural resources.

Space is running out for the storage and landfilling of unused FA and transforming landfills from a major cost to society into a resource recovery opportunity has received little or no attention. Landfills could be the future mines for construction materials. Utilising the stored FA in landfills could be possible through any of the methods mentioned in this thesis. Beneficial reuse of FA can potentially result in conserving production energy, providing sustainable construction and economic growth. It can be said that with a strong strategy and management from the manfacturers the rate of FA utilisation can become much higher than of its current value.

The long-term performance must be extrapolated from short-term laboratory tests, which are a source of uncertainty. As a result, more research should involve the topic of variation in results between tests in the field and laboratory tests. In research of the literature, it was found that one of the available methods to close this gap is to leave the sample for one to two hours after mixing to duplicate the conditions of the site. It should be pointed out that both the nature of the FA and the type of soil significantly influence the results of stabilisation and it is very challenging and unsafe to rely on research carried out with different soils and different FA quantities.

The characteristics of FA are changing as coal-fired power plants respond to increasing air pollution and environmental regulations. This means further investigation and laboratory tests being required for the analysis of changed FA characteristics. Furthermore, as there are a huge variety of soils, all with different characteristics and properties, further analysis should be carried out between the soil types to see how the soil type affects the achievable strength of that sample. It is recommended that more research be carried out in order to close the knowledge gap regarding the material. As the CBR values obtained for eight weeks curing showing the S-3C-15FA56 sample achieving lower CBR than S-3C-0FA56, further tests for these two variants are highly recommended, so that a more true analysis can be obtained. It is also possible to obtain more accurate and reliable CBR results for variation S-3C-15FA56, with further testing with a higher number of samples.

Moreover, the addition of binders is also dependable on the mechanical strength required for the project, which needs extensive laboratory testing for determining the most suitable percentage. It should also be pointed out that different stabilisers need different curing times in order to reach adequate strength, which likewise requires laboratory testing.

FA is regarded as a valued resource and with relevant research and investigations can be utilised in geo-engineering projects, as its utilisation is environmentally friendly as well as cost-effective. Based on the test results of this research, it is proven that FA, with an adequate cement addition, has the potential to be an effective material suitable for use in embankment construction and projects alike. It can reduce the environmental burdens currently faced while increasing the physical characteristics. Laboratory tests performed in this study show the possible strength gains that can be obtained for sandy soils and with further investigations and analysis could be potentially utilised for practical applications, i.e. roads, embankments and reclamation of low-lying areas. This will lead to a sustainable utilisation of FA, the chief constituent of coal byproducts. Subsequently, the manufacturers will be faced with lower landfill costs, and with landfill tax being increased continuously; it will be very financially beneficial to them.

FA stabilised samples, with an accurate mixture, were shown to have lower dry densities while producing higher strengths than the sand. This can cause a reduction in the overall thickness of pavement layers in embankment construction, and ultimately savings on the costs. Currently, there are inadequate data in the literature investigating the long-term performance of soil stabilisation. Also, as a significant amount of the FA produced around the world is still disposed of, and with utilisation rates at 16% worldwide, further examination and research on FA utlisation is highly recommended, particularly in the field of soil stabilisation, which has the lowest utilisation rates in the construction field.

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Appendices

The Appendices chapter is in three parts, Appendix A, Appendix B and Appendix C. Appendix A constitutes of the compaction results of each individual compaction curve for all the different variants tested throughout this research. Appendix B, presents each individual CBR results of all the variations of cement and FA contents and the different curing periods. In Appendix B the CBR results are also tabulated and averaged. Appendix C presents the COSHH risk assessment for the tasks undertaken in the laboratory.

Appendix A

This section presents five compaction curves for sand only and 3 compaction curves for the other mixtures.

Figure A.1 shows the results of sand (S-0C-0FA) compaction tests. It can be seen that samples 2, 3 and 5 have similar peak dry densities, while samples 1, 2 and 3 have similar water content at their peak densities. The maximum dry density and optimum moisture content of each sample is tabulated in Table A.1. The highest optimum moisture content belongs to sample 3 (13.75%), and the lowest (12.75%) to sample 5. However, the lowest and highest maximum dry density occurs in samples 4 and 1 respectively.

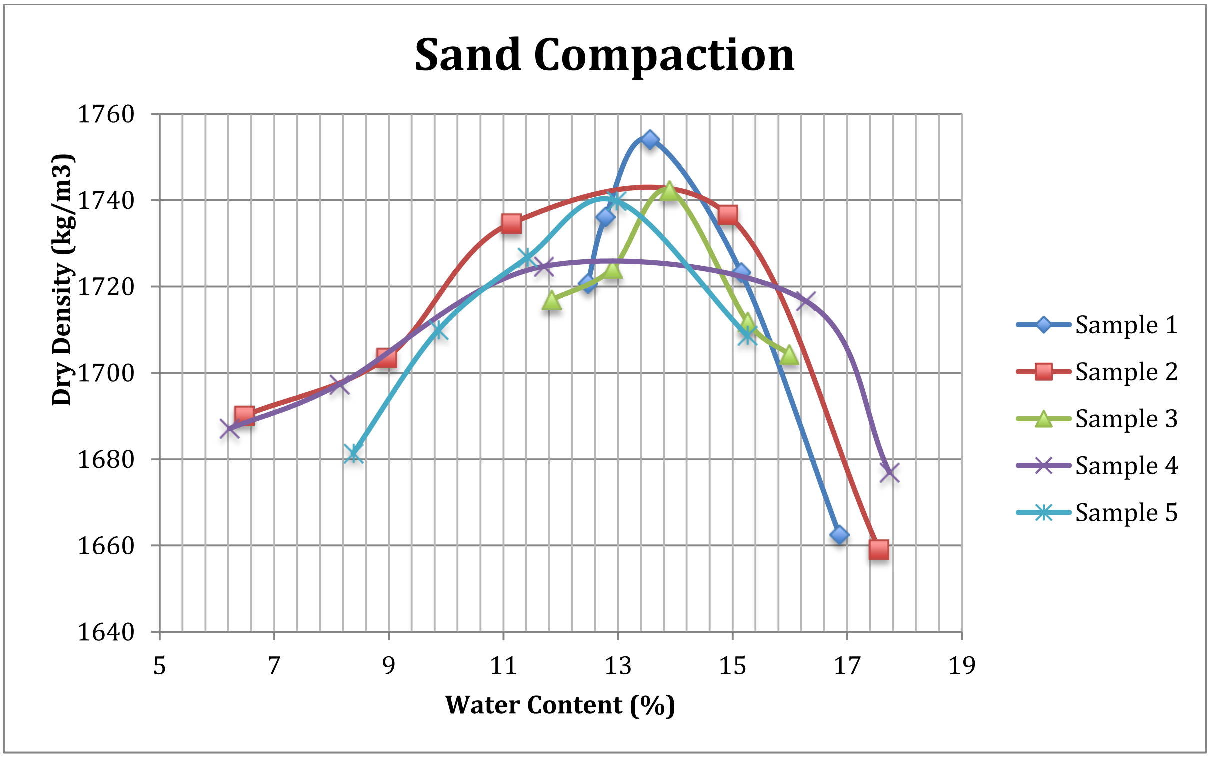

Figure A.1: Sand compaction test results (S-0C-0FA)

Table A.1: Average MDD and OMC of sand (S-0C-0FA)

Sample	OMC %	Average OMC	MDD kg/m^3	Average MDD
1	13.35		1755	
2	13.6		1742	
3	13.75	13.31 %	1743	1741.4 kg/m^3
4	13.1		1727	
5	12.75		1740	

The average OMC and MDD for sand alone were calculated to be 13.31% and 1741.14 kg/m^3. The derived moisture content of 13.31% was used to prepare the sand alone (S-0C-0FA) samples for CBR testing, where the material was at its optimum conditions. As sample 2 had the closest similarity in both MDD and OMC of the calculated average value in comparison to the other samples, it was chosen for the final compaction comparison graph, which was presented at the end of section 5.3.

The results of the compaction tests of soil with an addition of 3% cement are illustrated in Figure A.2. All three samples tested show very similar optimum moisture content as well as maximum dry density. The maximum dry density and optimum moisture content of each sample is tabulated in Table A.2. It can be seen that the range in OMC and MDD is 0.5% and 7 kg/m^3 respectively. As sample 2 has identical optimum water content to that of derived average value, it was chosen to be presented in the comparison compaction graph.

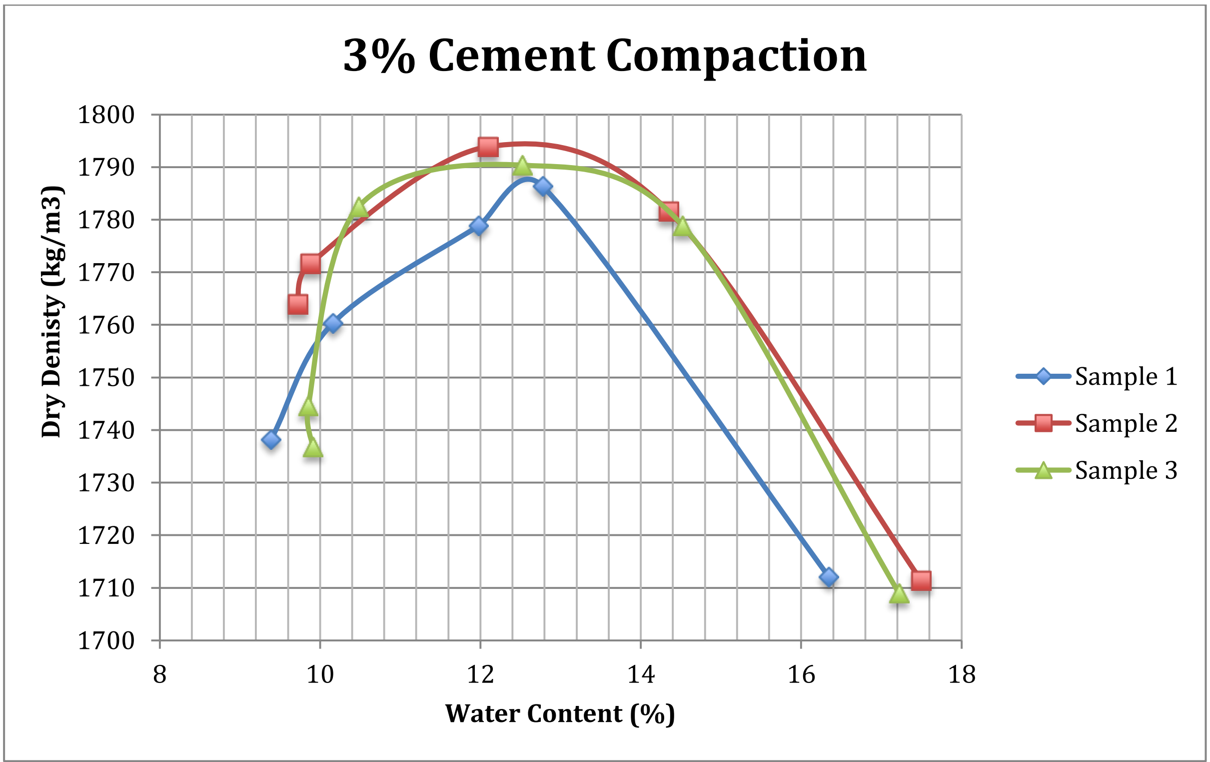

Figure A.2: Sand-cement (3%) compaction test results (S-3C-0FA)

Table A.2: Average MDD and OMC of sand and 3% cement (S-3C-0FA)

Sample	OMC %	Average OMC	MDD kg/m^3	Average MDD
1	12.6	12.35%	1787	1790.67 kg/m^3
2	12.35		1794	
3	12.1		1791	

The compaction results of soil with an addition of 5% cement are illustrated in Figure A.3. All three samples tested show almost identical optimum moisture content as well as maximum dry density. The maximum dry density and optimum moisture content of each sample is tabulated in Table A.3. It can be seen that the range in OMC and MDD is 0.5% and only 1 kg/m^3 respectively. As sample 2 has the closest optimum water content to that of derived average value, it was chosen to be presented in the comparison compaction graph.

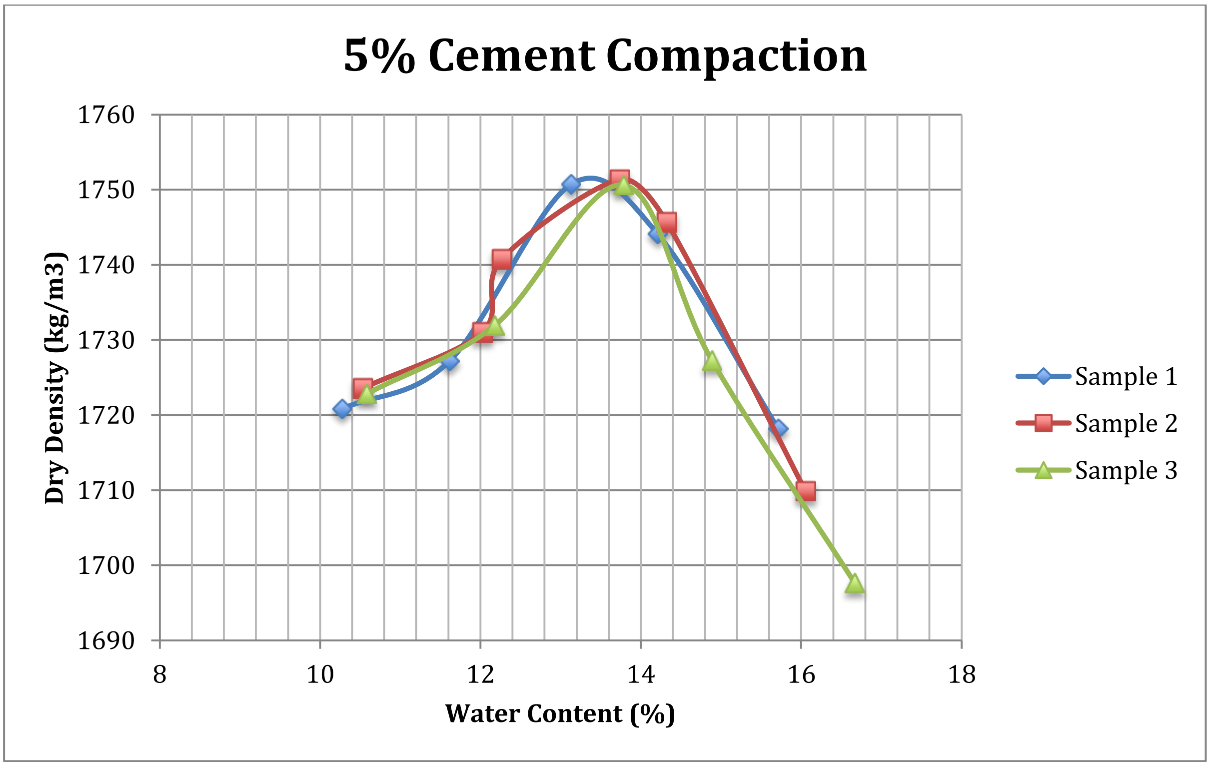

Figure A. 3: Sand-cement (5%) compaction test results (S-5C-0FA)

Table A.3: Average MDD and OMC of sand and 5% cement (S-5C-0FA)

Sample	OMC %	Average OMC	MDD kg/m^3	Average MDD
1	13.3		1751	
2	13.75	13.62%	1751.5	1751 kg/m^3
3	13.8		1750.5	

The compaction results of FA-soil mixtures with 5% FA content (S-3C-5FA) are shown in Figure A.4. The optimum moisture content has a range of 1.7% between the lowest and the highest samples, 1 and 2 respectively. The compaction tests were performed under the same conditions and on the same day. Table A.4 is the comparison table of the results of (S-3C-5FA) compaction. The maximum dry density for this variation was calculated to be on average 1812.67 kg/m^3 and the optimum moisture content to be on average 12.43%. Sample 3, having the closest similarity to these average values, was chosen for the final compaction graph.

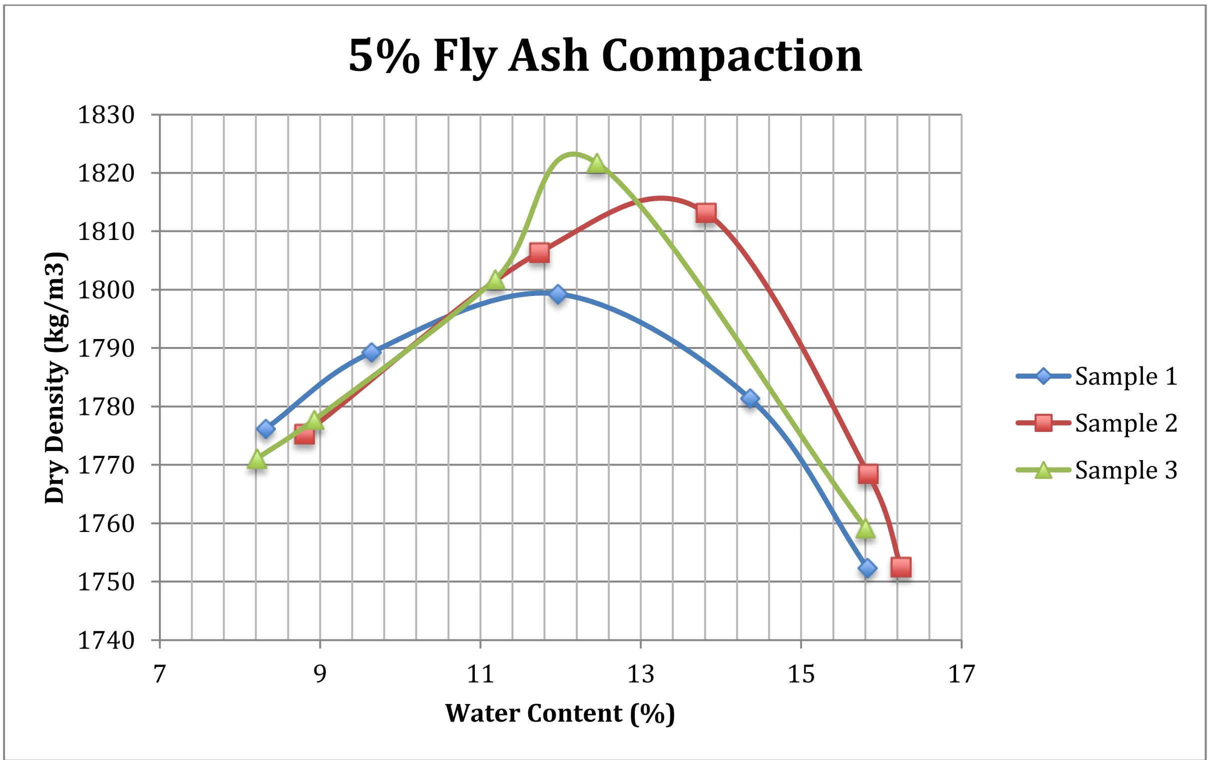

Figure A.4: Sand-FA (5%) compaction test results (S-3C-5FA)

Table A.4: Average MDD and OMC of sand and 5% FA (S-3C-5FA)

Sample	OMC %	Average OMC	MDD kg/m^3	Average MDD
1	11.7	12.43	1800	1812.67 kg/m^3
2	13.4		1815	
3	12.2		1823	

Figure A.5 shows the compaction curves as a result of the compaction testing of 10% FA content samples (S-3C-10FA). The optimum water content between the three samples has relatively high similarity with a range of less than 1%. Samples 1 and 3 also show significant similarity in their maximum dry density values, with a difference of only 1 kg/m^3. Table A.5 shows the results of both the MDD and OMC, including their derived average value. With an average OMC value of 14.2% and an average MDD value of 1778.67 kg/m^3, sample 1 shows the closest likeness to these average values. Therefore, sample 1 of S-3C-10FA variation was chosen as the representative sample for the final compaction comparison graph.

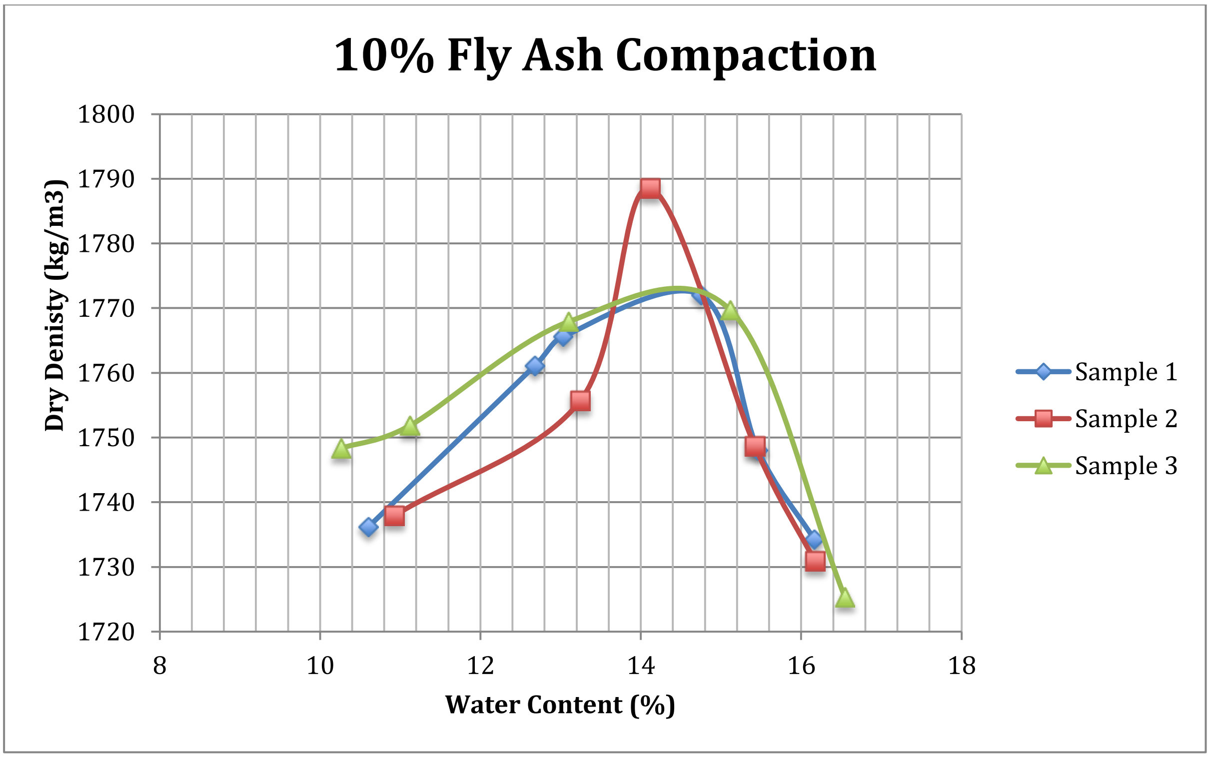

Figure A.5: Sand-FA (10%) compaction test results (S-3C-10FA)

Table A.5: Average MDD and OMC of sand and 10% FA (S-3C-10FA)

Sample	OMC %	Average OMC	MDD kg/m^3	Average MDD
1	14.25	14.2	1774	1778.67 kg/m^3
2	13.75		1789	
3	14.6		1773	

The final series of compaction tests, which were performed for identification of optimum moisture content and maximum dry density of S-3C-15FA samples, are shown in the compaction curve graph (Figure A.6). In this variation compaction test, the most significant similarity of both the maximum dry density and optimum moisture content values between the three samples can be seen. The range in OMC is only 0.25%, while the range in MDD is only 9 kg/m^3, in other words, a range of just 0.5% from the lowest to the highest value. The results of Figure A.6 are tabulated in Table A.6, where the average values of OMC and MDD were also calculated. Sample 3 shows the highest similarity between its OMC and MDD values and those of the derived average values. Consequently, sample 3 of S-3C-15FA compaction tests was chosen to be presented in the final compaction graph in the following section.

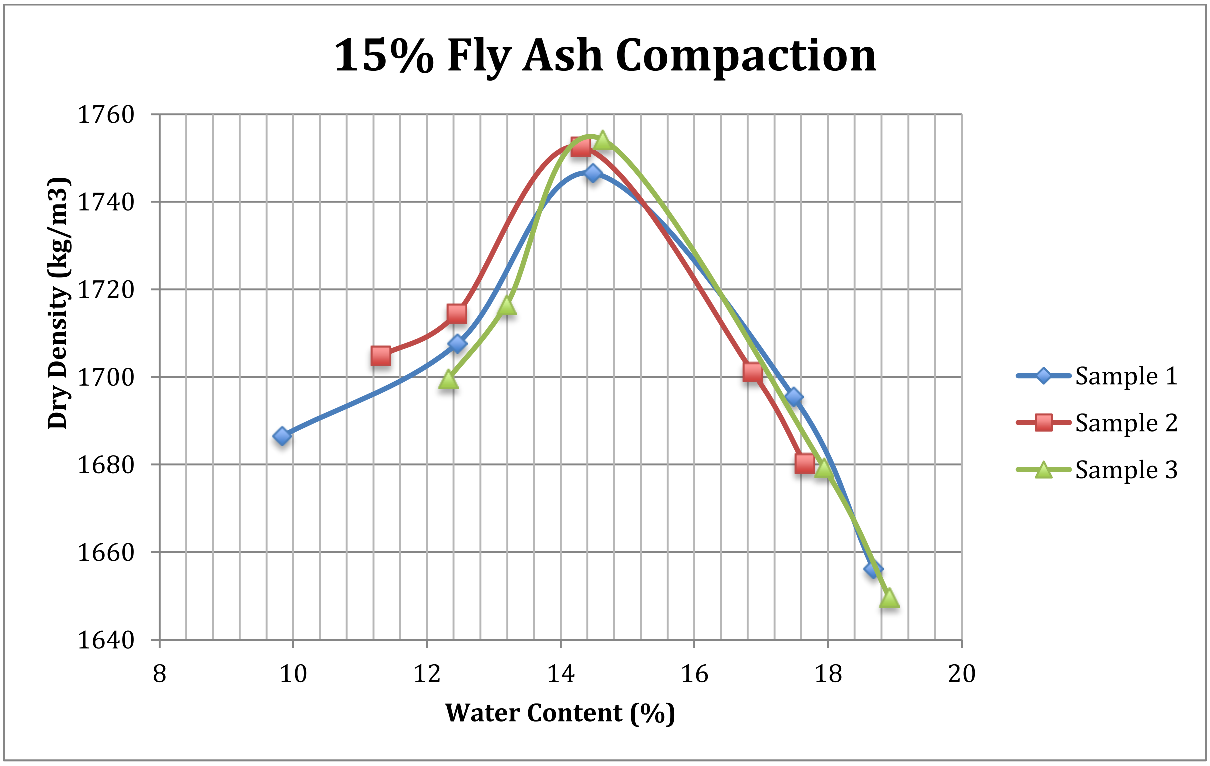

Figure A.6: Sand-FA (15%) compaction test results (S-3C-15FA)

Table A.6: Average MDD and OMC of sand and 15% FA (S-3C-15FA)

Sample	OMC %	Average OMC	MDD kg/m^3	Average MDD
1	14.45	14.35	1747	1752.33 kg/m^3
2	14.2		1754	
3	14.4		1756	

Appendix B

In this section the CBR results of series S-3C-0FA, S-5C-0FA, S-3C-5FA, S-3C-10FA and S-3C-15FA, with all the different curing periods are presented.

The CBR results of sand with an addition of 3% cement and curing period of seven days (S-3C-0FA7) are shown in Figure B.1. The force readings at 2.5mm and 5.0mm displacement were determined and their corresponding CBR values derived. This was followed by calculation of the average value of all the highest CBR values of each sample. The CBR calculations for S-3C-0FA7 samples are stated in Table B.1.

Table B.1: Average CBR value for S-3C-0FA7

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	7.4801	56.7	9.2093	46.0	56.7	41.4
2	4.7815	36.2	7.7159	38.6	38.6	
3	3.2488	24.6	5.8033	29.0	29	

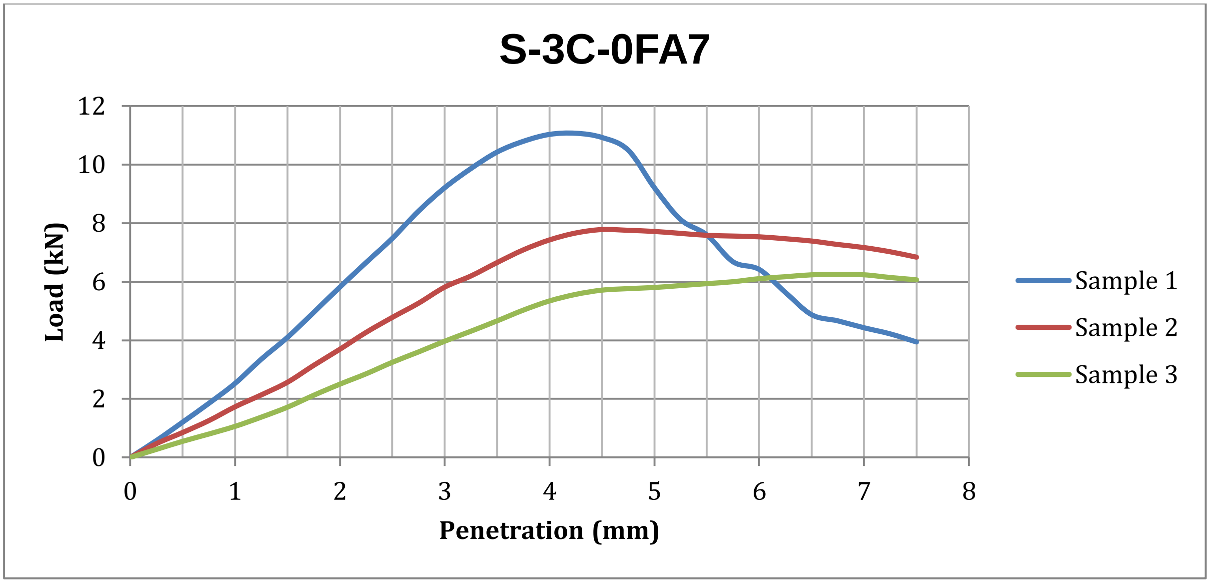

Figure B.1: CBR test results for S-3C-0FA7

The CBR values of all the samples are calculated to be on average 41.4%. The CBR values for sample 1 and 3 are substantially higher and lower, respectively, than the derived average value. For that reason sample 2 of this variation, S-3C-0FA7, was chosen to be presented in the final CBR analysis.

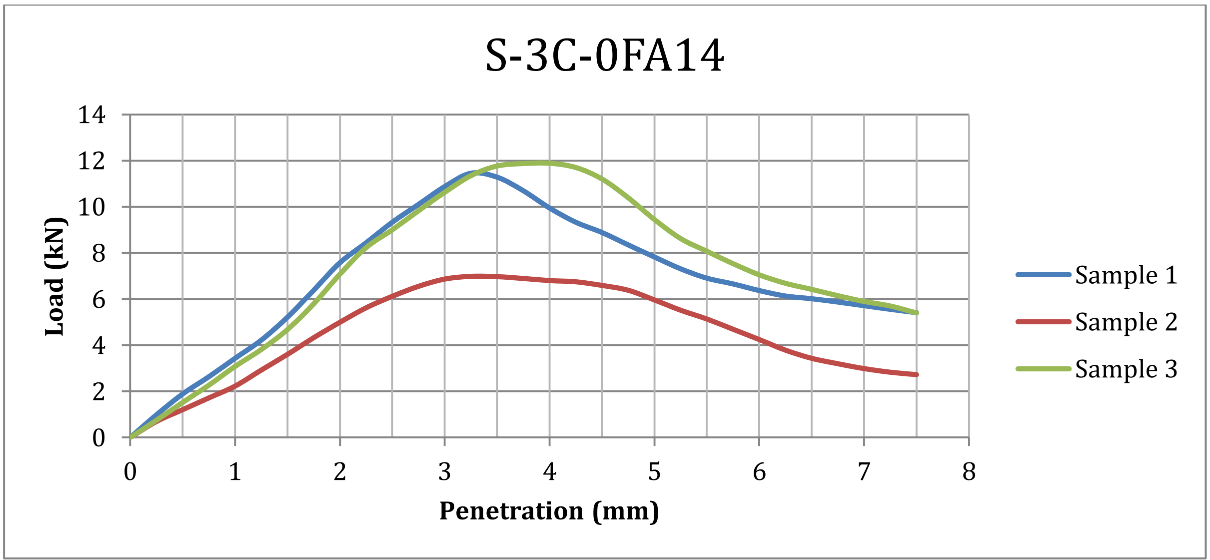

Figure B.2: CBR test results for S-3C-0FA14

The Force/Displacement graph, Figure B.2, presents the CBR results of sand with an addition of 3% cement with curing duration of fourteen days. The recorded forces at displacements of 2.5mm and 5.0mm were determined and then like before, converted into CBR values. These calculations are presented in Table B.2.

Table B.2: Average CBR value for S-3C-0FA14

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	9.3272	70.7	7.8207	39.1	70.7	61.7
2	6.1177	46.3	5.9605	29.8	46.3	
3	8.9997	68.2	9.4451	47.2	68.2	

Sample 3 has the highest similarity to the derived average CBR value, and as can also be seen in Figure B.2, it lies in between samples 1 and 2 (at 2.5mm displacement). It was therefore chosen as the representative sample of S-3C-5FA14 variation for the final CBR analysis.

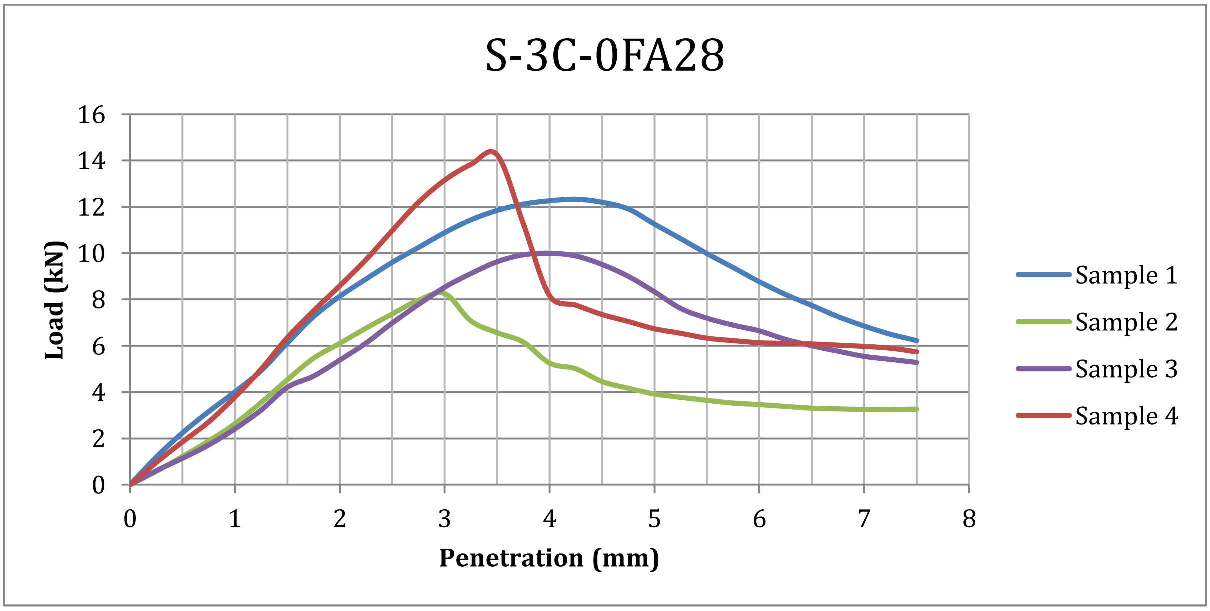

Figure B. 3: CBR test results for S-3C-0FA28

The results of CBR tests for 3% cement content samples that were cured for 28 days (S-3C-0FA28) are shown in Figure B.3. It can be seen that samples 3 and 4 have a very similar force at 2.5mm displacement, while samples 1 and 2 have a much higher force at the same penetration level. Sample 2 apparently peaked in force value after a displacement of 2.0mm and fail rather badly, dropping significantly after about 3.5mm displacement. The CBR values were obtained by converting the force values at 2.5mm and 5.0mm displacement. The calculations are stated in Table B.3.

Table B.3: Average CBR value for S-3C-0FA28

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	9.6023	72.7	11.2529	56.3	72.7	66.2
2	7.3753	55.9	3.9169	19.6	55.9	
3	6.9823	52.9	8.3316	41.7	52.9	
4	10.9778	83.2	6.7334	33.7	83.2	

The average value is about 6% less than the highest CBR in sample 1 and over 10% higher than highest CBR in sample 3. As sample 1 shows a better consistency in the graph and is closer to the derived average value, it was chosen as the representative of S-3C-0FA28 samples.

The CBR results of sand with an addition of 3% cement and curing period of eight weeks (S-3C-0FA56) are shown in Figure B.4. The force readings at 2.5mm and 5.0mm displacement were determined and their corresponding CBR values derived. This was followed by calculation of the average value of all the highest CBR values of each sample. The CBR calculations for S-3C-0FA56 samples are stated in Table B.4.

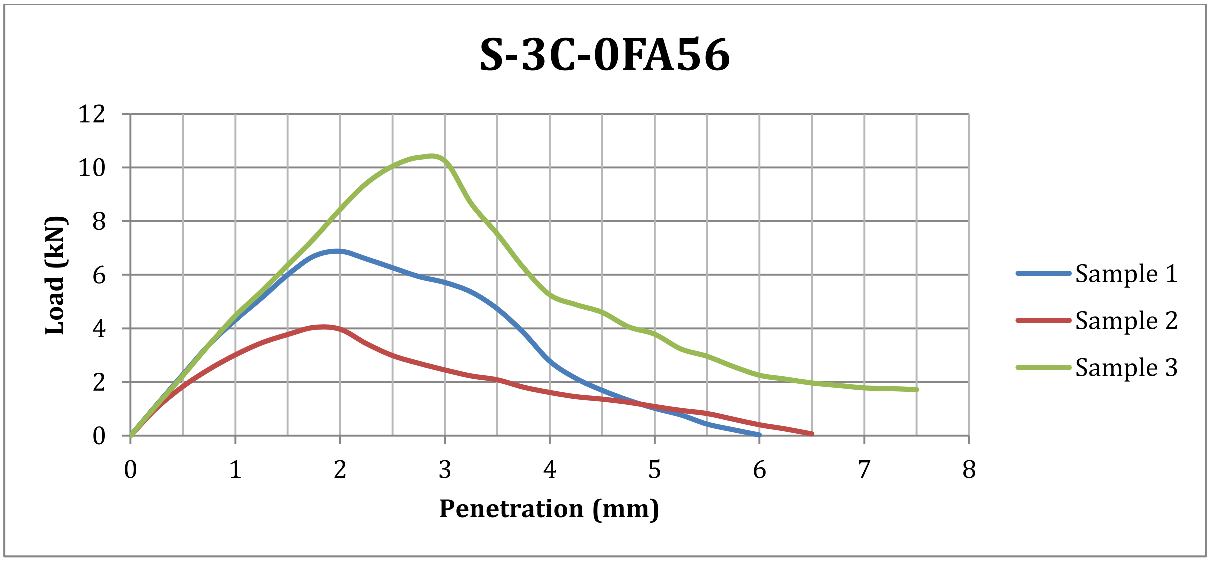

Figure B.4: CBR test results for S-3C-0FA28

Table B.4: Average CBR value for S-3C-0FA56

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	6.2618	47.4	1.0218	5.1	47.4	61.8
2	2.9868	22.6	1.0873	5.4	22.6	
3	10.0477	76.1	3.7859	18.9	76.1	

Sample 1 and 2 show failure before even reaching 2.5mm penetration. It can also be seen from Figure B.4 that the trend for these two samples can not be used for averaging a true value of CBR for S-3C-0FA56 variation. For that reason sample 3 was chosen to represent this variation.

The CBR test results for soil mixtures with addition of 5% cement only, and curing period of 7 days are illustrated in Figure B.5. It can clearly be seen that penetrated forces at 2.5mm displacement were nearly identical between all the three samples. Also, the same can be seen at 5.0mm displacement for samples 1 and 3, while it seems sample 2 failed after 3.5mm displacement. The CBR values were evaluated by converting forces and the calculations are shown in Table B.5.

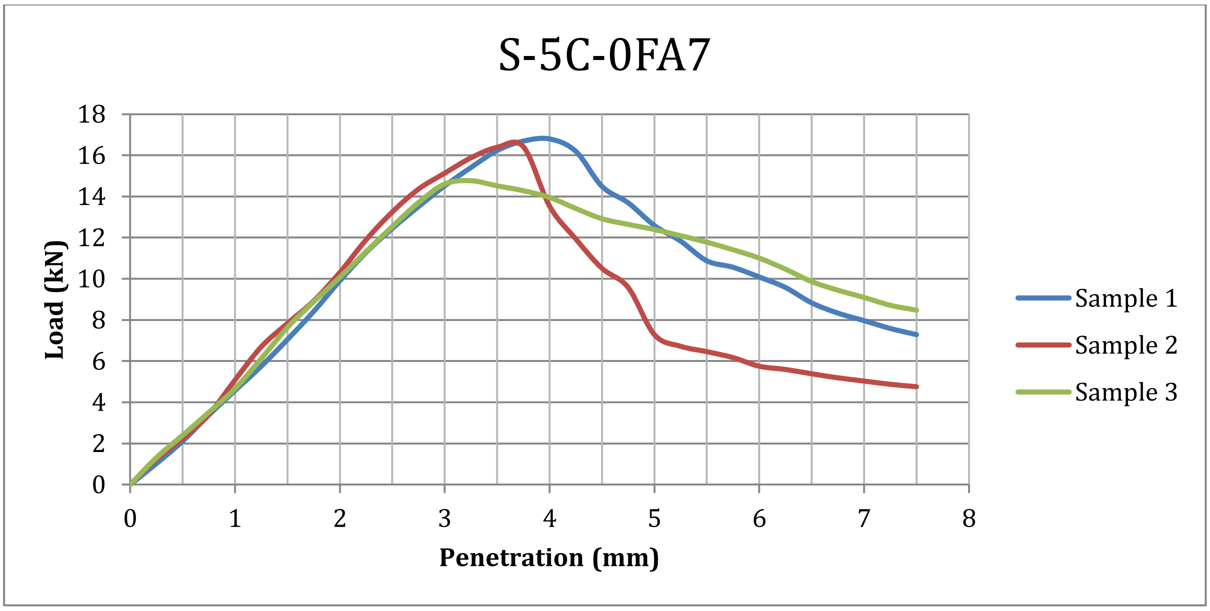

Figure B.5: CBR test results for S-5C-0FA7

Table B.5: Average CBR value for S-5C-0FA7

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	12.455	94.4	12.5891	62.9	94.4	96.6
2	13.2441	100.3	7.2836	36.4	100.3	
3	12.5367	95.0	12.3926	62.0	95	

Observing the exact achieved CBR values at 2.5mm and 5.0mm for samples 1 and 3, both achieved CBR values within 1% of one another. As sample 3 shows the most similarity with the averaged CBR value of all three samples, it was chosen to be presented in the final CBR Figure.

Figure B.6 presents the results of CBR tests performed after fourteen days of curing for samples stabilised with 5% cement content only. It can be seen that all the samples began to drop in applied force value post 2.5mm displacement. This behaviour was only observed for this variation (S-5C-0FA14), where all the samples began failing at either identical or almost identical displacement. The CBR calculations are presented in Table B.6.

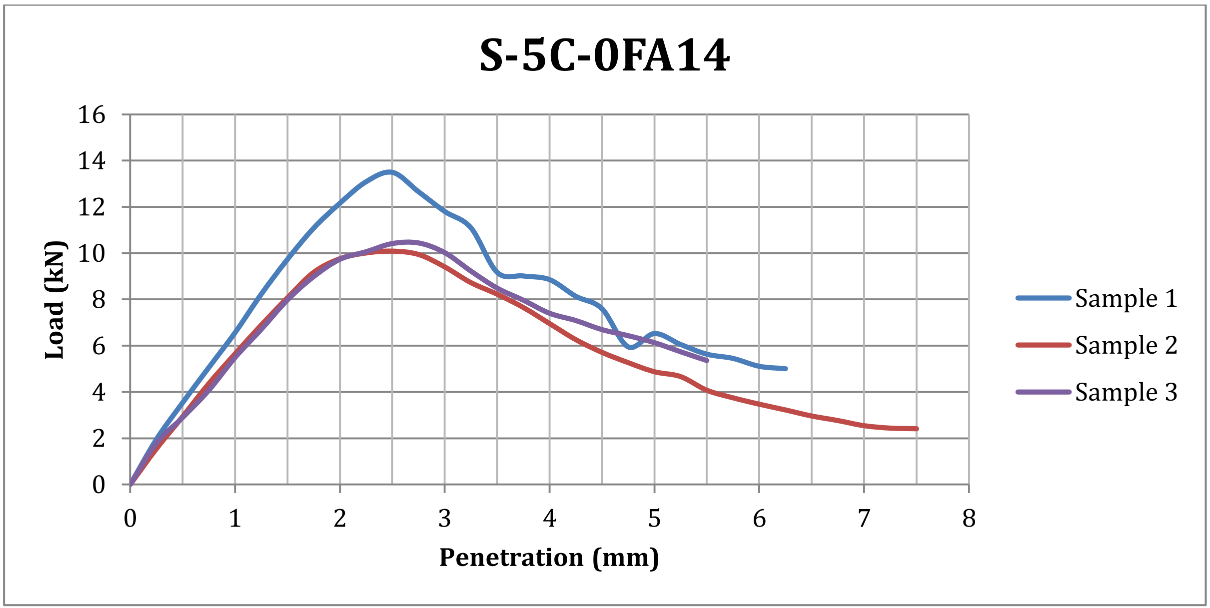

Figure B.6: CBR test results for S-5C-0FA14

Table B.6: Average CBR value for S-5C-0FA14

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	13.493	102.2	6.5238	32.6	102.2	85.8
2	10.087	76.4	4.8732	24.4	76.4	
3	10.4145	78.9	6.1308	30.7	78.9	

The average CBR value obtained for these samples, as stated above, is 85.8%. During the CBR testing of these samples, after sample 1, the CBR machine appeared begin penetrating without the loading gauge moving. It moved with a delay, for that reason, sample 1 was chosen to represent this variation.

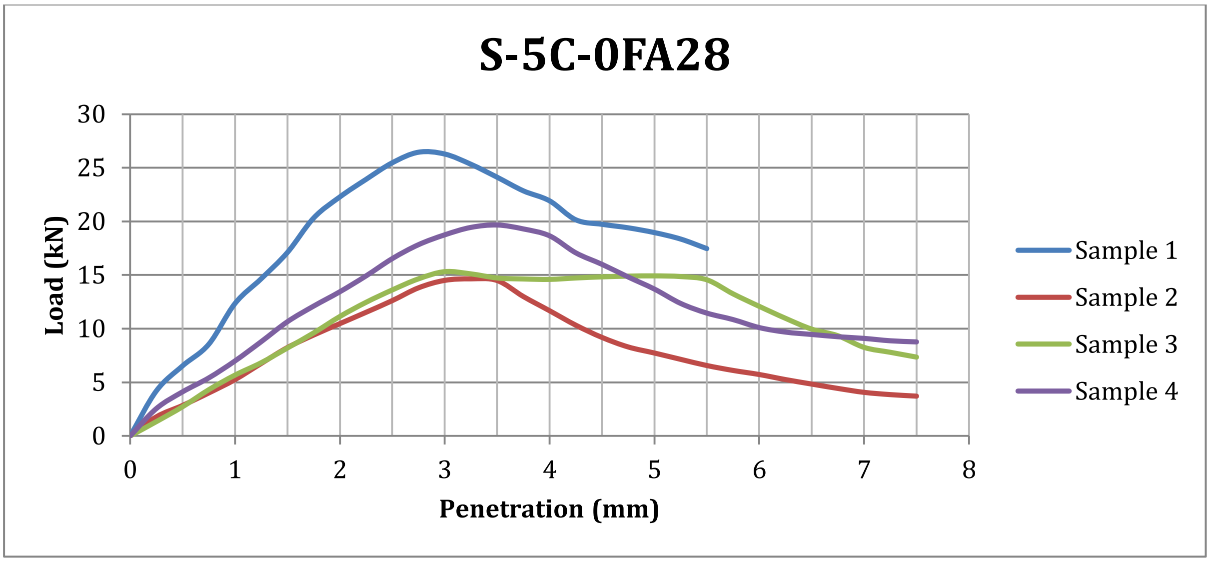

Figure B.7: CBR test results for S-5C-0FA28

The Force/Displacement graph, Figure B.7, presents the CBR results of sand with an addition of 5% cement with curing duration of eight weeks. The recorded forces at displacements of 2.5mm and 5.0mm were determined and then like before, converted into CBR values. These calculations are presented in Table B.7.

Table B.7: Average CBR value for S-5C-0FA28

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	25.4664	192.9	18.9557	94.8	192.9	129.2
2	12.6153	95.6	7.729	38.6	95.6	
3	13.6109	103.1	14.9209	74.6	103.1	
4	16.5322	125.2	13.6895	68.4	125.2	

The CBR values of all the samples are calculated to be on average 129.2%. The CBR values for sample 1 and 2 are substantially higher and lower, respectively, than the derived average value. Sample 4 has the closest maximum CBR value to that of average CBR, hence it was chosen to represent this variation.

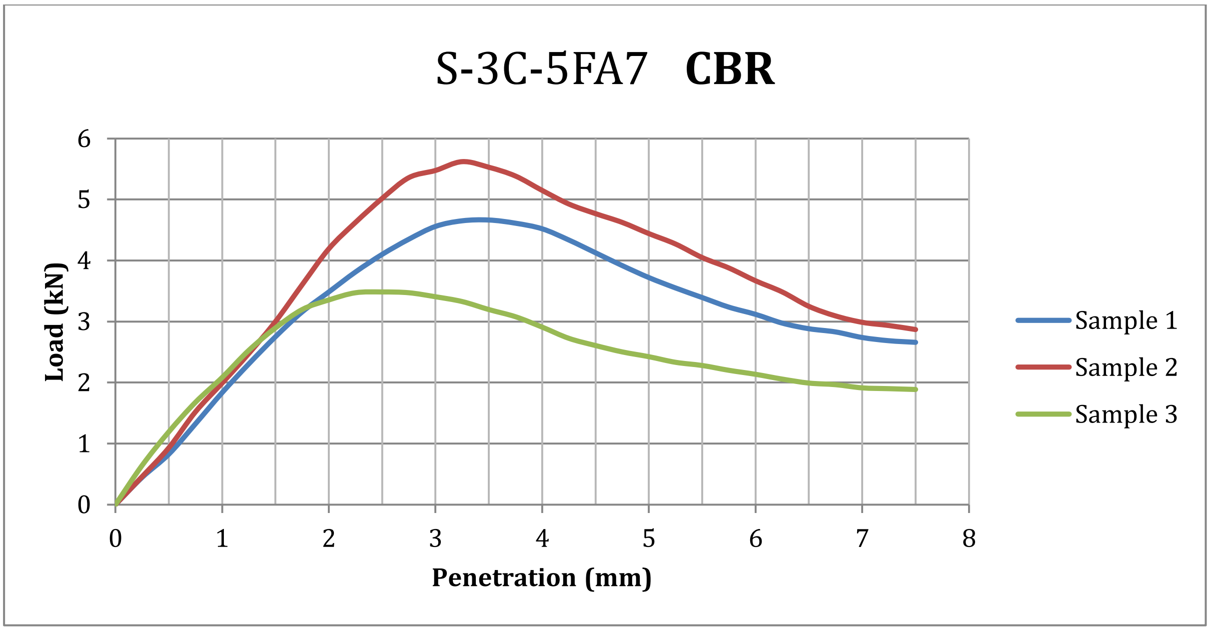

Figure B.8: CBR test results for S-3C-5FA7

The Force/Displacement graph, Figure B.8, shows the results of soil mixtures with 3% cement and 5% FA content, which were cured for a period of seven days. It can be observed that despite having very similar overall curves, until about 2.0mm displacement, all the three samples behaved very similarly, and after that point significantly changed, giving out various force readings at 2.5mm and 5.0mm. These force readings at these displacements were recorded and converted into CBR values as shown in Table B.8.

Table B.8: Average CBR value for S-3C-5FA7

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	4.1003	31.1	3.7204	18.6	31.1	31.8
2	5.0173	38.0	4.4409	22.2	38.0	
3	3.4846	26.4	2.4235	12.1	26.4	

Sample 1 lies between samples 2 and 3 as can be seen in Figure B.8. The obtained average CBR value of 31.8% also shows the highest similarity to maximum CBR achieved in sample 1 (31.1%). This clearly made it viable for sample 1 to be chosen to represent this variation, S-3C-5FA7.

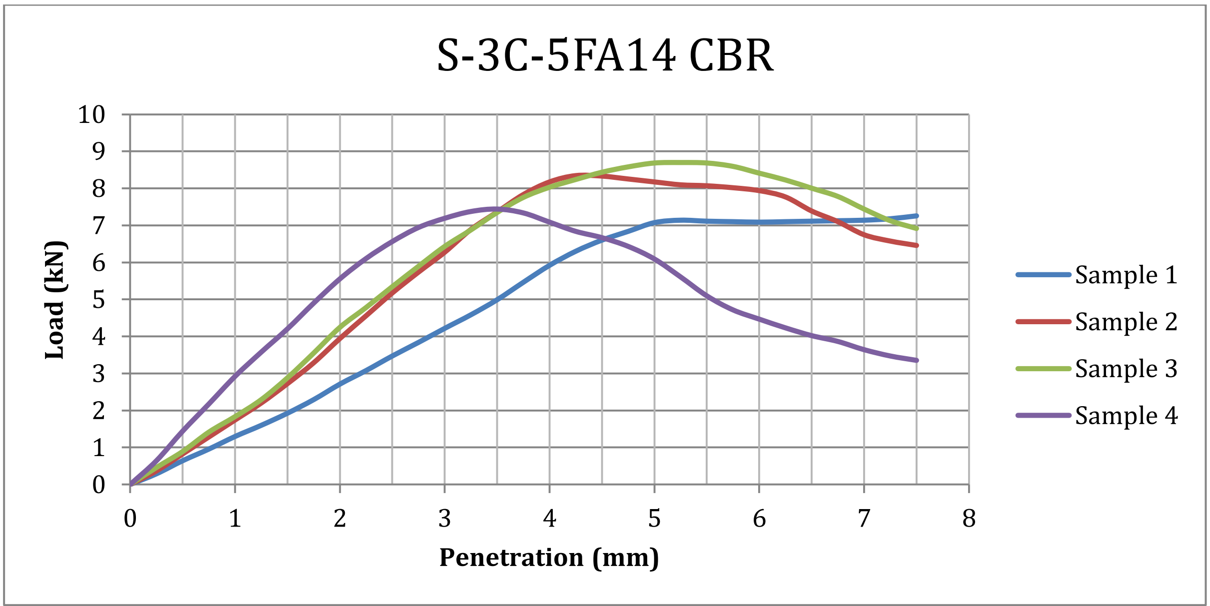

Figure B.9: CBR test results for S-3C-5FA14

The CBR test results of S-3C-5FA14 variation can be seen in Figure B.9. These samples were stabilised with 3% cement and 5% FA content and cured for fourteen days. Samples 2 and 3 show a very similar trend throughout the whole test with almost identical Force/Displacement curves. Samples 1 and 4 are positioned below and above these two samples and suggest a reliable average CBR value is attainable. The forces applied at 2.5mm and 5.0mm were converted into CBR values. These conversion calculations are presented in Table B.9.

Table B.9: Average CBR value for S-3C-5FA14

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	3.4715	26.3	7.074	35.4	35.4	42.4
2	5.1745	39.2	8.1744	40.9	40.9	
3	5.3448	40.5	8.6853	43.4	43.4	
4	6.5631	49.7	6.0915	30.5	49.7	

It would be viable to choose either sample 2 or 3 as the representative sample for this variation as they are positioned in the middle of samples 1 and 4 and also as they have the closest maximum achieved CBR to that of derived average CBR value, 42.4%. Sample 3, with a difference of only 1%, is closer to this average value than sample 2 with 1.5% difference. For that reason only sample 3 was chosen for the final CBR comparison.

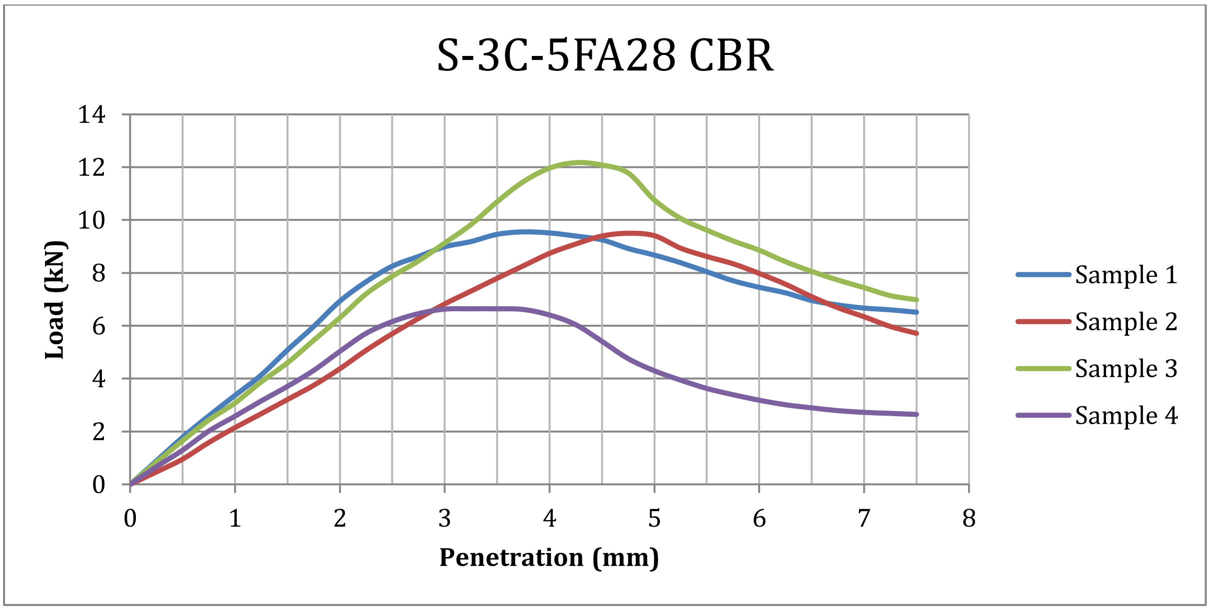

Figure B.10: CBR test results for S-3C-5FA28

Figure B.10 presents the CBR test results of soil mixtures with 5% FA content and addition of 3% cement content, which were cured for four weeks. At 2.5mm displacement, the samples can be divided into two groups of similar force value, samples 2 and 4 in one group, and samples 1 and 3 in the other. Sample 4 shows a failure post 4.0mm displacement, which clearly would suggest that the applied forces at 5.0mm would not be liable. Nevertheless, the CBR values of all the samples at both displacements, 2.5mm and 5.0mm, are evaluated as shown in Table B.10.

Table B.10: Average CBR value for S-3C-5FA28

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	8.253	62.5	8.6722	43.4	62.5	53.9
2	5.6985	43.2	9.4058	47.0	47.0	
3	7.8731	59.6	10.7551	53.8	59.6	
4	6.157	46.6	4.2968	21.5	46.6	

After obtaining the average CBR value of 53.9%, sample 3 has the closest maximum CBR value to this average value with a difference of below 6%. Despite having the highest peak between all the samples, its highest achieved CBR was achieved at 2.5mm displacement. For the reasons mentioned above, sample 3 was chosen to represent this variation S-3C-5FA28.

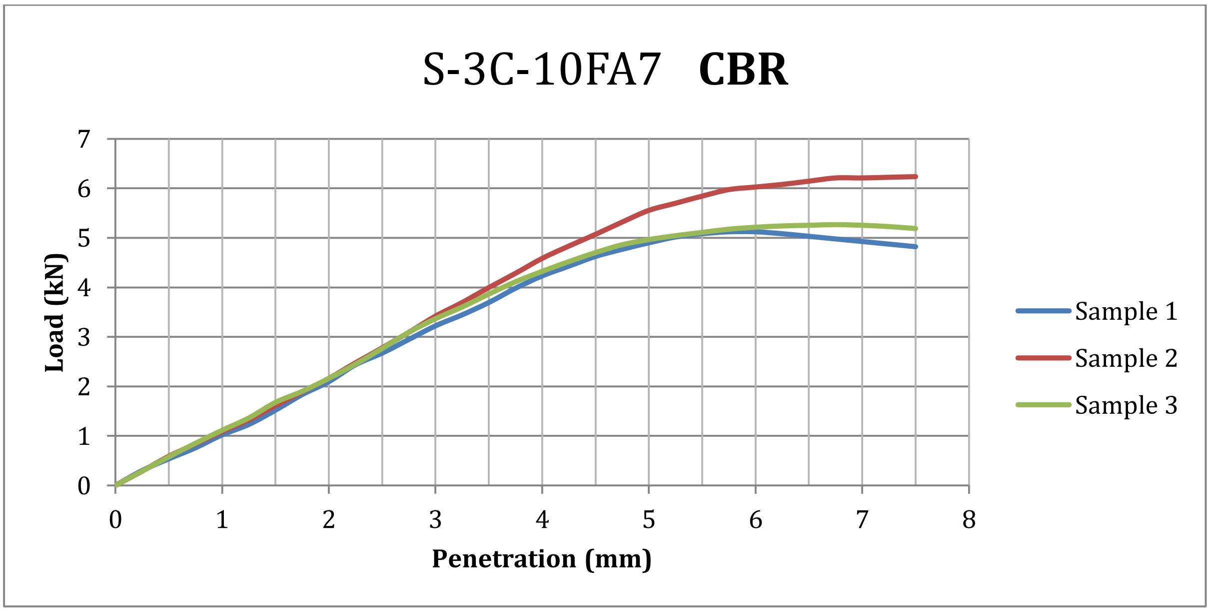

Figure B.11: CBR test results for S-3C-10FA7

The CBR test results of samples mixed with 3% cement and 10% FA content with a curing period of one week are shown in Figure B.11. For this variation, S-3C-10FA7, it can be seen that all the three samples have near identical curve, with almost matching applied forces at 2.5mm and 5.0mm (for sample 1 and 3). This similarity in both force values and the trend of the Force/Displacement curve is only seen in this variation with this much proximity. The CBR values are evaluated as stated in Table B.11.

Table B.11: Average CBR value for S-3C-10FA7

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	2.6724	20.2	4.8994	24.5	24.5	25.7
2	2.7772	21.0	5.5544	27.8	27.8	
3	2.7641	20.9	4.9649	24.8	24.8	

All the three samples have a maximum achieved CBR within 2% of the derived average value. As sample 3 shows the closest value to the average CBR, it was chosen to represent this variation for the final CBR comparison.

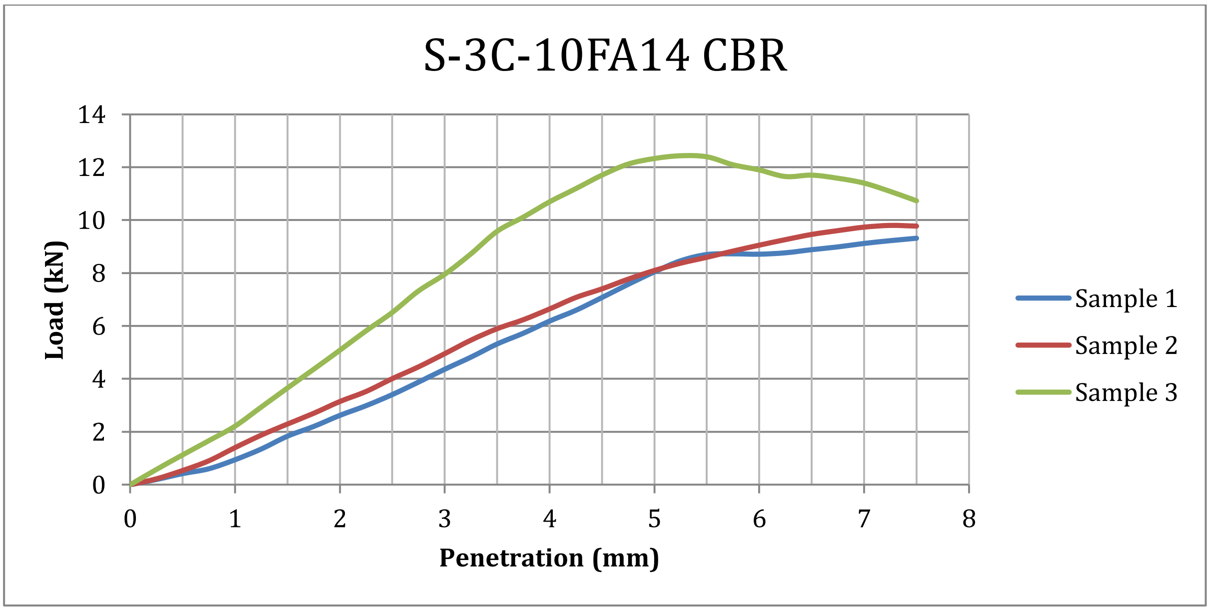

Figure B.12: CBR test results for S-3C-10FA14

The results of CBR tests for sand samples stabilised with 10% FA content with a curing period of fourteen days, inclusive of 3% cement addition, are presented in

Figure B.12. Samples 1 and 2 show a very similar trend between each other in comparison to sample 3, where the peak at both 2.5mm and 5.0mm displacement is significantly higher. The forces applied at these displacements were converted into CBR values as shown in Table B.12.

Table B.12: Average CBR value for S-3C-10FA14

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	3.406	25.8	8.0434	40.2	40.2	47.4
2	4.0086	30.4	8.0958	40.5	40.5	
3	6.5107	49.3	12.3271	61.6	61.6	

Samples 1 and 2's maximum achieved CBR, 40.2% and 40.5% respectively, are nearly the same. The derived average CBR value for all the three samples was calculated to be 47.4%. It has a difference of over 14% to the maximum achieved CBR value of sample 3, and a difference of fewer than 7% to that of sample 2. The Force/Displacement curve of sample 2 is positioned between samples 1 and 3 throughout the whole penetration. For the reasons mentioned above, sample 2 was chosen to represent this variation, S-3C-10FA14, for the CBR comparison.

Figure B.13 presents the results obtained through CBR tests performed for sand samples with 3% cement and 10% FA content with a curing period of four weeks. The forces applied at 2.5mm seem to be of similar value for all the three samples, and at 5.0mm are equally spaced out with sample 3 positioned in the middle. The forces these samples experienced at 2.5mm and 5.0mm were recorded and used to obtain CBR values. The calculations to obtain these CBR values are presented in Table B.13.

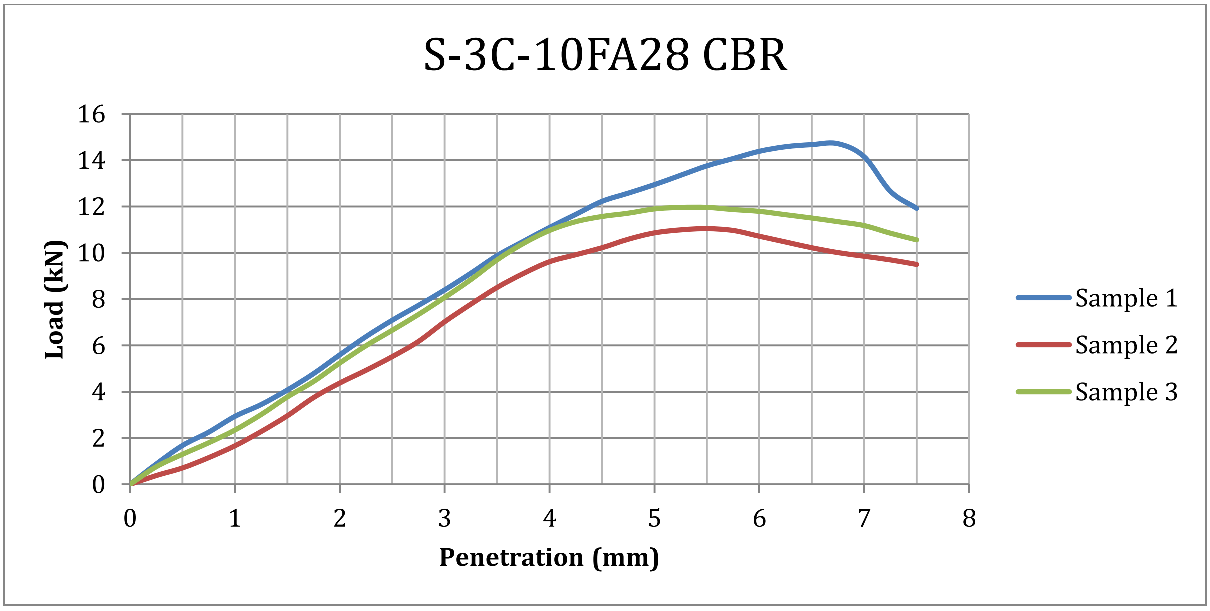

Figure B.13: CBR test results for S-3C-10FA28

Table B.13: Average CBR value for S-3C-10FA28

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	7.0871	53.7	12.9428	64.7	64.7	59.5
2	5.5151	41.8	10.8599	54.3	54.3	
3	6.6548	50.4	11.8948	59.5	59.5	

It was possible to estimate that sample 3 would have the closest similarity between its maximum achieved CBR and the derived average CBR value. As the calculations show, the maximum CBR of sample 3 is exactly identical to that of the average CBR value. Clearly, sample 3 had to be chosen as the representative of this variation.

The Force/Displacement graph, Figure B.14, illustrates the CBR results of the S-3C-15FA7 variation where sand samples were stabilised with 3% cement and 15% FA content and cured for seven days. By observing the force values at 2.5mm displacement, it could be said that samples 2 and 3 would have similar values, and the same could be said for samples 1 and 4. However, at a displacement of 5.0mm, all the four samples show very diverse forces. The CBR values at these two displacements were evaluated as shown in Table B.14.

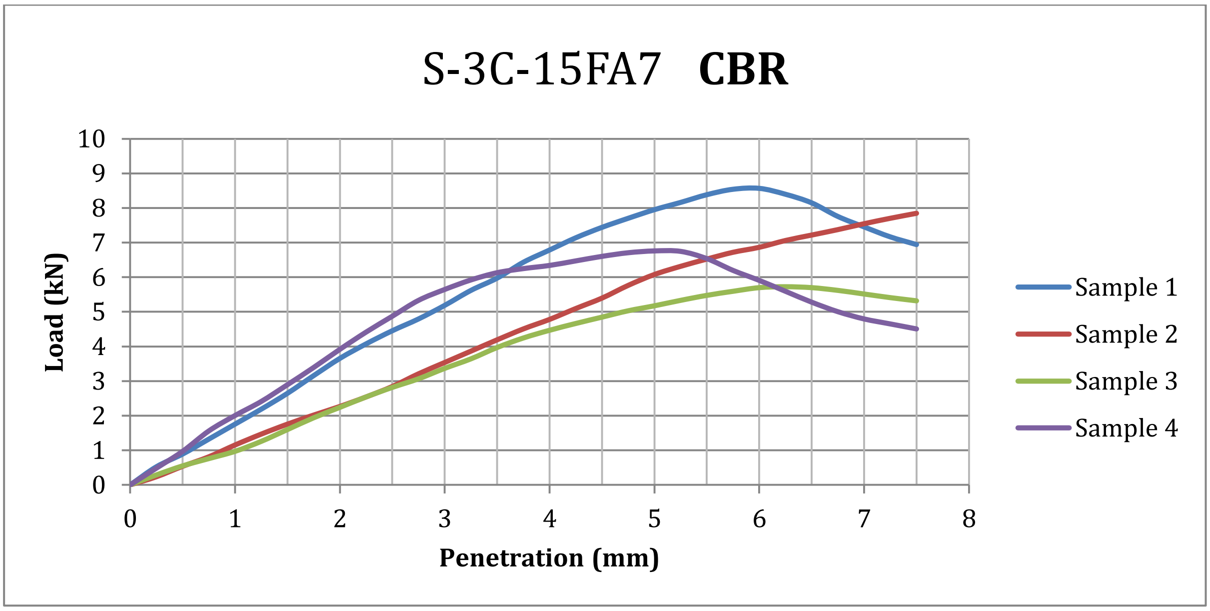

Figure B.14: CBR test results for S-3C-15FA7

Table B.14: Average CBR value for S-3C-15FA7

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	4.454	33.7	7.9517	39.8	39.8	33.3
2	2.8427	21.5	6.0784	30.4	30.4	
3	2.8165	21.3	5.1745	25.9	25.9	
4	4.8732	36.9	6.7596	33.8	36.9	

The maximum achieved CBR values between all the samples ranged from 25.9%, sample 3, to 39.8%, sample 1. The closest maximum achieved CBR values to the derived average value belong to sample 2 and 4. Although sample 2 has a slightly lower difference compared to the average value than that of sample 4, just 0.1%, both of the CBR values achieved in sample 4 show better similarity, at 33.8% and 36.9%. For the reasons mentioned above, sample 4 was chosen to represent this variation, S-3C-15FA7.

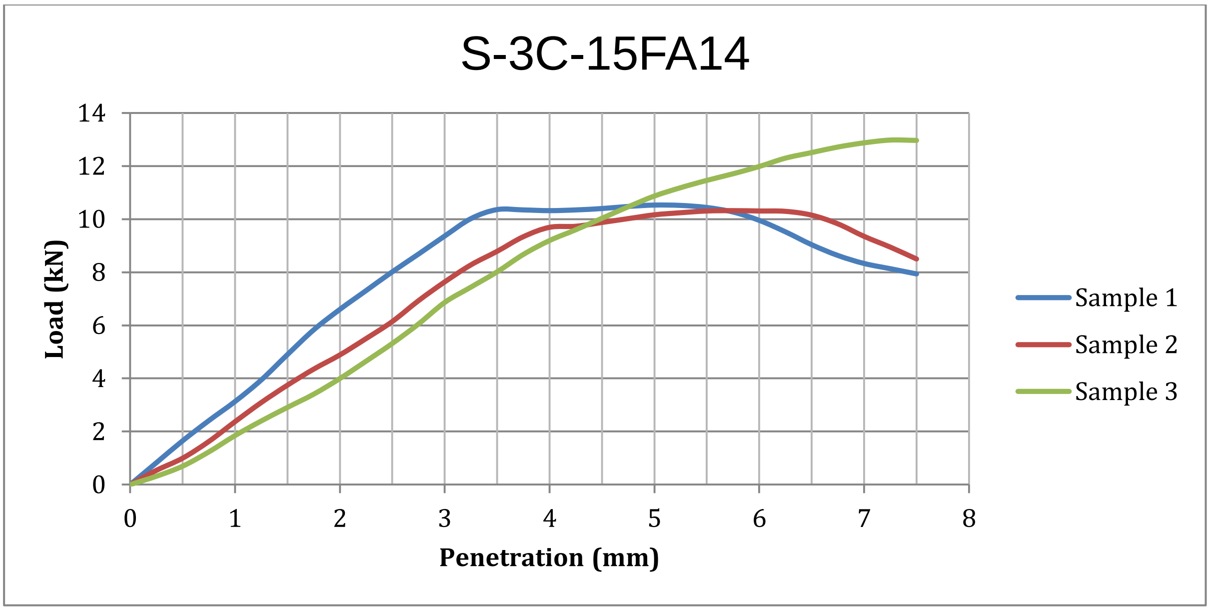

Figure B.15: CBR test results for S-3C-15FA14

The CBR results of samples mixed with 15% FA content and 3% cement content, which was cured for two weeks, are presented in Figure B.15. It can be seen that the samples have quite similar forces applied at 5.0mm displacement, while almost being equally spaced out at 2.5mm, with sample 2 positioned in the middle of samples 1 and 3. The forces applied at both 2.5mm and 5.0mm displacements were converted into CBR values. The conversion calculations are stated in Table B.15.

Table B.15: Average CBR value for S-3C-10FA14

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	8.0172	60.7	10.5324	52.7	60.7	55.3
2	6.1439	46.5	10.1656	50.8	50.8	
3	5.3186	40.3	10.873	54.4	54.4	

The CBR achieved at 5.0mm for all the samples ranged from 50.8 to 54.4%. The CBR values achieved at this displacement, for samples 2 and 3, was the maximum achieved CBR while sample 1 achieved a maximum CBR of 60.7% at 2.5mm.

Sample 3, having the closed CBR value to that of the derived average value of 55.3%, was chosen to represent this variation.

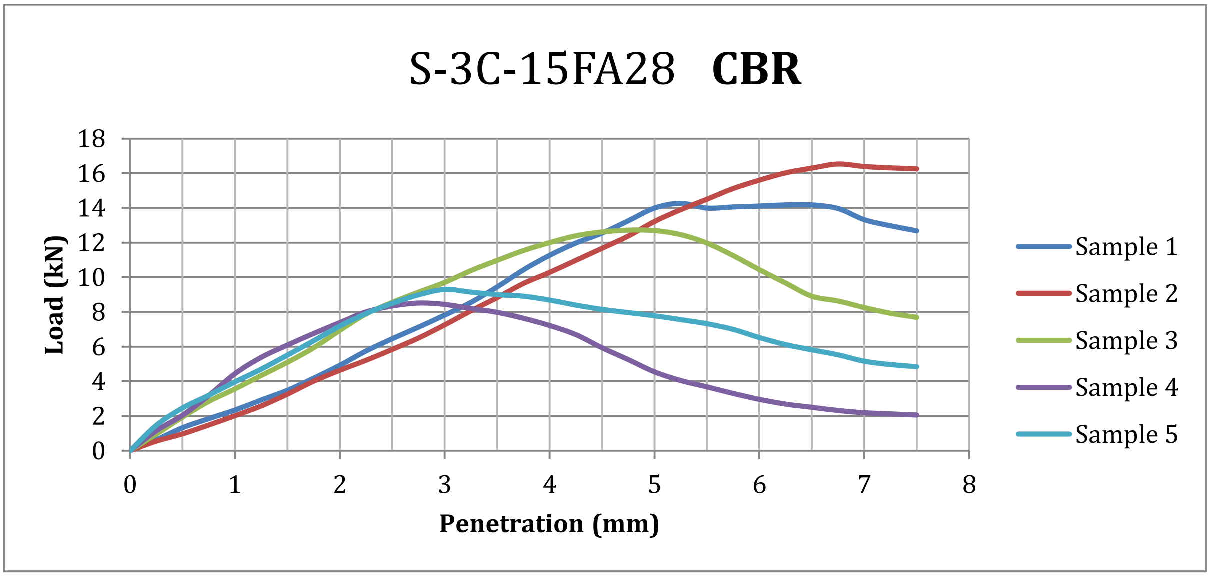

Figure B.16: CBR test results for S-3C-15FA28

Figure B.16 illustrates the CBR test results of sand samples stabilised with 3% cement and 15% FA content that were cured for four weeks. All the samples show a similar trend and behaviour all the way to 5.0mm displacement, which is one of the displacements CBR is derived from. The forces applied at both 2.5mm and 5.0mm, for all the samples, were converted into CBR values as shown in Table B.16.

Table B.16: Average CBR value for S-3C-10FA28

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	6.4583	48.9	13.9908	70.0	70.0	65.7
2	5.8426	44.3	13.2179	66.1	66.1	
3	8.5543	64.8	12.6939	63.5	64.8	
4	8.3447	63.2	4.5457	22.7	63.2	
5	8.5019	64.4	7.7814	38.9	64.4	

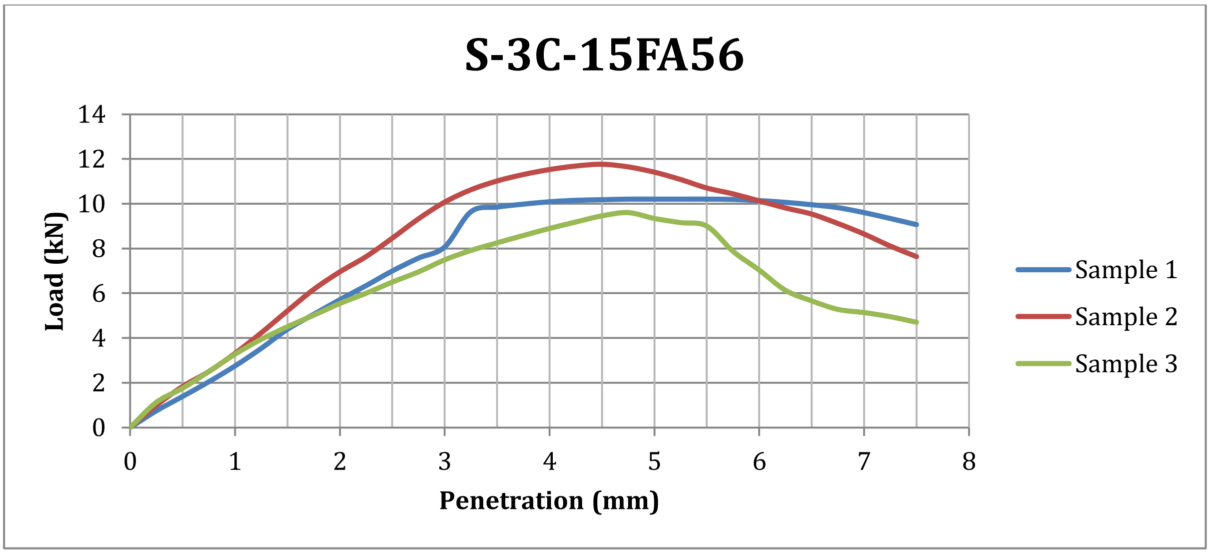

Figure B.17: CBR test results for S-3C-15FA56

The Force/Displacement graph, Figure B.17, presents the CBR results of sand with an addition of 3% cement and 15% FA content with curing duration of eight weeks. The recorded forces at displacements of 2.5mm and 5.0mm were determined and then like before, converted into CBR values. These calculations are presented in Table B.17.

Table B.17: Average CBR value for S-3C-10FA56

Sample	Force at 2.5mm (kN)	CBR at 2.5mm	Force at 5.0mm (kN)	CBR at 5.0mm	Maximum CBR	Average CBR
1	6.9954	53.0	10.2049	51.0	53.0	55.4
2	8.4626	64.1	11.4101	57.1	64.1	
3	6.4976	49.2	9.3403	46.7	49.2	

The CBR values of all the samples are calculated to be on average 55.4%. However, the CBR curves for sample 1 and 3 show an unusual trend with uncommon behaviour. Sample 2 has the most normal and common CBR trend, and for that reason this sample was chosen, not to only to represent this variation in the CBR comparison graph, but also as the CBR value for this variation.

Appendix C

In this section the COSHH (Control of Substances Hazardous to Health) risk assessment is presented.

COSHH Risk Assessment

<table>
<tr><td colspan="2">Assessment Reference Number:</td><td colspan="4">COSHH 1</td></tr>
<tr><td colspan="2">Date of Assessment :</td><td colspan="4">15 February 2016</td></tr>
<tr><td colspan="5">Review Date:
Annually as standard or more frequently if (see examples below):
Change to process or substance — Changes in personnel (vulnerability)
Control measures are failing — Following an incident/accident/case of ill health
Changes in toxicity information/revised MSDS — Changes in frequency/quantity used</td><td>15 February 2017</td></tr>
<tr><td colspan="2">Building /Laboratory/Work Area:</td><td colspan="4">Concrete Laboratory</td></tr>
<tr><td colspan="2">COSHH Assessors Name:</td><td colspan="4">David Barn</td></tr>
<tr><td colspan="2">Identify the persons carrying out the process/using this/these substance(s)</td><td colspan="4">Siavash Mahvash-Mohammadi
James Wood</td></tr>
<tr><td colspan="2">Who is likely to be exposed?
(circle as appropriate)</td><td><u>Staff and/or Student(s)</u></td><td>Visitors</td><td>Maintenance</td><td>Other Groups
Give details</td></tr>
<tr><td colspan="2">How many people are likely to be exposed?
(circle as appropriate)</td><td><u>0-5</u></td><td>6-9</td><td colspan="2">>10</td></tr>
<tr><td colspan="2">Any vulnerable or high risks groups likely to be exposed?
(circle as appropriate)</td><td>Young Person
(staff or student under 18)</td><td>Pregnant Workers
(staff or student)</td><td colspan="2">Other Groups
Give details</td></tr>
<tr><td colspan="6">Process details:</td></tr>
</table>

NB: If you are working with micro-organism(s) or biological agents please refer to the [**Microbiology Risk Assessment**]() *for information. For work with chemicals continue completing this form.*
Small quantities of cement will be used and mixed with fly ash and sand.

Hazard classification							
							
Irritant Harmful	Corrosive	Toxic Very toxic	Oxidising	Flammabl e Highly flammable	Explosiv e	Dangerous for environme nt	Long term Health effects
Y	**N**	**Y/N**	**Y/N**	**N**	**N**	**Y/N**	**Y/N**

What products/substances are being used in the process?

Products / Substance(s) in process	Hazard or Risk phrases defined for this product in the Material Safety Data Sheet	Red, Amber, Green, (R,A,G,)	What form is this hazard?		Quantity Used / Stored?	Length of Time Used? (Duration)	How often is it used? (Frequency)	Is there a Workplace Exposure Limit for this product / substance?
Portland Cement	*Irritant* R37/38 Irritating to respiratory system and skin R41 Risk of serious damage to eyes R43 May cause sensitisation by skin contact	*A*	Gas Liquid Vapour Fume Solid/ Powder/Dust	X (Solid/ Powder/Dust)	*30 bags of 25kg*	*3 Hours*	*Daily*	WEL 8hr Time Weighted Average (TWA): • Total inhalable dust 10mg/m3 • Respirable dust 4mg/m3
Fly Ash	*Similar to Portland Cement*	*A*	Gas Liquid Vapour Fume Solid/	X (Solid/)	*40 buckets of 25kg*	*3 Hours*	*Daily*	WEL 8hr Time Weighted Average (TWA): • Total inhalable dust 10mg/m3 • Respirable dust

What products/substances are being used in the process?

Products / Substance(s) in process	Hazard or Risk phrases defined for this product in the Material Safety Data Sheet	Red, Amber, Green, (R,A,G,)	What form is this hazard?		Quantity Used / Stored?	Length of Time Used? (Duration)	How often is it used? (Frequency)	Is there a Workplace Exposure Limit for this product / substance?
			Powder/ Dust					4mg/m3
Product / Substance Name	*e.g. Corrosive and give risk / hazard phrase R15(H261) / R38 (H315)*	*Insert all that apply*	Gas		*e.g. ppm mg/m³*	*Minutes Hours*	*Daily Weekly Monthly*	*Please list*
			Liquid					
			Vapour					
			Fume					
			Solid/ Powder/ Dust					
Product / Substance Name	*e.g. Corrosive and give risk / hazard phrase R15(H261) / R38 (H315)*	*Insert all that apply*	Gas		*e.g. ppm mg/m³*	*Minutes Hours*	*Daily Weekly Monthly*	*Please list*
			Liquid					
			Vapour					
			Fume					
			Solid/ Powder/ Dust					
Product / Substance Name	*e.g. Corrosive and give risk / hazard phrase R15(H261) / R38 (H315)*	*Insert all that apply*	Gas		*e.g. ppm mg/m³*	*Minutes Hours*	*Daily Weekly Monthly*	*Please list*
			Liquid					
			Vapour					
			Fume					
			Solid/ Powder/ Dust					

STOP CHECK AND CONSIDER THE NEXT QUESTION CAREFULLY

Can product(s) / substance(s) be substituted?	Y/N	Describe the options and the elimination / substitution process
Can you eliminate any of the substances?	**N**	
Can you substitute any of the substances with less hazardous products?	**N**	

Are any of the substances being mixed?

Number of substances being mixed	3	**Highest risk (RAG) of the substances to be mixed?**	**A**	**OVERALL RISK OF THE SUBSTANCE**(S) (without control measures in place)	**RED AMBER GREEN**

NB: Treat overall assessment as highest risk (RAG)

Is the process likely to create new hazards or enhance any existing hazards e.g. producing a violent or highly exothermic reaction, toxic fumes, by-products etc.?	**N**
If Yes, detail any additional control measures that need to be in place	

What are the risks of fire and/or explosion etc.?

Is there a risk of fire?	**N**
Is there a risk of explosion?	**N**
Is there a risk of toxic fumes?	**N**
Is there any other associated fire related risk with this process?	**N**
If Yes to any of the above, detail any additional control measures that need to be in place.	*Insert the type of extinguishing equipment to be used in case of fire (e.g. water, CO_2 etc.)*

Water	Carbon dioxide	Powder	Foam	Blanket	Automatic fire suppression	Other
Y/N	**Y/N**	**Y/N**	**Y/N**	**Y/N**	**Y/N**	**Y/N**

NB: A separate risk assessment may be also required in accordance with the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR).

What are the health effects?

Possible route of entry into the body?		**Detail the health effects? *(refer to the Material Safety Data Sheet)*** *Consider both short-term and long-term health effects where applicable*
Ingestion	**Y**	
Inhalation	**Y**	**Cement:** Frequent inhalation of large quantities of cement dust over a long period of time increases the risk of developing lung Diseases. **Fly Ash:** Chronic exposure may cause lung damage from repeated exposure. Chronic inhalation of dusts containing respirable crystalline silica may result in silicosis.
Contact e.g. skin	**Y**	**Cement** : may have an irritating effect on moist skin (due to transpiration or humidity) after prolonged contact. Prolonged skin contact with wet cement or fresh concrete may cause serious burns because they develop without pain being felt (for example when kneeling in fresh concrete even when wearing trousers). Repeated skin contact with wet cement may cause contact dermatitis. **Fly Ash:** Direct exposure, mechanical abrasion and product dust may cause skin irritation, dry skin and dermatitis. Product dust can dry and irritate the skin, cause dermatitis
Absorption via skin and/or mucus membrane e.g. eyes, nose, mouth	**Y**	Eye contact with cement (dry or wet) may cause serious and potentially irreversible injuries.
Other e.g. young persons, pregnancy	**Y/N**	

What are the first aid requirements: *(consult the MSDS for details)*

Ingestion	Do not induce vomiting. If person is conscious, wash out mouth with water and give plenty of water to drink. Get immediate medical attention or contact anti poison centre.	
Inhalation	Move person to fresh air. Dust in throat and nasal passages should clear spontaneously. Contact a physician if irritation persists or later develops or if discomfort, coughing or other symptoms do not subside.	
Contact e.g. skin	For dry cement or fly ash remove and rinse abundantly with water. For wet cement, wash skin with water. Remove contaminated clothing, footwear, watches, etc, and clean thoroughly before re-using them. Seek medical treatment in all cases of irritation or burns.	
Absorption e.g. eyes, nose, mouth, skin	Do not rub eyes, as additional cornea damage is possible by mechanical stress. Remove any contact lenses and open the eyelid(s) widely to flush eye(s) immediately by thoroughly rinsing with plenty of clean water for at least 45 minutes to remove all particles. If possible, use isotonic water (0.9% NaCl). Contact a specialist of occupational medicine or an eye specialist	
Health surveillance required	**N**	Describe the arrangements

What are the required controls measures?

		Describe the arrangements
Enclosed System e.g. glove box	**Y/N**	
Fume Cabinet	**Y/N**	
Extractor / Hood / Local Exhaust Ventilation	**Y/N**	
Ventilation / Air Change *(If unknown seek advice from EDS/Campus Services)*	**Y/N**	
Biological Safety Cabinet	**Y/N**	
Sensors and / or alarms	**Y/N**	
Personal Protective Equipment *(see details below)*	**Y**	**Goggles, Gloves, Lab coat**
Other:	**Y/N**	

What are the PPE requirements *(in addition to the standard issue laboratory coat)*

Eye Protection	**Face Mask**	**Face protection**	**Gloves**	**Hard Hat**	**Ear Defenders**	**Safety footwear**	**Outer layer**	**Apron**	**Other:**

Y	**Y**	**Y/N**	**Y**	**Y/N**	**Y/N**	**Y/N**	**Y**	**Y/N**	**Y/N**
Describe the type / make/ model of PPE to be used – refer to the Material Safety Data Sheet(s) for guidance									
Wear approved glasses or safety goggles according to EN 166	*If over the WEL mask must be worn*	*e.g. Non UV resistant / UV resistant*	*e.g. Nitrile / Latex*			e.g. toe protection / sole protection	Lab Coat		

	Half face respirator	Full face respirator	Powered respirator	Breathing apparatus
	Y/N	**Y/N**	**Y/N**	**Y/N**

STOP CHECK AND CONSIDER THE USE OF PERSONAL PROTECTIVE EQUIPMENT (PPE) CAREFULLY

Where Respirators (inc. FFP2 or 3 disposable masks) are required - face fit tests can be arranged for staff and students? Consult your Supervisor for advice or contact to book an appointment.
Are there any Health Surveillance requirements to be considered?
Consult your Supervisor for advice and guidance or contact to book an appointment

What actions to be taken in the event of spillage(s) and/or other emergency situations?	
NB: Refer to Material Safety Data Sheet(s) for guidance	
Small Quantity <500ml	***Dry cement:*** Use dry clean-up methods that do not cause airborne dispersion - eg: • Vacuum cleaner (Industrial portable units, equipped with high efficiency particulate filters (HEPA filter) or equivalent technique). • Wipe up the dust by mopping, wet brushing or water sprays or hoses (fine mist to avoid the dust becoming airborne) and remove slurry. If not possible, remove by slurrying with water (see Wet cement). When wet cleaning or vacuum cleaning is not possible and only dry cleaning with brushes can be done, ensure that the workers wear appropriate personal protective equipment and prevent dust from spreading. Avoid inhalation of cement and contact with skin. ***Wet cement:*** Clean up wet cement and place in a container. Allow material to dry and solidify before disposal
Large Quantity >500ml	*As above*
Do you have correct spill kit provisions to deal with spills (should they occur)?	**NA**
Are there any other emergency situations (*not referenced above*) to be considered?	**Y**

If Yes, detail any additional control measures that need to be in place	***Consider** evacuation and secure/closure of laboratory (major spillage*

What are the storage requirements for substances used during this process?	
NB: Refer to Material Safety Data Sheet(s) for guidance	
Are there any specific storage requirements for substances? *(Is there a maximum recommended volume/quantity to be stored in one place or a specific temperature, type of cabinet, segregation etc.?) Also consider in laboratory and in holding areas for disposal*	**Y**
If Yes, detail the storage arrangements that need to be in place ***Refer to Material Safety Data Sheet(s) for guidance***	Bulk cement should be stored in silos that are waterproof, dry (internal condensation minimised), clean and protected from contamination. ***Engulfment hazard:*** To prevent burial or suffocation, do not enter a confined space, such as a silo, bin, bulk truck, or other storage container or vessel that stores or contains cement without taking the proper security measures. Cement can build up or adhere to the walls of a confined space. The cement can release, collapse or fall unexpectedly. Packed products should be stored in unopened bags clear of the ground in cool, dry conditions and protected from excessive draught in order to avoid degradation of quality. Bags should be stacked in a stable manner

How should the substances used be disposed of? *(include environmental impacts and by-products in your explanation if appropriate)*
NB: Refer to Material Safety Data Sheet(s) for guidance
Product - cement that has exceeded its shelf life When demonstrated that it contains more than 0.0002% soluble Cr (VI): shall not be used/sold other than for use in controlled closed and totally automated processes or should be recycled or disposed of according to local legislation or treated again with a reducing agent. ***13.2 Product - unused residue or dry spillage*** Pick up dry. Mark the containers. Possibly reuse depending upon shelf life considerations and the requirement to avoid dust exposure. In case of disposal, harden with water and dispose according to 13.4. ***13.3 Product – slurries*** Allow to harden, avoid entry in sewage and drainage systems or into bodies of water (eg, streams) and dispose of as indicated in 13.4. ***13.4 Product - after addition of water, hardened*** Dispose of according to the local legislation. Avoid entry into the sewage water system. Dispose of the hardened product as concrete waste. Due to the inertisation, concrete waste is not a dangerous waste.

EWC entries: 10 13 14 (waste from manufacturing of cement – waste concrete or concrete sludge) or 17 01 01 (construction and demolition wastes - concrete). ***13.5 Packaging*** Completely empty the packaging and process it according to local legislation. ***EWC entry:*** 15 01 01 (waste paper and cardboard packaging). ***EWC entry:*** 15 01 02 (plastic packaging).		
What are the management arrangements i.e. Training, SOP's, Communication etc.?		
How will this risk assessment be communicated? This will be provided to staff and students.		
Risk assessment explained to staff and students by technicians and teaching staff. Safe handling and wearing of PPE to be demonstrated by technicians and teaching staff to staff and students.		
Are Safe Systems of Work (SSoW) / Standard Operating Procedure (SOP) needed for this product/task/process in addition to this risk assessment?		**Y**
If Yes, detail / append the SSoW and/or the SOP if applicable	**Method Statement reference number to be put hear and appended**	
Are training requirements necessary and who will provide this?		**Y**
If Yes, detail any specialist training required to undertake this process and who will provide said training	Safety measures demonstrated by technician and teaching staff	
Are there any remaining (residual) risks to be operationally managed?		**N**
If Yes, detail any specific risks to be considered (e.g. pregnancy, vulnerable people, etc.)?		

Actions

Use the table below to record actions to be taken if additional control measures are needed to meet the requirements of this risk assessment (identified above)

No.	**Action** *(describe)*	**By Who?**	**Target Date**	**Date Completed**

OVERALL RISK RATING OF THIS PROCESS (with control measures in place)

RED	Control Measures Cannot be Implemented - Refer to Supervisor – Do Not Proceed
AMBER	Partial Control Measures Implemented - Further Controls Required- Refer to Supervisor – Do Not Proceed
GREEN	All Control Measures Implemented - Assessor to sign the risk assessment, Approver can then complete their sections once satisfied that the process/task etc. can proceed

Approval Process	
COSHH Assessors Signature:	David Barn
Assessors Name:	David Barn
Date:	15 February 2016
Confirmation received that all actions have been completed and the required control measures are in place:	Yes
Process Supervisors Name: *e.g. Principal Investigator, Line Manager*	Dr Ali B-Jahromi
Approval Date:	17 February 2016
Confirmation that a copy is stored locally with the Laboratory Manager:	Yes