Faculty of Science and Engineering

Department of Civil Engineering

Study on Soil Stabilisation Technique

Using Lime & Fly Ash

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

The engineering properties of soil, along with associated economical and environmental aspects, are considered as the three main elements in building geotechnical constructions such as embankments, structures and roads. In some cases, the engineers of these structures have to find solutions to solve the mechanical and chemical problems of the in-situ soil. Soil stabilisation, as a cost-effective and environmentally friendly method, is used in the building of soil systems like roads, dams, canals and river levees. Chemical stabilisation of soil is carried out by adding binder or by-products like, lime, fly ash to the soil thereby modifying the geotechnical performance of the land. Various researches have been carried out on the properties of soil, such as its compaction, compressibility, hydraulic conductivity, and strength characteristics. However, the diversity of results is considerable. There is also limited availability of research on lime and fly ash's efficiency with regard to how quality and quantity may improve soil characteristics. Therefore the purpose of this research is to carry out an analysis and evaluation on the role of lime and fly ash in soil stabilisation techniques. A series of experimental and microanalytical tests investigated the effectiveness of lime and fly ash on material composites from a mechanical, structural/ microstructural, morphological-mineral and chemical-material perspective. The selected laboratory tests covered some important soil characteristics which were then accurately analysed by Optical microscopy, Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), X-Ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR). The laboratory results were confirmed, from a microstructural analysis standpoint, by SEM. Elemental analysis and chemical characterisation were both confirmed by EDS; mineralogical phases were determined by XRD, and changes in chemical composition by FTIR. It was posited that additives could improve the compressibility, hydraulic conductivity, strength, and compaction characteristics of pure compounds, due to key factors such as pozzolanic reactions, and the incrementing of the main chemical components associated with the generation of the polymerisation phenomenon, thereby creating the more uniform area noted in the composite's atoms.

It was concluded that the addition of stabiliser could improve the geotechnical performance of the pure compounds, due to pozzolanic reactions. Calcium (Ca), oxygen (O), silicon (Si) and aluminium (Al) were identified as the main chemical components presenting in the pozzolanic effect on pure compounds. The SEM/EDS results indicated that increments in the proportions of calcium, silicon and aluminium were associated with the generation of the aluminosilicate compound. The calcium silicate compound was characterised as a polymerization phenomenon, with both compounds thereby generating the more uniform area noted in the composite's atoms. The XRD investigation also confirmed the role of the pozzolanic reaction by identifying the compounds that could have a pozzolanic effect, and it improved the position of 2θ angles to a lower degree for the lime, fly ash, and lime-fly ash combination, in contrast with the pure composite. The FTIR analysis validated the XRD and SEM results by detecting the C–S–H, C–A–S–H phases, O-H vibration and Si–O stretching, Al–OH and Ca-O-H group vibration. Identification of some major compounds confirmed the presence of the main chemical components required for the chemical reaction, thereby improving the soil's geotechnical performance.

Keywords: Chemical-Material Characterisation, Fly ash, Lime, Microscopic/Macroscopic Scanning , Mineral- Morphological Analysis, Soil Stabilisation.

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DEDICATION

To

My parents

Reza and Saeideh

The angles of my life

The reason for my existence

To their endless love, sacrifices, and support.

To

My Dears

The shining stars of my life

Nastaran, Nasim, Houman, Mehdi, Hasti

RESEARCH PUBLICATIONS

Journal Papers

- ✓ Effect of Lime and Fly ash on Compaction and Strength Characteristics of Sand Composite. “Submitted to Australian Journal of Civil Engineering”2012

- ✓ Study of scale effect on strength characteristic of stabilised composite with sewage sludge. “Submitted to Construction and Building Materials”2013

- ✓ Microanalytical investigation on the consolidation characteristic of lime composites. International Journal of Engineering Research and Applications (IJERA) Vol. 3, Issue 6, 2013,ISSN: 2248-9622 1236-1241

- ✓ Investigation on the Effect of Lime and Fly Ash on Hydraulic Conductivity of Soil. “International Journal of Biological, Ecological and Environmental Sciences (IJBEES) Vol. 1, No. 3, 2012, ISSN 2277 – 4394”

- ✓ A Review on The Lime and Fly ash Application in Soil Stabilization. “International Journal of Biological, Ecological and Environmental Sciences (IJBEES) Vol. 1, No. 3, 2012, ISSN 2277 – 4394”

Conference Papers

- ✓ Laboratory Investigation on the Compaction Properties of Lime and Fly Ash Composite. “International Conference on Civil and Architectural applications (ICCAA'2012) December 18-19, 2012 Phuket (Thailand)”

- ✓ Laboratory Investigation on the Effect of Fly Ash on the Compressibility of Soil. “International Conference on Civil and Architectural applications (ICCAA'2012) December 18-19, 2012 Phuket (Thailand)”

- ✓ Laboratory Investigation on the Effect of Lime on Compressibility of Soil. International Conference on Civil and Architectural applications (ICCAA'2012) December 18-19, 2012 Phuket (Thailand).

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CHAPTER1

INTRODUCTION

1.1 Introduction

The phenomenon of the downward or outward mass-movement of rock and/or soil under the influence of earth's gravity is called a landslide. This phenomenon is devastating in terms of its effects on life, the natural environment and the economy. Many countries such as the United States, Canada, Italy, China, Thailand, India, and Brazil suffer continuing landslide fatalities(Glade et al., 2005). These landslides appear to be due to inappropriate soil properties like high plasticity, poor workability and low mechanical properties, although the full extent of all causes is not understood. The control of landslides is obviously a vital economic and geological issue. Soil stabilisation techniques, such as the addition of binders, have been introduced in order to improve the mechanical and chemical characteristics of its engineering performance. In addition, the utilisation of stabilising agents in roadwork and in sub-grade with poor soil condition improves other qualities such as cohesion, thereby contributing to the strengthening of the structure or embankment. This can eventually lead to a remarkable reduction in road building costs. Different additives like cement, lime or other minerals such as fly ash have been used for this purpose.

It is also well known that stabilising soil with local natural and industrial resources have a significant effect on the improvement of soil properties. Lime and fly ash in particular have been used as an appropriate additive in soil stabilisation in a variety of geotechnical constructions such as highways, foundation bases and embankments. The importance of utilisation of lime and fly ash in soil treatment has been recognised in Western of Australia and Australia as well. This method is applied in the wide range of civil engineering projects including road woks and pavement specifically. In understanding the triggering mechanisms of landslides, the examination of the geotechnical behaviour of gravelly soil is essential. Compaction properties, soil's permeability, consolidation and strength characteristics of soil as some of main geotechnical properties were considered in this research study.

1.2 Scopes and Aims

This project aims to conduct an accurate investigation into lime/ fly ash effect on the shear strength, compaction properties, compressibility and hydraulic conductivity of composite samples (i.e., those prepared with differing amounts of fly ash, lime, and lime-fly ash combination). The chemical and mechanical characterisation of composites were analysed from the geotechnical and material viewpoints. In order to systematically achieve this goal, the work has been separated into four key components. Briefly, these are:

1. To analyse the effects of lime on the characteristics of soil.

A series of geotechnical tests were conducted in order to characterise and investigate the effects of several percentages of lime on soil behaviour.

2. To analyse the effects of fly ash on the characteristics of soil.

In the second stage, the effects of various percentages of fly ash on the properties of soil were investigated through five geotechnical tests.

3. To analyse the effects of a combination of lime and fly ash on the characteristics of soil.

In the third stage, differing percentages of lime and fly ash were mixed with soil in order to find the optimal conditions for making a composite.

4. To assess the characteristic and mechanisms of lime/fly ash composite samples.

In the last stage, the microstructural characteristics of composites were accurately evaluated from the chemical and elemental point of view for microanalytical investigating into the stabilised composites properties.

1.3 Outline of the thesis

The research was carried out in five distinct phases as follows:

1. A general overview of the project consists of projects aims and scopes.
2. A presentation about the background of soil stabilisation including soft soil's problems, soli stabilisation history, lime and fly characteristics, main previous study on lime/fly ash stabilisation.
3. A general introduction of research methodology and selected material.
4. A presentation of microanalytical and geotechnical tests data, then analysis and discussion of results.
5. A general conclusion and recommendation for further researches.

1.4 Solution technique

Microanalytical investigation into the material characteristics of the soil composites obtained valuable results for clarifying the mechanisms of lime/fly ash's efficiency on soil. Furthermore, with regard to each geotechnical test, the given results illustrated the specific characteristics of the soil. The wide range of results provided thorough and reliable conclusions.

This thesis presents a series of geotechnical tests on a variety of soils stabilised with lime, fly ash and lime/fly ash combination. Microanalytical results indicated the chemical, mineralogical, morphological and elemental characteristics of soil combinations.

By comparing the results obtained from different experiments, and evaluating the effects of various percentages of additives in the tests, reliable conclusions were obtained about the effects of lime and fly ash on soil composite. The conclusions revealed that depending on the required parameters; either lime or fly ash could be applied for soil modification. Based on the obtained results and considering the economical and environmental aspects, utilisation of a specific dosage of additive leads to improvement in soil properties.

CHAPTER 2

BACKGROUND STUDY

2.0 Background to the research

The inefficient properties of soil are currently of critical concern in engineering projects. In some cases, improving the characteristics of unsuitable soils by stabilisation is a fundamental step prior to construction. Soil stabilisation is performed by adding a binder to the soil in order to improve its engineering performance.

Research has illustrated that additives lead to improvements in the workability and mechanical behaviour of soil after it has been stabilised. Therefore, in this investigation, lime and fly ash as local natural and industrial resources were applied for chemical stabilisation. These additives improve the mechanical properties of soil such as compaction, strength, swelling, the plasticity index and compressibility. One of the most frequent chemical stabilisation methods used is lime stabilisation. Fly ash as an additive may also be added in order to further improve the properties of the stabilised soil. In lime stabilisation, the lime reacts with the water contained within the soil and attracts the soil particles to one another.

2.1 Outline of background study

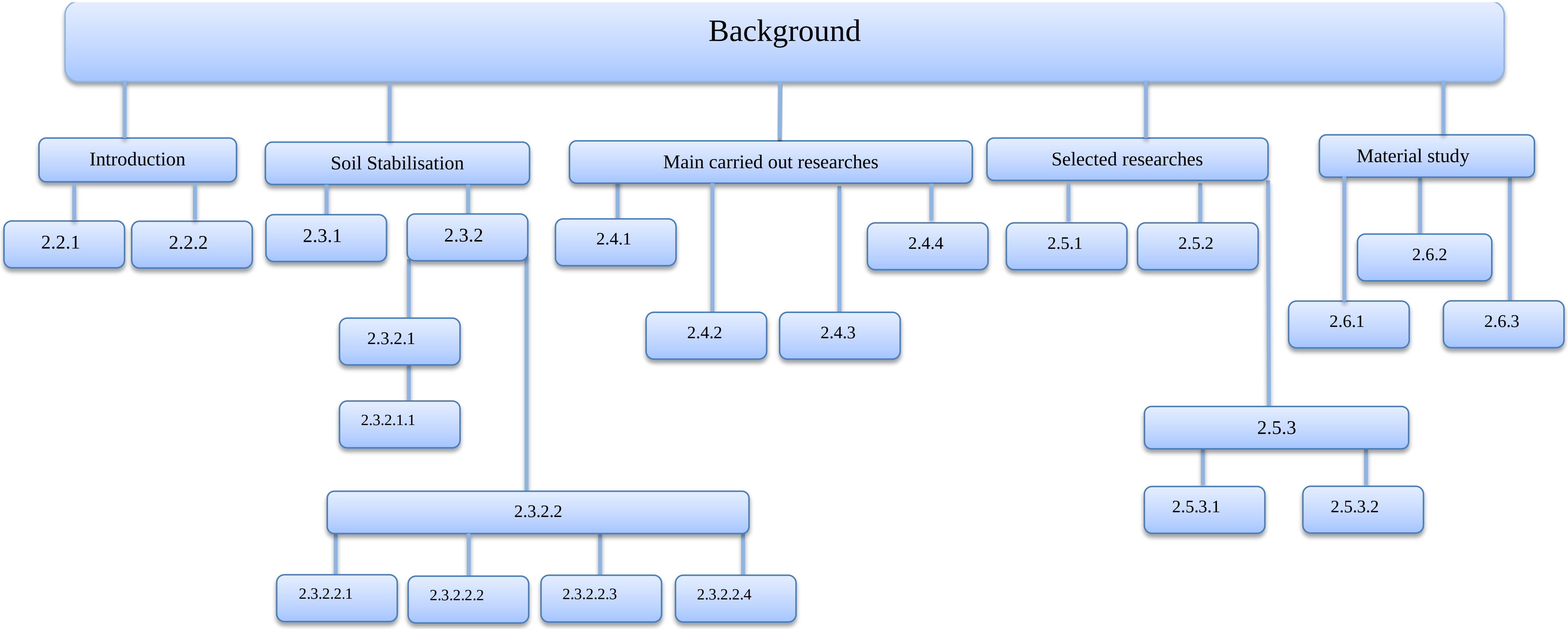
Given the fact that some fundamental aspects must be considered regarding the amounts of lime/fly ash, its mechanisms, application, and applicable combinations as an additive in soil stabilisation and some considerations about the economical and environmental problems, the objectives of this chapter are:

1. To review on some of the main problems of insufficient soil for construction purpose.
2. To review on the soil stabilisation history and application.

3. To review on some background and main studies on lime stabilisation.
4. To review on some background and main studies on fly ash stabilisation.
5. To review on some background and main studies on lime-fly ash stabilisation.
6. To review on material characteristics of lime and fly ash.

This chapter was separated in different phases as outlined in Chart1:

Chart 1. The outline of background study on soil stabilisation technique using lime and fly ash



2.2 Introduction

2.2.1 Landslide disaster

Landslides are a major geological hazard causing damage to a country's land and economy(Fowze et al., 2012). Landslides may be triggered by powerful or prolonged rainfall, earthquakes, rapid melting of snow, volcanic activity, human activity, and associated engineering properties of the soil. Various studies indicate that inappropriate soil properties such as high plasticity, poor workability and low mechanical properties are the main causes of landslide disasters (Fowze et al., 2012, Netto et al., 2011, Seco et al., 2011, Amiralian et al., 2012e, Amiralian et al., 2012a, Amiralian et al., 2012b, Amiralian et al., 2012c, Amiralian et al., 2012d). Many countries including the United States, Canada, Italy, China, Thailand, India, and Brazil suffer continuing landslide fatalities (Fowze et al., 2012, Glade et al., 2005, Amiralian et al., 2012e).

In this field, the establishment of a project on expansive soils could lead to extensive destruction due to the unpredictable swell and shrink behaviour of soil(Fowze et al., 2012). As cited by researchers(Fowze et al., 2012), a catastrophic landslide in Thailand in 1988, resulted in the death of 373 people in addition to $280 million in financial losses. In August 2001, a similar event resulted in the death of 136 people and $5 million in property damage (Fowze et al., 2012, Glade et al., 2005, Amiralian et al., 2012e).

Despite these events, prevention of landslides is a complex issue due to a lack of understanding as to the exact mechanisms causing damage. In January 2011, a landslide and flooding event in the

Serrana mountain region of the State of Rio de Janeiro, Brazil, led to the worst-ever natural disaster in Brazil. A series of flash floods and landslides claimed 895 lives and caused major damage to urban and rural infrastructure (Ferreira et al., 2011, Netto et al., 2011).

2.2.2 Soft soil

Another common problem for construction projects in many countries such as Australia (Lay and Metcalf, 1983, Wilkinson et al., 2010, Clarke et al., 2010, Liu et al., 2010),USA(Senol, 2006) India(Ghosh, 2009), and some European countries(Seco et al., 2011, Castro-Fresno et al., 2011, Sezer, 2006, Göktepe et al., 2008) is the building of construction and roadwork on soft and inadequate soil(Senol, 2006, Parsons and Kneebone, 2005).This issue poses great challenges in finding solutions to improve the problematic and inadequate soil which is utilised for building projects.

In tropical regions, lateritic soil is common. Chemical weathering, extreme temperatures and prolific rainfall produce this type of soil which has a variety of thicknesses and properties. Lateritic soil is widely used in engineering constructions such as embankment dams and airfields and it is also used in roadwork as layers and embankments. However, utilisation of this soil has been reduced due to problems with workability and compaction(Singh and Goswami, 2012).The main problems with organic soil are its low shear strength property and high compressibility characteristics. Essential treatment of the soil is carried out for construction projects like airports, runways, highways, some roadworks, railways, bridge foundations and foundation of high-rise buildings(Azadegan et al., 2012, Tastan et al., 2011).

The type and prioritising of soil treatment depends on the building conditions such as the geotechnical properties of land resources, accessibility of materials, economical and environmental aspects, and predicted risks.

Diverse techniques have been introduced to modify soil performance to a desired level for construction projects(Amiralian et al., 2012e, Amiralian et al., 2012a).

In order to improve the properties of some problematic soil, several mechanical and chemical methods have been introduced and implemented. Some of these methods consist of densifying treatments (like preloading or compaction), applying a pore water pressure method (such as dewatering or electro-osmosis), displacement-replacement (i.e., removing the soft soil and replacing it with strong soil), stage loading and the use of reinforcement elements (such as geotextiles), pile supported embankments, lightweight fill rafts, and deep in situ-chemical stabilisation(Senol, 2006, Harichane et al., 2011a, Harichane et al., 2011b, McCarthy et al., 2012, Patel and Patel, 2012, Amiralian et al., 2012e). Most of these methods are costly (Ghosh, 2009, Azadegan et al., 2012, Senol, 2006, Tastan et al., 2011). However, soil stabilisation is deemed to be the most efficient and cost effective technique. Some scholars report varying results from using soil stabilisation. Despite this, the section below will review the various studies aimed at investigating the effect of chemical stabilisation on soil properties using lime and fly ash.

2.3 Soil Stabilisation

A lack of land and financial resources are issues that projects must contend with when using local land. The evaluation of the soil quality in many sites reveals unsuitable soil characteristics with undesirable engineering properties such as low bearing capacity, high shrink and swell potential and high moisture susceptibility (Sharma et al., 2012, Harichane et al., 2011a, Harichane et al., 2011b).

An example of the consequences of using inadequate soil in construction may be found in the utilisation of soft soil in a sub-grade layer of pavement.

The pavement becomes damaged rapidly and the result is premature failure of the pavement (Sharma et al., 2012). However, the geotechnical engineers responsible for the pavement have to contend with the limited funds available to them, depending upon the financial state of their country, along with the limited availability of adequate resources. Therefore, a compromise in quality and longevity must sometimes be made. In the meantime, cost-effective techniques and improved stabilisation methods are being developed.

It is for the above reasons that soil stabilisation has been used for many years as a cost effective, environmentally friendly and efficient method for soil treatment. It is a method that may be adapted to meet the requirements of specific engineering purposes in particular projects (Harichane et al., 2011a, Harichane et al., 2011b, Castro-Fresno et al., 2011, Ramadas et al., 2011, Kolias et al., 2005, Amiralian et al., 2012e, Amiralian et al., 2012a).

2.3.1 Mechanical stabilisation

The implementation of soil stabilisation minimises the cost of earthworks and provides a process of soil treatment to sustain, modify or progress the soil's performance (Patel and Patel, 2012). The soil stabilisation method is applied in two ways; the mechanical (i.e., by changing its gradation) and the chemical (i.e., by creating a change in the soil’s chemical combination)(Amiralian et al., 2012e).

Mechanical stabilisation is performed by mixing two or more types of natural soil to achieve a soil combination of high quality and gradation in comparison with its separate components. In order to prepare the desired combination and create the necessary specifications, the proportion of fine and coarse particles of the blend is adjusted by adding or removing each soil component. Eventually, the correct mix of materials is appropriately located and compacted. The newly prepared soil combination should improve the strength properties of the soil by controlling both internal friction and cohesion, along with increasing the load carrying capacity of the soil as it has become a more stable composite (Ramadas et al., 2011).

2.3.2 Chemical stabilisation

2.3.2.0 Introduction on chemical stabilisation

In addition, the utilisation of a stabiliser develops soil engineering parameters in weak soil which is used in construction, roadwork, and sub-grade with soft soil. Strength properties are improved by cohesion, which leads to reinforcement of the structure, such as an embankment. This treatment will eventually reduce construction costs (Patel and Patel, 2012). Some studies report effective use of different additives such as cement, lime, fly ash, silica fume, and rice husk for the chemical stabilisation of soft soils (Amiralian et al., 2012e, Amiralian et al., 2012a).

It is also well known that stabilising soil with local natural and industrial resources, particularly lime, has a significant effect on the improvement of soil properties (Amiralian et al., 2012a, Castro-Fresno et al., 2011, Harichane et al., 2011a, Kavak and Akyarl, 2007, Kavak and Baykal, 2012, Seco et al., 2011),and fly ash (Degirmenci et al., 2007, McCarthy et al., 2012, Tu, 2009, Kim and Prezzi, 2008). The choice of stabilisers however, depends on the condition of the area selected for construction, along with economic considerations. For instance, in countries such as Nigeria, due to financial constraints, most of the research into chemical stabilisation was carried out using lime as opposed to other stabilisers (Castro-Fresno et al., 2011).

In soil stabilisation with lime and fly ash, additives are combined with specific moisture content, and then applied in order to improve the soil properties in engineering projects.

2.3.2.1 Lime Stabilisation

2.3.2.1.1 Lime application history

Some studies show that the utilization of lime turned goes back over 2000 years, where it was used as a soil-lime combination for roadwork in ancient Mesopotamia and Egypt, by the Greeks and Romans (Dash and Hussain, 2012, Bell, 1996). However, due to some limitations in modern geotechnical applications during recent decades, namely a lack of appropriate understanding of the utility and safety aspects, along with a limitation of natural resources, lime stabilisation was not widely applied.

Despite this, lime stabilisation has been used in earth construction such as highways, dams, runways, airports, embankments, foundation bases, and for slope protection, and canal linings, all within given economic limitations. Lime was first used in modern highways in 1924, when hydrated lime was applied to strengthen short stretches of highway (Bell, 1996, Dash and Hussain, 2012, Harichane et al., 2011a, Wilkinson et al., 2010). The efficiency and simplicity of this method as well as associated economic factors resulted in the widespread application of lime as a stabiliser to modify the engineering properties of soft soil (Dash and Hussain, 2012, Harichane et al., 2011a, Harichane et al., 2011b).

Moreover, lime treatment applications to roadwork and construction have markedly lessened the environmental impact. This includes a reduction in the excavation and compaction that is required and that is also associated with unpleasant visual and auditory amenity, along with pollution (Kavak and Akyarl, 2007).

2.3.2.2 Fly ash stabilisation

2.3.2.2.1 Fly ash application and history

Various fly ash stabilisation methods have been introduced throughout history. Chemical stabilisation is one of these favoured methods. In recent years, the potential for applying natural resources and industrial minerals in soil stabilisation has been explored. In an industrial context, there are three types of ash created during coal combustion, namely fly ash, bottom ash, and pond ash (Ghosh, 2010, Bera et al., 2007). Fly ash is one of the most abundant and versatile waste byproducts. This industrial grey powder contains non-combustible, glass-like particles and produces residues from the combustion of powdered coal from thermal power plants. The process is performed by flue gases in the boilers and then collected by mechanical or electrostatic precipitators or cyclone separators and filter bags (Sezer, 2006, Ghosh, 2010, Kim and Prezzi, 2008, Bose, 2012, Senol, 2006, Ramadas et al., 2011, Behara and Mishra, 2012). Bottom ash is prepared from the ash found at the bottom of the furnace. The amount of pond ash production, which is produced from a mixture of fly ash and bottom ash stored in an ash pond, is more than two other ashes(Ghosh, 2010).

2.3.2.2.2 Geo-environmental aspect of fly ash

A critical issue all around the world is a lack of conventional construction. At the same time, huge amounts of industrial waste material cause serious environmental issues and ecological imbalances. In addition, some unpredictable failures of ash ponds could affect agricultural land and pollute rivers up to100 kilometres away, thereby endangering human life(Ghosh, 2010, Das and Yudhbir, 2006).

It has been observed the same environmental problem for fly ash application. However, the consideration of fly ash as a "Polluting Industrial Waste" was changed a decade ago and reconsidered as a resource material in construction projects (Behara and Mishra, 2012). Despite the creation by fly ash of some environmental hazards such as leaching, dusting and damage to fertile land, it has been found to be useful in engineering constructions (Ghosh, 2010, Das and Yudhbir, 2006, Ramadas et al., 2011, Behara and Mishra, 2012).

Regarding the potential impact on the environment, further research is needed to understand the physical, chemical and engineering characteristics of fly ash in order to justify its use. (Bose, 2012, Das and Yudhbir, 2006).Furthermore, the production of materials from either the same or different plants could be variable due to utilisation of diverse coal sources, applied operating techniques, and variations in power generation in plants (Das and Yudhbir, 2006).

2.3.2.2.3 Fly ash production

Differing current assessments have reported that the utilisation of fly ash is less than the amount produced, although use will increase in future (Behara and Mishra, 2012). Based on evaluations, fly ash of around 500 million tons constitutes approximately 75% - 80% of the world’s total production (i.e., around 600 million tons). For example, yearly fly ash production in the US is 75 million tons; China produces more than 100 million tons, India, 112 million tons and Australia, 10 million tons (Figure 1)(Behara and Mishra, 2012, Sezer, 2006, Pandey and Singh, 2010).

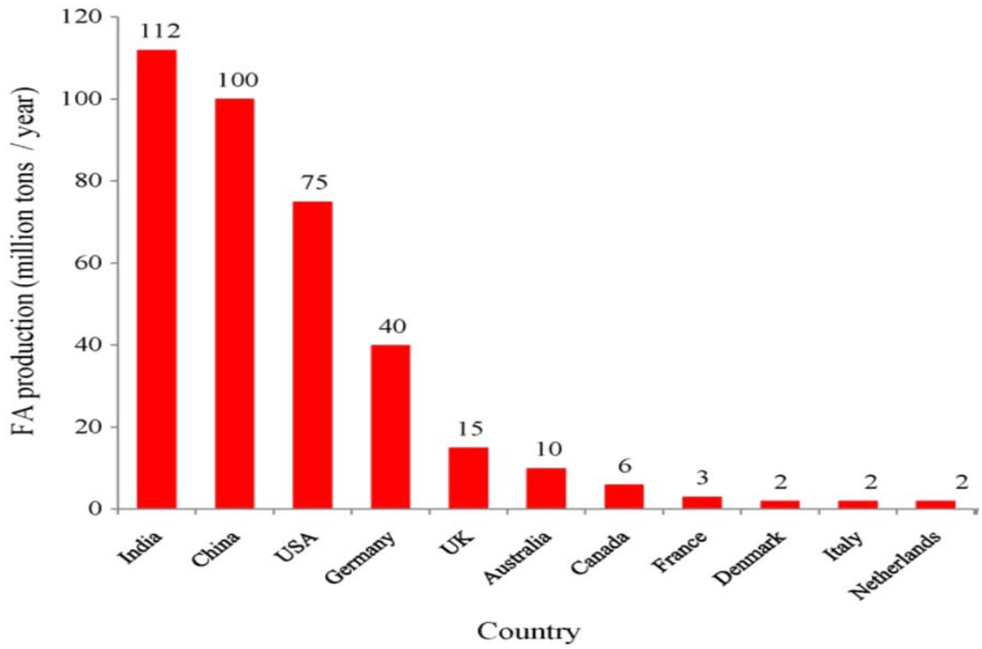


Figure 2. Fly ash production in different countries (data source: http://www.tifac.org.in/)(Pandey and Singh, 2010)

2.3.2.2.4 Fly ash utilisation in construction projects

A more productive and targeted utilisation of fly ash as an alternative material in geotechnical building and geo-environmental infrastructures could actually produce some remarkable environmental advantages, for example, a reduction in air and water pollution (Bose, 2012, Sezer, 2006).

The application of fly ash in engineering projects not only offers the advantage of partial resource conservation but it is also a most promising economic solution for geo-environmental problems. Fly ash may be used in cement manufacturing, as a part replacement for cement in mortar and concrete, in the manufacture of bricks, blocks, tiles, roofing sheets and other building components, in structural fills and dykes, for construction of roads /embankments, reclamation of low lying areas and back-filling of mines (Sezer, 2006, Ramadas et al., 2011, Ghosh, 2010, Kim and Prezzi, 2008, Senol, 2006, Yadu et al., 2011, Malik and Thapliyal, 2009, Behara and Mishra, 2012, Flrat et al.).

Regarding low unit weight and compressibility (Seco et al., 2011, Yarbaşı et al., 2007) , cost-effective and energy saving benefits (Sezer, 2006), fly ash has been found to be one of the most plentiful and flexible waste materials that may be extensively applied to developing the properties of soft soil in geotechnical engineering constructions (Yarbaşı et al., 2007, Harichane et al., 2011b, Ghosh, 2009).

The application of fly ash in soil treatment might enhance the physical and chemical characteristic of soil, although the level of change depends on the properties of the soil and fly ash. Incremental usage of fly ash as a high energy based material instead of partial cement or lime use could also have some advantages in energy saving (Degirmenci et al., 2007, Sezer, 2006, Yarbaşı et al., 2007, Malik and Thapliyal, 2009).

2.4 Main carried out research lime/fly ash stabilisation

Chemical stabilisation with lime leads to an alteration of some of the major engineering properties of soil such as volume stability, strength properties, stress-strain characteristics, permeability, and soil durability(Castro-Fresno et al., 2011, Dahale et al., 2012), reported that in the same condition and with the same amount of additive, the required time for a reaction between lime and the composite material was less than with other stabilisers. It also demonstrated an extensive alteration in the chemical properties of the soil.

This change could be due to the establishment of a cementitious combination, which is a result of the hydration of available cement agents in lime(Dahale et al., 2012). This tendency confirmed the results of soil modification studies using lime. The lime leads to the assembling of particles and the sticking of the soil atoms to one another, thereby establishing larger particles. This alteration leads to the creation of some short-term changes in soil characteristics, such as increments in the optimum moisture content, CBR values, a reduction in proctor densities, and plasticity indices (Kavak and Akyarl, 2007).

This section, was provide the result on five main groups based on the applied geotechnical tests including compaction properties, hydraulic conductivity, consolidation properties strength properties.

2.4.1 Compaction properties

Some surveys have reported that lime has no efficient effect on compaction parameters; however, in comparison with other binders, lime creates a quick and extensive chemical reaction with soil particles. Changing the characteristics of soil as result of chemical interaction leads to a change in soil properties, such as its compaction characteristics (Kavak and Akyarl, 2007, Kavak and Baykal, 2012, Castro-Fresno et al., 2011, Harichane et al., 2011a, Harichane et al., 2011b, Guney et al., 2007).

In comparison with unstabilised soil, lime treatment not only causes a remarkable increase in the optimum moisture content, but the results also indicate a decrease in the maximum dry density after lime stabilisation (Castro-Fresno et al., 2011, Harichane et al., 2012, Harichane et al., 2009, Harichane et al., 2011b, McCarthy et al., 2012, Michael J McCarthy, 2009, Kavak and Akyarl, 2007, Dash and Hussain, 2012, Lim et al., 2002, Yarbaşı et al., 2007).

Moreover, several studies were carried out into lime's efficiency on soil stabilisation using differing experimental procedures. The California bearing ratio (CBR) test and unconfined compressive strength test results of lime modified soils showed an improvement in its mechanical capacity (i.e., Unconfined Compressive Strength value and CBR value). However, in some cases this amount was inadequate for use in construction materials (Lim et al., 2002, Kolay, 2011, Seco et al., 2011).

Several researchers have conducted investigations into the compaction characteristics of soil (Degirmenci et al., 2007, Michael J McCarthy, 2009, Sezer, 2006, Senol, 2006). They have established that adding fly ash to soils changed the range of porosity and void ratio of soils. Through soil stabilisation, soil particles can attract greater amounts of water. This interaction leads directly to an increase in optimum moisture content and a decrease in maximum dry density.

2.4.2 Hydraulic conductivity

Chemical stabilisation is sometimes applied for constructing soil systems such as dams, canals and river levees. However, the research about the consequences and effectiveness of lime or fly ash treatment on the hydraulic conductivity of soil is extremely limited and varies widely (Nalbantoglu and Tuncer, 2001, Cuisinier et al., 2011, National Research Council . Transportation Research, 1991).

The most common proposition regarding hydraulic conductivity in this context is that it may be associated with the compressibility characteristics of soil (Nalbantoglu and Tuncer, 2001). In addition, based on several investigations, the hydraulic conductivity of soil depends upon the compaction procedure used. Consequently, in spite of the equivalent dry density and moisture content, the difference in compaction energy could lead to a different result for the same sample (Nalbantoglu and Tuncer, 2001, Cuisinier et al., 2011, Runigo et al., 2009, Cuisinier et al., 2008). Therefore, the compaction properties of soil due to chemical and mechanical improvements have an effect on the hydraulic conductivity of soil as well. For this reason, the lower dry density of treated soil may lead to higher hydraulic conductivity (Cuisinier et al., 2008, Cuisinier et al., 2011, Runigo et al., 2009, Locat et al., 1996).

On the other hand, some studies have demonstrated that hydraulic conductivity of stabilised soil decreases due to reducing the level of consolidation. Moreover, investigations have shown that increasing the amount of additives and the actions of hydraulic conductivity together have an inverse relationship (Cuisinier et al., 2011, Nalbantoglu and Tuncer, 2001).

2.4.3 Consolidation properties

The compressibility property of soil, as a pivotal part in the building of roads, airports, structural foundations and embankments, is defined by the consolidation process. Consolidation is a method whereby water particles and voids are extruded by applying loads, which have a relationship with the volume of air, the permeability of the soil and pozzolanic activity (Cetin, 2004, Moghal et al., 2011). By loading the soil, atoms are reorganised into a new pattern to increase the stability of the soil structure (Amiralian et al., 2012e, Amiralian et al., 2012a, Cuisinier et al., 2011, Nalbantoglu and

Tuncer, 2001, Tiwari and Ajmera, 2011). In order to minimise settlement in geotechnical structures, the rate of soil settlement can be limited by lime/fly ash treatment. The experiment results reported a small amount of the coefficient of secondary compression in the fly ash treated specimens. This advantage could reduce the possibility of settlement due to secondary consolidation of structures (Tu, 2009).

2.4.4 Soil's strength

Some scholars posit varying suggested amounts of lime to improve soil strength and this may be related to the type of clay mineral that was utilised in their experiments on soil modification. In this context, the availability of kaolinite, illite and montmorillonite could be helpful in increasing the bearing value of the soil (Manasseh and Olufemi, 2008). The studies also reported that the mineralogical components and surrounding atmosphere played a pivotal role in the swelling and shrinkage potential of soils (Manasseh and Olufemi, 2008, Akawwi and Al-Kharabsheh, 2002).

The determination of a sufficient dosage of lime as an important factor in soil stabilisation is a topic that has been studied by many researchers. The reason for the significance of the modifier dosage is in its ability to produce the opposite effect to that which is desired. There are also economic considerations.

Many different studies have been published in this field. Dash and Hussain (2012) reported that utilisation of lime beyond the specific amount caused a reduction in soil strength, which led to inappropriate cohesion and friction angles in the stabilised soil. According to various studies (Manasseh and Olufemi, 2008, Akawwi and Al-Kharabsheh, 2002, Phanikumar, 2009), a diverse range of lime amounts, between 0.5% and 10 % was suggested for soil treatment.

Furthermore, many studies (Harichane et al., 2011a, Kim and Prezzi, 2008, Parsons and Kneebone, 2005, Prabakar et al., 2004)have reported on the efficacy of fly ash on the strength of soil. The obtained results indicated that the incorporation of fly ash into soil particles resulted in a significant improvement in the strength properties of the soil. Therefore, the bearing capacity of fly ash treated soil may be effectively developed due to improvements in the shear strength, and cohesion of soil.

2.5 An overview on some selected comprehensive researches

In this section some of the comprehensive studies was selected and presented.

2.5.1 Lime-Fly ash application

With a view to further improving soil quality, further studies have investigated the possible improvements that a combination of lime and fly ash might make to unstabilised soil.

Based on published research (Zha et al., 2008) regarding the stabilisation of different soils using fly ash and lime-fly ash, the following conclusions can be drawn:

Lime-fly ash stabilisation reduces both the swelling and shrinkage properties of soil. Reduction of free swell, swell potential, swelling pressure, and linear shrinkage decreases with lime-fly ash content. Moreover, the swelling potential and swelling pressure of fly ash stabilised soil lessens with increments in the curing time (Phanikumar, 2009). Some of the research points to a significant role for a lime-fly ash mixture in the reduction of the swelling potential of expansive soil. The mixture is also seen as being a cost-effective and environmental friendly soil treatment (Ji-ru and Xing, 2002).

Investigation into the compaction properties of soil reveals various results depending on the soil used. Zha et al. (2008) have investigated the lime-fly ash effect on Hefei expansive soil and found that an increase in the dosage of additives led to a reduction in both the optimum moisture content and maximum dry density parameters of soil, and this result was then confirmed by other studies (Phanikumar, 2009). However, further studies (Zha et al., 2008) presented different results through a comprehensive study on the compaction properties of lateritic soil. Zha et al. (2008) studied the dosage of additives, compaction delay, and the effect of recompaction cycles on soil.

Various dosages of additives (i.e., a lime dosage of between 2% to 4% and up to 50% fly ash) were applied to evaluate the effects of lime-fly ash on soil. Increments in the amount of additives led to an increase in the optimum moisture content and a reduction in maximum dry density(Ji-ru and Xing, 2002). In the context of compaction delay, the MDD and OMC have a reverse correlation. A longer compaction delay leads to a gradual lowering of the MDD, and conversely, the OMC progressively increases. Due to the effect of the recompaction cycle on lime-fly ash treated lateritic soil, the MDD and OMC increase and reduce respectively.

Studies on plastic limit and liquid limit indices have shown that whenever a lime and fly ash mixture is applied to expansive soil treatment, the PI values were reduced, thereby leading to improved soil workability (Harichane et al., 2011a, Harichane et al., 2011b, Michael J McCarthy, 2009, Ji-ru and Xing, 2002, Yarbaşı et al., 2007, Goswami and Singh, 2005).

Some other published research has suggested a role for the lime-fly ash mixture in incrementing soil strength (Ji-ru and Xing, 2002, Zha et al., 2008) and reducing the sulphate-heave of treated soils (McCarthy et al., 2012).

2.5.2 Fly ash/lime application

Of the many of the studies carried out on fly ash efficiency on lime treated samples, some of the latest and more comprehensive research will be discussed in this section.

Bose (2012), studied the efficiency of fly ash on expansive soil (i.e., Sodium bentonite) with various dosages of fly ash ranging from 0% - 90%. In order to investigate the geotechnical behaviour of the soil, Atterberg limits, specific gravity, compaction characteristics, free swell, swell potential, swelling pressure, axial shrinkage percentage, and unconfined compressive strength tests were carried out. The results show that the addition of fly ash could reduce the plasticity properties of expansive soil. The plasticity index, and linear shrinkage decreased greatly and the shrinkage limit was increased by increasing the fly ash content. The maximum dry density and maximum unconfined compressive strength showed an incremental trend up to the point of 20% fly ash, whilst the optimum moisture content decreased with increases in the dosage of fly ash.

According to Tastan et al. (2011), the efficiency of fly ash applications on organic soil treatment is associated with the type of soil and characteristics of the utilised fly ash. The unconfined compression strength and resilient modulus tests were implemented for use with a combination of fly ash and organic soil and unstabilised samples. The UCS results showed that the addition of fly ash could lead to an increase in soil strength. The resilient moduli of organic and slightly organic soil improved markedly with the addition of fly ash.

A series of compaction tests, one-dimensional compression tests, direct shear tests and consolidated-drained triaxial compression tests were conducted on three kinds of fly ash (Kim and Prezzi, 2008). The compressibility, compaction and shear strength results revealed that the mechanical properties of fly ash can be compared to a typical sandy soil.

The long-term performance of soil stabilisation with fly ash has been investigated by some scholars. The application of various dosages of fly ash were recommended for the investigation into the soft clay subgrade Izmir, Turkey for example (Sezer, 2006). The unconfined compressive strength and shear strength parameters, cohesion and internal friction angles were investigated three months after the sample preparation. The results show that by increasing the dosage of modifier, the maximum dry density decreases, and optimum moisture content increases. The efficiency of fly ash on the unconfined compressive strength of soil was appreciable after 28 days. The strength parameter results found a significant improvement in cohesion which increased with time and stabiliser content.

In addition, Bin-Shafique et al. (2010) carried out plasticity index tests, unconfined compression tests, and vertical swell tests to evaluate soft clay modification. Several specimens were left for seven days curing, and six specimens were then subjected to 12 wet-dry cycles while three samples were subjected to 12 freeze-thaw cycles. The simulation of weathering action was created in a laboratory-controlled environment. The results showed a reduction of up to 40% in strength due to freeze-thaw cycles. Nevertheless, this amount was three times higher than that of untreated soils. The swell potential, and vertical swell of modified soils also increased due to the freeze-thaw cycles.

As mentioned, numerous researches on fly ash treatment has been conducted, the summary of some of the main results will be presented below.

Some studies (Degirmenci et al., 2007, Parsons and Kneebone, 2005), disagree on the effect of fly ash on the soil plasticity index. It can be observed that fly ash treatment could lead to a decrease in the plasticity index as a result of an increase in liquid values. Subsequently, reduced soil plasticity relates to lessening the degree of damaging sulphate-heave and the potential for swelling. On the other hand, the results of other studies reveal that applying only fly ash may be insufficient for developing the properties of highly plastic soil (McCarthy et al., 2012, Michael J McCarthy, 2009, Parsons and Kneebone, 2005).

2.5.3 An overview on the other experimental results

2.5.3.1 Plasticity index

One of the most noticeable benefits of lime, which was reported by many scholars, is the capability of lime to alter the plasticity of soil. In this field, some scholars stated that the reduction in the plasticity index was caused by increasing the amount of lime in the chemical stabilisation process. In some cases, the obtained results reported a multiplied reduction in the plasticity index of pure soil after lime treatments (Amiralian et al., 2012e, Amiralian et al., 2012a, Castro-Fresno et al., 2011, Harichane et al., 2011a, Kavak and Akyarl, 2007, Dash and Hussain, 2012, Harichane et al., 2009, Guney et al., 2007, Manasseh and Olufemi, 2008, Goswami and Singh, 2005).

If plastic limits present a soil's plasticity as a result of lime modification, there is a thickness of diffuse hydrous double layers. These are surrounded by clay particles, which affect the plasticity index of the soil. Increments in the amount of lime lead to a decrease in the liquid limit of the soil. This then increases the plastic limit (Dash and Hussain, 2012, Barker et al., 2006).

Consequently, the mathematical calculation of the plasticity index of the soil, using the difference between the liquid limit and plastic limit, will logically produce a lower result, compared with unmodified soil. The reduction of the plasticity index, is directly associated with the creation of a more friable and workable soil. Some investigations into the CH class (Fat clay) and CL class (Lean clay) indicated that the lime increase which modified both clays led to a reduction in the plasticity index (PI) (Harichane et al., 2009). In general, high plastic soils have some clay minerals including montmorillonite which strongly attract water. This behaviour increases the chance of swelling, thereby overlaying the construction after it has been damaged (Guney et al., 2007, Petry and Little, 2002).

2.5.3.2 *Swelling characteristic*

In addition, the plasticity index of soil is directly associated with the swelling pressure and swell potential of the soil(Phanikumar, 2009). Through chemical stabilisation, lime may efficiently limit the swelling potential of soils. Therefore, the swell pressure would reduce as a direct result of a decrease in the plasticity index of the stabilised soil. This characteristic would eventually considerably lessen the deformations found in construction (Castro-Fresno et al., 2011, Harichane et al., 2011a, Harichane et al., 2011b, Kavak and Baykal, 2012, Kavak and Akyarl, 2007, Wilkinson et al., 2010).

Apart from lime’s ability to adjust plasticity and swelling properties, lime modification can affect soil strength through its cementitious properties (Rajasekaran and Rao, 2000, Consoli et al., 2010). Although investigations into the specimens stabilised with lime revealed a shear failure mode such as a failure in brittle materials (Harichane et al., 2011a, Lin et al., 2007), further studies (Tu, 2009, Harichane et al., 2011a, Harichane et al., 2011b, Seco et al., 2011, Kavak and Baykal, 2012), established the effective role of lime in progressing the strength characteristics of soils (Dash and Hussain, 2012).

2.6 Material characterisation study on the lime/fly ash

2.6.1 Lime properties

One of the most frequently used chemical stabilisation methods is lime stabilisation, which was found to be a well-established technique for developing the plastic properties and the strength of cohesive soil. The application of lime, known as CaO, or $Ca(OH)_2$, and its byproduct (from burning the limestone) $CaCO_3$, have a very long history.

2.6.2 Fly ash properties

The fly ash is divided into class-C and class-F, based on the type of coal burned (Degirmenci et al., 2007, Kim and Prezzi, 2008, Senol, 2006). Class-C fly ash is normally created by burning sub-bituminous or lignite pulverised coal, while class-F fly ash is generated by bituminous or anthracite coals from a combustion heater (Sezer, 2006, Kim and Prezzi, 2008, Senol, 2006).

Overall, fly ash consists mainly of oxides of silicon, aluminium, iron and calcium. Magnesium, potassium, sodium, titanium and, occasionally, sulphur are detected as well. Class-C fly ash typically contains calcium alumina-sulphate glass in addition to quartz, tricalcium aluminates and more than 20% CaO. The American Society for Testing and Materials specification (ASTM- C618) classifies fly ash based on its CaO content (Table 1)(Dahale et al., 2012).

Table 1. Fly ash classification

Chemical composition	Fly ash Class F	Fly ash Class C
Silicon dioxide (SiO_2) + aluminium oxide (Al_2O_3) + iron oxide (Fe_2O_3), min, %	70.0	50.0
Sulphur trioxide (SO3), max, %	5.0	5.0
Moisture content, max, %	3.0	3.0
Loss on ignition*, max, %	6.0**	6.0

*ASTM- D7348 −8: Loss on ignition (LOI): "Loss on ignition (LOI) is determined by measuring the loss in mass of the test specimen when heated under controlled conditions of temperature, time, atmosphere, specimen mass, and equipment specifications."

**Regarding acceptable performance records or laboratory tests results by user, the utilisation of Class F consisting of up to 12% LOI might be acceptable.

2.6.3 Previous studies on material characterisation of stabilised soils

The composition specifications are determined by factors such as pH value, solubility of silica and alumina, mineralogical properties, and curing time consideration. Regarding the necessity of a sufficient alkaline environment for an ion-exchange reaction, the evaluation of the pH value is a significant factor (Solanki and Zaman, 2012).

The results of some studies indicate lime/fly ash stabilisation as an effective method for the controlling and modifying of soil characteristics. The method controls the variation of each parameter by altering environmental conditions such as moisture and pressure (Manasseh and Olufemi, 2008).

The calcium ions in the lime affect the properties of the soil as a cation exchange by associating with the metallic ions of the surface soil particles. However, increasing the amount of fly ash can reduce the resultant degree of damaging sulphate-heave. Moreover, this leads to an increase in the Optimum Moisture Content (OMC), Maximum Dry Density (MDD), consolidation properties, and strength characteristics of the soil (Amiralian et al., 2012e, Amiralian et al., 2012b).

Experiments on the physical and chemical reaction of stabilised soil, conducted by Ramadas et al., 2011, reveal that lime, fly ash, and a mixture of both have short and long-term effects on the characteristics of soil. Short-term effects are flocculation and agglomeration of soil particles on the surface of soil caused by cation exchanges and leading to improved plasticity and shrinking properties of the soil. Long-term effects are: development of workability, improved compaction and strength properties and reduction in swell characteristics due to textural changes (Harichane et al., 2011a, Harichane et al., 2011b, Michael J McCarthy, 2009, Kavak and Akyarl, 2007, Ramadas et al., 2011, Lin et al., 2007, Kavak and Baykal, 2012). Although the results of soil stabilisation with lime and fly ash in a variety of geotechnical constructions are varied, some of the soil properties, which have been studied in reasonable depth, will be explored in the following steps.

The two main mechanisms of soil modification that enhance the consolidation properties of soil are pozzolanic reactions and flocculation agglomerations (discussed in the chapter four)(Lin et al., 2007).

On the other hand, despite several reports about lime's efficiency in enhancing the performance of problematic soils (Petry and Little, 2002, Wilkinson et al., 2010), some cases studies showed an adverse effect of lime on soil treatment (Dash and Hussain, 2012). For example, increments in the plasticity index of lime treated soil are associated with an increase in the liquid limit and the plastic limit indices. This effect may suggest the role that hydroxyl ions play in adjusting the water affinity of the soil atoms (Dash and Hussain, 2012).

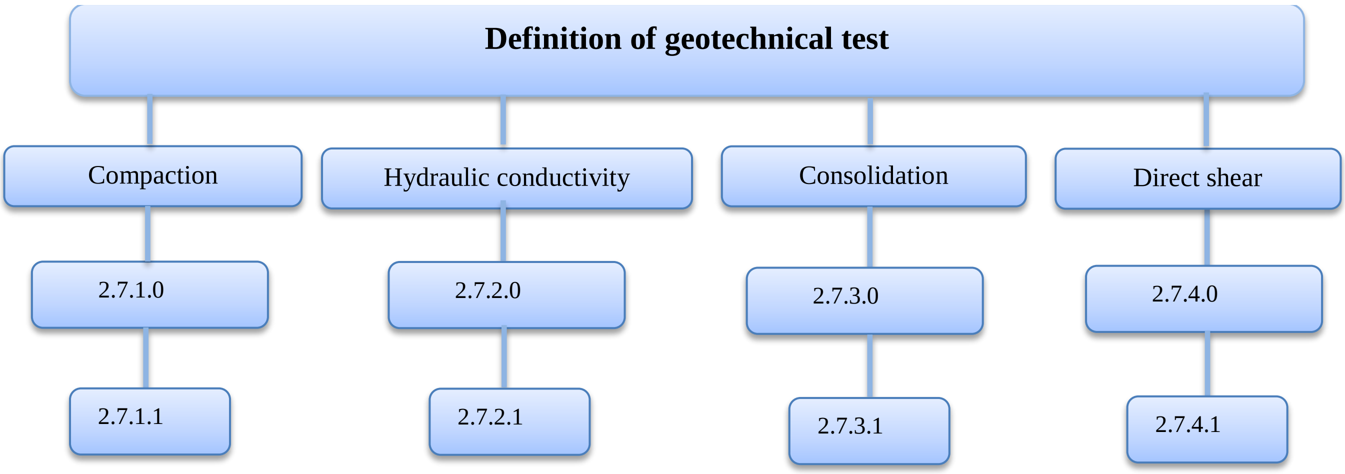
Based on several reports, increments in the strength and stiffness of soil due to cementation may be related to the reaction between soil and lime particles. This is known as a pozzolanic reaction (Amiralian et al., 2012e). The pozzolanic characteristics of lime may produce a long-term effect on the modified soil (Kavak and Akyarl, 2007, Kavak and Baykal, 2012, Rogers et al., 2006, Barker et al., 2006, Harichane et al., 2011a, Harichane et al., 2011b, Manasseh and Olufemi, 2008, Hossain et al., 2007).

In considering soil stabilisation dependency upon elements such as soil type, mineralogical properties, additives content, and environmental conditions, and the differing results achieved, it can be seen that lime stabilisation amounts require an accurate reappraisal.

2.7 Definition of geotechnical test

The theories of main experimental tests were presented in this section as show in chart 2:

Chart 2. The outline of geotechnical test's definition



2.7.1.0 Standard Compaction test

The standard compaction test (AS1289.5.1.1, 2001) was carried out for determining the maximum dry density and optimum moisture content, using a standard compaction procedure. The densification of soil was determined with the standard proctor test, which is typically carried out using mechanical compactors, rollers, and rammers along with water. Soil densification occurs when there is a reduction in the void ratio and air is expelled via the rearrangement of soil particles. The main objectives of the compaction process include increasing the bearing capacity and stability of slopes and limiting undesirable settlement and volume changes. Compacted soil is widely used in geotechnical constructions such as earth dams, landfill liners, highway base courses and subgrades, and embankments.

2.7.1.1 Definition and Theory

The standard compaction test consists of combining a dry soil with varying percentages of water. It is then compacted in a cylindrical mould (i.e., volume of mould: $9.44*10^{-3}m$). The soil is compacted in three equal layers by applying 25 blows of a hammer weighing 2.5 *kg* and this is dropped from a height of 305*mm*.

The applied energy by hammer is calculated by:

E_{comp}: $m_h g\ N_b\ N_l$

m_h : Mass of the hammer | g : Acceleration due to gravity

h_d : Height of fall of the hammer | V : Volume of compacted soil

N_b : Number of blows | N_l : Number of layers

E_{comp}: $2.5 * 9.8 * 25 * 3 * 10^{-3}$: 594 KJ/m^3

The degree of compaction is measured by dry unit weight. Based on the moisture-dry density curves, the maximum dry density and optimum moisture content of soil are achieved. In practice, at least 95% of maximum dry unit weight was performed for compaction application. This level of compaction could be achieved at two water content measurement points, i.e., before and after the maximum dry unit weight (Budhu, 2011, Kalinski, 2011).

The "dry of optimum" that is attained before the maximum dry unit weight, is usually applied in cases of soil with small volume changes due to alterations in water content, those soils being granular soils, clayey-sand and sandy clay. On the other hand, for soil with large volume changes due to alterations in water content, like expansive and collapsible soils, the “wet of optimum” is determined. However, in order to prevent sudden failure, which occurs in some cases, it was a requirement that the compaction wet of optimum was set at a 5% to 15% level to avoid a less acceptable range of optimum moisture content (Budhu, 2011).

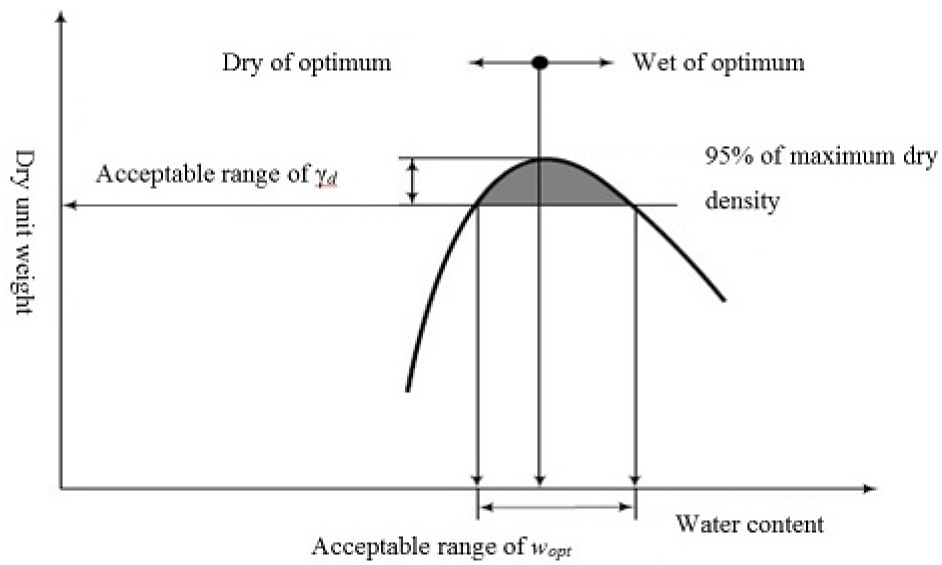


Figure 3. Desired compaction curve(Budhu, 2011).

2.7.2.0 Hydraulic conductivity test

The falling head test (AS1289.6.7.2, 2001) was performed to determine the permeability of sand and sand composites. This test was performed due to availability of fine grain material including lime and fly ash. Through the flow of water over the sample the effect of a falling head of water is quantified as a coefficient of permeability. Through the hydraulic conductivity test the volume of groundwater flow from a high potential area to low potential area can be measured. Some of the application areas for hydraulic conductivity are in estimating the performance of landfill liners and following the migration of contaminated groundwater.

The falling head test is generally used for less permeable soil (i.e., fine-grained soil). Due to the slow flow of water through the soil, this method provides more accurate estimates than the constant head test (the constant head method is applied to coarse-grained soils). However, with lime and fly ash being used as a fine-grained additive, the falling head test was performed (Budhu, 2011, Kalinski, 2011).

2.7.2.1 Definition and Theory

The falling head test device consists of a permeameter and a standpipe with a cross-sectional area. During the permeation period, the measurement of the head was taken at the beginning and end of the test in order to calculate the hydraulic conductivity in the vertical direction.

The schematic form of the falling head device is shown below (Figure3).

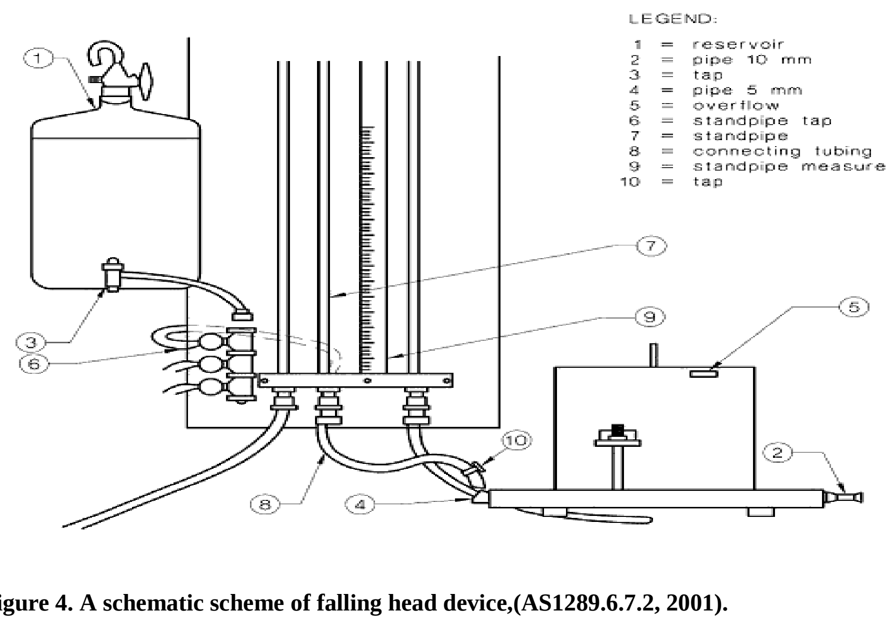


Figure 4. A schematic scheme of falling head device,(AS1289.6.7.2, 2001).

Darcy's Law is used to determination the coefficient of permeability in the falling head test method. Darcy's Law can be expressed as:

1) $q\text{: } K\frac{H}{L}A$

q: The rate of flow through the soil *K*: Hydraulic conductivity of soil

H: The instantaneous head across the sample

L: Length of sample in the cylinder *A*: Cross-sectional area

2) $q\text{: } a\,\frac{\Delta h}{\Delta t}$

a: Cross-sectional area of supply reservoir

3) $a\,\frac{dh}{dt}\text{: } K\frac{H}{L}A$

Through the separating of each side and integrating between the appropriate limits:

4) $\int_0^t Kdt\text{: } \int_{H2}^{H1}[\frac{aL}{A}*\frac{dh}{H}]$

H_1 is the initial head, at time: 0

H_2 is the final head at time: t

$K\text{: } \frac{aL}{At}\,Ln\,[\frac{H1}{H2}]$

2.7.3.0 One-Dimensional Consolidation test

The consolidation test (AS1289.6.6.1, 2001) was carried out to evaluate the rate and magnitude of consolidation of soil when it is restrained laterally and loaded and drained axially. Through incrementing the overburden stress on a layer of cohesive soil, the soil undergoes a long-term reduction in void ratio that is associated with settlement of the soil layer. By measuring the amount and duration of settlement in the soil layer, the settlement behaviour of soil can be anticipated. The consolidation test is performed by incremental loading on the soil specimen and this was doubled after each loading. The one-dimensional consolidation test may also include an unloading step. The pressure-void ratio relationship curve can then be drawn from the data and results. The consolidation curve is useful for evaluating some soil properties such as the compression index, recompression index and coefficient of consolidation (Budhu, 2011, Kalinski, 2011).

Incremental stress is applied axially, when a soil sample is restrained laterally. Each loading is continued until the excess pore water pressure has completely dissipated. The sample in this experiment was located between porous stones in a rigid, cylindrical container with a frictionless inside wall. To simplify pore water drainage, the porous stones and filter paper were placed on the top and bottom of the soil. Pore pressure is considered to be dissipated by referring to the elapsed deformation time and constant applied stress. In this case the soil was assumed to be a completely saturated sample. Through analysis, the changes in the sample height determined the effective axial stress and void ratio. For the time of deformation, the rate of consolidation is evaluated with the coefficient of consolidation (Kalinski, 2011, Budhu, 2011).

2.7.3.1 Definition and Theory

The results of the consolidation data provide useful information for the prediction and evaluation of soil settlement behaviour. This consists of: the coefficient of consolidation, primary consolidation, secondary compression, compression index and swelling index or recompression index (Budhu, 2011).

- ✓ Primary consolidation: Alteration in the volume of a cohesive soil as a result of water exclusion from the voids, thereby transferring excess pore water pressure to the soil particles.
- ✓ Secondary compression: Occurs after primary consolidation due to modification of the internal structure of soil.
- ✓ Compression index: Known as C_v , it is calculated from the slope of the average of the consolidation line, in a plot of the logarithm of vertical effective stress versus void ratio curve.
- ✓ Swelling index (C_s) or recompression index (C_r): Is calculated from the normal slope of the unloading curves in a plot of the logarithm of vertical effective stress versus void ratio.

Based on Terzaghi's Theory of Consolidation, the coefficient of consolidation is lessened as it is associated with stress increments as a reduction in hydraulic conductivity (Budhu, 2011, Kalinski, 2011) . The coefficient of consolidation (C_v) for each load application is measured by time-deformation data and the deformation corresponding to the end of the primary consolidation (d_{100}). There are two common methods that may be used to calculate C_v and d_{100}:

➢ *Log Time Method*

The coefficient of consolidation was calculated by the log time method. In the log time method, displacement, d, versus time, t, are plotted on a semi-log plot.

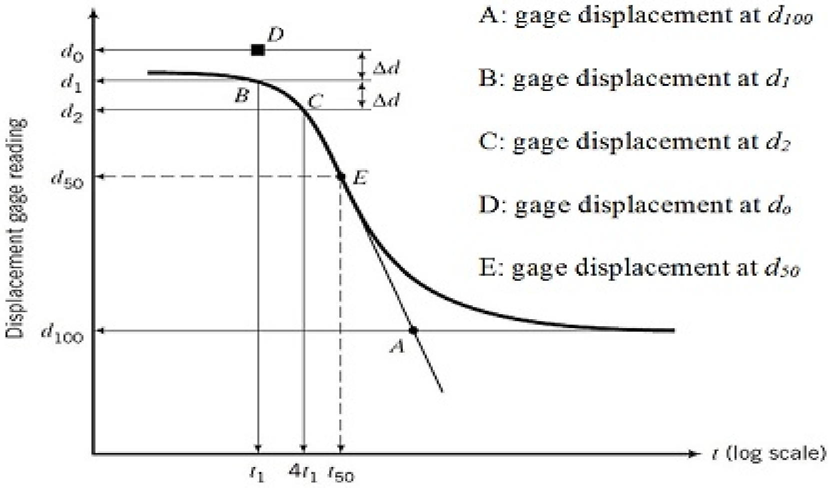


Figure 5. Consolidation log- time method curve (Budhu, 2011)

$t_1 = t_2/4$ d_{100} : 100% primary consolidation

$\Delta d = d_2 - d_1$ d_{50} : 50% consolidation, $d_{50} = (d_0 + d_{100})/2$

$d_0 = d_1 - \Delta_d$

From the d_{50} , could calculate the degree of consolidation of 50%:

H_{dr} : $\frac{Ho-d50}{2}$ C_v : $\frac{T50(Hdr)^2}{t50}$

T_{50} : The time factor for 50% consolidation is 0.197

C_v : $\frac{0.197(Hdr)^2}{t50}$

2.7.4.0 Direct shear test

The direct shear test (AS1289.6.2.2, 2001) was used to determine the shear strength of a consolidated-drained soil by direct shearing in a shear box. Shear strength is one of the most critical engineering properties of sand; it is used to assess the soil's resistance to shear stress. This is essential for engineering calculations like determination of stability of earth slopes or cuts and finding the bearing capacity of foundations. Regarding the difficulties of sample preparation of cohesionless soil for triaxial tests, a direct shear box is commonly used for estimating the shear strength of sand and gravel. The soil's shear strength depends on the interaction between soil particles. This interaction is related to cohesion and frictional resistance between particles (Kalinski, 2011, Budhu, 2011).

2.7.4.1 Definition and Theory

The automatic direct shear test was performed to investigate the shear strength properties of modified and unmodified sand. The strength properties of sand were determined by direct shear results such as shear stress, vertical-confining stresses, horizontal displacement, vertical displacement, soil frictional angle and cohesion (Budhu, 2011).

- ✓ Shear strength (τ): the maximum internal resistance to applied shearing force under a specific normal stress.
- ✓ Cohesion (C): A measure of the intermolecular force.
- ✓ Internal friction angle (ϕ): A measure of the shear strength parameter of soil due to friction.
- ✓ Dilation (α): A measure of the alteration in the volume of a soil when the soil is distorted by shearing.

From the abovementioned data the following typical curve was plotted (Figure 5).

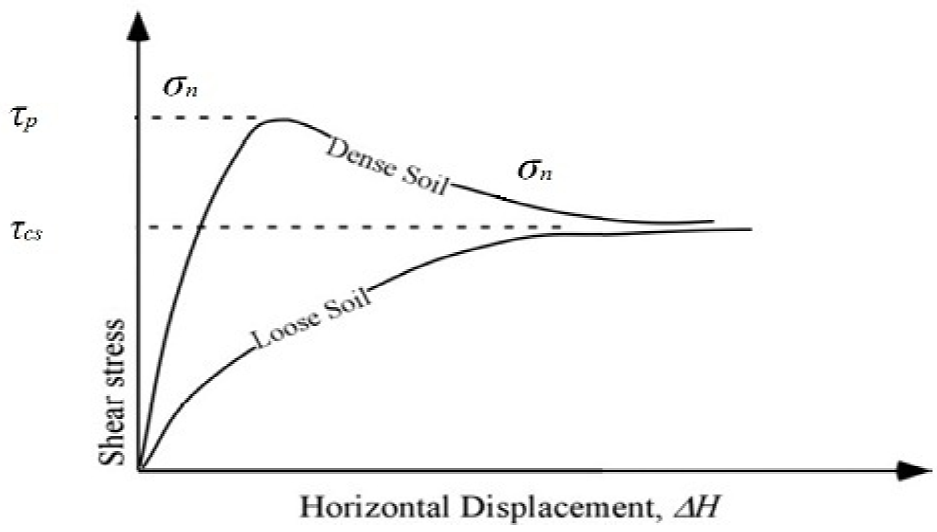


Figure 6. Typical shear stress- horizontal displacement curve of soils (Kalinski, 2011).

Based on the Coloumb Failure Criterion:

τ_p: peak shear strength	τ_p: $\sigma_n \tan \phi_p$
τ_{cs}: critical state shear strength	τ_{cs}: $\sigma_n \tan \phi_{cs}$
ϕ_p : friction angle at the peak	ϕ_p: $\tan^{-1}(\frac{\tau p}{\sigma n})$
ϕ_{cs}: friction angle at the critical state	ϕ_{cs}: $\tan^{-1}(\frac{\tau cs}{\sigma n})$
α_p : peak dilation angle	α_p: $\phi_p - \phi_{cs}$

The typical ΔV- ΔH curves for loose and dense soils are illustrated schematically in Figure 6 (i.e, ΔV: is a change in vertical displacement under the applied normal stress, ΔH: is a change in horizontal displacement under the applied shear stress).

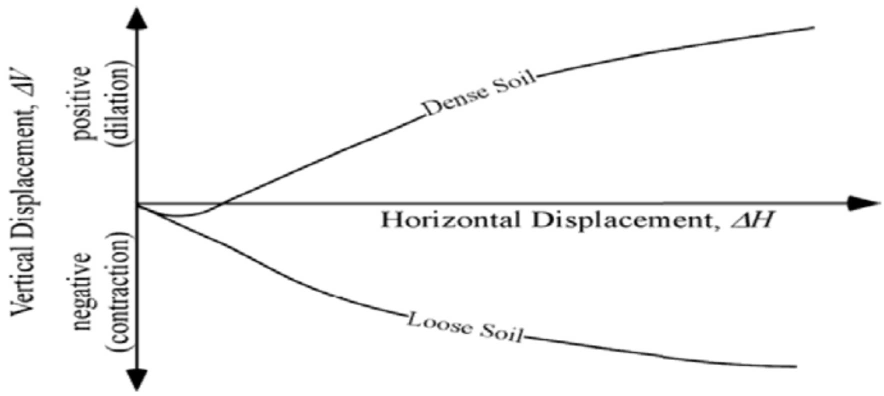
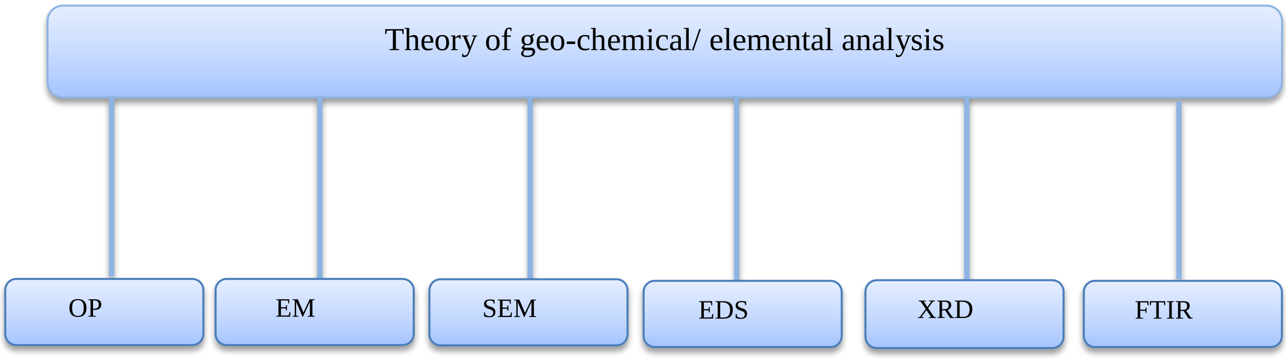


Figure 7. Typical vertical displacement-horizontal displacement curve of soils (Kalinski, 2011).

2.8 Theory of geo-chemical/ elemental analysis

The definitions of main selected chemical and elemental examination were presented in this section as show in chart 3:

Chart 3. The outline of microanalytical method's theory



2.8.1 Optical microscopy (OP)

The application of optical microscopy has been significant in the exploration of the micro-scale aspect of materials. The light microscope is widely used for studying the micron range in particles. The principle of optical microscopy is based on the magnification of the size of particles. As is shown by Figure 7, the image of the specimen (objective) is processed through an objective lens that magnifies the size of particles in a magnification range that is generally 10*x* to 100*x*(Carlsson, 2007).

This enlarged image is then observed through an eyepiece with a magnification in the range of 10*x*. Hence, the total magnification of a microscope is normally in the range 100*x* to 1000*x(Carlsson, 2007)*.

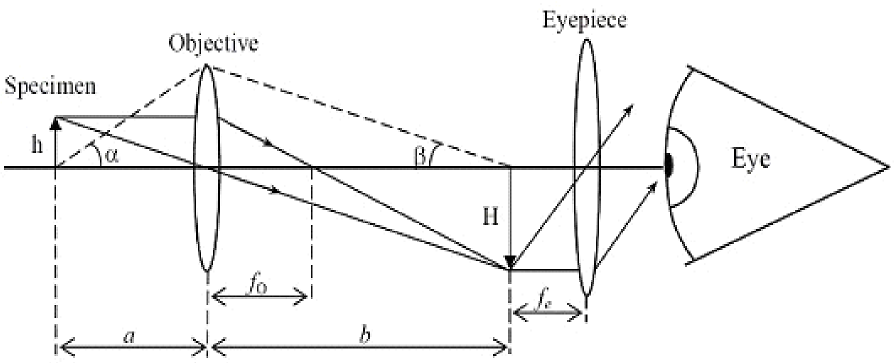


Figure 8. A schematic view of optical microscopy mechanism (Carlsson, 2007).

2.8.2 Electron microscopy (EM)

Light microscopy has some limitations including the visible spectrum range (i.e., approximately 550*nm*) and the low resolution of optical microscopic images (i.e., approximately 300*nm*). Due to the limitations of light microscopic instruments, electron microscopy was introduced (Tarrant, 2011).

Based on the de Broglie theory, all particles such as electrons have wave-like characteristics, and the momentum p of particles might be associated with its wavelength λ via Planck's constant, *h* (Tarrant, 2011):

$$\lambda : \frac{h}{p}$$

Electron microscopy (EM) examines material on a micro-scale by utilisation of a high-energy electron beam. The overall function of EM is to stream a beam of electrons with an electron gun, and then accelerate by positive electrical potential to keV energies. In addition, the electromagnetic lenses focus and control the electron beam. Consequently, the interactions which occur inside the irradiated specimens are identified and converted as an image (Tarrant, 2011).

The EM results in this research provided a wide range of information including: topography, morphology, composition, and crystallography of material.

- ✓ Topography: Information about the surface structures of a material
- ✓ Morphology: Information about the form and dimension of particles material
- ✓ Composition: Quantitative and elemental information of components of each material
- ✓ Crystallography: Information about the ordering and arrangement of the material's particles

Electron microscopes can be separated into two basic types; scanning electron microscopes (SEM), and transmission electron microscopes (TEM) (Figure 8).

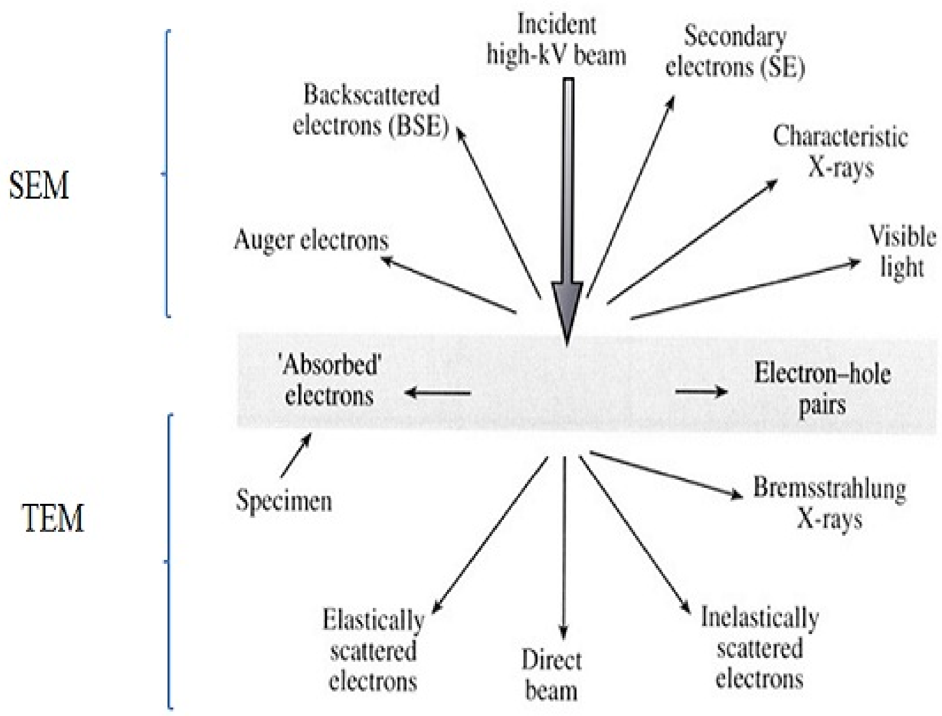


Figure 9. Introduction of different type of electron microscope by striking the electron with materials (Tarrant, 2011).

2.8.3 SEM (Scanning Electron Microscopy)

There are two type of scattering; elastic and inelastic, and this scattering occurs due to the interaction between the electron beam and the atoms in the sample. The interaction in a thick or bulky sample is observed by scanning electron microscopy (SEM). Information is obtained from the surface of the sample and recorded. The electron beam and accelerating voltages are usually used in the "*nA*" range and 1kV - 30kV, respectively (Piburn and

Barron, 2012). Based on the electron emission from the surface of a sample, micrographs are carried out in two ways; secondary electrons (SE) and backscattered electrons (BSE) (Tarrant, 2011).

- ✓ Secondary Electron (SE): The released electrons from the surface shell of atoms bombard the samples with high energy electrons. Typically, SE has a low energy (i.e., 5eV). Regarding this factor, the results related to topographic data form the surface of the sample (< 10 *nm*).
- ✓ Backscattered Electron (BSE): The high-energy electron of the electron beam, which is elastically scattered by atomic nuclei in the back of the sample. The high range of energy (i.e., between 1kV - 30kV) in BSE creates a reflection of the compositional information of the sample.

In this context, the compositional investigation of material is carried out by the BSE method associated with an energy-dispersive spectrometer (EDS).

2.8.4 EDS (Energy-Dispersive Spectrometer)

As mentioned in the previous section, the impact of electron beams on the specimen object creates a diversity of emissions, such as x-rays. Energy-dispersive X-ray spectroscopy (EDS) is performed for finding the chemical composition of materials on a micro-scale. The data produced may assist in the creation of element composition maps from the sample. Therefore, this analytical method is applied for analysing a sample from a chemical and elemental point of view (Tarrant, 2011, Goodge, 2011).

Using this method, the characteristic x-rays of each element were divided and the energy spectrum was then analysed, based on the determination of the abundant elements. This characterisation can be performed due to the specific peak found in each element which is associated with its own unique atom structure. The analysis was carried out along with a backscattered electron examination at a working distance of 8.5mm. The combination of these factors allows the determination of basic compositional information about the materials utilised (Goodge, 2011, Tarrant, 2011).

The projection of electron beams resulted in the ejection of inner shell electrons in the sample atoms. From this, two basic types of quantitative data connected with elemental properties may be produced:

- ✓ Line identification: The elemental data of material is illustrated by lines in the X-ray spectrum. Each specific line tendency presents the amount of atom availability in each area of the sample.
- ✓ Element mapping: The elemental data of material is presented by spots in the X-ray spectrum. The area and amount of illustrated spots relate to the unique atoms in a sample.

Thus, SEM micrographs and EDS examination can separately analyses the topographical and compositional characteristics of sand, lime, and fly ash.

2.8.5 XRD (X-Ray powder Diffraction)

X-ray powder diffraction (XRD) is performed as an analytical method for mineral identification of materials. This rapid technique is used for determining the atomic structure of crystalline material.

The XRD function is based on the constructive interference of monochromatic X-rays on crystalline specimens. The X-rays are generated by a cathode ray tube that is filtered to generate monochromatic radiation (Langford and Lou¨er, 1996).

The monochromatic radiation produced is released as a parallel line travelling toward the center of the specimen. This interaction generates a constructive interference phenomenon, which results in the production of diffraction peaks. Based on Bragg's Law, the position of the diffraction peaks is determined by the distance between the parallel planes of atoms (Goodge, 2011, Langford and Lou¨er, 1996).

$$\lambda\text{: } 2d\sin\theta \quad \left\{ \begin{array}{l} \lambda\text{: Wavelength of electromagnetic radiation } (\lambda\text{: constant}) \\ d\text{: Lattice spacing in crystalline specimen} \\ 2\theta\text{: Diffraction angle} \end{array} \right.$$

By counting and processing the diffracted X-rays associated with a range of 2θ, all possible diffractions of the lattice could be detected (Figure 9) (Goodge, 2011, Langford and Lou¨er, 1996).

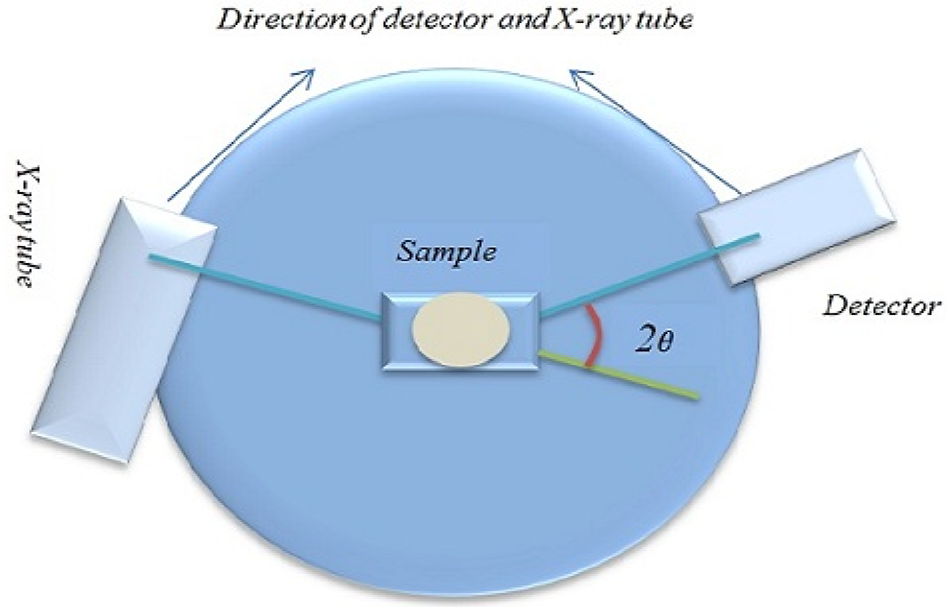


Figure 10. A schematic plan of XRD defractometer mechanism

For composite characterisation, XRD analysis can determine the proportion of available minerals in the mixture. The phase identification of material can provide some helpful information on unit cell dimensions. One of the applications of XRD information is in the identification of crystalline compounds through their unique diffraction pattern (Goodge, 2011, Tarrant, 2011). Along with the degree of crystallinity of the mineral, XRD may be used for identifying several aspects of a material:

- ✓ Identification of chemical compounds of material
- ✓ Characterisation of crystal material
- ✓ Structural analysis of mineral materials
- ✓ Identification of amorphous material

Thus XRD investigation into lime, fly ash and sand can obtain useful information for identifying the key chemical compounds and mineralogical characteristics of each component. XRD results are able to demonstrate any changes in the crystallinity of a composite after lime/fly ash stabilisation.

2.8.6 FTIR (Fourier Transform Infrared Spectrometry)

Infrared radiation which passes through a sample in order to measure the transmission or absorption of infrared light by a material is called Infrared (IR) spectroscopy.

IR radiation can be absorbed or transmitted by a sample as a function of the wavelength or frequency of materials. The IR spectrum is the range of behaviour within each material illustrated as a plot of absorption/transmission versus wavelength/ frequency. The molecular transmission or absorption of each molecule is unique and presents a "molecular fingerprint" of the sample (Gaffney et al., 2012, Meyer-Jacob, 2010).

IR spectroscopy operates on the basis of a thermal spectrum of materials. Basically, a thermal spectrum is principally caused by the vibration and associated rotational absorption banding of molecules. A relationship can be established between absorption bands and vibrations of particular functional groups within the molecule. Thus, the identification of bands can lead to the identification of the molecules that create a material (Gaffney et al., 2012, Meyer-Jacob, 2010).

As mentioned, each molecule absorbs a specific frequency of IR light. IR light is electromagnetic radiation in the region of wavelengths of approximately 0.78μm to 1000μm (Gaffney et al., 2012, Meyer-Jacob, 2010). Electromagnetic radiation is described by two parameters:

- λ : Wavelength (cm)
- υ : Frequency (s^{-1})

In addition to being a common unit, the wave number (cm^{-1}) is used for specifying the frequency in IR absorbance:

- $\overline{\upsilon}: \upsilon/(c/n)$

Where:

- ✓ c : The velocity of light in a vacuum : $3 * 10^{10} \frac{cm}{s}$
- ✓ c/n : The velocity of light in a medium of refractive index n (air: 1.00)
- ✓ $\overline{\upsilon}: \frac{1}{\lambda}$

The wavenumber is directly associated with frequency and the energy of IR absorption (Gaffney et al., 2012, Meyer-Jacob, 2010).

- $E: h\upsilon : h\overline{\upsilon}c$

Therefore, the wave numbers region is from 4000 $^{cm-1}$ to 200 $^{cm-1}$.

However, IR spectrometry has some limitations such as a slow scanning process and its ability to recognise only organic materials. The Fourier Transform Infrared (FTIR) method was introduced as an improvement to IR spectrometry and as a rapid method which covers an extensive diversity of materials. The interpretation of data is effectively accomplished with the Fourier transformation mathematical method.

The advantages of FTIR spectroscopy include:

- ✓ Compound identification
- ✓ Structural clarification

- ✓ Quantitative analysis of one or more recognised species
- ✓ Measurement of the basic characteristics of a molecule

However, identification of a compound is the most significant function of FTIR spectroscopy. In addition, the unique IR spectrum of each compound assists in recognising and determining the molecules and structure of a particular material (Gaffney et al., 2012, Meyer-Jacob, 2010).

The main goal of IR spectroscopy is to motivate or agitate polar bonds of molecules via absorption of radiation in the IR region of the electromagnetic spectrum. The light atomic bonds including C-H, C-O, C=C, are mainly the result of absorption of hydrogen, carbon, oxygen and nitrogen. This phenomenon results in a molecular vibration with a lifetime of 10^{-9}_10^{-6} *s* respectively, after motivation (Gaffney et al., 2012, Meyer-Jacob, 2010).

The frequency of molecules is associated with some factors such as the type of atom vibration (i.e., atomic mass), the molecular structure and bond strength. This dependency is called normal vibration and is improved by separating the vibrations of atoms in the molecule, which move with similar frequency and various amplitudes (Gaffney et al., 2012, Meyer-Jacob, 2010, Kellner et al., 2004).

Some of the main modes of normal vibrations are: stretching (i.e., stretching and shortening of chemical bonds, symmetric or asymmetric), bending (i.e., in-plane movement of atoms changing the angle between bonds), wagging (in-phase, out- of-plane movement of atoms, whereas other atoms of the molecule are in-plane), rocking (in-phase back and forth swinging of atoms in the symmetry plane of the molecule), and twisting (rocking vibration with twisting of the plane during the movement of the atoms) (Meyer-Jacob, 2010).

Thus, due to the change of the dipole moment phenomenon, any alteration of a composite's structure of normal vibration is detected and results in recognition of fingerprint-type polyatomic molecules (Meyer-Jacob, 2010, Gaffney et al., 2012, Kellner et al., 2004).

In contrast to normal vibrations, the absorption bands of functional groups are unrelated to the structural and compositional characteristics of molecules. The absorption of functional groups is known as a group frequency, which is markedly developed in functional groups consisting of H atoms or isolated double and triple bonds (Gaffney et al., 2012, Meyer-Jacob, 2010).

The group frequencies correspond to the wave number positions higher than1300cm^{-1}. Moreover, the group consisting of heavy atoms is detected in the wavelength region below 400cm^{-1}. Thus, the wavelength ranges between 1300 cm^{-1}_ 400 $cm^{-1}$is called the fingerprint region (Gaffney et al., 2012, Kellner et al., 2004).

To sum up, the elemental analysis and chemical characterisation were confirmed by EDS. Mineralogical phases were determined by XRD, and changes in chemical composition by FTIR.

In spite of the long-term utilisation of lime and fly ash as a common stabiliser in soil modification, most research has been limited to investigations into the geotechnical aspects of soil stabilisation by civil engineering experimental tests. However, the necessity for further studies into soil stabilisation with lime, fly ash, and a lime fly ash mixture from a chemical and material standpoint is evident. This research paper attempts to open up a new avenue through which a chemical and material analysis can be connected to civil engineering research and thus create a new and comprehensive area of research.

This current study focused on some fundamental and essential parameters of soil's geotechnical properties from the three different and comprehensive viewpoints. In order to systematically and accurately study the shear strength, compaction properties, compressibility and hydraulic conductivity of composite samples, the research was carried out in three different stages. The first stage examined the geotechnical and mechanical effects of additives on sand by a series of standard compaction, hydraulic conductivity, consolidation and small direct shear tests.

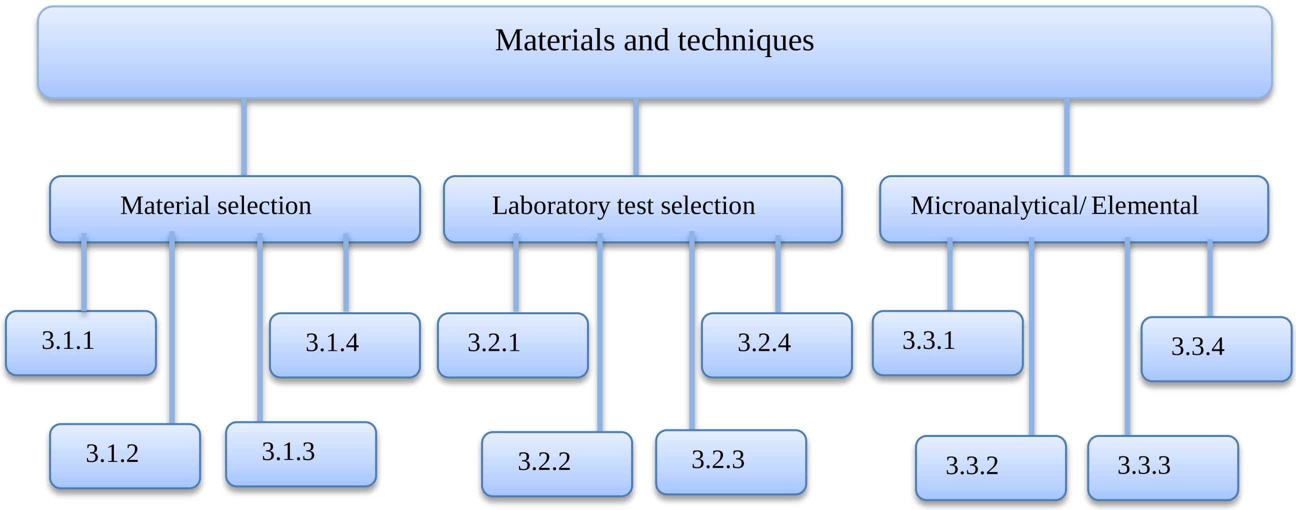
Results were then precisely analysed form a microstructural point of view, through optical microscopy and scanning electron microscopy examination. These examinations were then analysed to determine structural changes on a micro- scale.

CHAPTER3

MATERIAL AND TECHNIQUE

This chapter was separated in different phases as outlined in Chart4:

Chart 4. The outline of material and technique chapter



3.1 Material selection

The materials utilised in this research were selected with consideration given to two factors; the economic aspect and the prevalence of materials used in construction projects in Western of Australia and Australia. All of the selected materials were available in Perth, and were already widely applied in building and road construction projects.

3.1.1 Sand

The soil samples used in this research were collected from Baldivis, 50km south of Perth WA. Baldivis Yellow Concrete Sand is widely used as an appropriate material for mixing, footings, and making concrete and mortar in geotechnical constructions in WA. The dimensional information of Baldivis sand is presented in Table

2. The overall amounts of material, which were finer than 75μm and 2μm constituted less than 3% of the materials. The water absorption was evaluated as being between 1.5% and 3 % (Figure 10).

Table 2. Sand grain distribution

Sieve size (*mm*)	Passing amount (*%*)
6.7	100
4.75	100
2.36	98
1.18	95
0.6	86
0.3	24
0.15	3
0.075	1

Figure 11. Baldivis Yellow Concrete Sand

3.1.2 Clay

The preformed kaolin clay used was designed for construction purposes such as blunging in slurries, filter pressing and extrusion, mulling prior to extrusion and spray drying. Kaolin clay is easily dispersed in water, and is designed for increasing strength in plastic formation and extrusion operations. The plastic properties of kaolin clay have a wide moisture range which provides it with the enduring characteristics to resist cracking or deformation.

The rapid equilibration of fluid in kaolin clay leads to a minimising of batching and blending time. In this experiment, the water absorption and liner shrinkage (dry-fired) were 11.5% and 14.8 % correspondingly. The fineness index of kaolin clay was 95% residue when passed through a 10 μm sieve (Figure 11).

Figure 12. kaolin clay

3.1.3 Lime

Hydrated lime, with "slaked lime" being its traditional name, by Ca $(OH)_2$ chemical formula, was used as one of the stabiliser in this research. Calcium Hydroxide, in the form of a white powder with a free moisture content which was less than 2.5%, was produced by the combination of adequate water and slake quicklime. Hydrated lime is utilised as a neutralising agent in water and sewage treatment, a binder in mortars and renders, and for soil stabilisation and maintaining alkaline conditions for mineral processing.

The lime and carbon dioxide availability (as Calcium Hydroxide) was more than 65%, and less than 4% respectively. The determined fineness index of hydrated lime (i.e., wet sieved hydrated lime) was less than 5% residue on passing through a 600 μm sieve (Figure 12).

Figure 13. Hydrated lime

3.1.4 Fly ash

Collie fly ash, a class F fly ash of fine cream/grey powder was utilised in this experiment. Fly ash has been successfully mixed with other materials to create a high-quality and economical material for use as a concrete additive, bulk filler, fine filler in asphalt and other products. It is also used in soil amendment and stabilisation and as a stabilising agent for liquid wastes and road bases.

The fineness of fly ash is measured by determining the wet sieve residue on a 45 micron sieve, which in this instance was 86%. The evaluated loss on ignition (LOI) of fly ash was 0.5% (Figure 13); an indication of coal existing in the ash.

Figure 14. Collie fly ash

- The pH value and solubility of lime and fly ash are:
  - ✓ Lime pH value: Approximately 12
  - ✓ Lime solubility: Slightly soluble
  - ✓ Fly ash pH value: Acidic (3.9)
  - ✓ Fly ash solubility: Negligible solubility in water

3.2 Laboratory test selection

A series of experimental tests was indicated for a comprehensive laboratory investigation into the determined materials. Laboratory tests were selected to examine the geotechnical properties of sand composite in all its different aspects; compactibility, hydraulic conductivity, compressibility and strength.

3.2.1.0 Standard Compaction test

The standard compaction test method, which was mentioned in chapter two, was performed to determine the maximum dry density (MDD) and the optimum moisture content (OMC) of the soils (Figure 14).

3.2.1.1 Sample preparation

In the sample preparation, steps were taken to remove the natural moisture in Baldivis Yellow Concrete Sand which was dried in the oven at a temperature of 100±1 *°c* for 24 hours and then passed through a US Number 4 sieve (4.76*mm* aperture). The first series of compaction tests were intended to determine the compaction properties of the non-stabilised soils. Based on the dry weight of the sand, other specimens were mixed with various percentages of the lime (1%, 2% and 3%), fly ash (5%,10% and 15%), and mixtures of each combination. In the last step after combination, the specimens were wrapped up in plastic bags for a curing time of one-hour before running the standard compaction test.

Samples were compacted in a 105*mm*-diameter mould applying the standard proctor effort. Dry unit weight and moisture content for each sample were obtained by the achieved unit weight at an optimum moisture point, which was obtained by the intersection of slopes drawn from the wet-side and dry-side soil of the compaction curve of at least five compaction tests.

Figure 15. Standard compaction apparatus

3.2.2.0 Hydraulic conductivity test

The hydraulic conductivity test (falling head) which was mentioned in chapter two, was carried out for determining the permeability characteristic of sand and sand treated samples (Figure 15).

3.2.2.1 Sample preparation

Baldivis Yellow Concrete Sand was dried in oven at a temperature of 100±1 *ºc* for one day. This was then was passed through a US Number 4 sieve (4.76*mm* aperture) and prepared for testing. The sand specimens were mixed with a calculated amount of additive and moisture content. In order to investigate the relationship between the maximum dry density from the standard compaction test and the hydraulic conductivity of sand, the obtained results of the compaction test were applied. The amount of optimum moisture content, maximum dry density and dry weight of sand in the hydraulic conductivity test were determined based on the results of the standard proctor compaction test, as will be detailed in the chapter5. The moist soil was then stabilised by adding a specific percentage of lime, fly ash, and lime-fly ash. The tests were performed with different percentages of lime (1%, 2%, and 3%), fly ash (5%, 10%, and 15%) and a mixture of each combination based on the dry weight of the sand. In the final step, after combination, the specimens were sealed in a plastic bag for one hour before the hydraulic conductivity test.

Figure 16. Falling head permeability apparatus

3.2.3.0 One-dimensional consolidation test

The consolidation test (one-dimensional) which was mentioned in chapter two was carried out for evaluation the rate and magnitude of consolidation of sand-clay composites and stabilised composites. An automatic consolidation device was used in this research study (Figure 16).

3.2.3.1 Sample preparation

Due to the unsuitability of the consolidation test for sand settlement, kaolin clay was implemented for mixing with the sand and for the preparation of the sand-clay mixture (pure composite). The optimum moisture content and maximum dry density for materials was obtained by a standard proctor compaction test, specifically tailored for each compound as will be detailed in the chapter5.

In this research, 50% kaolin clay and 50% sand was used for pure composite and six lime composites, eight fly ash combinations, and nine lime-fly ash mixtures were then prepared with different dosages of stabilisers (i.e., Lime:1%-3%, fly ash 2.5%- 20%, and a mixture of lime-fly ash composite the same as in the compaction tests). Samples were prepared and stored in the laboratory room at 22.5 *°c* for a curing time of one hour. The results are separated into three sections, based on the utilised modifiers.

Figure 17. Automatic consolidation device

3.2.4.0 Direct Shear test

The small direct shear test, which was mentioned in chapter two, was implemented to determine the shear strength of the soil under examination. The automatic direct shear machine was performed for this research study (Figure 17).

3.2.4.1 Sample preparation

A series of experimental tests was performed on both the pure sand and treated sand under various vertical applied loads of 50, 100 and 200 kPa. These loads were chosen for finding the correlation between soil's shear strength and soil characteristic. The amount of optimum moisture content, maximum dry density and dry weight of sand in the direct shear test were determined based on the results of the standard proctor compaction test, as will be detailed in the chapter5.

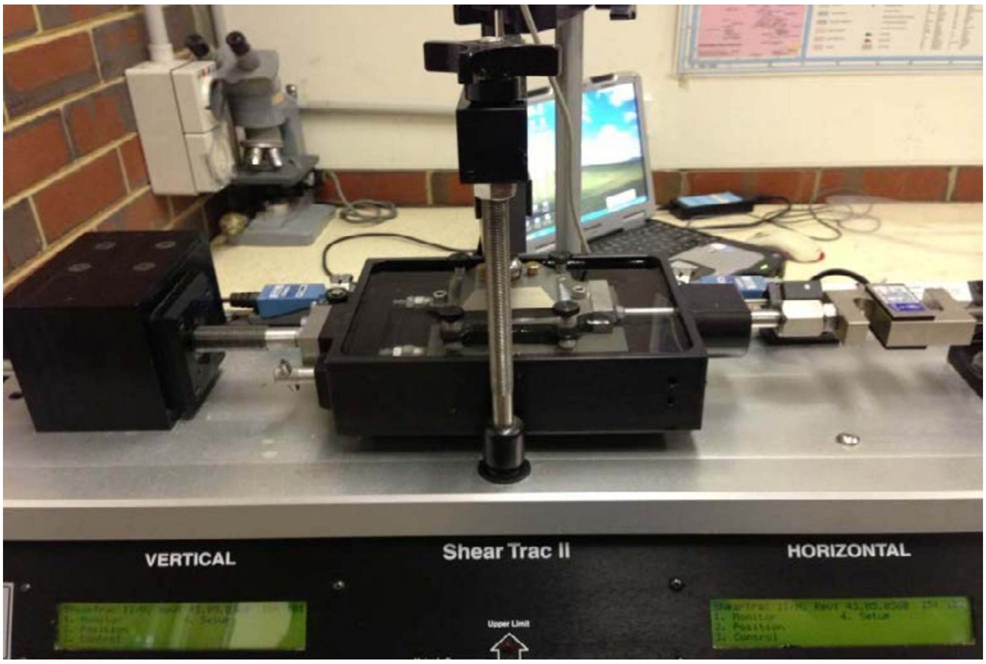


Figure 18. Automatic direct shear machine

3.3 Microanalytical/ Elemental Characterisation

This section presents a microanalytical study of the material and structural properties of lime and of fly ash, with sand as the composite component. A diversity of comprehensive studies on the mineralogical, morphological, and compositional characteristics of sand composites were carried out by:

3.3.1 Optical microscopy

Optical microscopy, which was performed with a Nikon SMZ800 stereo microscope, containing a Spot Insight Colour camera, and the data was then analysed with Image Pro Plus software (Figure 18).

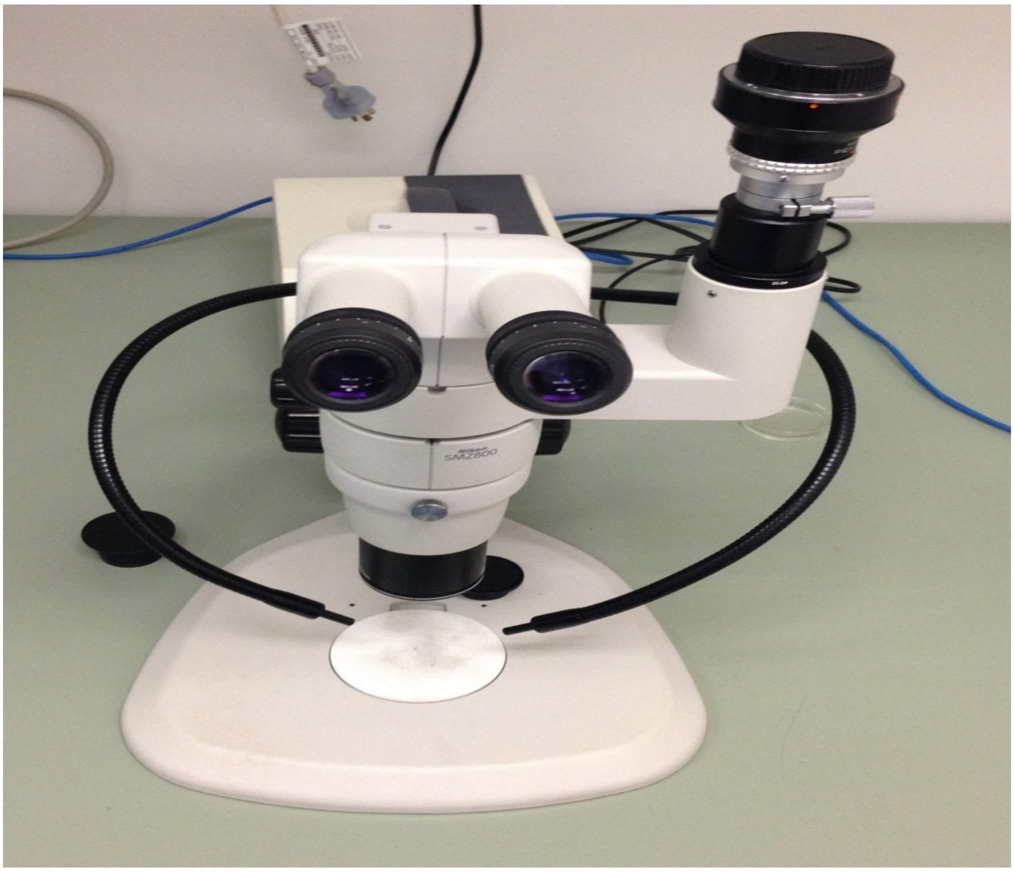


Figure 19. Optical microscopy device

3.3.2 SEM (Scanning Electron Microscopy):

Investigation into the microstructure and morphology of the platinum coated specimens, which was conducted via Zeiss Evo 40XVP scanning electron microscope (SEM) at the different accelerating voltages of 15kV and 20kV. The samples were scanned using a secondary electron detector and a backscattered electron detector (Figure19).

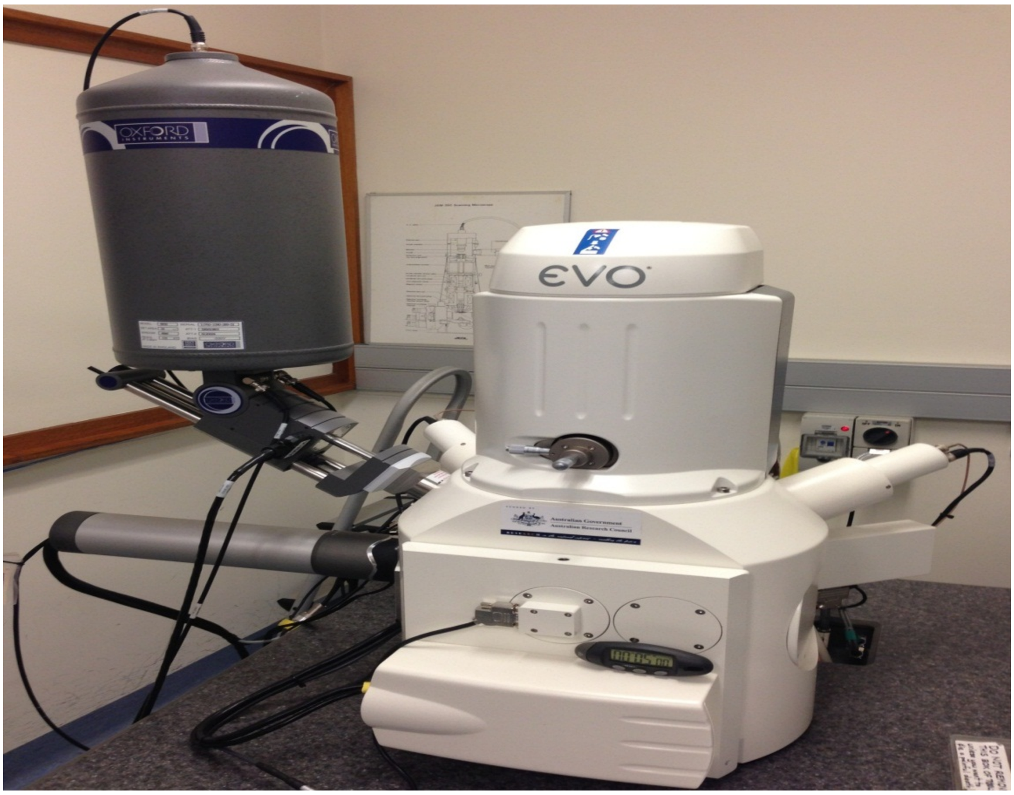


Figure 20. SEM device

3.3.3 EDS (Energy-dispersive X-ray spectroscopy):

The elemental and chemical compositions of specimens were monitored by an energy-dispersive X-ray (EDS) detector. The SiLi X-ray detector with an ultrathin window and Oxford Inca software illustrated the X-ray spectra, qualitative and quantitative numeric data and element maps (Figure 19).

3.3.4 XRD (X-ray Powder Diffraction)

The mineralogical composition of the specimens was determined by X-ray diffraction (Bruker-AXS D8 Advance Powder Diffractometer). The radiation was performed with a Cu-Ka X-ray beam (λ= 0.15404 *nm*) at 40 kV and 40 *mA*. The XRD measurement collected was 2θ data in the range of 0° to 60° with a scanning rate of 0.02◦/*s* (Figure 20).

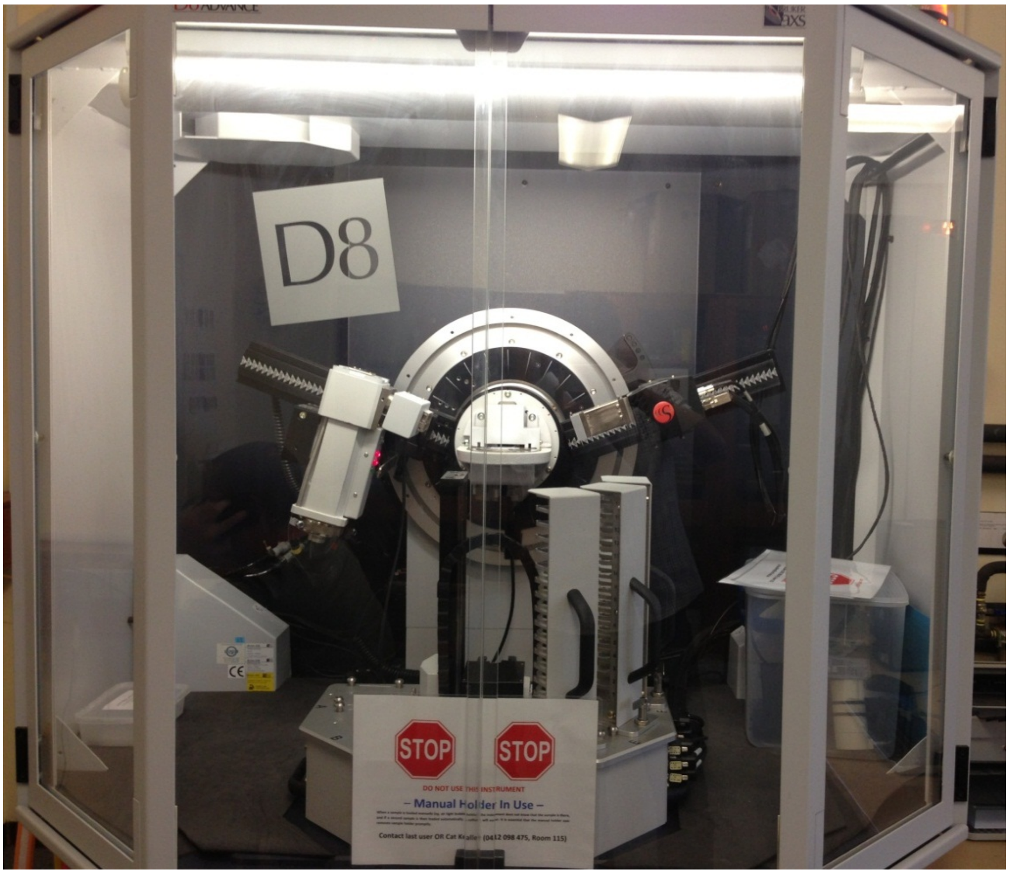


Figure 21. XRD device

3.3.5 FTIR (Fourier Transform Infrared Spectroscopy)

Fourier transform infrared spectroscopy (FTIR) which was performed in a PerkinElmer Spectrum 100 FTIR Spectrometer. The spectrum was recorded as being in the range of 4000–650 cm^{-1} with a 4 cm^{-1} resolution, by implementing the attenuated total reflectance (ATR) technique. FTIR was used to analyses the interaction level between lime and soil particles (Figure21).

Figure 22. FTIR device

3.3.6 A summary of the tests objectives

A summary of the aims, as well as, methodology of selected tests is presented in Table 3.

Table 3. Summary for the thesis program

Test Objectives	Methodology	Section
	Geotechnical test	
To assess the soil's compactibility (MDD &OMC)	Standard Compaction test	*3.2.1.0 & 3.2.1.1*
TO assess the soil's permeability (K)	Hydraulic conductivity(Falling head)	*3.2.2.0 & 3.2.2.1*
To assess the soil's compressibility (Cc &Cs)	Consolidation test	*3.2.3.0 & 3.2.3.1*
To assess the soil's strength(τp, ϕp, αp)	Direct shear test	*3.2.4.0 & 3.2.4.1*
	Microanalytical examination	
To analysis the sample's surface structure	Optical microscopy	*3.3.1*
To analysis the sample's microstructural and morphological properties	SEM	*3.3.2*
To analysis the sample's elemental and chemical compositions	EDS	*3.3.3*
To analysis the sample's mineralogical composition and crystallinity characteristics	XRD	*3.3.4*
To analysis the sample's chemical compound and atomic bond	FTIR	*3.3.5*

CHAPTER4

RESULTS AND DISCUSSION

4.0 An overview of the chapter's content

The analysis on the lime/fly ash effect on sand composites was carried out by a series of geotechnical, microstructural and material tests. The geotechnical/material structures of additives, sand, and composites were thoroughly investigated to provide an improved observation of the new intermolecular structure of the components of the materials.

The results were separated into two main groups;

- Material characteristic results
- Laboratory investigation

Then, each section was precisely focused on the defined objectives, as were presented in Table 3, by analysing the related geo-chemical/ elemental.

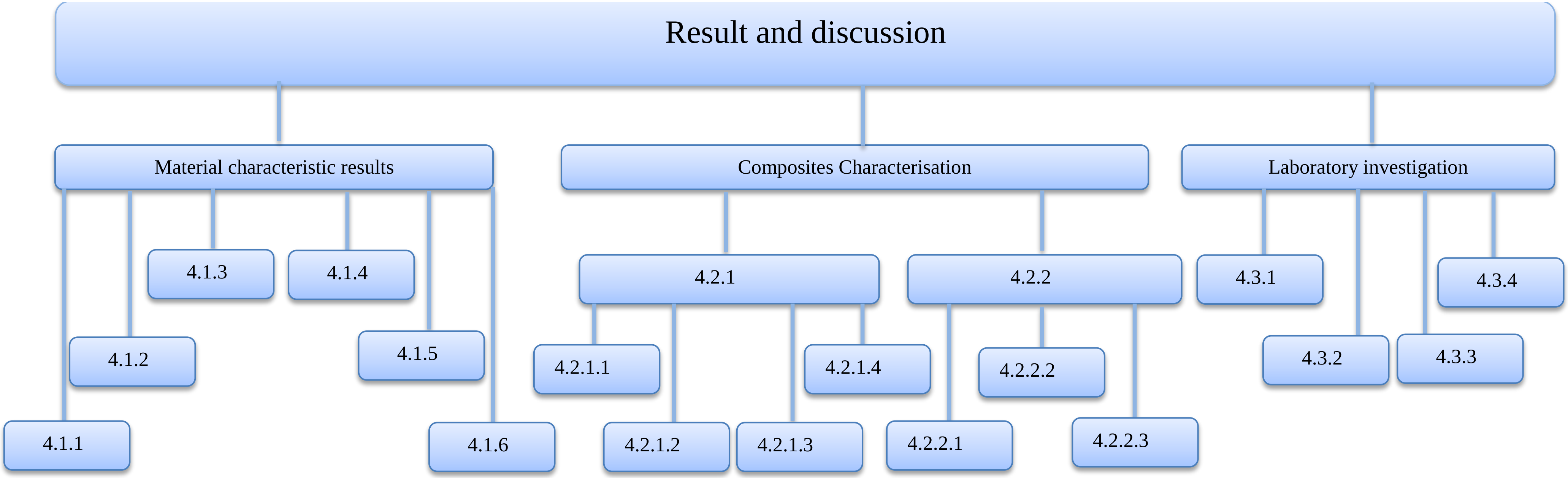
Investigation into the material characterisation of additives and material of composites was carried out in two main steps:

- ✓ Examining the chemical and structural characteristics of the composite's ingredients (i.e., lime, fly ash, lime-fly ash, sand, clay, and sand-clay) which were separately analysed.
- ✓ After accomplishing the geotechnical test, the laboratory specimens were accurately examined to identify the effect of additives on the structural and chemical properties of sand composites.

The association between the material characterisation data and experimental results was then comprehensively studied to determine how additives affect sand composite properties.

This chapter was separated in different phases as outlined in Chart5:

Chart 5. The outline of result and discussion chapter



4.1.0 Material characteristic results

The study on component characterisation was carried out by scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray powder diffraction (XRD), and Fourier transform infrared spectrometry (FTIR).

It is important to note that in this process, a sample with a smooth surface was not used. The EDS spectrum presented was collected from the broken surfaces of sand and sand-clay treated and untreated samples. Therefore, the EDS results (i.e., the line spectrum and element mapping results) were just used for a qualitative measurement as an element of the whole of the sample.

The optical microscopy results and efficiency of lime, fly ash and lime-fly ash mixture on sand stabilisation is discussed in the laboratory results chapter, in the compaction test section.

4.1.1 SEM and EDS (Lime results)

The scanning electron microscope is one of the ideal techniques for investing the structure of material. It provides a three dimensional image, high resolution, and an in-depth focus the morphological and elemental characteristic of hydrated lime were examined with SEM / EDS analysis by two voltage energies (i.e., 15kV, 20kV) at working distances of 5.5 *mm*, 8.5*mm*. The secondary electron micrograph and scanning with a mix of secondary electrons and backscatter electrons was performed.

Figure 22 and Figure 23 show the SEM micrograph of hydrated lime at a focus of 10μm and 1μm with 15kV of voltage energy. The secondary electron SEM micrograph of hydrated lime particles revealed the polygonal structure of lime, and its brightness in colour.

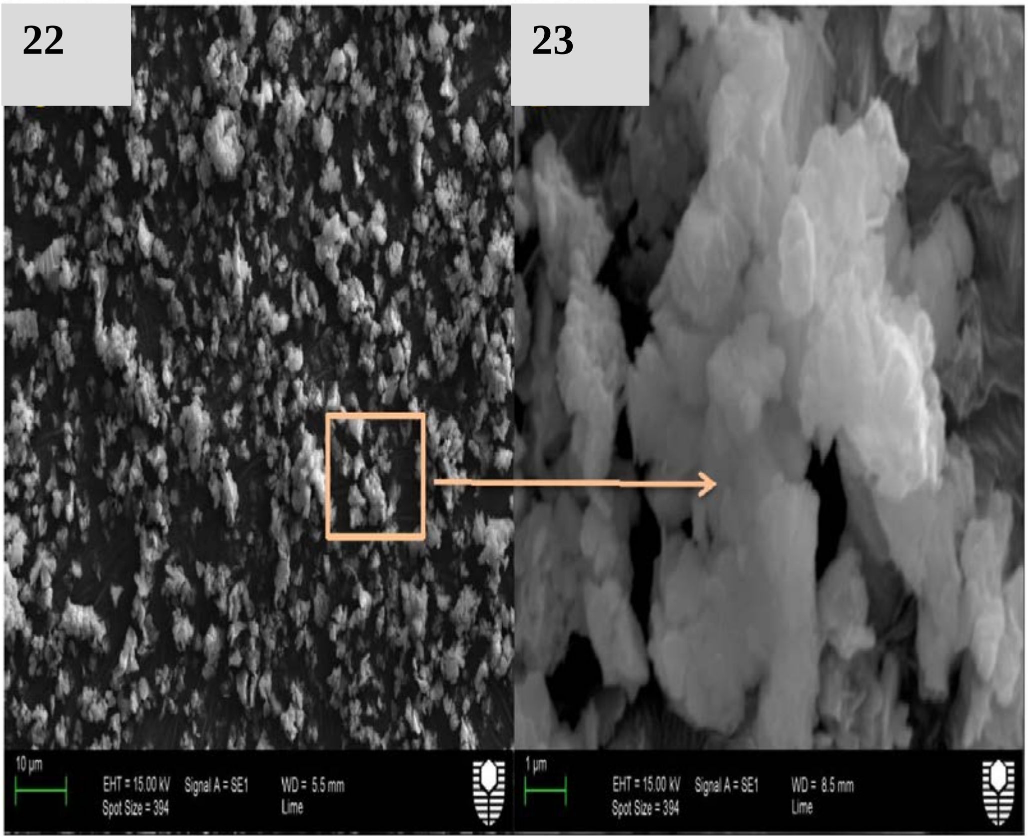


Figure 23. SEM micrograph of lime particles at 5.5*mm* working distance

Figure 24. SEM micrograph of lime particles at 8.5*mm* working distance

A further investigation on the lime component was performed by adding the backscatter electrons to the secondary electrons. By increasing the voltage to 20kV the hydrated lime micrograph at 2μm revealed the polygonal structure of the lime particles, which stuck uniformly to each other.

For elemental investigation, the EDS was then applied to analyse the material components of the hydrated lime.

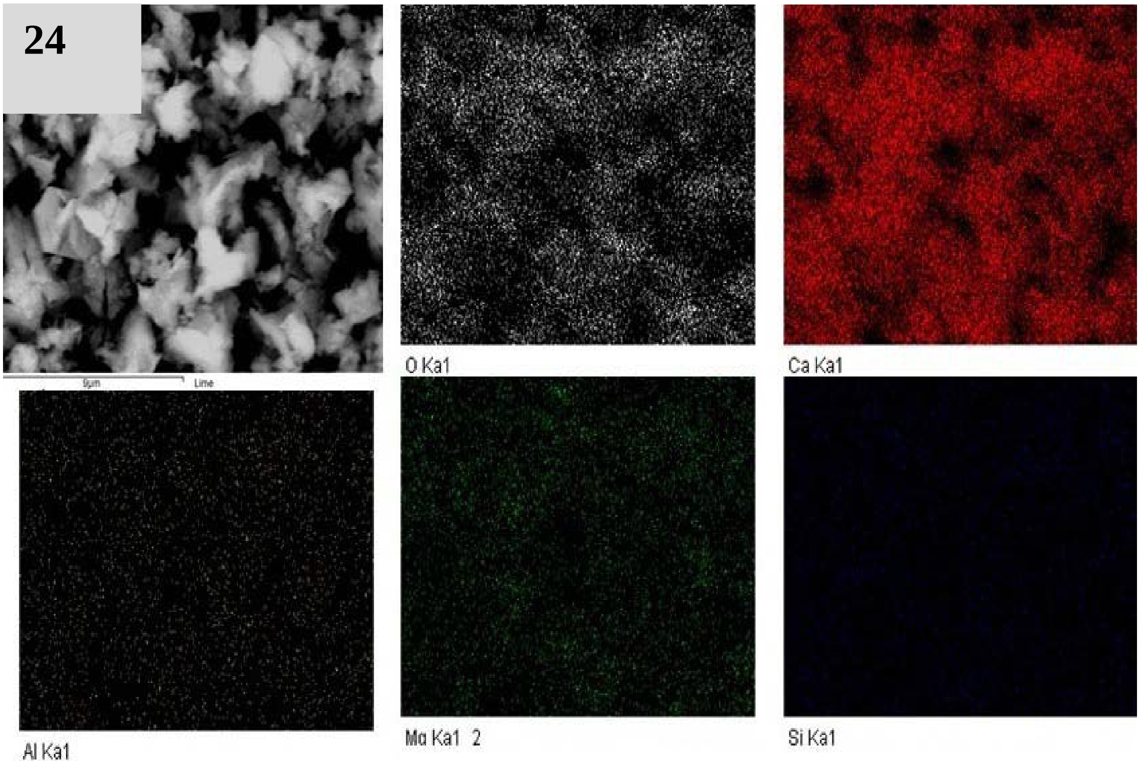


Figure 25. Elemental mapping result of lime particles.

The elemental data and spectrum line results of hydrated lime are presented in Figure 24 and Figure 25 respectively. The elemental map of lime shows the domination of calcium (Ca) content compared with the other lime components. The other chemical components which are detected by EDS examination are: oxygen (O), silicon (Si), aluminium (Al), iron (Fe) and magnesium (Mg). The line spectrum data shows the high proportion of calcium (Ca) content, as a main component in hydrated lime.

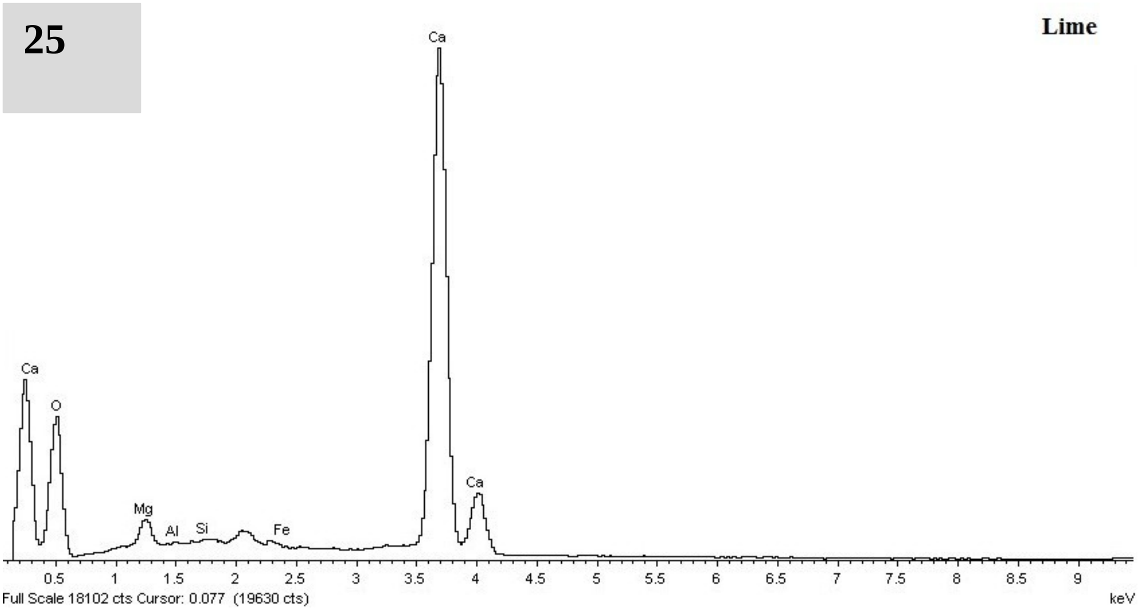


Figure 26. Line spectrum data of lime particles

These elemental mappings and the line spectrum of lime confirmed the approximate percentage of each component, which is presented in Table 4.

Table 4. Lime components data

Ingredient	Formula	Concentration
Calcium Hydroxide	*$Ca(OH)_2$*	80 – 95%
Magnesium Hydroxide	*$Mg(OH)_2$*	0 – 6%
Silicon Dioxide	*SiO_2 Crystalline*	0 – 8%
Aluminium Oxide	*Al_2O_3*	0 – 1%
Iron (III) Oxide	*Fe_2O_3*	0 – 0.5%

4.1.2 SEM and EDS (Fly ash results)

As with the microstructural analysis of lime, the morphological and elemental investigation of fly ash was carried out by SEM / EDS analysis with two voltage energies (i.e., 15kV, 20kV) at a working distance of 7.5 *mm*, 8*mm*. Figure 26 and 27 present the SEM micrograph of fly ash at a focus of 20μm and 2μm with a voltage of 15kV. The secondary electron micrograph of fly ash shows the sphere-shaped microphysical characteristic of fly ash. The fly ash particles are mostly circular and have a diversity of dimension.

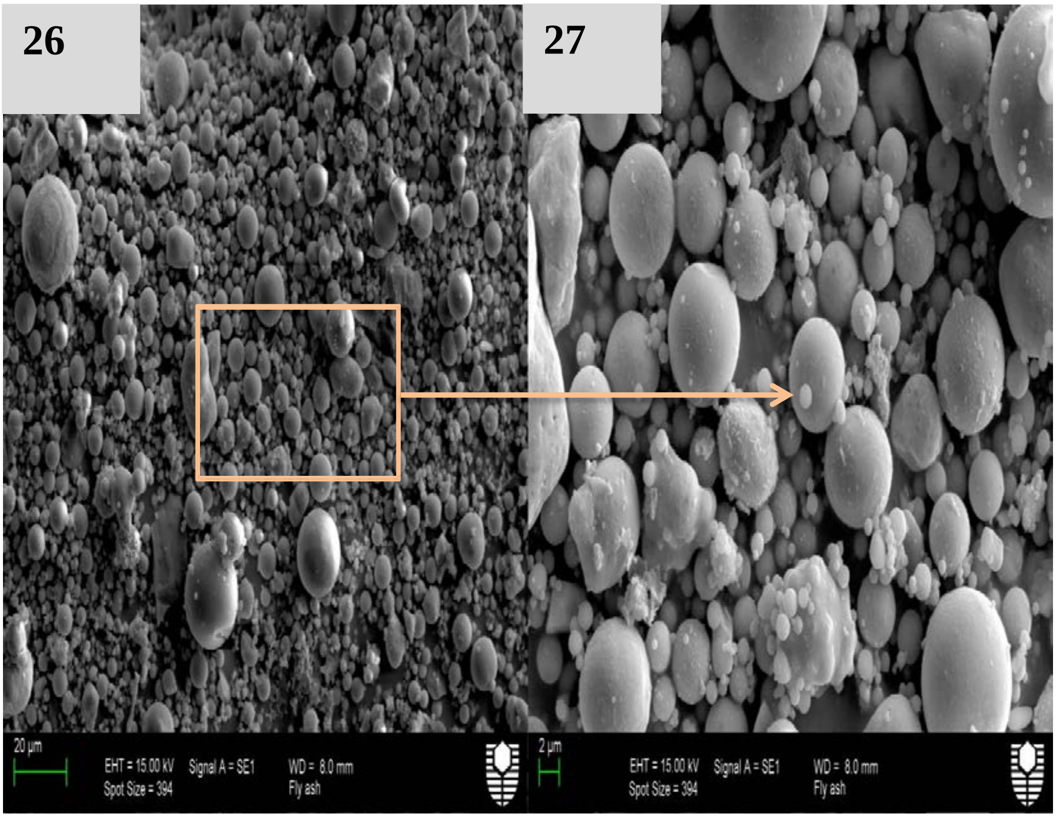


Figure 27. SEM micrograph of fly ash particles at focus of 20 μm

Figure 28 . SEM micrograph of fly ash particles at focus of 2 μm

By adding backscatter electrons to the secondary scanning at a working distance of 7.5 *mm* more morphological information on fly ash particles was obtained. Figure 28 illustrates an SEM micrograph of 20kV at a focus of 10μm.

The fly ash micrograph presents numerous globular particles, which beside each other and collected up by different sizes of atoms.

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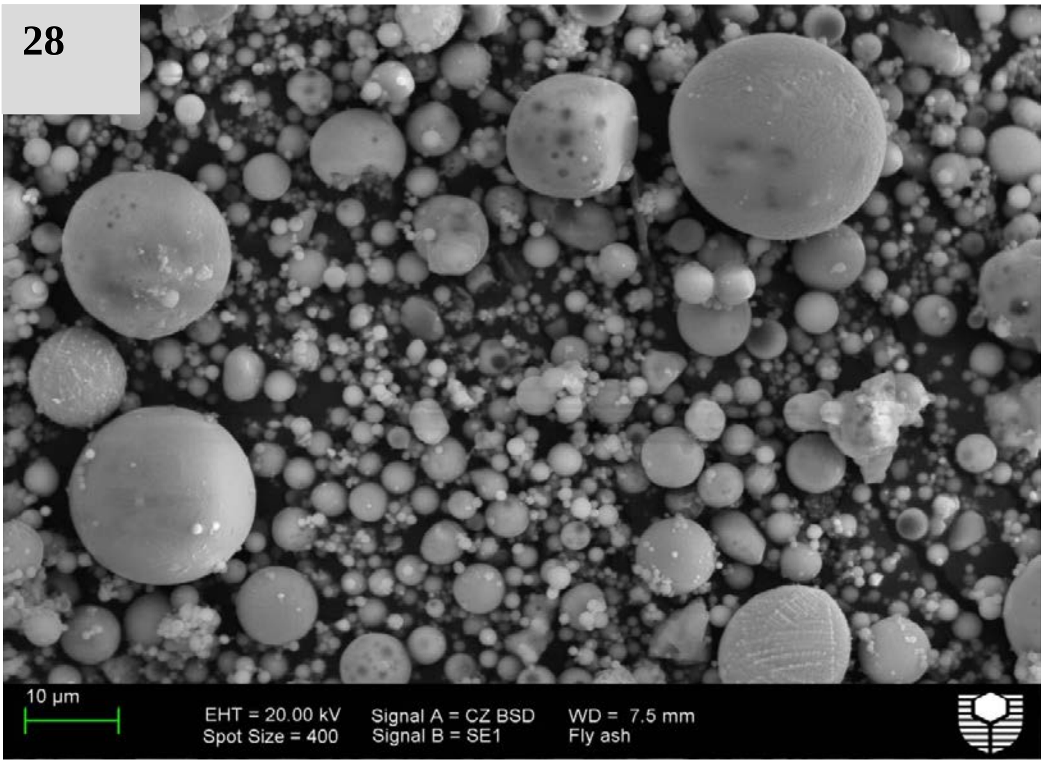
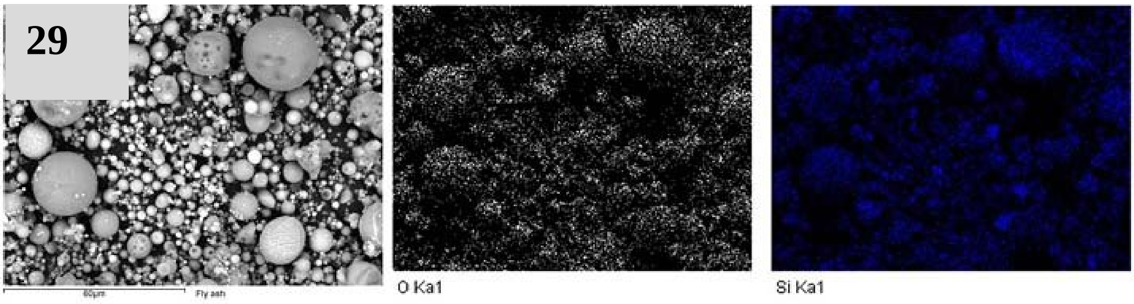


Figure 29. SEM micrograph of fly ash particles at 7.5 *mm* working distance

The radiation scattering or fly ash atoms reveals further information on fly ash, which is associated with the elemental and chemical data of the fly ash component. The compositional results of fly ash indicated that silicon (Si), aluminium (Al), iron (Fe) are the most dominant elements in fly ash (Figure 29).

The results show that Si, by 51.8% has the highest proportions compared with other components. The AL and Fe have a medium proportion of fly ash ingredients by 26.4 and 13.2 dosages respectively. However, due to low amounts of Ca, Ti, and K in the fly ash combination, the elemental mapping of these particles is removed.



Element	Percentage%
SiO_2	51.8
AL_2O_3	26.4
Fe_2O_3	13.2
Cao	1.61
TiO_2	1.44
K_2O	0.68

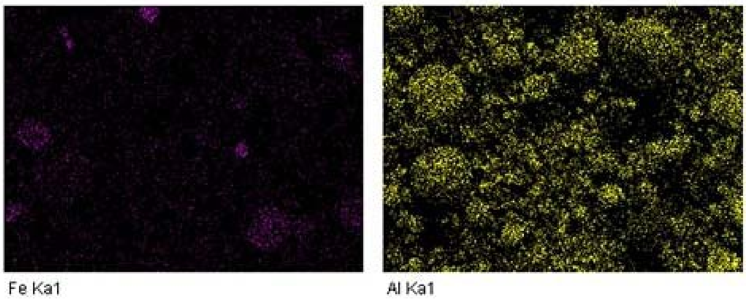


Figure 30. Elemental mapping result of fly ash particles

The line spectrum microscopy of fly ash is confirmed by the element mapping results, by associating the maximum peak on the spectrum graph to Si Figure 30. The results show the low peak amounts of Ca, Ti, and K that have a low proportion compared with other major elements including Si, Al, and Fe.

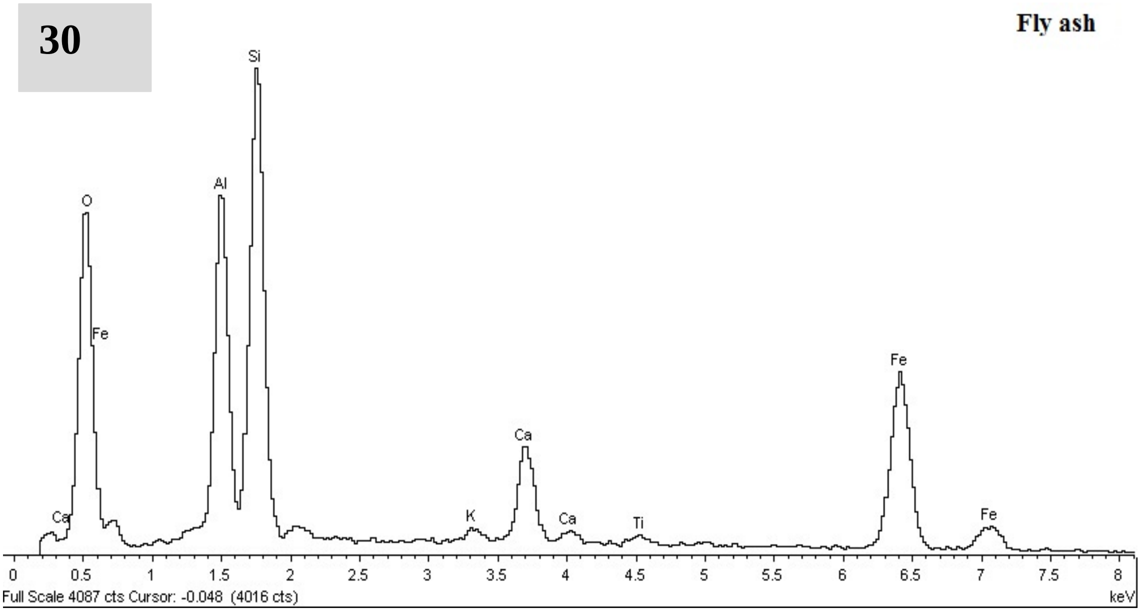


Figure 31.Line spectrum data of fly ash particles

4.1.3 SEM and EDS (Lime-Fly ash mixture results)

In order to accurately illustrate the lime-fly ash combination, the mixtures were analysed individually.

Investigations into the morphological and elemental parameters of the lime-fly ash mixture are presented in Figure 31 and Figure 32. For providing the lime-fly ash combination, secondary electrons, in addition to the backscatter method, were applied. The scanning was performed at a working distance of 6.5 *mm* and 8.5*mm* with a voltage of 20kV. Figure31 shows an area with different forms of particles, a combination of circular and polygonal atoms sticking to each other and showing a more uniform area compared with the lime or fly ash micrographs. The globular particles of fly ash and polygonal structure of lime can be clearly seen.

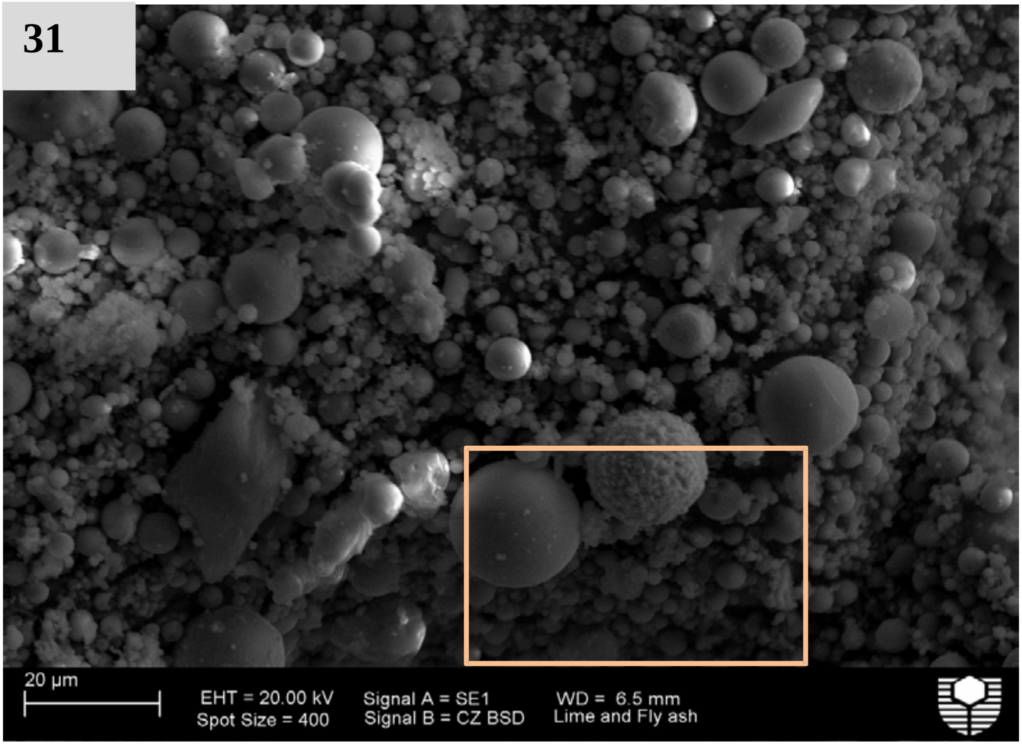


Figure 32.SEM micrograph of lime-fly ash mixture at 6.5 *mm* working distance

Figure 32 reveals the new structure of additives that is created by combination of two stabilisers. Through the reduction of the focus area from 20μm to 2μm, a clear micrograph can be obtained of the lime-fly ash combination. It appears that in some areas fly ash atoms are surrounded by lime particles and they create a shape or form that is different to the form of the lime or fly ash. The creation of this phenomenon was observed on different scales and in different areas.

From the morphological results, it could be suggested that this change related to an alteration of the elemental parameters of the lime-fly ash mixture.

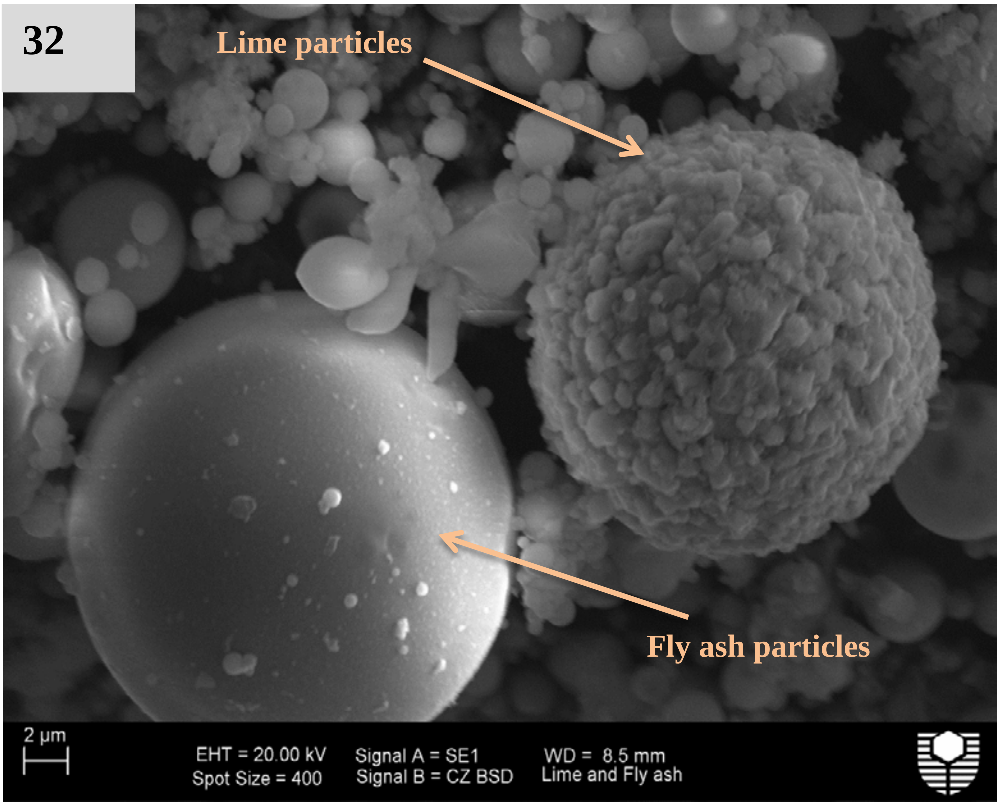


Figure 33. SEM micrograph of lime-fly ash combination at 8.5*mm* working distance

In order to investigate this hypothesis, an EDS examination was carried out on the lime-fly ash combination.

Figure 33 presents the elemental mapping results of lime-fly ash mixture. It can be clearly seen that all four fundamental elements have a roughly similar contribution to make in the lime-fly ash composition preparation. The greatest change occurred in the dosage of Fe and Al. The compression between the SEM micrograph and the element mapping results of lime fly ash mixture revealed the types of components which are increased by mixing two additives.

Investigation into the element mapping results suggested that the particles sticking to the fly ash atoms were mostly iron. The yellow colour in Figure 33 shows the increments of dosage of Fe in the lime-fly ash combination.

Moreover, the results show the high participation of silicon due to the availability of a higher amount of Si in the fly ash component. Nevertheless, this amount increased slightly due to the addition of lime, which contains a small amount of Si. This tendency is similar to that of the Aluminium content in a lime-fly ash mixture, illustrated by the red colour on the elemental mapping in Figure 33. The combination of lime and fly ash is directly associated with mixing and then incrementing the dosage of Al.

However, the elemental mapping of this area cannot correctly illustrate the proportions of calcium, which have an unclear colour in this result.

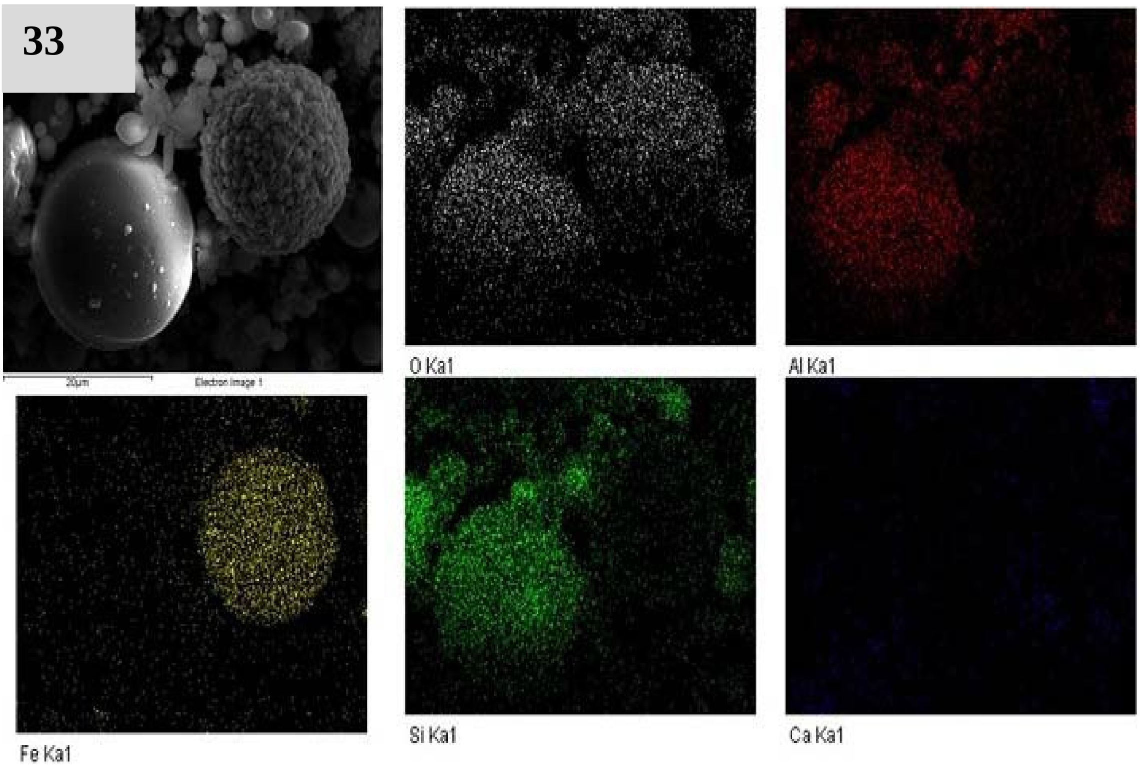


Figure 34. Elemental mapping of lime-fly ash combination results

For improving the accuracy of the EDS results, the line spectrum of lime-fly ash combination was implemented (Figure 34). The result on the calcium, which was unclear on the element mapping pictures, was investigated by the line spectrum data. The graph illustrates the different peaks in the lime-fly ash mixture which indicates the availability and amount of the lime and fly ash components.

Figure 34 shows the high proportion of four basic components (Ca, Si, Fe, Al) in the lime-fly ash combination. This level of Ca is achieved due to the presence of calcium in both fly ash and lime, which increased significantly compared with either lime or fly ash individually. Other significant peaks of the line spectrum graph related to Si, Al and Fe with more proportion among the other elements, correspondingly.

33

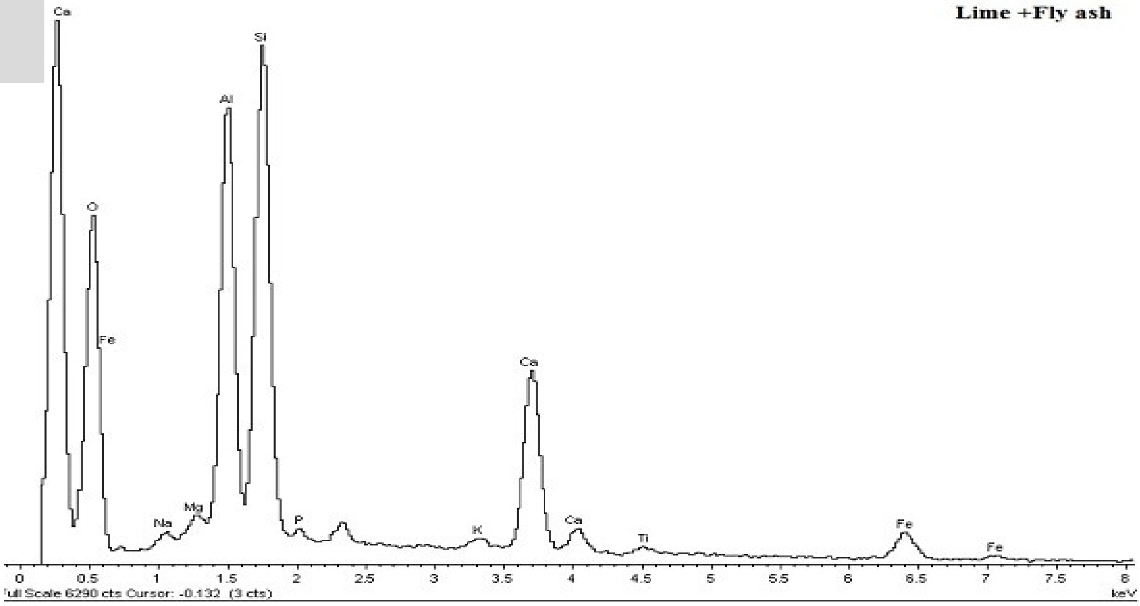


Figure 35. Line spectrum result of lime-fly ash combination

4.1.4 SEM and EDS (Sand results)

Microstructural and elemental study on sand particles was carried out by microscope analysis in combination with the backscatter electron method. The micro-graphical investigation into sand particles with a voltage of 20kV was performed at a working distance of 8.5*mm* (Figure 35). The coarse grained structure of sand particles, which have a different size, is presented at a focus area of 200μm. The granular atoms of sand were roughly separate, loose and next to each other. From the sand micrograph it appeared that the connection between particles was not sticky.

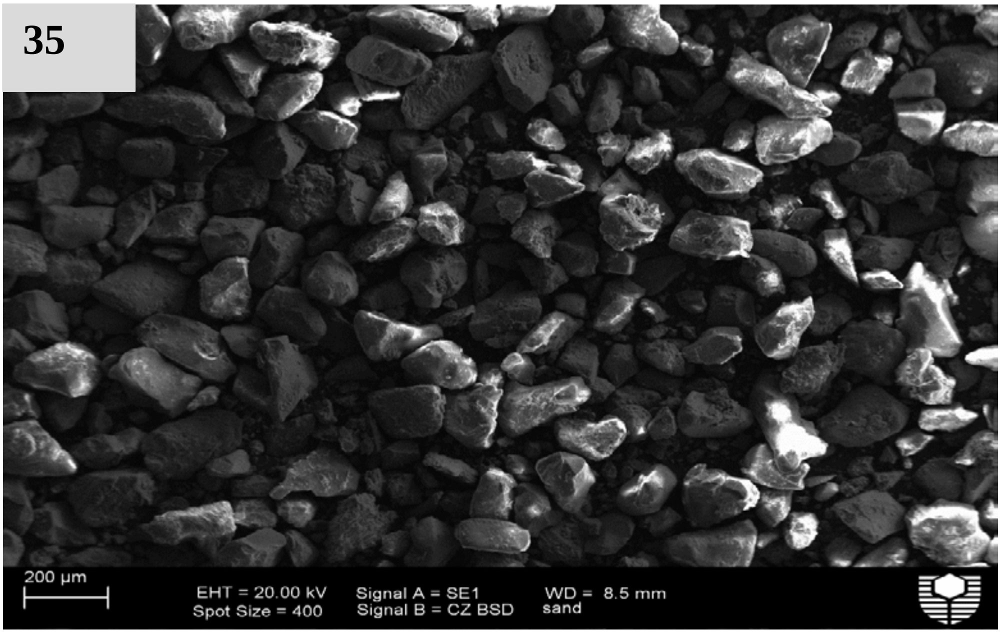


Figure 36. SEM micrograph of sand particles at 8.5*mm* working distance

In order to investigate the sand component, the EDS examination analysed the elemental properties of sand. The element mapping results (Figure 36) show the existence of Ca, Fe, Al, Si, and potassium (K) atoms. The highest proportion among the other components related to Si, shown in green. The amount of Al was found to be almost the same as the dosage of Fe.

36

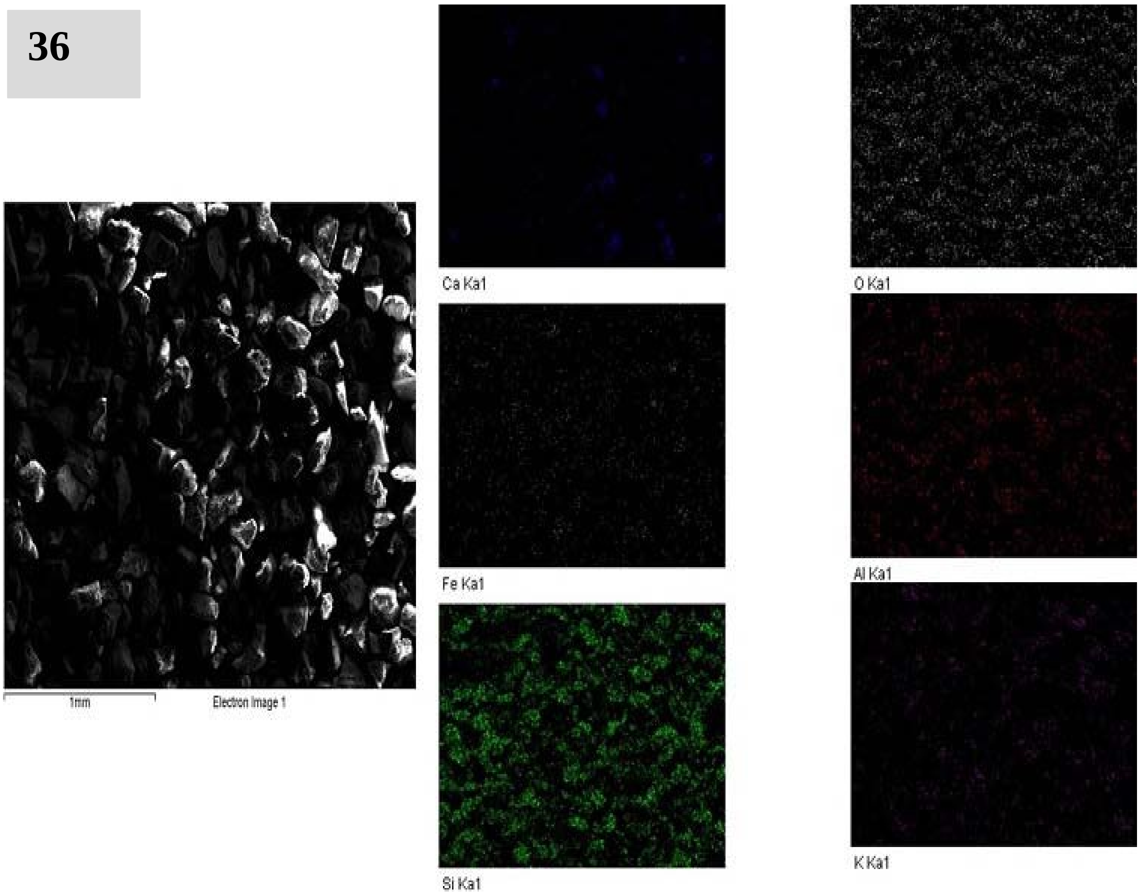


Figure 37. Elemental mapping results of sand particles

The line spectrum of sand particles is presented in Figure 37 and shows the five basic chemical components of sand which are the same as in the element mapping results. The high peak corresponding with the Si parameter has a significant proportion compared with other components. A small amount of K and Ca is recognised by the EDS spectrum.

37

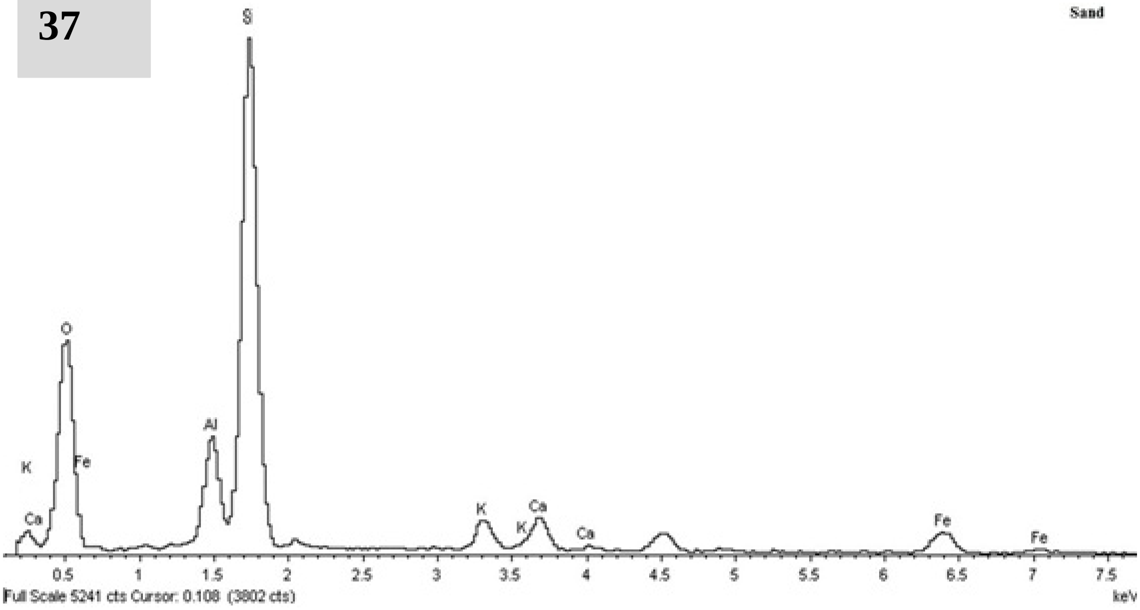


Figure 38. Line spectrum result of sand particles

4.1.5 SEM and EDS (Clay results)

The microstructure and components of kaolin clay as a fine grained material were investigated, which were obtained at a working distance of 7.5*mm* with a voltage of 15kV. The morphological study on clay structure revealed a different microstructure of fine material. The secondary examination at 1μm illustrated a multi-layered sheet structure of particles. This micrograph suggests that kaolin is a kind of allophone which is associated with non-crystalline silicate clays (Figure 38).

The component characteristics are presented in Table 5. The results show that the most dominant proportions related to Si and Al with 46.1% and 36.5% respectively. The other components (i.e., Ti, Fe, Ca, Mg, k, and Na) have a lesser ratio of kaolin composition.

38

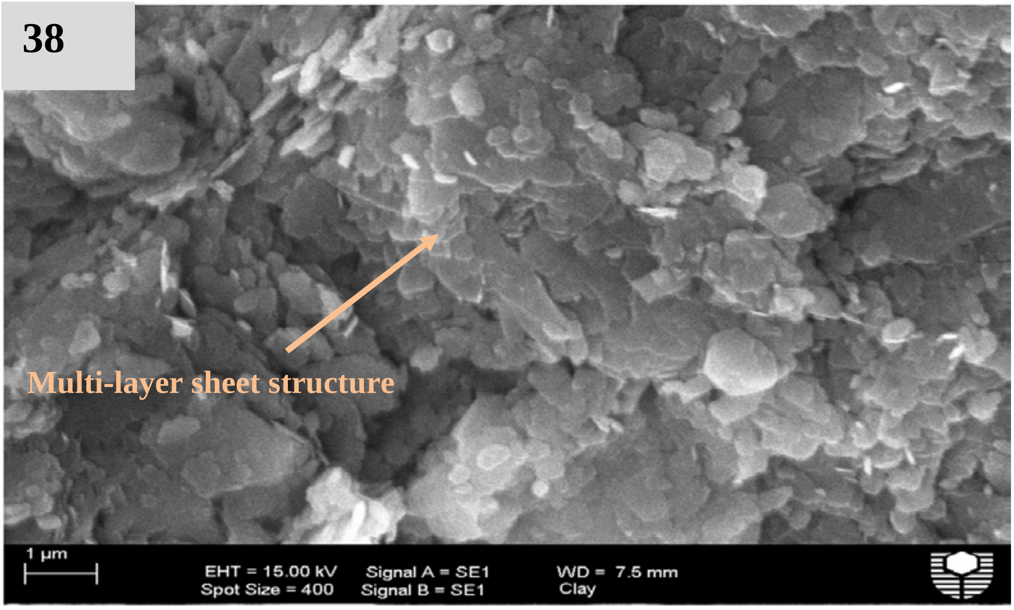


Figure 39. SEM micrograph of clay particles at 7.5*mm* working distance

Table 5. Kaolin clay composition

Oxide composition	Value %
Silicon Dioxide (SiO_2)	46.1
Aluminium Oxide ($Al_2 O_3$)	36.5
Titanium Dioxide ($Ti O_2$)	0.8
Iron Oxide (Fe_2O_3)	0.9
Calcium Oxide (CaO)	0.9
Magnesium Oxide (MgO)	0.5
Potassium Oxide (K_2O)	0.2
Sodium Oxide (Na_2O)	0.1

4.1.6 SEM and EDS (Sand-Clay combination results)

The mixture of sand and clay was investigated as a sand-clay composite, which was used in the consolidation test. The micrograph investigation SEM analysis was performed using a voltage of 20kV at a working distance of 5.5*mm*. Figure 39 illustrates the SEM micrograph of sand-clay combination at a focus of 20μm. This micrograph presents the combination of clay and sand's structural properties. The mixture of the granular structured material and sheet structural particles created a sticky area with some fluctuation on the surface of the sample. Consequently, in the context of component characteristics, a sample which has a higher dosage of chemical elements might be preferable.

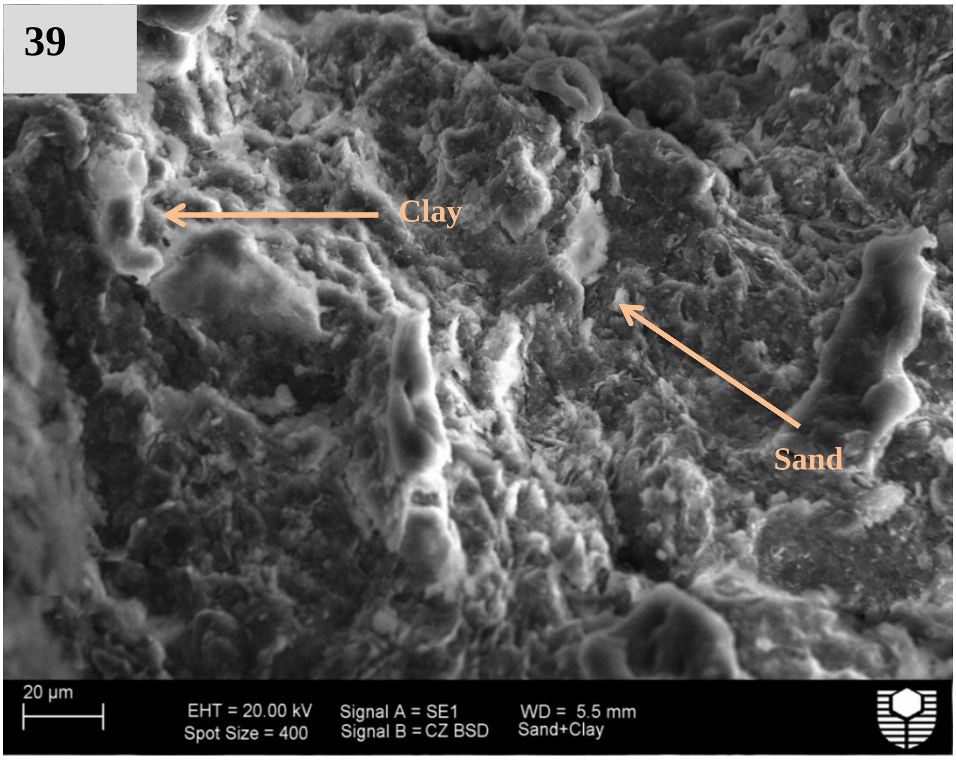


Figure 40. SEM micrograph of sand-clay composite

In the field of elemental analysis the element mapping and line spectrum were obtained by EDS examination.

Figure 40 presents an elemental mapping of the sand-clay composite. This combination is known as a pure composite, which was utilised for consolidation as an unstabilised sample. As is shown by the element mapping of the sand-clay mixture, silicon (Si) and aluminium (Al) have the highest proportions of composite components. However, regarding the limited availability of potassium (K), the element mapping is different to the sand and clay element mapping.

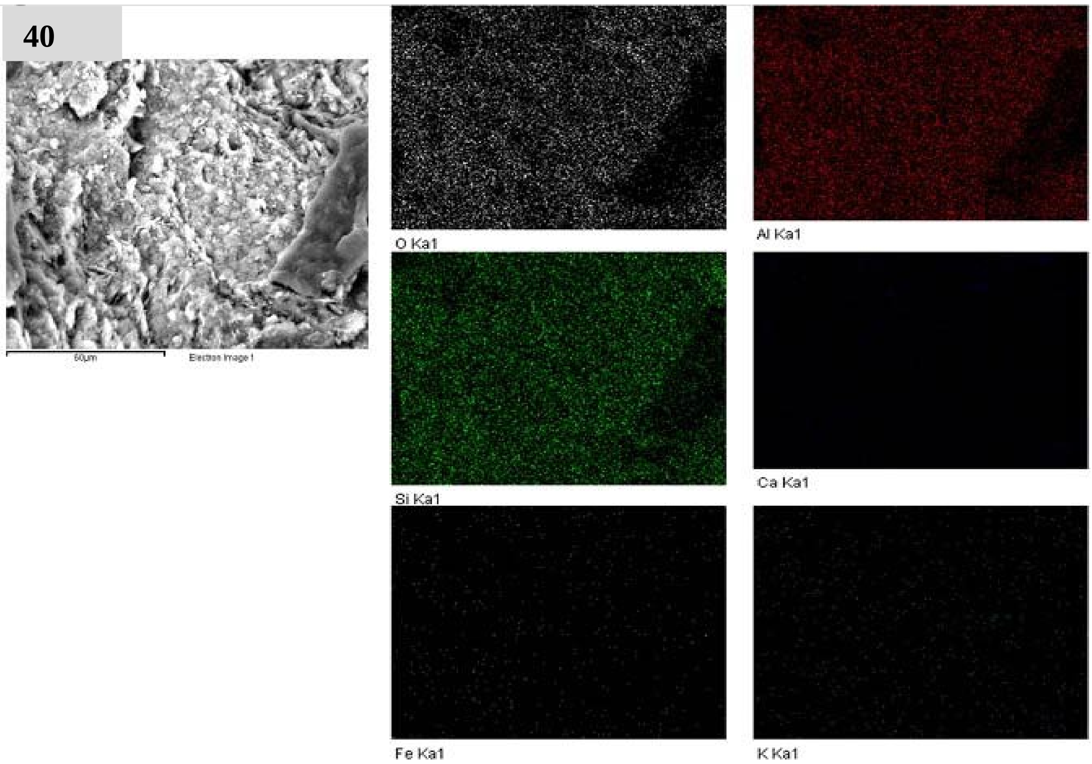


Figure 41. Elemental mapping result of sand-clay composite

In addition, the line spectrum graph presents the same results in the context of the sand-clay mixture. Silicon, aluminium, calcium, iron and potassium are found as the five main components of pure composite, with the high peaks related to Si and Al (Figure 41).

Comparisons between the sand line spectrum graph and the sand-clay line spectrum shows increments in the dosage of AL due to the presence of aluminium in the kaolin clay.

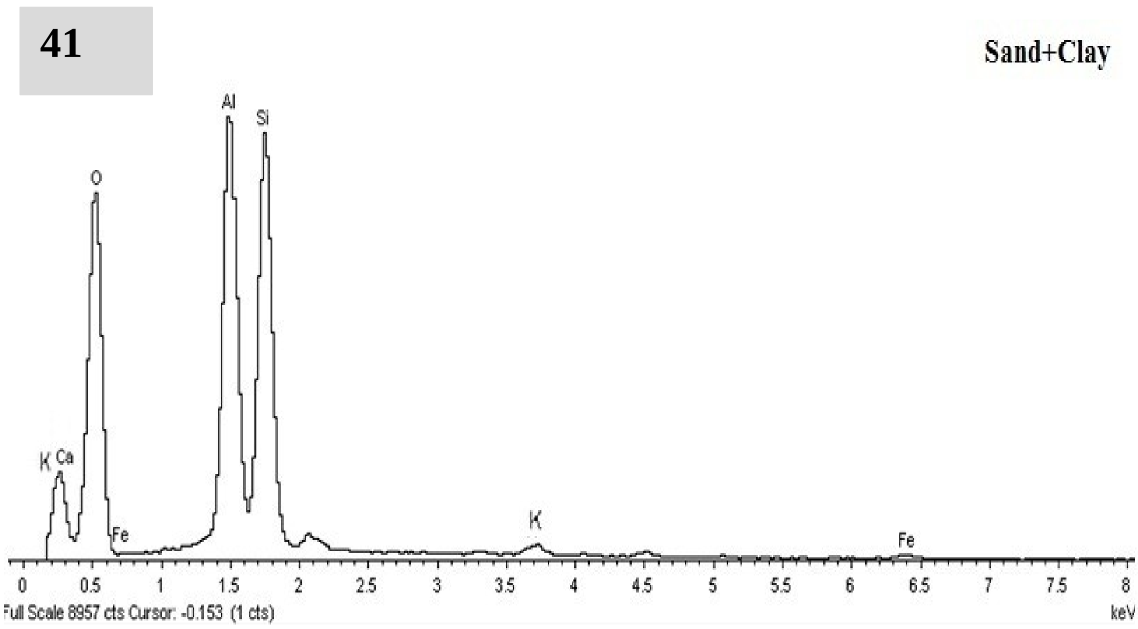


Figure 42. Line spectrum of sand-clay composite

Thus the SEM and EDS results have provided detailed information about the physicochemical, microstructural, and compositional results of the raw materials (i.e., sand, clay, lime, fly ash). Overall, the pure soil, with voids between atoms and no hydration products, has a discontinuous structure. Lime as an amorphous powder consists of mainly calcium (Ca), and a small amount of silicon (Si), aluminium (Al), iron (Fe) and magnesium (Mg). Fly ash as a circular powder consists generally of silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), Titanium (Ti), Potassium (K).

The collected results regarding the material characterisation of the components could be helpful for predicting and understanding any changes (i.e., either chemical/material or structural/mechanical changes), which may occur due to the elemental and compositional properties of the materials.

The supportive hypotheses of this prediction could be related to some short-term and long- term chemical phenomena. With the addition of water, the calcium ions released from the additives lessened the thickness of the double diffused layer by reactions including cation-exchange, and flocculation/agglomeration. Subsequently, a pozzolanic reaction occurred due to the calcium ions of modifiers and the silica and alumina of the mineral; a long term chemical phenomenon. Eventually, the polymerisation process led to the creation of a cementitious composite including calcium-silicate-hydrates (C-S-H), calcium-aluminate- hydrates (C-A-H), and calcium-aluminium-silicate-hydrates (C-A-S-H) ,which bound the atoms on a nano-metric scale(Solanki and Zaman, Harichane et al., 2011b, Saeid.Amiralian et al., 2012a, Cuisinier et al., 2011, Lin et al., 2007, Kumar, 2007).

- ✓ Lime ionisation : $Ca(OH)_2 \longrightarrow Ca^{2+} + 2(OH)^-$
- ✓ Soluble clay silica: $Ca^{2+} + OH^- + SiO2 \longrightarrow$ C-S-H gel
- ✓ Soluble clay alumina $Ca^{2+} + OH^- + Al_2O_3 \longrightarrow$ C-A-H gel

In addition, the Cation Exchange Capacity (CEF) is associated with an ion-exchange reaction. The amounts of cations that are required for balancing the charge shortage on the surface of the soil are evaluated by Cation Exchange Capacity (CEF) (Solanki and Zaman). The reduction of thickness in the double diffused layer is created as a result of replacing the cations of soil (i.e., Na^+, K^+) by cations of cementitious additive (Ca^{2+}) during the ion-exchange process.

Calcium silicate hydrate (C-S-H gel) is formed due to the hydration of C_3S and is known as tobermorite gel. The tobermorite gel in structure and composition is recognised by a weak bond structure in the XRD pattern, poor crystalline content.

On the other hand, C-A-H is created as platelets with hexagonal symmetry with the same morphological characteristic of tobermorite. In addition, the C-A-S-H gel (Calcium- aluminium-silicate-hydrates) has a similar morphology to tobermorite gel.

Another hydration phenomenon occurs in ettringite, which is created as a result of calcium sulphate availability. The ettringite mineral has the chemical formula (Ca6[Al(OH)6]2.(SO4)3.26H2O) and has a prismatic crystal and hexagonal cross-sectional structure.

- ✓ Ettringite : $6Ca^{2+} + 2Al(OH)_4^- + 4OH^- + 3SO_4^{2-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2.(SO_4)_3.26H_2O$

Hence, the creation of all aforementioned cementitious components resulted in an improved geotechnical performance of the soil.

4.2 Composites Characterisation

Investigation into the composite characterisation and additive efficiency on utilised soil was carried out by scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray powder diffraction (XRD), and Fourier transform infrared spectrometry (FTIR). The experimental samples were accurately analysed to determine how the stabiliser effect could improve soil performance.

4.2.1 .0 SEM and EDS Investigation

4.2.1.1 Lime treated sand

To study the microstructure of lime modified sand/sand-clay samples, laboratory specimens were examined using SEM micrographs and EDS examination. Figure 42 shows the microstructure of lime-stabilised sand at a working distance of 8.5*mm* with a voltage of 15kV. From Figure 42, it is clear that the untreated sand structure has transformed from a particle based form to a more joined composition as a result of cementitious reactions. This alteration occurred through the surrounding of the sand particles by numerous lime atoms which stuck to each other. The flower- structure of lime atoms can be clearly seen in the SEM result. This structural alteration may have occurred due to cementitious reactions.

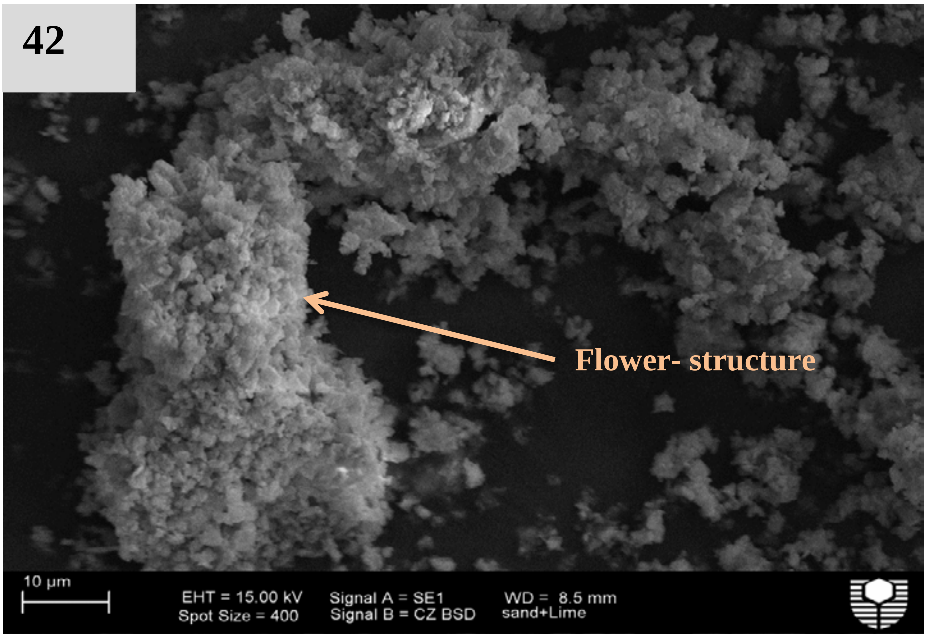


Figure 43. SEM micrograph of lime treated sand

Further, an EDS examination was performed to monitor any alteration in the chemical composition of the lime-stabilised sand particles.

The elemental mapping result of the lime modified sample is presented in Figure 43. As is evident from Figure 43, adding the lime to the sand resulted in high amounts of calcium (Ca) compounds. Silicon (Si) atoms, one of the main elements in the sand, were also detected. This is illustrated by the green colour in the element mapping results. The availability of Ca and Si could cause the creation of tobermorite gel in the lime composite.

43

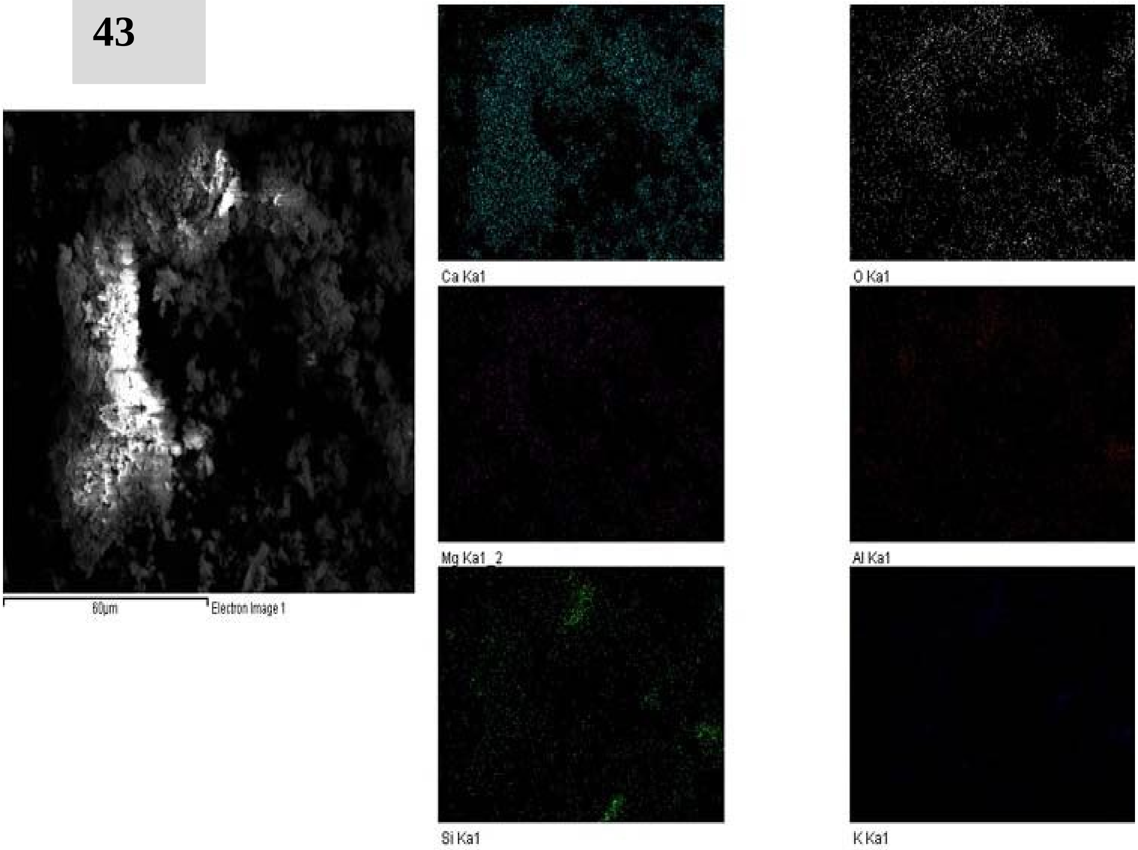


Figure 44. Elemental mapping of lime treated sand

Figure 44presents a high peak of Ca, and medium peak of Si in the line spectrum graph of the lime treated specimen. It also confirms the low dosage of aluminium (Al), iron (Fe), potassium (K), and titanium (Ti). Therefore, the analysis of the cementing phases (evidenced by the presence of Ca and Si with a high Ca-Si ratio), resulted in the presence of calcium-silicate-hydrate (xCaO.ySiO2.zH2O). The establishment of tobermorite gel (C-S-H) as a cementitious product may lead to improved soil performance (Solanki and Zaman).

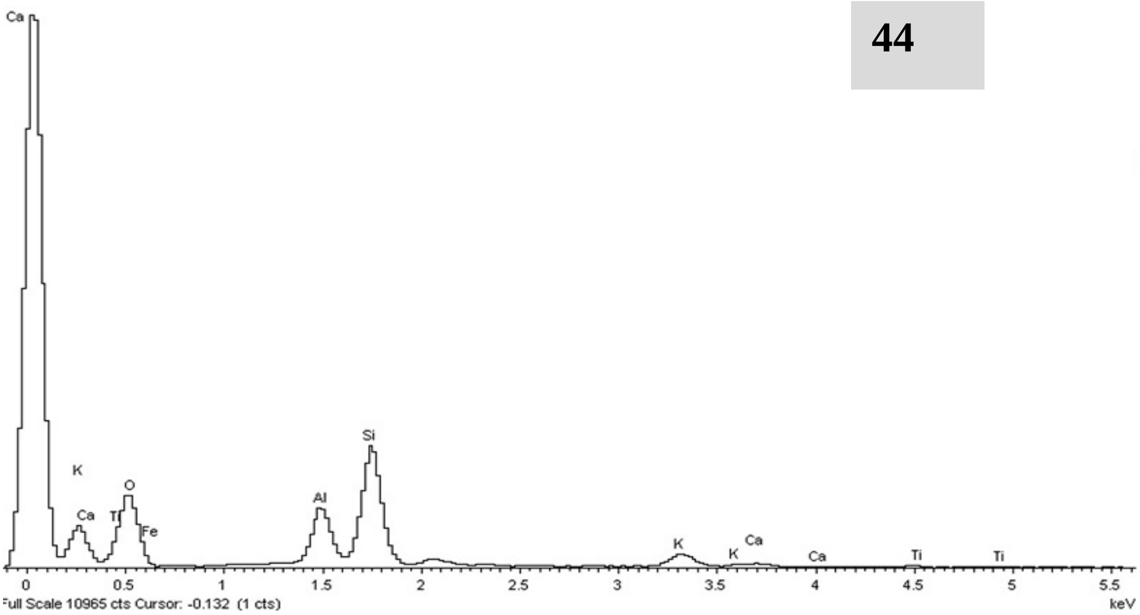


Figure 45. Line spectrum result of lime treated sand

4.2.1.2 Lime stabilised sand-clay composite

Moreover, similar investigations into lime’s efficiency on the sand-clay mixture by SEM/EDS examination confirmed the generation of the cementing phase. Examination of the addition of lime to the sand-clay combination was performed by SEM analysis at a working distance of 7.5*mm* with a voltage of 20kV (Figure 45). The SEM micrograph of lime treated sand-clay composite illustrates the generation of the cementitious compound onto the composite.

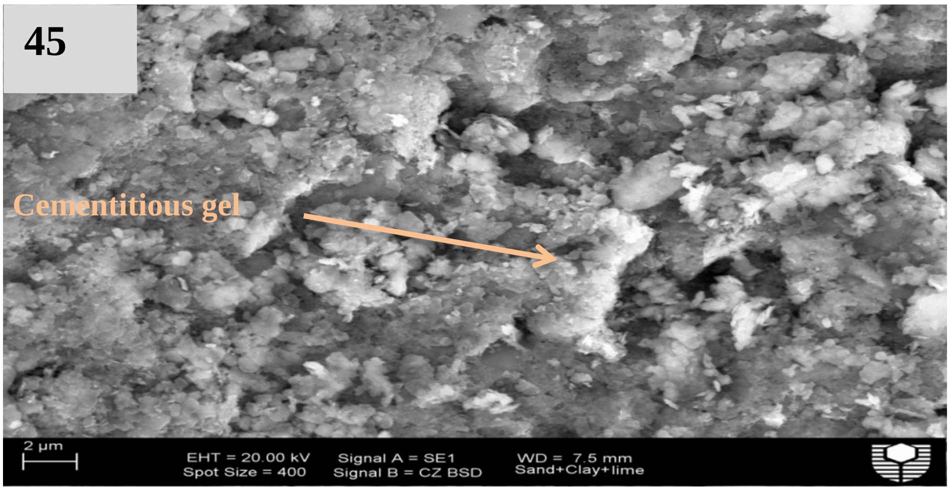


Figure 46. SEM micrograph of lime stabilized sand-clay composite

The EDS pattern was performed for observing how the chemical components could play a pivotal role in the generation of the cementitious phase. As with the lime treated sand specimen, it can be observed that there was a high amount of Si, Ca, and Al, with traces of Fe, K, and magnesium (Mg) as impurities (Figure 46). However, the high dosage of Al and Si is clearly shown by the red and green colours in the element mapping results.

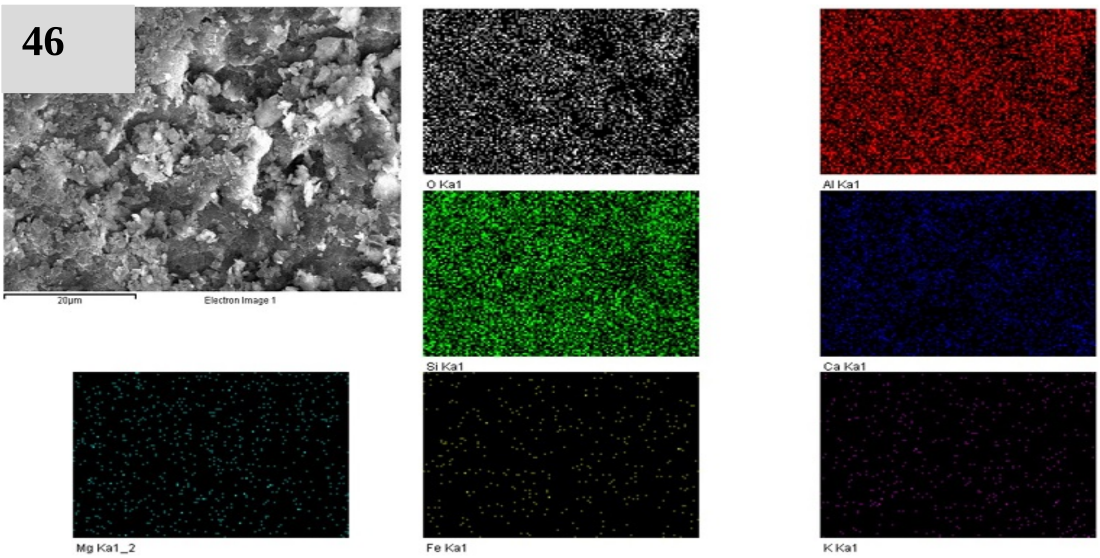


Figure 47. Elemental mapping of lime stabilized sand-clay composite

Figure 47 shows a similar dosage of Al and Si along with several peaks corresponding to the Ca line spectrum of lime-modified sand-clay composite and reveals the high proportion of Ca, Al, and Si that result in the generation of the cementitious phase. This interaction is caused by the presence of Calcium-aluminium-silicate-hydrates gel (C- A-S-H).

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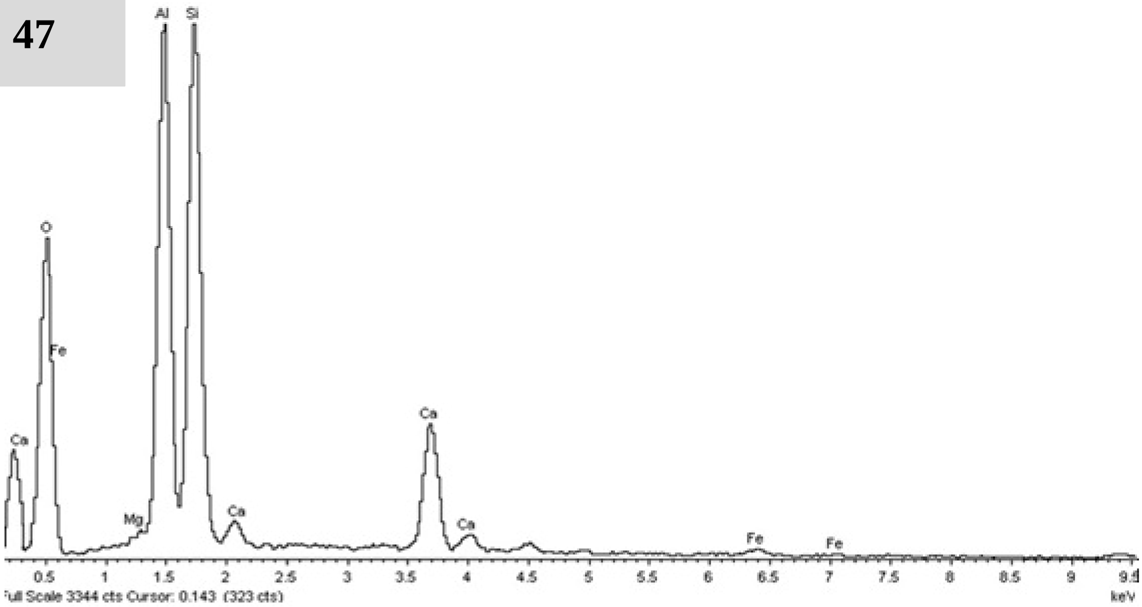

Figure 48. Line spectrum result of lime stabilized sand-clay composite

On the other hand, the effect of fly ash on sand and sand-clay properties was evaluated by investigation into the fly ash stabilised laboratory specimens.

4.2.1.3 Fly ash stabilised sand composite

The SEM micrograph of sand stabilised with fly ash is presented in Figure 48. Figure 48 reveals the presence of different sizes of circular shaped fly ash on the surface and among the sand particles. The addition of fly ash leads to a connection with the sand atoms and thereby sticking composite atoms to each other. In the sand- stabilised fly ash, additive particles fill the existing voids among the composite particles along with creating cementitious products. This reaction occurred through the fly ash particles coming together and creating a form of rod-silk.

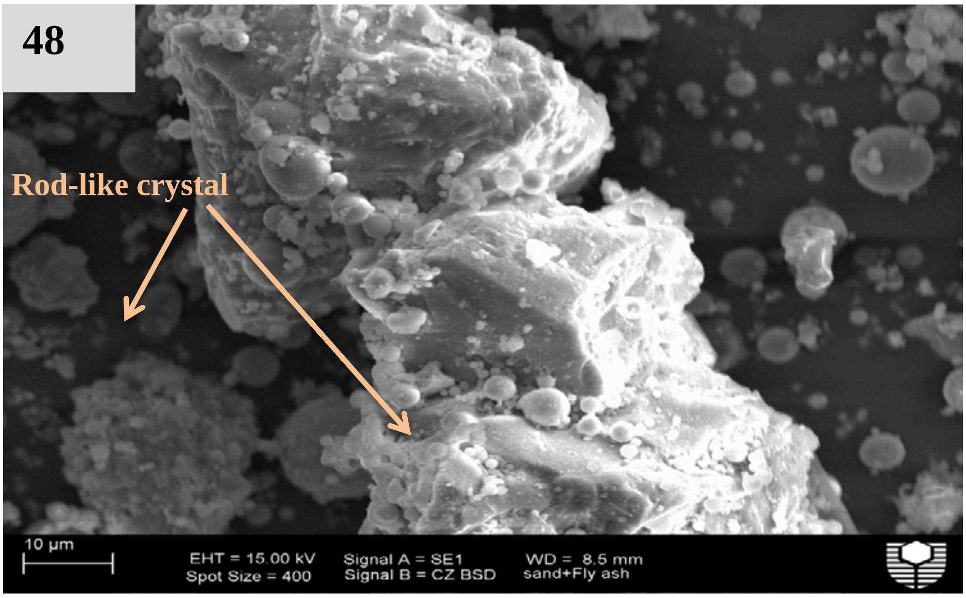

Figure 49. SEM micrograph of fly ash stabilised sand composite

The EDS analysis was performed to examine either chemical components or alterations of component amounts and their chemical composition. The element mapping results are shown in Figure49, with four main components of fly ash-sand composite. The greatest component proportion is associated with Si, among Al, Fe, and K. It can be seen that there is an acceptable amount of Al, which is shown by the red colour in the element mapping results. The elemental mapping data suggests that the existence of Si and Al could instigate the creation of cementitious products.

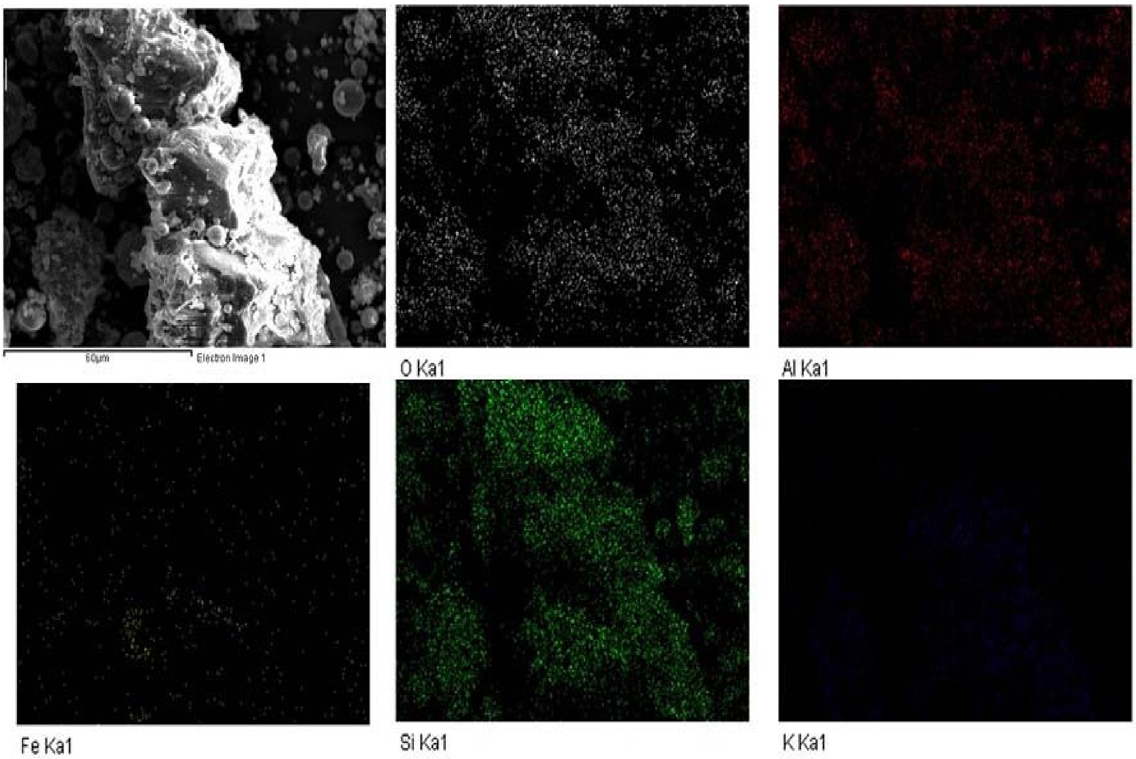

Figure 50. Elemental mapping of fly ash stabilised sand composite

The line spectrum graph presents comprehensive information about the material components of sand fly ash treated samples (Figure 50). The element mapping results were improved by the line spectrum result, which shows Si as dominant among Ca, K, and Fe, in addition to the presence of several peaks of Ca and Ti.

Therefore, the presence of Si, Al, and Ca suggests the existence of calcium-silicate-hydrate (*x*CaO.*y*SiO2.*z*H2O). The availability of C-S-H gel is revealed by SEM/EDS examination, which could confirm the role of cementitious products in increasing the soil's workability.

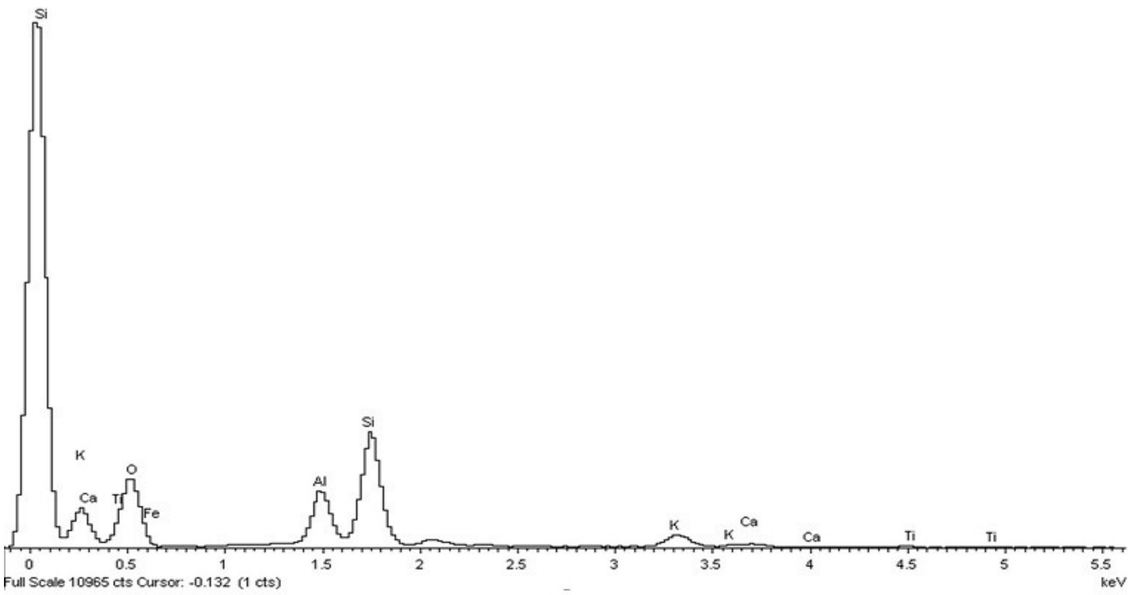

Figure 51. Line spectrum of fly ash stabilised sand composite

Further investigations carried out on fly ash efficiency on sand-clay composite properties.

4.2.1.4 Fly ash stabilised san-clay composite

Figure 51 presents an SEM micrograph of fly ash stabilised sand-clay composite. It can be clearly seen that the numerous fly ash atoms connect the clay and sand particles to each other. In observing this specimen, one observes that the fly ash atoms with a spherical structure have stuck strongly to the clay and sand particles.

Figure 51 also suggests the key role of fly ash in the growth of hydration products. This reaction directly leads to the creation of more cementitious products, thereby creating more sticky composites.

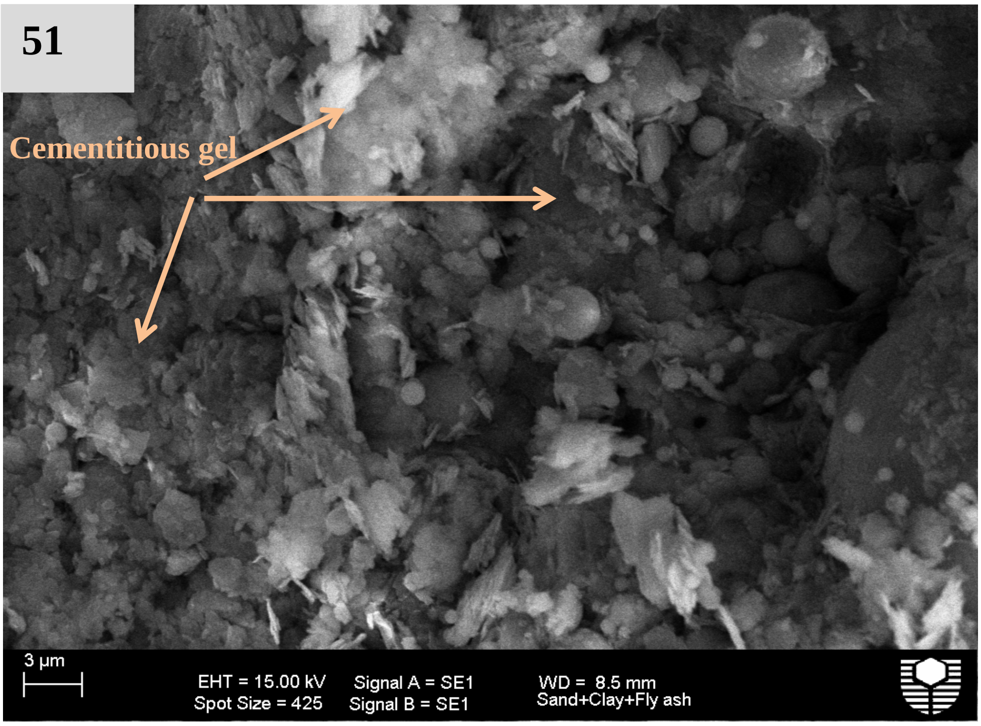

Figure 52. SEM micrograph of fly ash stabilised sand-clay composite

This hypothesis was confirmed by further EDS investigations into fly ash stabilised sand-clay composites. Figure 52/ Figure 53 shows the element mapping and line spectrum graph of the EDS examination. The results suggested the presence of Al, Si, and Ca with traces of Fe and Ti as impurities. The high proportions are associated with Al content. The availability of Al, Si, and Ca causes the creation of calcium-aluminium-silicate-hydrates (C- A-S-H gel) as a hydration product.

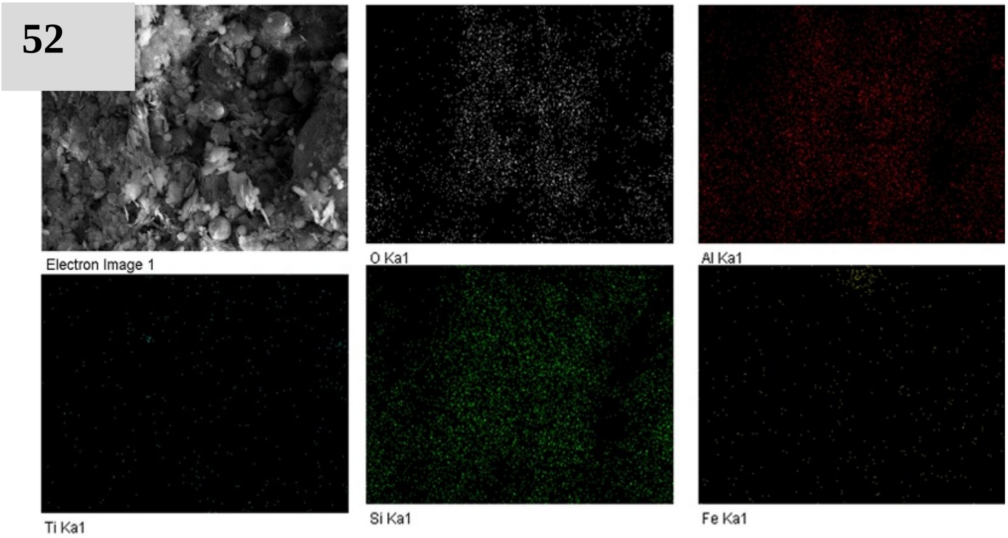

Figure 53. Elemental mapping of fly ash stabilised sand-clay composite

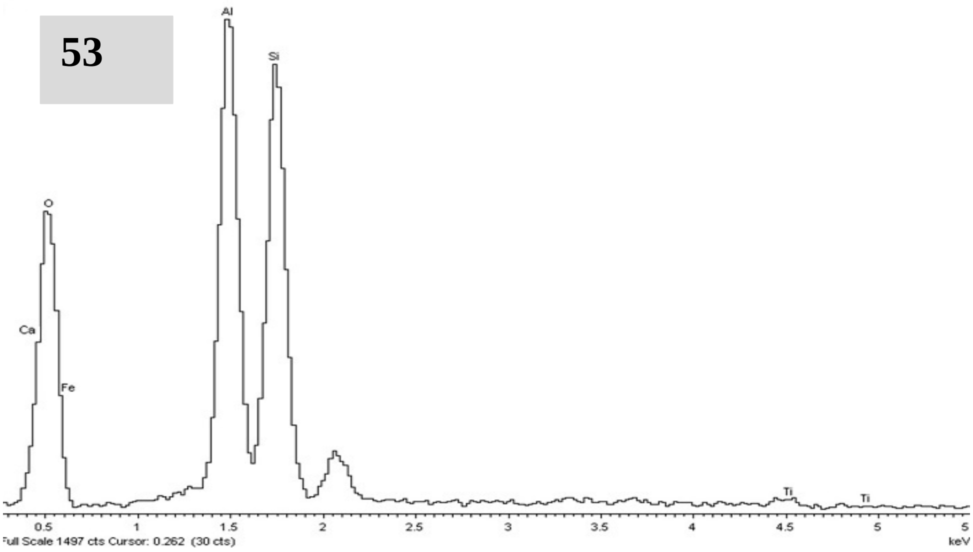

Figure 54. Line spectrum of fly ash stabilised sand-clay composite

Thus, the microstructural alteration and compositional characteristic of stabilised soils was analysed through the SEM/EDS investigation. The data suggested the availability of the components required for creating C-S-H, C-A-H, and C-A-S-H. These components are known as the main composition elements in cementitious products and known for improving the soil's geotechnical productivity.

4.2.2.0 XRD (X-ray powder diffraction)

The mineralogical analysis of the modified sand and sand-clay specimens is very significant for determining the alteration in the mineralogical phases due to pozzolanic reactions. Through the SEM/EDS investigation some of main elements for creating the cementitious compound were detected. However, the occurrence of the pozzolanic reaction depends on the chemical and mineralogical composition of the stabiliser and sand/sand-clay samples.

X-ray powder diffraction analysed the mineralogical and crystalline properties of the prepared specimens. The data was illustrated by different peaks in the line graph results. The x-ray beam was spread through X-ray powder diffractogram with the peak positions occurring where the X-ray beam was diffracted by the crystal lattice. Due to the exclusive characteristics of each mineral particle, unique generated d-spacing can be performed to 'fingerprint' the mineral.

4.2.2.1 Mineral composition of material

The XRD measurement collected was 2θ data in the range of 7.4° to 33.4° with a scanning rate of 0.02°/s. The XRD patterns of the sand, clay, lime, and fly ash are presented in Figure 54. It can be clearly seen that quartz (SiO_2) is the only detected element in the sand XRD pattern. These two peaks occurred at 20.54° and 26.63° and confirmed the availability of Si in the sample by SEM/EDS investigation.

Moreover, the clay XRD result showed the presence of clay minerals including Kaolinite [Al2Si2O5(OH)4], Illite (K,H3O)(Al,Mg,Fe)2(Si,Al)4O10[(OH)2,(H2O)]), mica [AlSi2O6(OH)2], feldspar ((K,Na)Si3O8), as well as quartz.Figure 54 shows that the key elements in the lime component are calcite (CaCO3) and calcium hydroxide (Ca(OH)2). The diffractogram of fly ash illustrated the availability of four main minerals, namely quartz (SiO_2), mullite ($Al_6Si_2O_{13}$), microcline [$K(AlSi_3O_8)$] and merwinite [$Ca_3Mg(SiO_4)_2$].

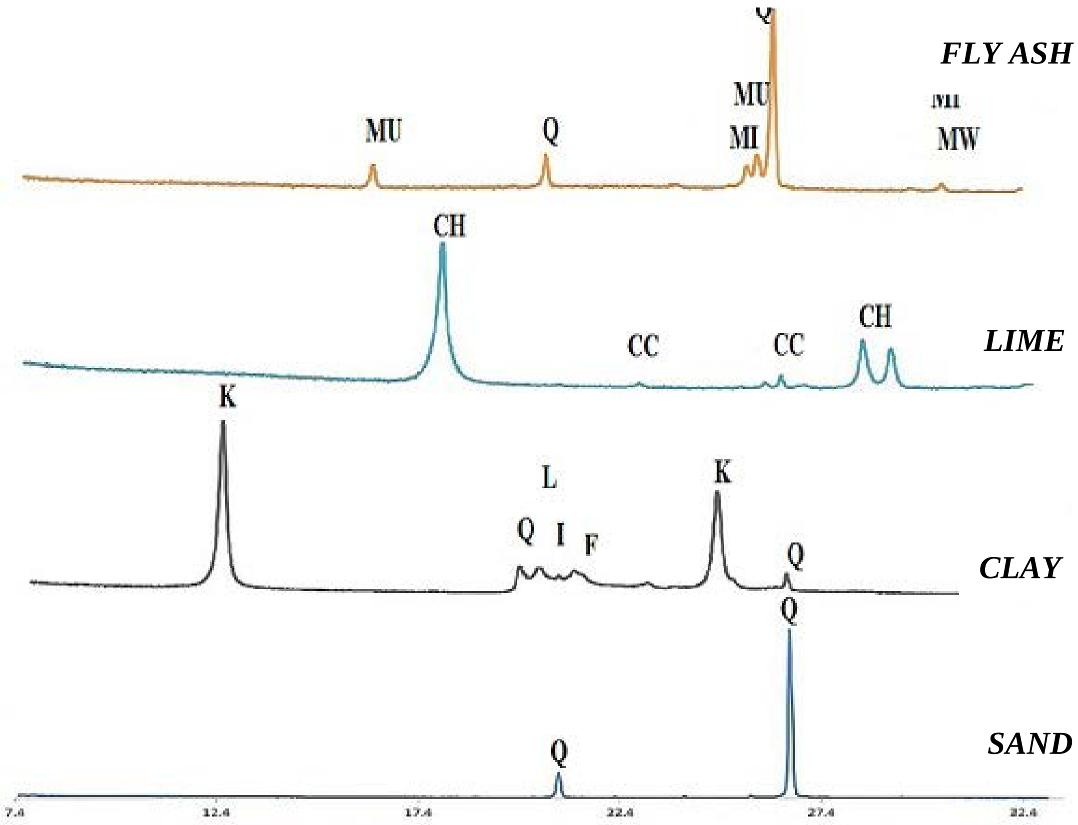

Figure 55. X-ray results of composite's component

4.2.2.2 Mineral composition of composites

Figure 55 reveals the mineral composition of lime-fly ash treated sand. The data collected was 2θ data in the range of 0° to 60° with a scanning rate of 0.02°/s. The X-ray powder diffraction pattern of the stabilised sample collected more accurate and comprehensive mineral information on the sand composite particles. The phase identification of the sand sample treated with lime-fly ash additive is presented in Table 6.

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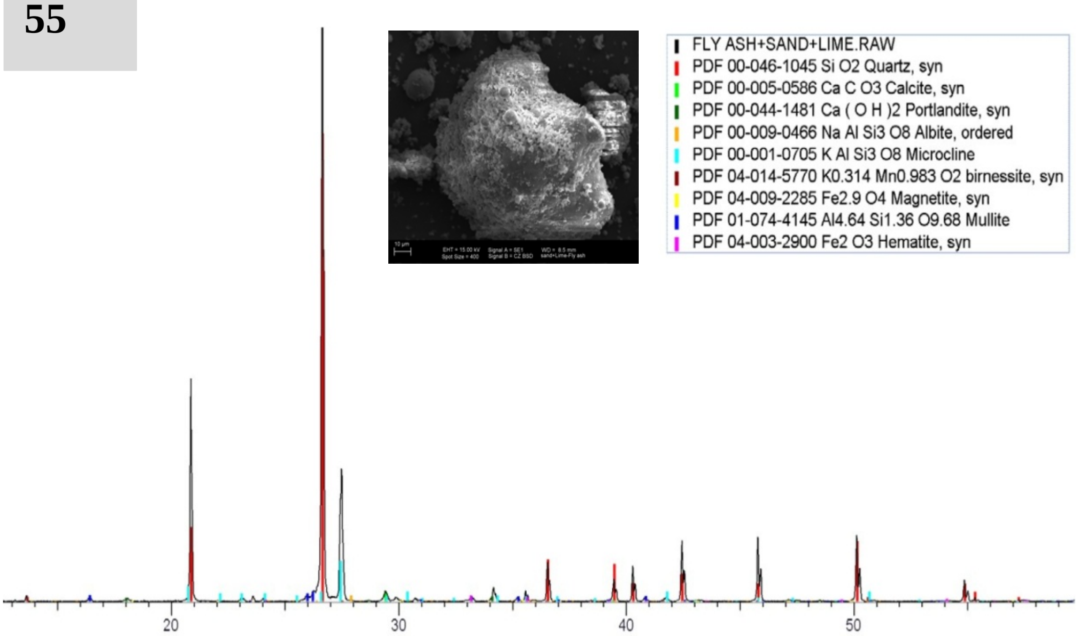

Figure 56. XRD result of lime-fly ash modified sand

Table 6. Phase identification result of lime-fly ash modified sand

Phase	FA	L	S	S+L	S+FA	S+L+FA
Albite, ordered					✓	✓
Aragonite		✓				
Birnessite						✓
Calcite		✓	✓	✓	✓	✓
Diaspore			✓	✓		
Halite		✓				
Hematite	✓				✓	✓
Magnetite	✓		✓		✓	✓
Microcline					✓	✓
Microcline,intermediat			✓	✓		
Mullite	✓				✓	✓
Periclase		✓		✓		
Portlandite		✓		✓		✓
Quartz	✓	✓	✓	✓	✓	✓

The potential phases present include:

- Albite, ordered [$NaAlSi_3O_8$]
- Aragonite [$CaCO_3$]
- Birnessite [$K_{0.314}Mn_{0.983}O_2$]
- Calcite [$CaCO_3$]
- Diaspore [AlO(OH)]
- Halite [NaCl]
- Hematite [Fe_2O_3]
- Magnetite [$Fe_{2.9}O_4$]
- Microcline [$K(AlSi_3O_8)$]
- Microcline, intermediate [$K(AlSi_3O_8)$]
- Mullite [$Al_{4.64}Si_{1.36}O_{9.68}$]
- Periclase [MgO]
- Portlandite [$Ca(OH)_2$]
- Quartz [SiO_2]

These results confirmed the data obtained by SEM/EDS examination, showing the possibility of the creation of cementitious products and the pozzolanic reaction.

4.2.2.3 Crystallinity change of samples

4.2.2.3.1 Sand composites

Investigation into the crystallinity change of stabilised sand specimens was performed by comparison between modified and unmodified samples. Figure 56 presents the XRD patterns of unstabilised sand, lime treated sand, fly ash modified sand, and lime-fly ash stabilised sand.

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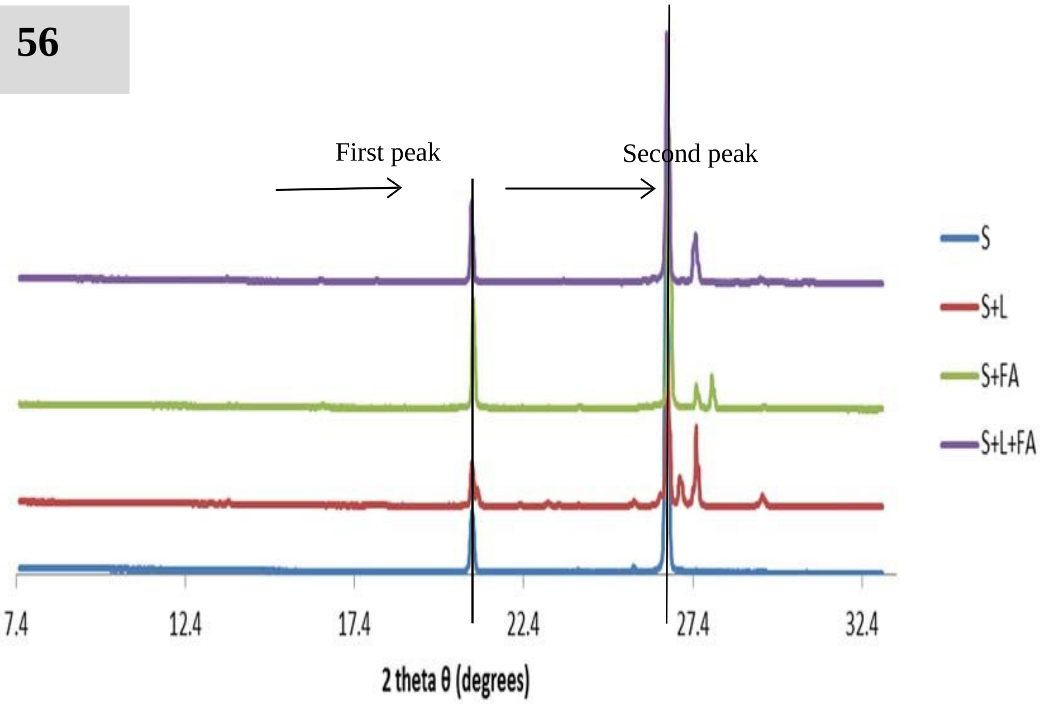

Figure 57. Crystallinity change of treated and untreated sand samples

Figure 56 reveals that the sand and stabilised samples produced prominent diffraction peaks at 2θ angles of approximately 20.8°, 21.4° for the first peak, and 26.3°, 27.1° for the second peak. The XRD results indicate that the first and second peaks with a minor change shifting to lower 2θ angles was the result of the stabiliser's effect on the behaviour of the sand. The optimum shift related to sand stabilisation was with the mixture of 3% lime-15% fly ash at 20.5°, 21.1° in the first peak, and 26.09°, 26.99° in the second peak.

4.2.2.3.2 Sand-clay composites

The investigation into sand-clay composites shows the change in the crystallinity of the composite by the addition of either lime or fly ash. This comparable investigation was carried out in order to study the individual effect of lime or fly ash on sand- clay modification (Figure 57).

The mineral characteristics of each material are indicated by the marked diffraction lines. In the field of lime and fly ash mineralogical characteristics, the XRD results revealed the existence of some major compounds such as Aragonite and Calcite with the chemical formula [$CaCO_3$], Periclase [MgO], Portlandite [Ca(OH)] and Quartz [SiO_2]. Moreover, the X-ray diffraction test identified a crystalline phase similar to that of Ettringite hydrates that justifies the reaction of the lime modified compound. Ettringite, with the chemical formula [3CaO-Al2O3-3CaSO4-32H2O] (Lin et al., 2007, Lim et al., 2002), is created due to the addition of lime.

However, the diffraction peaks of C–S–H hydrate became higher due to the availability of quartz in the sand combinations, or due to a reaction with the aluminosilicate of clay (Lin et al., 2007). The hydrate of calcium silica and aluminiumsilica was then created as a result of the pozzolanic reaction.

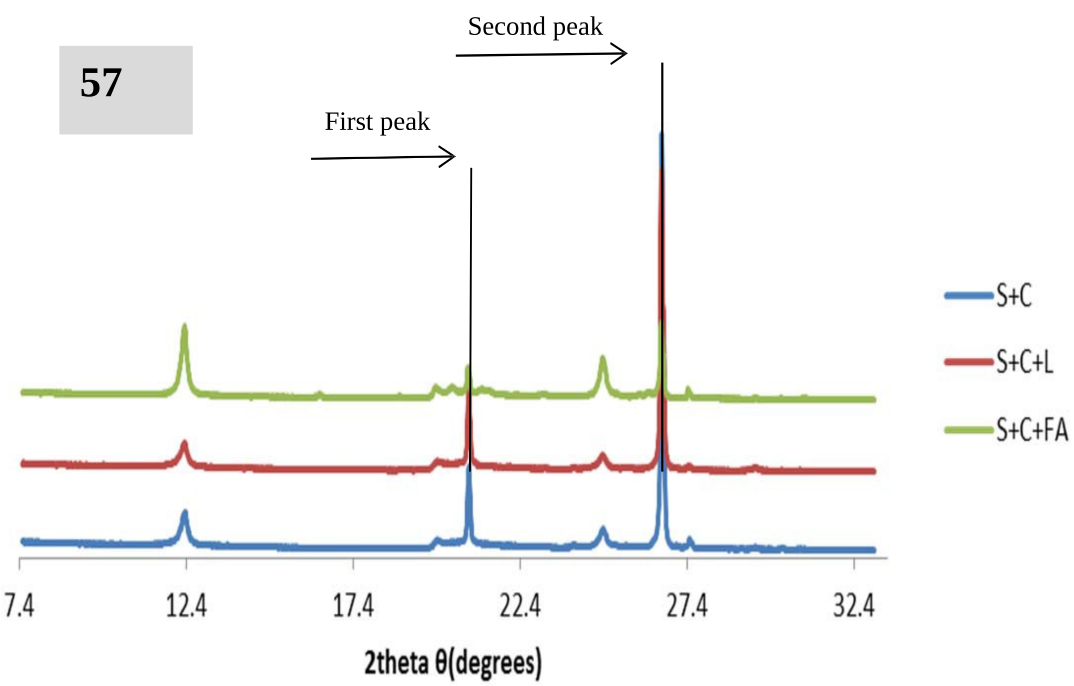

Figure 58. Crystallinity change of treated and untreated sand-clay composites

In the each of lime-modified or fly ash-treated mixtures, the reflections of the treated samples were attributable to a new formation that shifted to a lower angle. The XRD results indicate that the first and second peaks with a minor change shifting to a lower 2θ angle were the result of the additive's effect on the behaviour of the pure composite. This modification related to the lime treated pure mixture, which showed peaks at 20.84°, 21.00° in the first peak and 26.43°, 26.83° in the second peak, modified to a lower angle at 20.50°, 20.78° in the first peak, and 26.28°, 26.77° in the second peak. This modification occurred due to the occurred due to the fly ash addition to a lower angle; 20.42°, 20.66° in the first peak, and 26.15, 26.55° in the second peak.

This tendency may have been due to the stabiliser component reaction with aluminosilicate, thereby creating a dense area of soil particles. Overall, this led to improved sand-clay composite performance, although the fly ash application was seen to be slightly more efficient than the lime treatment.

4.2.3.0 FTIR (Fourier transform infrared spectrometry)

The changes in composition in the pure composite and lime/fly ash composite were examined by Fourier Transform Infrared Spectroscopy (FTIR). In the FTIR technique, the infrared spectra are applied to achieve the absorption bands, which are identified by intensity, shape, and position (cm^{-1}) in the spectrum. In the area of hydrogen-bonding, the absorption bands appear in a variety of frequencies, and these are associated with cations related to the OH vibrations. The FTIR technique determined the cation distribution around the hydroxyls and thereby assessed the short-range cation ordering (National Research Council . Transportation Research, 1991). The FTIR spectra of fly ash, lime, clay, sand, sand-clay mixture, and lime/fly ash composite are indicated in Figure 58. It can be seen that the hydrated lime, identified by two strong peaks at 3642 cm^{-1} was assigned with the Ca-O-H group of Portlandite (CH) and 1461 cm^{-1} is ascribed to calcite, possibly formed due to the aeration of the pastes (Saikia et al., 2002). Two intense bands at 1062 and793 cm^{-1} were detected by FTIR spectra. The T-O at 1062 cm^{-1} of the original fly ash is associated with mullite vibrations. In addition a 793 cm^{-1} adsorption band corresponds to alkali activated fly ash, which is generated by the quartz creation part of fly ash.

For the sand-clay stabilised with fly ash, seven main bands were detected at 3691, 3619, 1028,911,788, 751, and 688 cm^{-1}. Two intense bands at 3691 and 3619 cm^{-1} were assigned to Al–O–H and indicated the possibility of the hydroxyl linkage. The Si–O stretching vibration was observed at 1028 cm^{-1} , revealing the presence of quartz. The bands at 911 and 788 cm^{-1} could be assigned to quartz as the crystalline phase in fly ash and they show the availability of kaolin. These bands are allocated with Al–OH at 911 $cm^{-1}$and

Si–O–Al at 788 cm^{-1}, which indicate the possibility of the presence of illite. The presence of Si–O (perpendicular) is observed by bands at 751, and 688 cm^{-1}.

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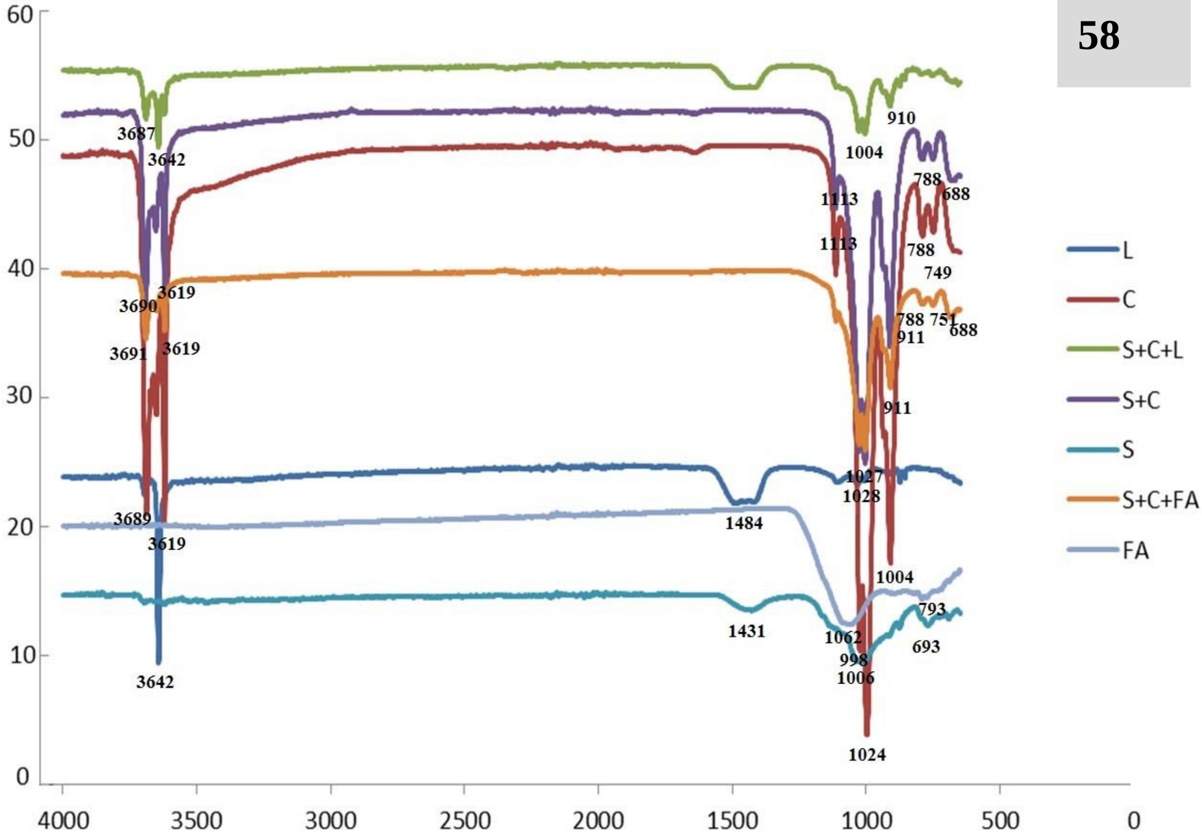

Figure 59. FTIR spectrum results of selected samples, which show the chemical compound in specimens.

The band identified at 1006 cm^{-1} has been ascribed to the Si-O stretching group in sand. Typical Kaolin spectrums indicate six bands, at 3689,3619,1113,1024,911, and 788 cm^{-1}. Two intense bands at 3689 and 3619 cm^{-1} were assigned to the inner OH and external hydroxyl vibration. In the IR spectra of the Kaolin, the main Si–O stretching bands were revealed at 1113, 1024, which may have been due to the formation of a new C–S–H phase or transformation of the C–S–H phase (Saikia et al., 2002, Saikia et al., 2003, Eisazadeh et al., 2012). The adsorption peak at 911 cm^{-1} is attributable to Al–OH groups that showed OH deformation, associated with $2Al^{3-}$. The OH deformation, linked to Al^{3-}, Mg^{2-} was identified at 788 cm^{-1}. The IR spectrum of the sand-clay combination showed similar behaviour to the pure clay by one more bands in the fingerprint region at 1004 cm^{-1}, which relates to the stretching of the Si–O group vibration.

Although the lime-modified sample revealed just four adsorption peaks, the FTIR spectrums of lime-treated soil consisted of the combination of specific peaks of lime, clay, and sand. The comparison of the IR spectra of untreated composite with the lime compound shows that the FTIR peaks were saved or that they shifted slightly to a lower wave. It seems that the lime composites retained the chemical parameters of the material.

To sum up, the FTIR analysis confirmed the XRD and SEM results by recognising the chemical compound and compositional changes in the laboratory specimens. The results confirmed the creation of chemical compounds which generated the cementitious products and the pozzolanic reaction associated with improved soil performance.

4.3.0 Laboratory investigation

The geotechnical experimental work is presented in this section by four separated tests;

- Standard compaction
- Hydraulic conductivity
- One dimensional consolidation
- Direct shear

4.3.1.0 Standard compaction

4.3.1.1 Geotechnical results

Figure 59-56 and Table 7 illustrate the compaction properties of pure sand, lime, fly ash and a lime-fly ash mixture of sand. It can be seen that compaction characteristics of the sand treated with additives changed, due to an increase in the OMC and MDD.

Table 7. Laboratory compaction results

Specimen	Moisture Content (%)	Dry Density (gr/cm3)
Sand	11.20	1.63
% 1L	13.74	1.68
% 2L	13.08	1.70
% 3L	12.99	1.71
%5FA	12.98	1.75
%10FA	12.49	1.82
%15FA	12.05	1.89
%1 L-%5FA	13.79	1.78
%1 L-%10FA	12.62	1.85
%1 L-%15FA	11.13	1.90
%2 L-%5FA	13.87	1.80
%2 L-%10FA	12.75	1.86
%2 L-%15FA	11.19	1.91
%3 L-%5FA	14.09	1.81
%3 L-%10FA	12.91	1.87
%3 L-%15FA	11.26	1.92

The combination of lime and fly ash mix produced optimum compaction characteristics, with Table 7 illustrating the most effective results related to the 3% lime-15% fly ash mixtures. This particular combination produced the greatest MDD of all the samples.

Table 7 also illustrates that the utilisation of the combination of 1% lime-15% fly ash caused minimum OMC in stabilised samples.

Investigation into the lime/fly ash combination results for sand treatment illustrate the lime's capability for producing growth of the OMC in sand samples when compared with fly ash specimens alone (Figure 59). It can be seen from Figure 59 that increments in the OMC of lime-treated samples were higher than the OMC of samples that were stabilised with fly ash only.

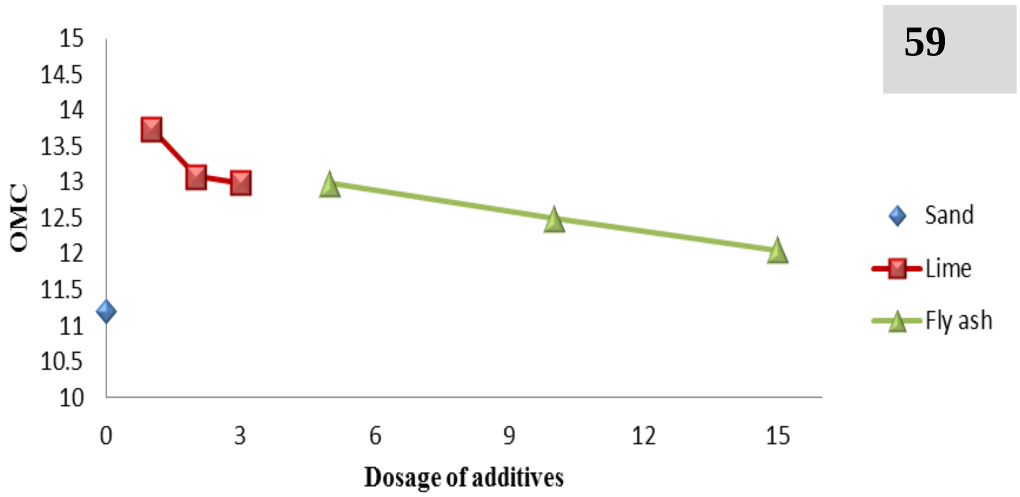

Figure 60. OMC variation of sand blends with lime and fly ash.

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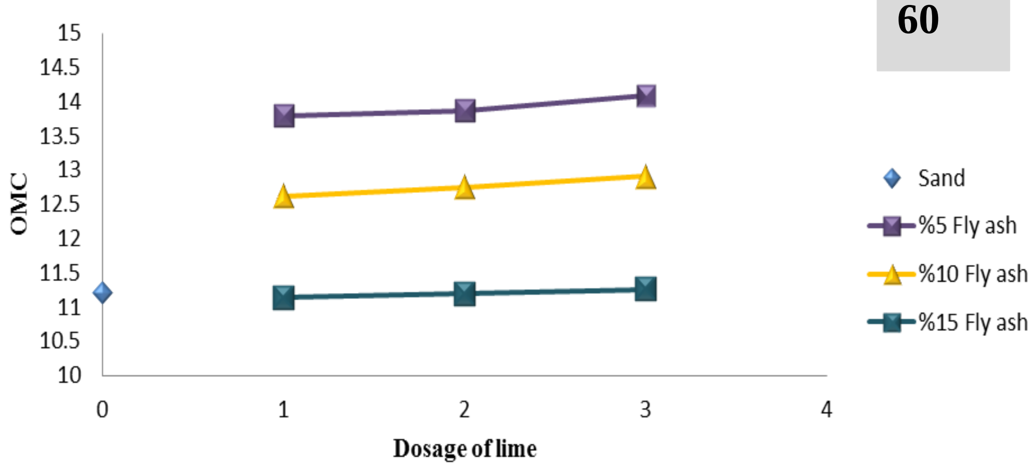


Figure 61. Compaction results showing optimum moisture content for samples of lime/fly ash combination.

However, in proportion to the combination of the same percentage of fly ash with different amounts of lime, increments in the dosage of lime in these mixtures led to an increase in the moisture content of the stabilised samples (Figure 60). On the other hand, for the same amount of lime, increments in the dosage of fly ash led to a reduction in the optimum moisture content amount. The maximum amount of optimum moisture content was found in the combination of 3% lime-5% fly ash (Table 7).

In terms of the application of either lime or fly ash with regard to improving MDD, fly ash was found to be the more effective stabiliser for sand treatment when compared to lime (Figure 61).

Figure 61 shows the upward tendency of MDD in stabilised samples due to incrementing the dosage of fly ash; whilst the MDD of lime-treated sand had a lower MDD than the other stabilised samples.

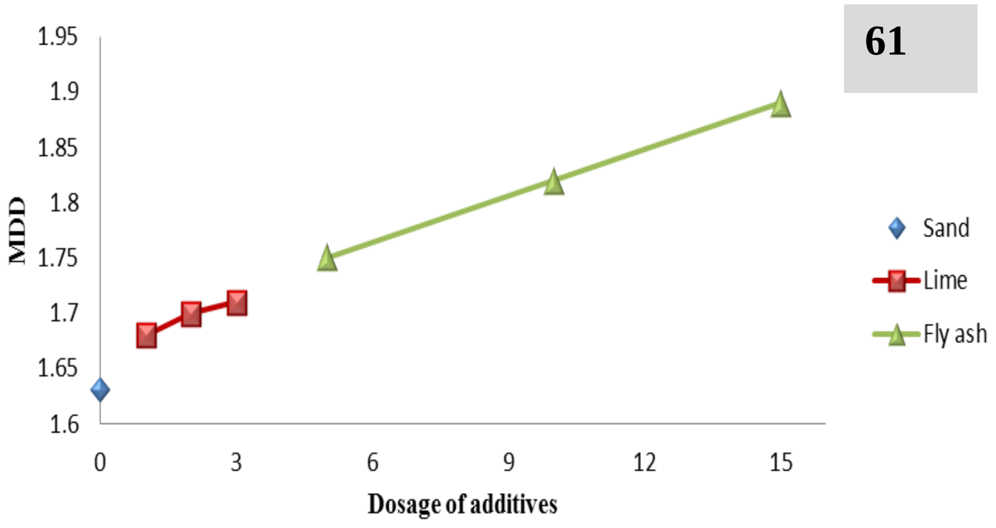


Figure 62. Compaction results showing maximum dry density for lime and fly ash samples.

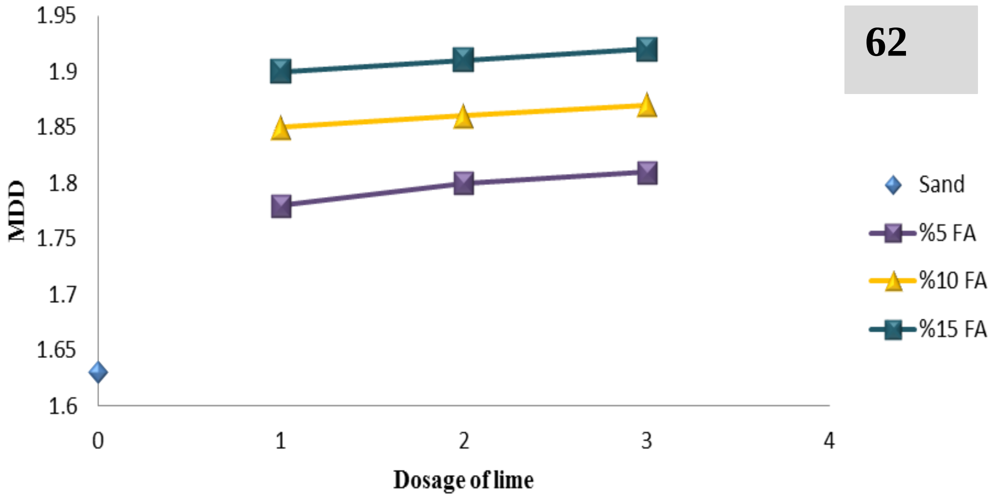


Figure 63. compaction results showing maximum dry density of lime/fly ash combination samples.

Figure 62 illustrates that the efficiency of lime-fly ash combination is greater when the fly ash proportion was increased. For a constant amount of lime, the most effective results were achieved by a lime combination with 15% of fly ash (Figure 62).

Thus, although utilisation of lime and fly ash as an additive led to increased moisture content, due to increase in the maximum dry density of sand, lime and fly ash could be an appropriate stabiliser for improving the compaction properties of sand.

The effect of additives was investigated for examining the structural and microstructural change of specimens. The two following sections are presented the microscopic analysis for compacted samples.

4.3. 1.2 Optical microscopic examination on compaction specimens

Figures 63-66 illustrate optical microscopy morphological images from the surface of three stabilised specimens and one unstabilised specimen that were collected from the laboratory compaction tests. Through optical microscopy one can observe the stabiliser's efficiency in bringing about a mechanical improvement in the treated samples.

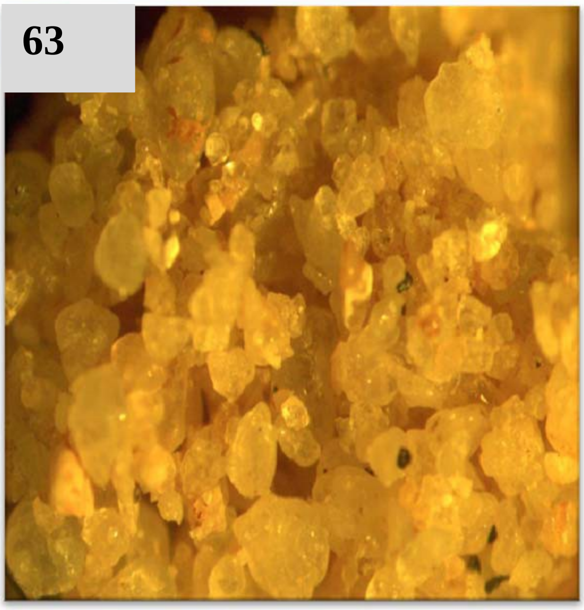


Figure 65. Optical microscopy image of compacted pure sand

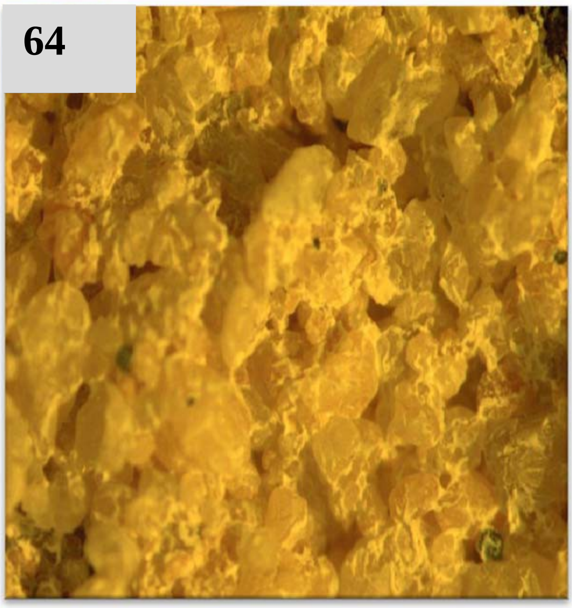


Figure 64. Optical microscopy image of compacted sand with 3% lime composite

As shown in Figure 63, the inability of sand particles to create a uniform unit resulted in a high porosity and a high void ratio of the pure sand sample, which correlates to the low maximum dry density that was achieved on compaction in the experimental test.

Figure 64 suggests that the utilisation of 3% lime for sand stabilisation contributes to an improvement in the physical behaviour of compacted sand. Establishing a uniform particle as the result of the addition of lime leads to an increase in the water absorption ability of sand, which is associated with increasing the optimum moisture content of the sample.

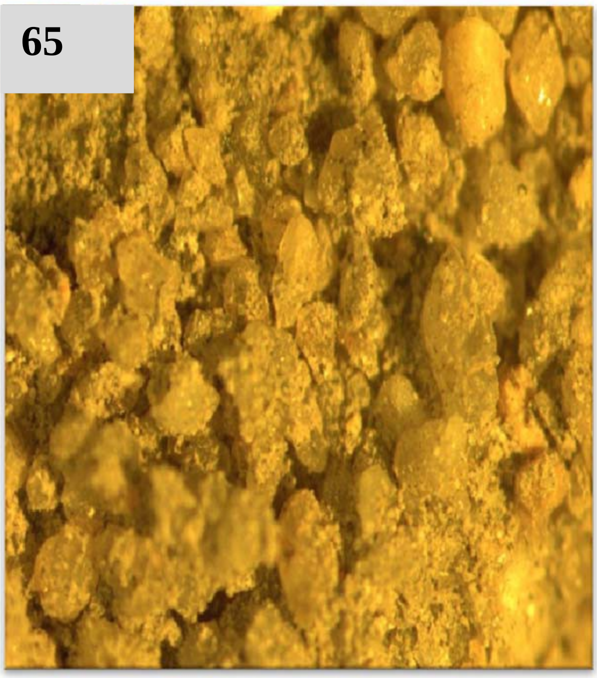


Figure 67. Optical microscopy image of compacted sand with 15% fly ash composite

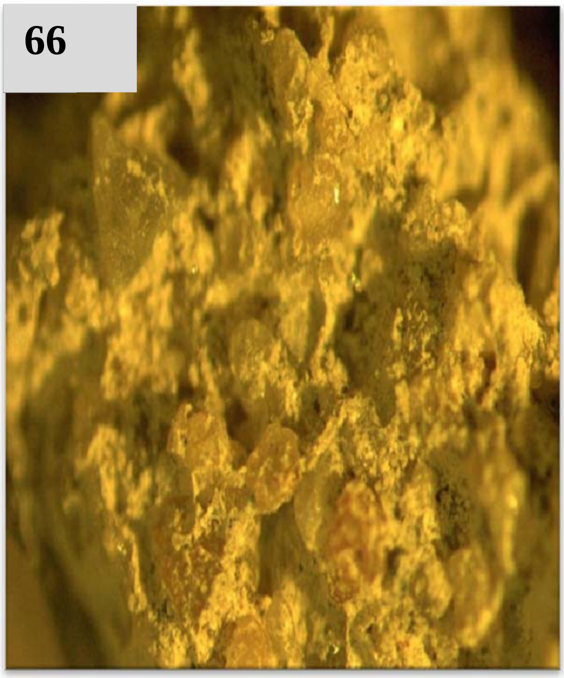


Figure 66. Optical microscopy image of compacted sand with 3%lime-15%fly ash composite

On the other hand, it can be seen from Figure 65, that fly ash treatment creates a homogeneous complex among the sand and stabiliser particles. It seems that the significant cohesion ability of fly ash particles in attracting and connecting the smaller units of sand is the major cause of reduction in the void ratio and increases the maximum dry density of fly ash treated samples. However, Figure 66 shows the combination of 3% lime-15% fly ash can give rise to optimum effect in sand stabilisation. The optimum desired effect in lime-fly ash treated sample stemmed from sticking sand particles together, and finally generating a perfect uniform area compared with the other specimens.

4.3.1.3 SEM investigation on compacted samples

The interaction between sand and stabiliser particles on a micron and sub-micron scale was evaluated through high-resolution micrograph images with significant depth. The SEM micrographs of sand and stabilised sand were thoroughly analysed for any changes in the microstructure of the pure sand as the result of stabilisation (Figure 67). The black areas on the images represent voids in the samples. Figure 67 shows the pure sand particles separated and with numerous gaps between each unit. The wide unfilled area between particles illustrates the low compaction properties of sand. Conversely, the introduction of lime into the sand stabilisation procedure led to an agglomeration effect, whereby large particles formed in the sand mixture (Figure 68).

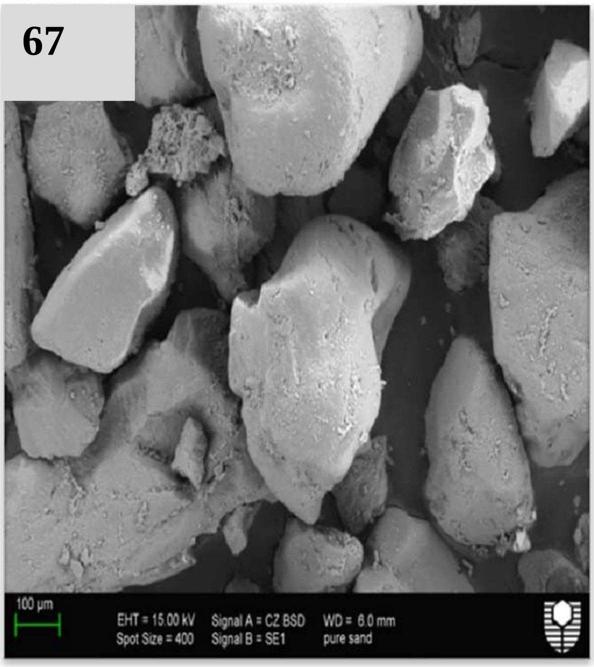


Figure 69. Secondary and backscattered electron SEM micrograph of sand compacted particle at 6*mm* working distance and 15kv voltage energy at 100*µm*

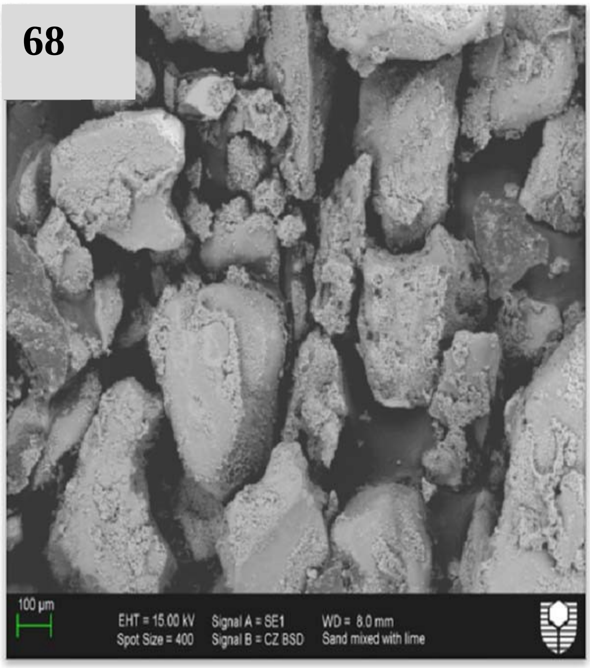


Figure 68. Secondary and backscattered electron SEM micrograph of compacted sand with 3%lime composite at 8*mm* working distance and 15kv voltage energy at 100*µm*

Although this interaction consequently led to sand particles sticking together, fly ash established the greatest connection of sand particles due to an abundance of fly ash particles (illustrated in the micrograph results in Figure 69. Regarding micro- size and abundance of fly ash particles, this stabiliser could extensively fill in around the sand unit and make a uniform particle. Figure 70 shows the maximum effect achieved by utilisation of the lime-fly ash combination. It is acknowledged that lime's water attraction ability and fly ash's cohesion characteristics are known as two key factors in the sticking of sand units and collection in a uniform area among sand particles.

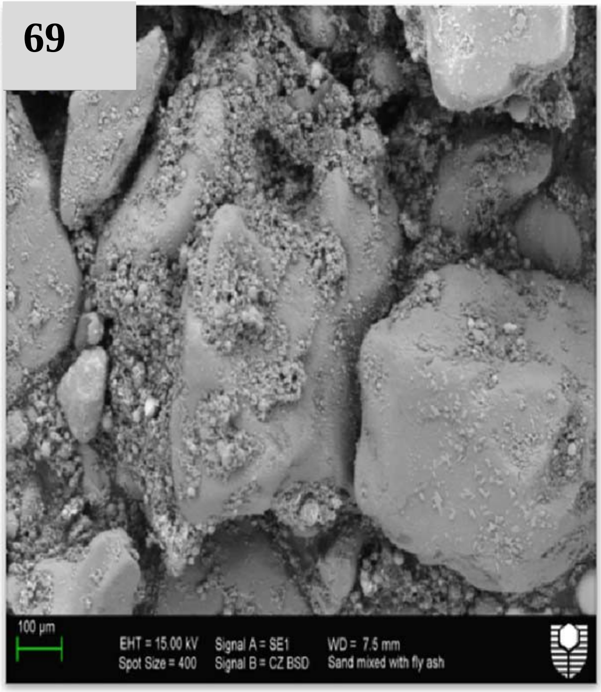


Figure 70. Secondary and backscattered electron SEM micrograph of mixing the compacted sand with 15%fly ash composite at 7.5*mm* working distance and 15kv voltage energy at 100*µm*

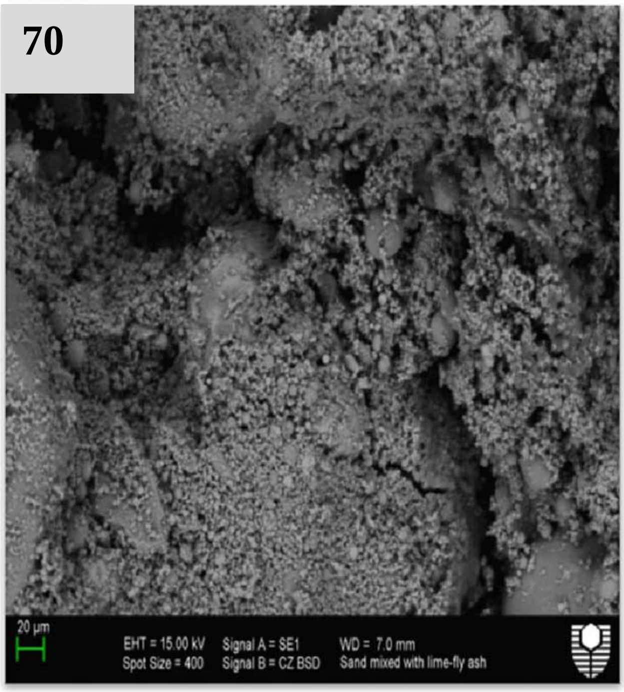


Figure 71. Secondary and backscattered electron SEM micrograph of mixing the compacted sand with 3%lime-15%fly ash composite at 7*mm* working distance and 15kv voltage energy at 20*µm*.

To sum up, the optical microscopic and microstructural morphology results reveal the water absorption ability of lime, and the cohesion capability of fly ash particles. For compaction and strength properties, these two factors could play a key role in triggering the chemical components among water molecules and additive particles. Fly ash addition, by creating a uniform and cohesion area could increase sand compactibility.

On the other hand, based on the SEM micrographs, lime addition to sand caused the creation of a combination with various sizes of sand particles. This factor could play a pivotal role in sand's shear strength due to the creation of a comprehensive area in the lime composite. The generation of different sizes of composite particles leads to more resistance against shear and movement.

However, these suppositions require evaluation by chemical investigation. The compaction properties of all stabilised specimens are improved in contrast with pure sand. However, it seems that, utilisation of fly ash is more effective than sand treated with lime only. In all specimens a development tendency was observed in the maximum dry density after sand stabilisation with the increase of additive amounts. In addition, there was a remarkable improvement in the maximum dry density of samples which had fly ash, while lime treated samples had a moderate increase in maximum dry density compared with other stabiliser combinations. The highest increment of maximum dry density related to the combination of 3% lime-15% fly ash.

In general, utilisation of additives increased the optimum moisture content of sand and was associated with stabiliser increments. Based on the results, the increase of the moisture content in the samples after lime stabilisation was greater than that of the treatment with fly ash and lime-fly ash. Although the lime treated sand showed a decrease in optimum moisture content with the increase in lime content, the decrease of moisture content in the sand stabilised with fly ash was more notable than in the lime specimens.

Applying the combination of 3% lime-5% fly ash leads to a greater moisture content compared to the other samples. In contrast, a combination of lime additives with 15% fly ash leads to maximum improvement in the maximum dry density and a lower optimum moisture content among the other samples.

4.3.2 Hydraulic conductivity

The results of the hydraulic conductivity tests are illustrated in Table 8 and Figures71-73. These tests results may help to evaluate the effect of lime and fly ash on the hydraulic conductivity of sand. The main consequence of the additives was a reduction in the hydraulic conductivity of the stabilised sand. As illustrated in Table 8 and Figure 71, after lime-fly ash treatment, the hydraulic conductivity of the sand specimens decreased about 180 times in comparison with the hydraulic conductivity results for pure sand. The maximum change in hydraulic conductivity occurred due to the combination of 3 % lime with 15 % fly ash among the other specimens.

Table 8. Hydraulic conductivity results

Specimen	Hydraulic conductivity cm/sec
Sand	7.6742×10^{-3}
1% Lime	2.0758×10^{-3}
2% Lime	1.5333×10^{-3}
3% Lime	1.1768×10^{-3}
5% Fly ash	1.8391×10^{-3}
10% Fly ash	9.6554×10^{-4}
15% Fly ash	1.1993×10^{-4}
1% Lime&%5 Fly ash	4.7783×10^{-4}
1% Lime&%10 Fly ash	8.1279×10^{-5}
1% Lime&%15 Fly ash	7.3451×10^{-5}
2% Lime&%5 Fly ash	7.0526×10^{-5}
2% Lime&%10 Fly ash	4.3215×10^{-5}
2% Lime&%15 Fly ash	3.7825×10^{-5}
3% Lime&%5 Fly ash	2.2561×10^{-5}
3% Lime&%10 Fly ash	1.8161×10^{-5}
3% Lime&%15 Fly ash	1.2705×10^{-5}

It seems that the mixture of lime and fly ash can lead to a significant reduction in the hydraulic conductivity of sand in comparison with the application of other additives alone, such as lime and fly ash.

Incrementing the dosage of lime-fly ash had a mutual correlation with the reduction in the hydraulic conductivity of the sand samples. This tendency was initiated by the addition of 1% lime-5% fly ash and continually reduced in all lime-fly ash stabilised samples.

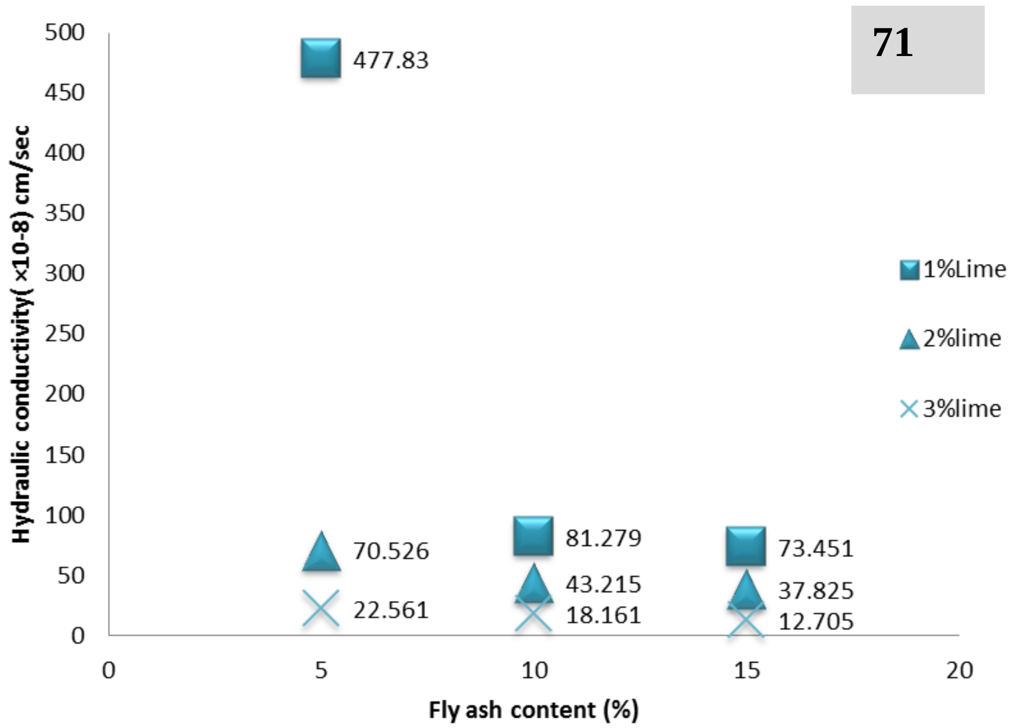


Figure 72. The effect of lime-fly ash combination on sand's hydraulic conductivity

Moreover, it can be seen from Figure 72 that the utilisation of fly ash for the hydraulic conductivity of sand was more effective than the sand treated with lime. As is shown by Figure 72, applying fly ash could reduce the hydraulic conductivity of sand by roughly 65 times.

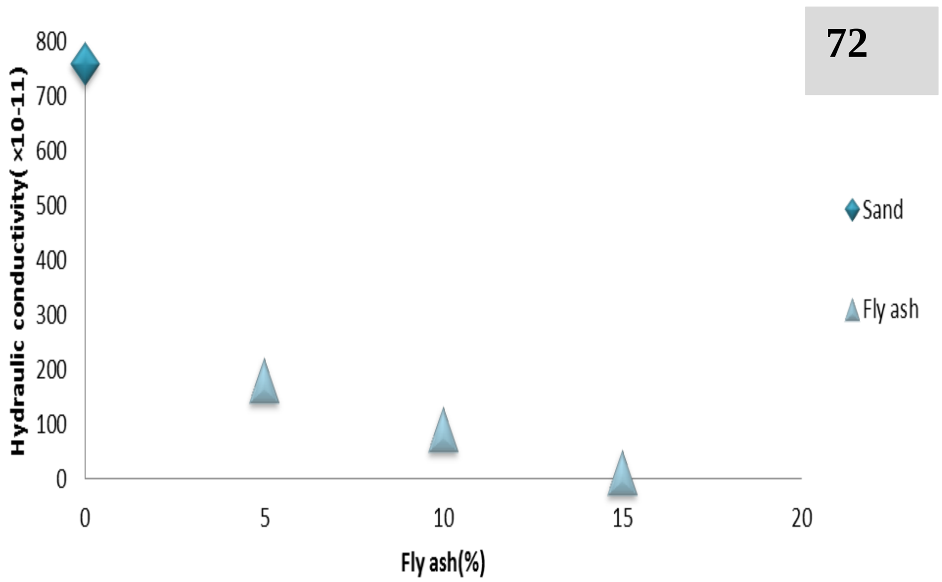


Figure 73. The effect of fly ash combination on sand's hydraulic conductivity

Figure 73 presents the relationship between the addition of lime and the addition of fly ash (using a consistent amount of each of additive). It can be clearly seen that for all three groups, incrementing the dosage of additive leads to a lessening of the coefficient of permeability of treated specimens.

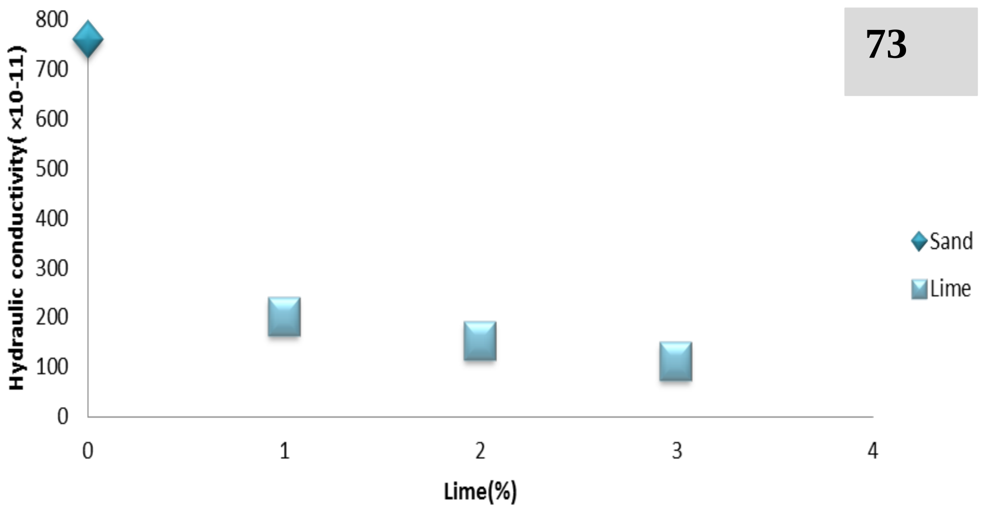


Figure 74. The effect of lime combination on sand's hydraulic conductivity

Whilst Figure 73 illustrates that sand treatment by lime led to just a seven-fold reduction in the coefficient of hydraulic conductivity of sand, nevertheless, this amount is not noticeable compared with the effect of fly ash.

On the other hand, the given result revealed that the maximum decrease in hydraulic conductivity related to the specimen with the maximum amount of dry density (Table 6). However, this tendency is not constant and systematic for other samples that have a high maximum dry density. Based on the results, an equivalent increase in the proportion of lime and fly ash may have a positive effect on the hydraulic conductivity of sand (by reducing it). The data illustrates that increases in the percentages of lime and fly ash was reduce the hydraulic conductivity of sand.

To sum up, a series of hydraulic conductivity tests was performed on 16 sand specimens with various amounts of lime, fly ash, and lime-fly ash. The dry density, moisture content and dry weight of sand samples were defined based on the standard proctor compaction test results.

This study demonstrates that lime and fly ash treatment could reduce the hydraulic conductivity of sand. Investigation into lime, fly ash and lime-fly ash specimens indicated that of all the additives to the samples, the combination of lime and fly ash had the most significant effect on sand. The lime-fly ash stabilisation had a 180-fold reduction approximately in sand’s hydraulic conductivity. However, the hydraulic conductivity of sand decreased by 65 times with the addition of flies ash and 7 times with the addition of lime.

Therefore, the combination of lime and fly ash could be more effective than using one additive alone (i.e., lime or fly ash) in sand stabilisation. In addition, it seems that an equivalent increase in the ratio of lime and fly ash may lead to an effective reduction in the hydraulic conductivity of sand.

It can be concluded that a reduction in the hydraulic conductivity of sand-stabilised specimens with fly ash was greater than that of the sand-stabilised specimens which were treated with lime.

On the other hand, the obtained results revealed that the specimens with the maximum amount of dry density had a maximum reduction in hydraulic conductivity (i.e., the specimen with the combination of 3% lime and 15% fly ash). Overall, the hydraulic conductivity of other specimens with a high dry density had a noticeable decrease in hydraulic conductivity. However, a logical connection or definite relationship could not be established between the dry density and hydraulic conductivity for sand.

Hence, it seems that applying lime and fly ash and a combination of lime-fly ash to earthen structures in permanent contact with water such as dams, river levees and canals would be effective for improving the quality of the structures.

4.3.3.0 One dimensional consolidation

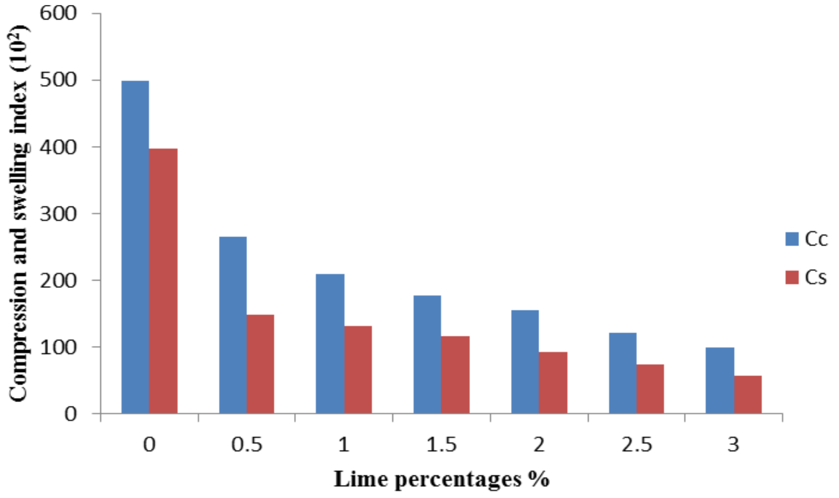
4.3.3.1 Lime addition

Table 9 and bar chart 1 illustrate the compression index (C_c) and swell index (C_s) results of lime treated specimens. These are the results of the pure mixture sample and six lime combination specimens used for evaluating the mechanical effects of lime on the consolidation and swelling characteristics of a pure composite. In general, lime modification reduces the consolidation-swelling behaviour of pure compounds. Moreover, Appendix 17-23 presents individual graphs by void ratio and effective vertical stress on a log scale ($e\_\sigma'p$) for sand and lime composites with a various amount of lime as 0.5%, 1%, 1.5%, 2%, 2.5% and 3%.

Table 9. Consolidation test data of lime treatment (C_c :Compression index, C_s: swelling index, and e_0: initial void ratio)

Sample (%)	C_C	C_S	e_0
0 LIME	$4.98{*}10e^{-2}$	$3.98{*}10e^{-2}$	0.520
0.5 LIME	$2.65{*}10e^{-2}$	$1.49{*}10e^{-2}$	0.462
1 LIME	$2.10{*}10e^{-2}$	$1.32{*}10e^{-2}$	0.417
1.5 LIME	$1.77{*}10e^{-2}$	$1.16{*}10e^{-2}$	0.382
2 LIME	$1.55{*}10e^{-2}$	$9.13{*}10e^{-3}$	0.372
2.5 LIME	$1.21{*}10e^{-2}$	$7.47{*}10e^{-3}$	0.369
3 LIME	$9.96{*}10e^{-3}$	$5.81{*}10e^{-3}$	0.361

The initial void ratio in the pure composite was 0.520, the compression index was $4.65{*}10e^{-2}$, and the swell index was $1.66{*}10e^{-2}$. The range of lime amounts and its efficiency on pure compounds was estimated by investigating a range of results from the lime mixtures.



Bar Chart 1. The correlation between lime addition and Cc and Cs of soil

From the Bar chart 1, for lime treated specimens with a continuous trend, the amount of the compression index was reduced by increasing the dosage of additive. Bar chart 1 illustrates that adding 0.5% of lime to a pure sample causes a remarkable decrease in the compression index of the soil, which dropped to $2.65{*}10e^{-2}$. Subsequently, the lowest settlement related to a modified sample with 3 % of lime with a $9.96{*}10e^{-3}$ compression index.

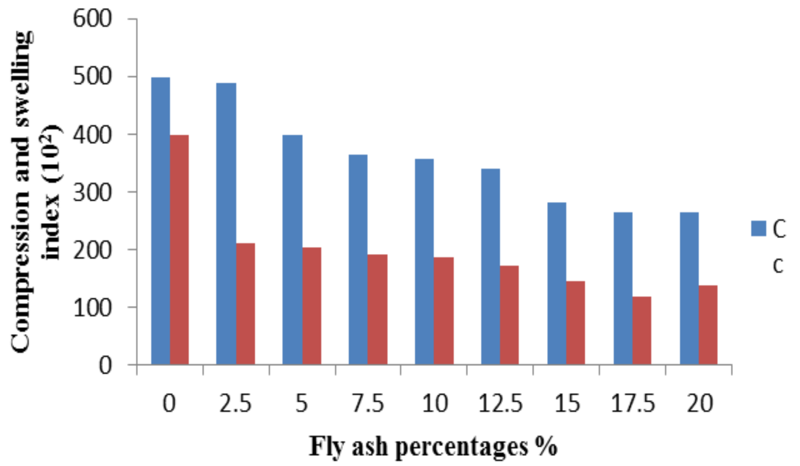
Furthermore, it can be clearly seen from Table 9, that the correlation between the initial void ratio and the coefficient of consolidation confirmed the relationship between the amount of additive with e_0 and Cv. Adding a greater amount of additive to the combinations led to a reduction in the coefficient of consolidation. As is represented by Table 9, the sample with 3% of lime had the minimum amount of initial void ratio in contrast with the non-stabilised sample that had the maximum e_0 out of all the samples. A correlation can be found between the dosage of lime and a reduction in the compression and swelling indices.

4.3.3.2 Fly ash addition

With regard to the rate and amount of consolidation settlement, and the void ratio of the samples, the consolidation characteristics of soil were investigated in this research. Furthermore, the swelling behaviour of specimens was studied. Figures 24-31 (presented in Appendix) contain graphs of the void ratio and effective vertical stress in a log scale (e–$\sigma'p$) for sand and fly ash combination with different amounts of fly ash as 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, and 20 %. The data revealed that fly ash stabilisation could improve the consolidation properties or swelling behaviour of the compressibility of the non-stabiliser samples. The compression index (Cc) and swell index (Cs) present the compressibility of soil as illustrated in Table 10 and bar chart 2.

Table 10. Consolidation test data of fly ash treatment (Cc :Compression index, Cs: swelling index, and e0: initial void ratio)

Sample (%)	C_c	C_s	e_0
0 FA	$4.98{*}10e^{-2}$	$3.98{*}10e^{-2}$	0.523
2.5 FA	$4.89{*}10e^{-2}$	$2.12{*}10e^{-2}$	0.490
5 FA	$3.98{*}10e^{-2}$	$2.05{*}10e^{-2}$	0.465
7.5 FA	$3.65{*}10e^{-2}$	$1.92{*}10e^{-2}$	0.439
10 FA	$3.57{*}10e^{-2}$	$1.86{*}10e^{-2}$	0.416
12.5 FA	$3.40{*}10e^{-2}$	$1.72{*}10e^{-2}$	0.389
15 FA	$2.82{*}10e^{-2}$	$1.46{*}10e^{-2}$	0.361
17.5 FA	$2.65{*}10e^{-2}$	$1.19{*}10e^{-2}$	0.340
20 FA	$2.65{*}10e^{-2}$	$1.39{*}10e^{-2}$	0.319



Bar Chart 2. The correlation between fly ash addition and Cc and Cs of soil

The compression curve and swelling curve of soil-stabilised samples with stabiliser reveal that soil characteristics of treated samples demonstrate a diversity of behaviour in each mixture with additives bar chart 2. In general, the compression index was reduced in fly ash treated samples. This decrease showed a continuous trend until a sample with 17.5% of fly ash was examined. After that, the data showed that adding more fly ash to the combination was not effective on the C_c of the samples. The compression index of a sample with 20% of fly ash was fixed in comparison with samples with lesser combinations (i.e., 17.5%).

As shown in bar chart 2,the lowest settlement levels related to the fly ash treated sample with 17.5% and 20% of fly ash. It can be seen from Table 9 that the compression index in the sample with 17.5 percentage of fly ash was $2.65*10e^{-2}$, whilst settlement reduction did not change after adding more than 17.5% of fly ash to sand. Bar chart 2,shows that the Cc, by adding 20% of fly ash was $2.65*10e^{-2}$ again, which is the same as the compression index that was obtained in the previous mixture.

It seems that utilisation of 20 % fly ash had not more effect on reduction of compression index. Moreover, the achieved results on Table 10 illustrate an association between the initial void ratio and the amount of additives. For instance, in Table 10, the sample with 20% of fly ash had the minimum initial void ratio, whilst soil treatment with 2.5% of fly ash had the maximum e_0 of the stabilised samples. This correlation could not be extended to establish a relationship between the amount of additive, e_0 and the C_c of the samples. Nevertheless the effective role of fly ash in the reduction of the compression index of samples was confirmed. Thus, it seems that stabilisations with 17.5% of fly ash and 20% of fly ash had the same effect along with an optimum effect on the compression index of soil.

On the other hand, in the field of swell characteristics of sand, the obtained data about the swelling behaviour of fly ash treated specimens illustrated that fly ash was effective on the swelling index of sand.

Upon initial observation, the tendency of reduction in the swelling index was constant until the final mixture, which was stabilised with 20% of fly ash. As is shown by Table 10, Cs in the sand specimen is $3.98*10e^{-2}$ which is more than the swelling index level in the sand treatment with fly ash. This reaction was similar to the settlement behaviour of stabilised soil after adding 20% fly ash.

As in shown in the graphs, the slope of the unloading period, which illustrated the swelling properties of soil, was reduced by increments in the dosage of fly ash. It seems that by adding more fly ash, up to17.5%, the Cs was $1.19*10e^{-2}$, which had the most significant effect on the swelling index of sand treated with fly ash. Nonetheless, sand stabilisation with more than 17.5% of fly ash led to increments in the swelling index such that the Cs increased to$1.39*10e^{-2}$.

Therefore, the application of fly ash for sand-clay modifying is efficient up to a specific dosage. Fly ash addition of more than 17.5% had a reverse effect on the compressibility of sand-clay composites.

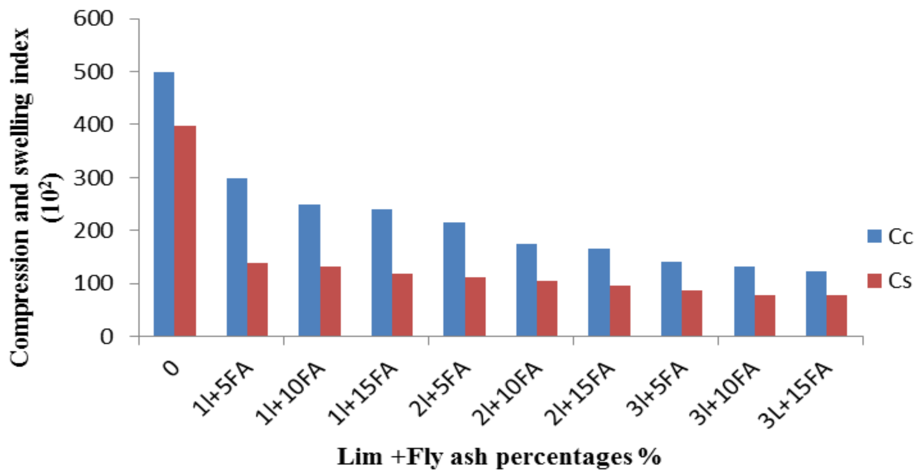
4.3.3.3 Lime-fly ash addition

The compression index (C_c), swell index (C_s) results of lime-fly ash modified specimens is presented in Table 11 and bar chart 3. These are the results of the pure mixture samples and nine lime- fly ash combination specimens used for evaluating the mechanical effects of lime-fly ash mixture on the consolidation and swelling characteristics of pure composite. Overall, lime-fly ash modification lessens the consolidation-swelling behaviour of pure compounds. Moreover, Figures (Appendix 32-40), present individual graphs of the void ratio and effective vertical stress in the log scale ($e\_\sigma'p$) for sand and lime-fly ash composites with a various amount and combination of additives.

Table 11. Consolidation test data of fly ash treatment (Cc :Compression index, Cs: swelling index,)

SAMPLE	C_C	C_S
SAND-CLAY	$4.98{*}10e^{-2}$	$3.98{*}10e^{-2}$
1%L+5%FA	$2.98{*}10e^{-2}$	$1.39{*}10e^{-2}$
1%L+10%FA	$2.49{*}10e^{-2}$	$1.32{*}10e^{-2}$
1%L+15%FA	$2.24{*}10e^{-2}$	$1.19{*}10e^{-2}$
2%L+5%FA	$2.15{*}10e^{-2}$	$1.12{*}10e^{-2}$
2%L+10%FA	$1.74{*}10e^{-2}$	$1.06{*}10e^{-2}$
2%L+15%FA	$1.66{*}10e^{-2}$	$9.96{*}10e^{-3}$
3%L+5%FA	$1.41{*}10e^{-2}$	$8.63{*}10e^{-3}$
3%L+10%FA	$1.32{*}10e^{-2}$	$7.97{*}10e^{-3}$
3%L+15%FA	$1.24{*}10e^{-2}$	$7.97{*}10e^{-3}$

The utilisation of lime-fly ash in sand-clay treatment resulted in improvements in the compression and swelling indices of pure composites.



Bar Chart 3. The correlation between lim-fly ash addition and Cc and Cs of soil

However, this reduction is not a remarkable change compared with the application of either lime or fly ash. By increasing the dosage of additive, the compression index reduced only slightly in contrast with previous stabilised specimens (bar chart 3).

This change however, occurred with the addition of the first combination of lime-fly ash by $2.98*10e^{-2}$ Cc and it continued to a maximum modification in the last mixture of stabiliser by $1.24*10e^{-2}$ Cc.

Simultaneously the same approximate tendency can be observed in the swelling index parameters of sand-clay treated composites. Reduction in the amount of C_s , by increasing the modifier content was initiated by adding 1% lime-5% fly ash. The swelling index of pure composite went down from $3.98*10e^{-2}$ by the addition of the first additive combination and it then reduced continuously until the lowest amount of Cs $7.97*10e^{-3}$ was reached.

This amount was achieved by the addition of 3% lime-10% fly ash and remained constant when adding more stabilisers.

To sum up, although some factors such as curing time, duration and amount of loading and unloading pressure were applied in this test, affecting the compressibility and swelling properties of soil, the achieved results suggested the efficiency of fly ash stabilisation on soil. Hence, the application of additives led to a reduction in the compression index and the swelling index in sand stabilisation. This optimum desired improvement was achieved by the addition of lime, whereas fly ash had only a slight effect on the swelling and consolidation properties of pure composite. In the context of the lime-fly ash combination, according to lime's high capability for improving the composite's compressibility, the compression and swelling indices of the composite slightly improved compared with fly ash treatment. However, this amount was still less than the compressibility result of lime composites.

4.3.4 Direct shear

Generally speaking, friction angle and cohesion serve a pivotal role in the design of various engineering constructions in soil. These parameters are associated with the strength characteristics of the soil. The direct shear test is one of the oldest strength tests used in the laboratory for determining the shear strength of sand.

The achieved shear stress–horizontal displacement curves from the untreated and treated samples are illustrated in Figures 74-90 and Tables 12-13. Overall, maximum shear strength is a key factor in calculating and designing slope stability in roadwork.

The results present the efficiency of lime, fly ash and lime-fly ash mixture on the shear properties of sand. Figures 74-78 present the obtained stress-displacement curves at 50kpa constant normal stress of the samples that were treated with lime, fly ash, and lime-fly ash.

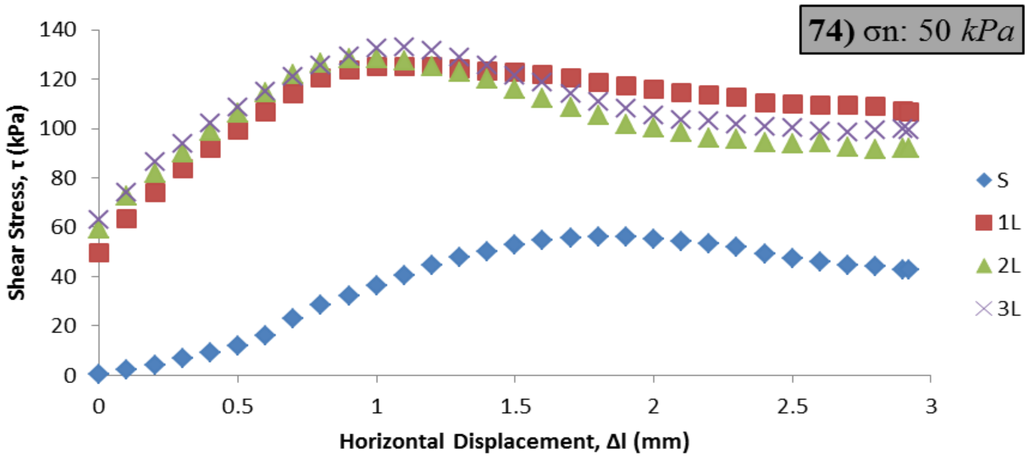


Figure 75. Shear stress–horizontal displacement for pure sand and lime stabilised sand at 50 kpa

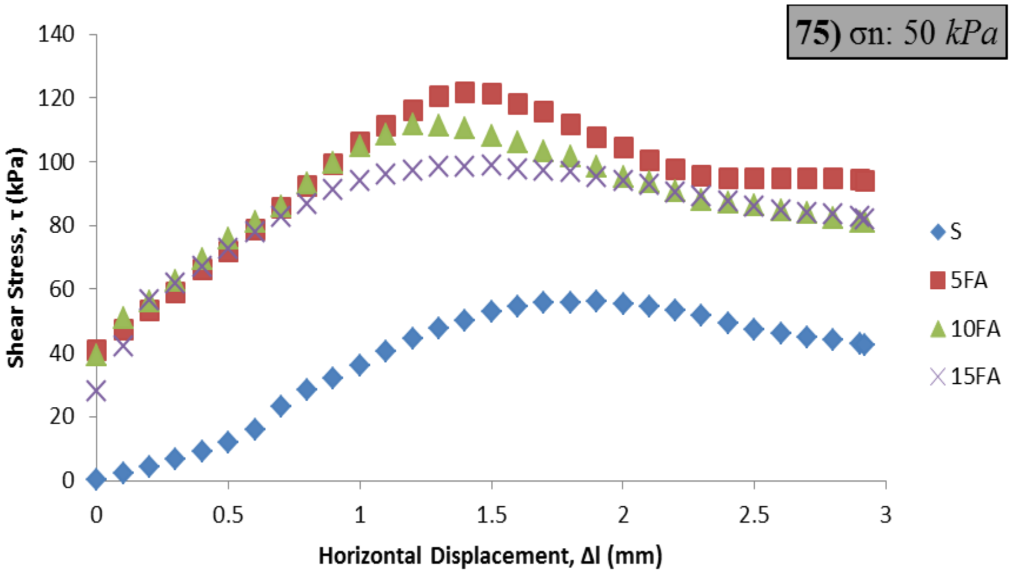


Figure 76. Shear stress–horizontal displacement for pure sand and fly ash stabilised sand at 50 kpa

In the context of either lime or fly ash stabilisation, the initial slope of the shear stress–horizontal displacement curves changed. For the same normal stress in pure sand, the modifier addition to sand led to increments in the initial stiffness of modified samples.

Nevertheless, in contrast with lime, this increment did not have a mutual relationship with the dosage of additive in fly ash. It seems that incrementing the fly ash content has a reverse effect on the shear strength of sand. Thus the best results are achieved by utilisation of 3% lime, with the shear failure occurring at 133kpa shear stress.

As shown in Figures 76-78, at 50kpa vertical load, the combination of 1% lime with 5% fly ash was more effective than in other mixtures.

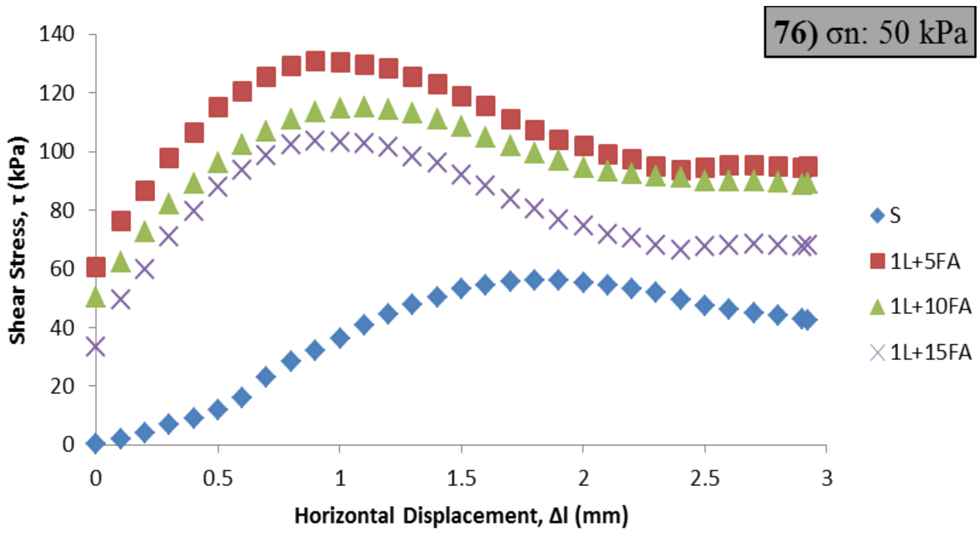


Figure 77. Shear stress–horizontal displacement of stabilised sand with 1% lime and different fly ash content at 50 kpa

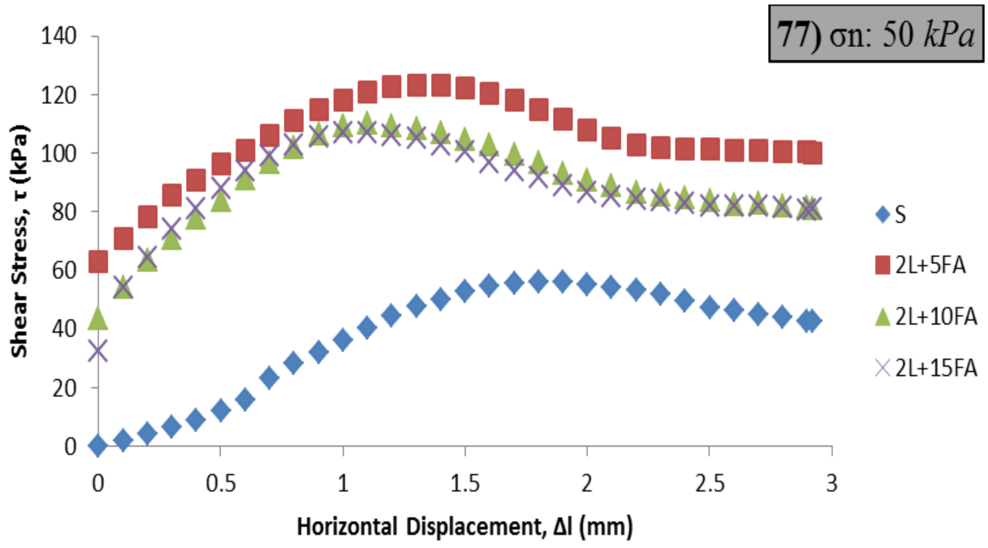


Figure 78. Shear stress–horizontal displacement of stabilised sand with 2% lime and different fly ash content at 50 kpa

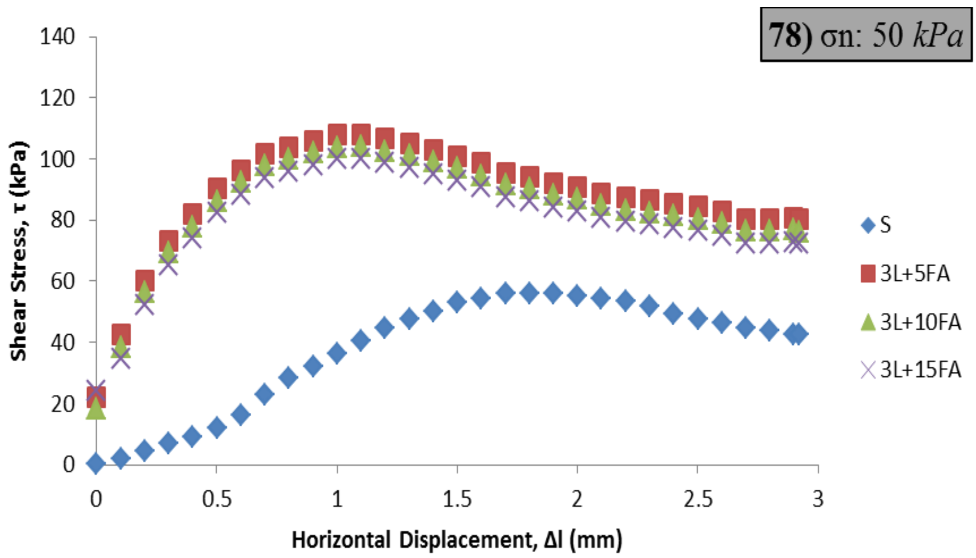


Figure 79. Shear stress–horizontal displacement of stabilised sand with 3% lime and different fly ash content at 50 kpa

However, adding the fly ash to 1% lime caused the shear peak to go down and the optimum result related to failure at 131kpa shear stress which was ascribed to sand treatment with 1% lime-5% fly ash. Moreover, the initial slope of the shear stress–horizontal displacement curves had the same tendency with maximum shear failure. The entire three components with 3% lime had roughly similar initial stiffness and of a lesser amount than the other lime-fly ash combinations.

Figures 79-83 illustrate the stress-displacement results at 100kpa constant normal stress for all specimens.

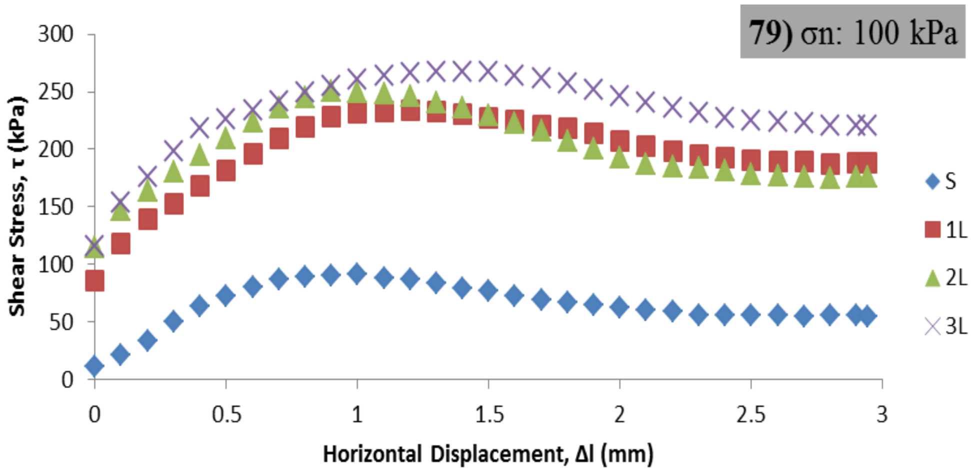


Figure 80. Shear stress–horizontal displacement for pure sand and lime stabilised sand at 100 kpa

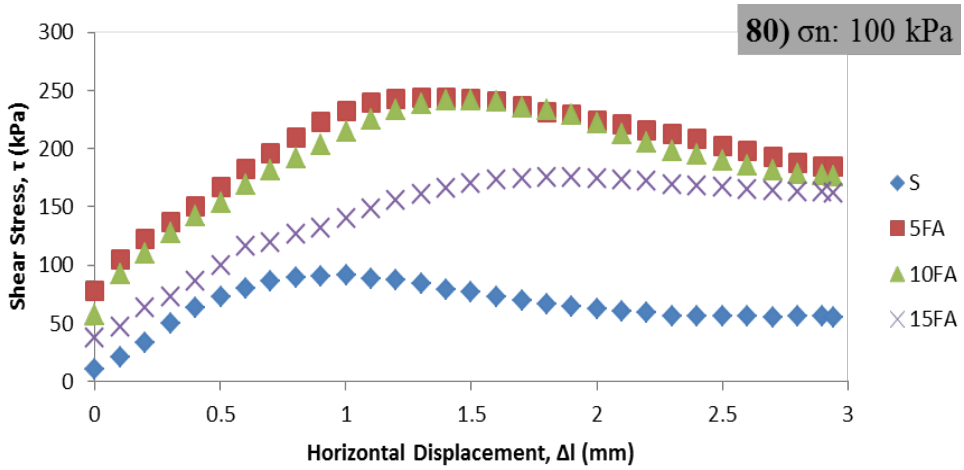


Figure 81. Shear stress–horizontal displacement for pure sand and fly ash stabilised sand at 100 kpa

At 100kpa normal stress, a similar tendency in the shear failure behaviour of treated specimens can be observed, with the shear failure occurring at a greater displacement. Similar behaviour was observed in the incremental amounts of shear failure in sand treated samples with normal stress at 50kpa. Moreover, lime was more efficient than fly ash for sand strength modification, while fly ash content increments had a reverse effect. However, some positive change occurred with an increase in vertical pressure. The horizontal displacements of modified samples at the peak of shear stress were significantly increased and failure occurred after further displacement (Figures 79, 80).

Figures 81-83 illustrate the direct shear results at an application of 100kpa normal stress, on various combinations of lime and fly ash content. In general, notable progress was observed in the strength behaviour of sand after stabilisation. The horizontal failures improved as with previous vertical loading (i.e., 50kpa) and were mobilised to create greater displacement.

However, the achieved results confirmed the previous hypothesis regarding a correlation between the dosage of additives and the amount of shear failure.

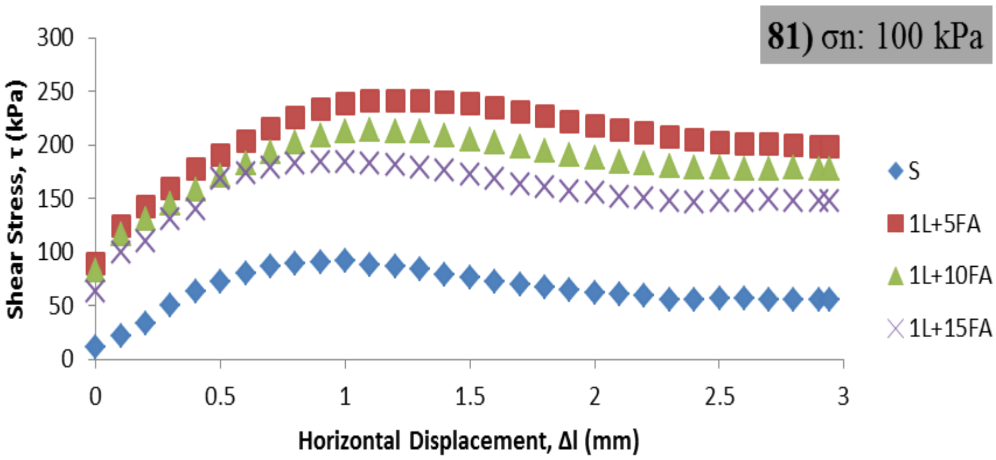


Figure 82. Shear stress–horizontal displacement of stabilised sand with 1% lime and different fly ash content at 100 kpa

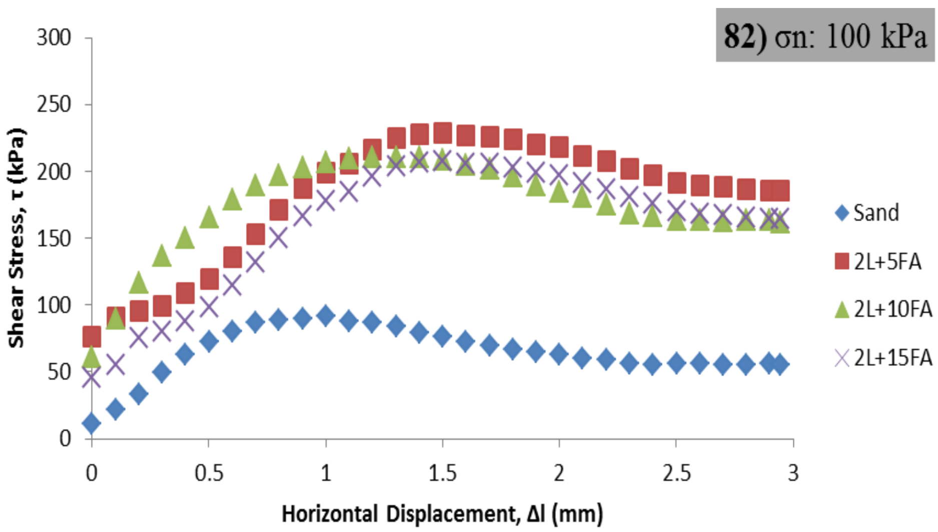


Figure 83. Shear stress–horizontal displacement of stabilised sand with 2% lime and different fly ash content at 100 kpa

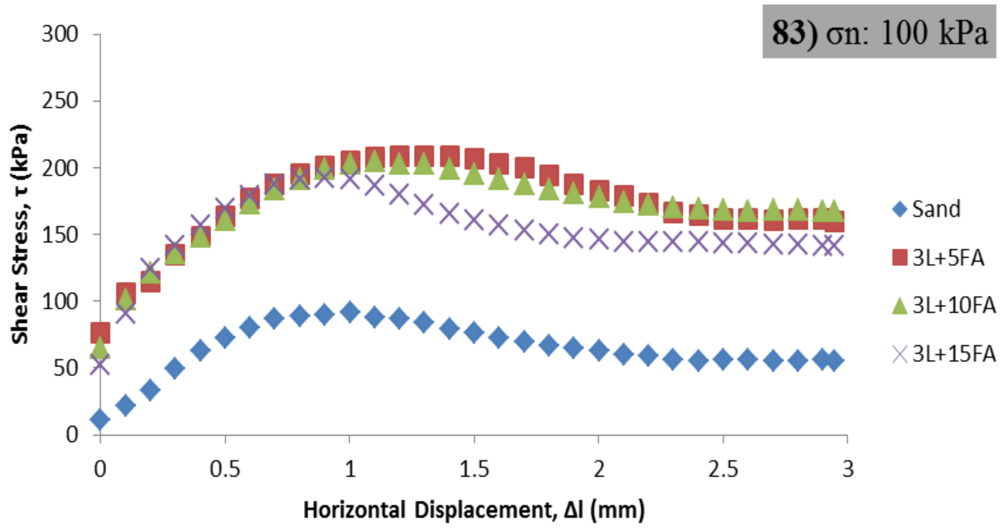


Figure 84. Shear stress–horizontal displacement of stabilised sand with 3% lime and different fly ash content at 100 kp

On the other hand, with the application of 200kpa normal stress, the shear stress of stabilised samples keeps their progressive behaviour in terms of maximum shear failure and failure displacement. The horizontal failures improved as with the previous vertical loadings (i.e.50kpa, 100kpa) and were mobilised after 1.5*mm*.

Figures 84-88 illustrate the stress-displacement results at 200 kpa constant normal stress for untreated and treated specimens.

Overall, soil strength performance is improved due to lime, fly ash, and lime-fly ash modification.

In comparing investigations into either lime or fly ash efficiency, with the same behaviour as in the two previous vertical pressure instances, lime was found to be more effective than fly ash in increasing the sand's workability (Figures 84, 85). In lime composites, shear failure occurred with higher shear stress and lower displacement occurring simultaneously, which illustrates the behaviour of fine grained materials.

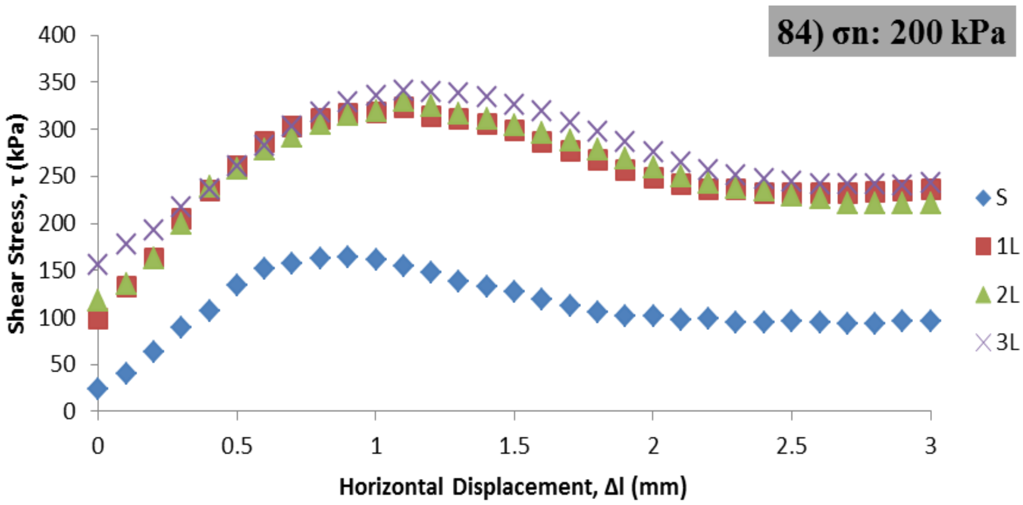


Figure 85. Shear stress–horizontal displacement for pure sand and lime stabilised sand at 200 kpa

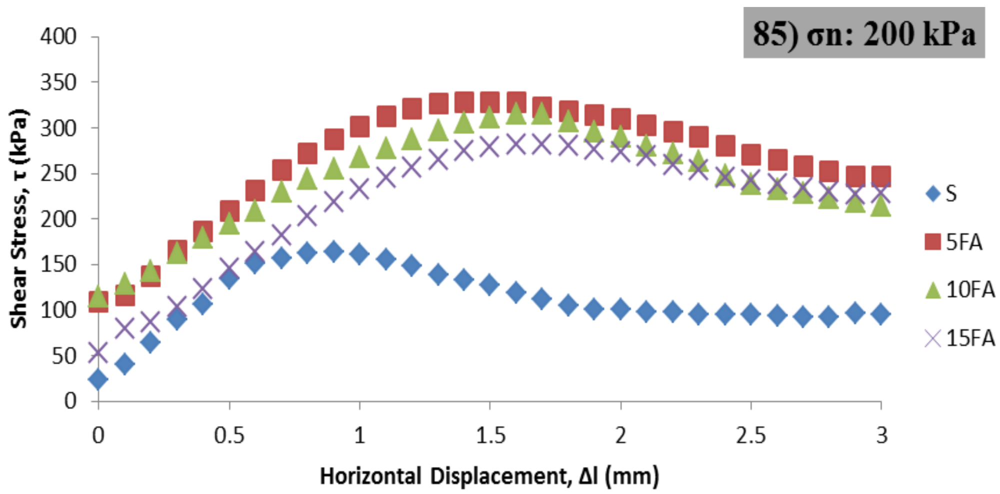


Figure 86. Shear stress–horizontal displacement for pure sand and fly ash stabilised sand at 200 kpa

Investigation into lime-fly ash's efficiency on sand reinforcement is shown in Figures 86-88. To some extent, the results of lime-fly ash modification differed to the two previous vertical loads, and the best result was achieved, when the sand was modified with 2% lime and three different percentage of fly ash. At 50kpa and 100kpa normal stress this occurred only when 2% lime and 15% fly ash were added. However, in the context of additive content, the behaviour of stabilised sand did not change in contrast with other normal loadings. The lowest amount of shear strength was achieved by the application of 3% lime and differing fly ash dosages.

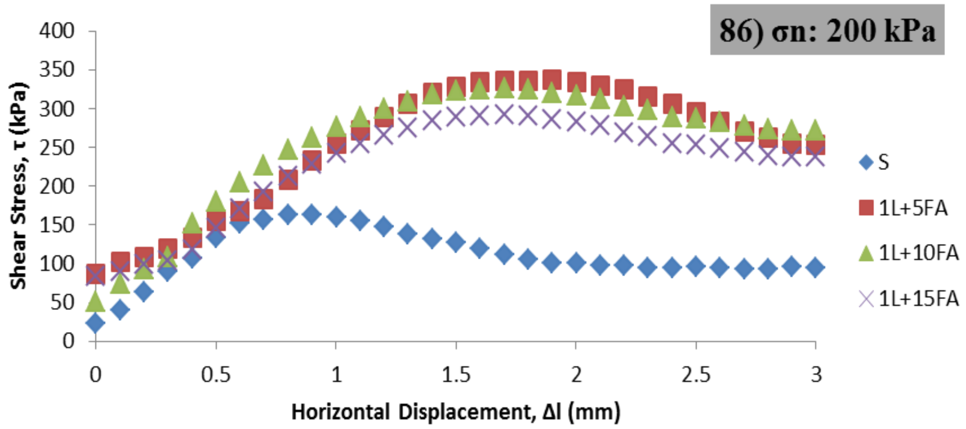


Figure 87. Shear stress–horizontal displacement of stabilised sand with 1% lime and different fly ash content at 200 kpa

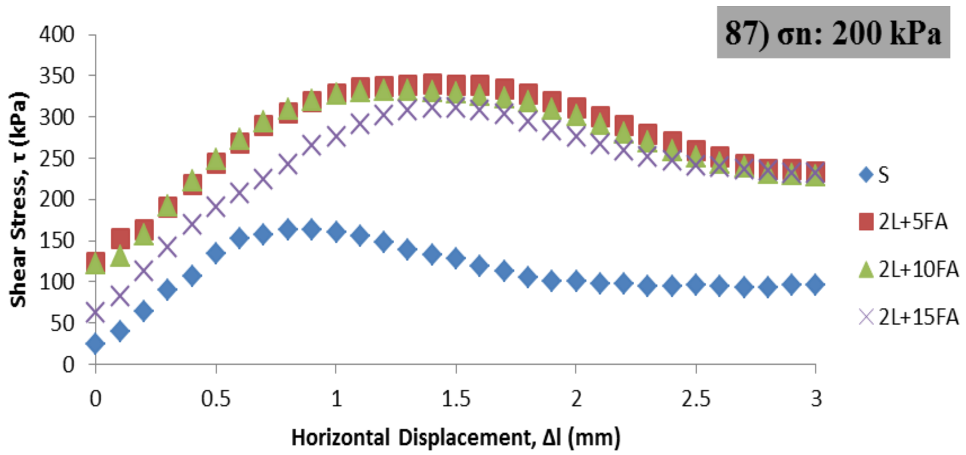


Figure 88. Shear stress–horizontal displacement of stabilised sand with 2% lime and different fly ash content at 200 Kpa

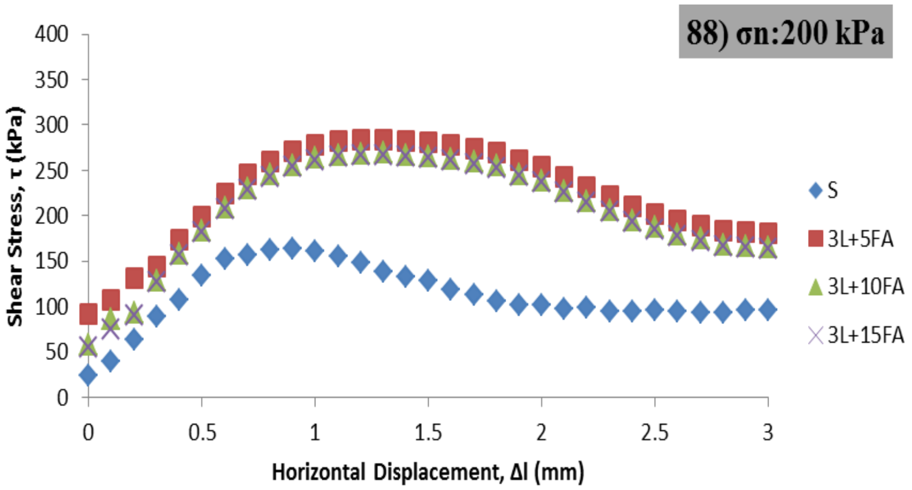


Figure 89. Shear stress–horizontal displacement of stabilised sand with 3% lime and different fly ash content at 200 kpa

The values of normal stress (σ_n) and shear stress (τ) at the failure point of each samples are presented in Table 12. Investigation into the shear stress–horizontal displacement of each normal stress and the results in Table 12 may help to better understand the effects of lime, fly ash, and lime-fly ash on the strength properties of sand.

Hence, the application of both lime and fly ash in sand treatment leads to an increase in the sand's shear stress. However, the lower amount of lime-fly ash mixture was more efficient than other lime-fly ash combinations. By adding lime, the shear stress showed a significant improvement in contrast with unstabilised sand.

Table 12. The shear stress results of treated and untreated samples at different vertical loads

	SHEAR STRESS (*kpa*)															
	Sand	1L	2L	3L	5FA	10FA	15FA	1L+5FA	1L+10FA	1L+15FA	2L+5FA	2L+10FA	2L+15FA	3L+5FA	3L+10FA	3L+15FA
NORMAL STRESS 50*kpa*	56	125	128	133	122	112	99	131	115	104	123	110	107	108	104	100
NORMAL STRESS 100*kpa*	91	234	250	267	243	242	176	241	214	184	228	211	207	209	204	192
NORMAL STRESS 200*kpa*	163	323	330	341	328	315	282	336	326	292	340	333	311	284	269	267

On the other hand, in the fly ash treatment, the optimum improvement in sand's strength property was obtained by the addition of 5% fly ash. Adding more fly ash had a reverse effect, although all the fly ash treated samples were more resistant than pure sand samples.

The progressive result for the shear stress of lime-fly ash modified sand can be seen in Table 12. Increasing the dosage of additives had a significant effect on sand reinforcement, but this behaviour deteriorated, when the proportion of fly ash was significantly more than the lime content.

The effects of lime, fly ash and their mixtures on the shear characteristics, dilatancy, cohesion and friction angle on the sand are shown in Figure 89 and in Table 13. Figure 89 presents the shear stress tendency of untreated samples and tread specimens with different vertical loads. It can be clearly seen that the highest result is associated with the application of three per cent lime for sand stabilisation.

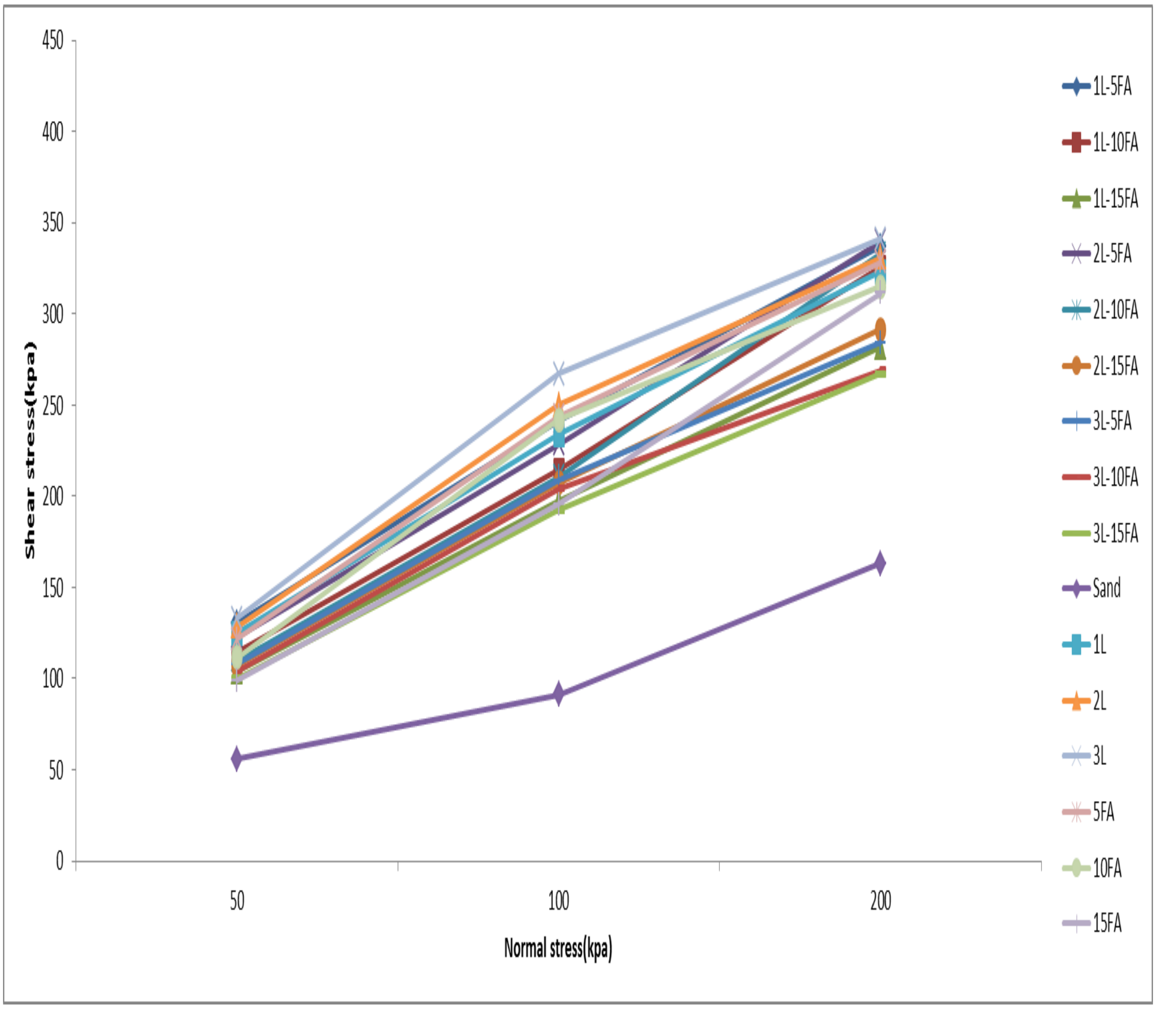


Figure 90. Sand composite's shear stress produced under different normal stress

Table 13illustrates the dilatancy, cohesion and friction angle of sand and 16 modified specimens. From the results it can be seen that the friction angle is increased by the addition of stabilisers. In general, the range of change of the friction angle is the same in the stabilised samples. The maximum increase occurred with the addition of 2% lime-10% fly ash. In the context of stabiliser content, the results show an approximation of the reverse relation between the amount of additive and the degree of friction angle.

The lime had a significant effect in enhancing sand cohesion. By increasing the lime content the composite cohesion was increased. At the same time, the addition of fly ash had a reverse effect and a reduction in sand cohesion was noted.

Table 13. The direct shear result of stabilised and unstabilised samples (*Φ: Friction angle, α:Dilatancy angle, C: Cohesion)*

Sample	*Φ (◦)*	*α(◦)*	*C(kpa)*
Sand	43.2	11.7	0
1Lime	52	5.9	29.1
2Lime	53	8.7	34.2
3Lime	54	6.4	39.1
5Fly ash	54	6.6	24.7
10Fly ash	53	8.4	19.4
15Fly ash	54.9	6	10.5
1Lime+5Fly ash	53.9	6.2	30.1
1Lime+10Fly ash	54.5	5	7.5
1Lime+15Fly ash	49.8	7.5	16.3
2Lime+5Fly ash	55.3	6.4	13.6
2Lime+10Fly ash	56	7.9	5.1
2Lime+15Fly ash	45.5	6.2	17.2
3Lime+5Fly ash	49.5	13.1	24.3
3Lime+10Fly ash	49.2	8.8	27.5
3Lime+15Fly ash	44.5	9.9	19.5

The lime-fly ash combination improved the sand cohesion generally. However, a specific correlation among the dosage of additive and sand cohesion was not found. Overall, the modifier resulted in a reduction in the dilatancy angle, creating a dense specimen. Although high in the amount of additives, dilatancy tendency seems has a reverse effect.

To sum up, sand stabilisation leads to improved soil workability and strength. The application of lime, fly ash and the lime-fly ash combination resulted in improvements to the shear failure point, increments in the friction angle and soil cohesion. For sand treatment, lime utilisation is more effective than both fly ash and lime-fly ash applications. However, the additive content plays a pivotal role in improving the soil performance. The higher the amount, the more the result changed and had a reverse effect.

CHAPTER5

SUMMARY & CONCLUSION

5.0 Summary & Conclusion

This section consists of a summary of the previous chapters, which is presented in seven separated subsections;

- A summary of soil stabilisation and applied methodology
- A summary of standard compaction results
- A summary of hydraulic conductivity results
- A summary of one-dimensional consolidation results
- A summary of direct shear results
- A summary of microanalytical results
- Recommendation

5.1 A summary of soil stabilisation and applied methodology

In 1904, the process of soil stabilisation was introduced in the USA as a cost-effective and “environmentally-friendly” technique. Chemical stabilisation of soil is carried out by adding stabilisers to the soil thereby joining soil particles together to fulfil the main objective of developing the geotechnical performance of land (Castro-Fresno et al., 2011, McCarthy et al., 2012). The unwanted mechanical and chemical properties of soil can be improved by adding binder or byproducts like cement, lime, fly ash and bottom ash to soil (Harichane et al., 2012, Senol, 2006).

In this area, lime and fly ash stabilisation lead to improvements in soil compactibility, permeability, compressibility and shear strength via a series of chemical, mineralogical and microstructural changes in the original characteristics of the soil. The use of lime/fly ash allows cation exchange, flocculation, agglomeration and pozzolanic interactions, leading to an increase in the size of soil particles. There are limitations to the various investigations conducted into some aspects of lime/fly ash stabilisation, along with a diversity of data. However, due to the popularity of this method in Western of Australia this study attempted to improve the method by presenting a novel and accurate study on the application of lime, fly ash, and lime-fly ash mixture in sand stabilisation. The purpose of the research was to create a connection between chemical examination and geotechnical laboratory research.

In order to systematically and accurately study the shear strength, compaction properties, compressibility and hydraulic conductivity of composite samples, this research was carried out in three different stages. The first stage was to examine the geotechnical and mechanical effects of additives on sand by a series of standard compaction, hydraulic conductivity, consolidation and small direct shear tests. Results were then accurately examined form a microstructural point of view, through optical microscopy and scanning electron microscopy analysis. Eventually, the elemental analysis and chemical characterisation were confirmed by EDS; mineralogical phases were determined by XRD, and changes in chemical composition by FTIR.

Despite the probable limitations in the laboratory tests, the following conclusion can be drawn from the experimental and microanalytical results of as numerous numbers of specimens, which are separated based on the materials (i.e., Sand, clay, lime, fly ash lime-fly ash combination).

5.2 A summary of standard compaction results

The results indicate that the compaction properties of all stabilised specimens improved in contrast with pure sand. Investigation into the maximum dry density and moisture content of stabilised samples with lime/fly ash has revealed the efficiency of fly ash in increasing the MDD, and the ability of lime to increase the OMC of sand. In addition, the laboratory compaction tests have shown the mixture of lime-fly ash to have an optimum effect on sand compaction. Further investigations revealed that this improvement was due to a combination of the material characteristics of lime and fly ash. The highest increment of maximum dry density related to the combination of 3% lime-15% fly ash samples.

In general, utilisation of additive increased the optimum moisture content of sand and this was associated with the stabiliser increments. Based on the obtained results, the increase in the moisture content of the samples after lime stabilisation was greater than in the sand treatment with fly ash and lime-fly ash. Although the increase in lime caused the optimum moisture content to decrease in the lime-treated sand, the decrement of moisture content in sand stabilised with fly ash was more noticeable than that found in the lime specimens.

5.3 A summary of hydraulic conductivity results

A series of hydraulic conductivity tests was performed on 16 sand specimens with varying amounts of lime, fly ash, and lime-fly ash. The dry density, moisture content and dry weight of sand samples were defined based on the standard proctor compaction test results. This study demonstrated that lime and fly ash treatment could reduce the hydraulic conductivity of sand. Investigation into lime, fly ash and lime-fly ash specimens indicated that a combination of lime and fly ash has the most significant effect on sand, out of all the other samples. The lime-fly ash stabiliser had produced a 180-fold reduction in sand's permeability. However, the hydraulic conductivity of sand was decreased 65 times (by fly ash) and 7 times (by lime).

Therefore, the combination of lime and fly ash could be more effective than the use of just one additive alone (i.e., lime or fly ash) in sand stabilisation. In addition, it seems that equivalent increases in the ratio of lime and fly ash may lead to an effective reduction in the hydraulic conductivity of sand.

The efficiency of lime and fly ash has been confirmed with regard to the hydraulic conductivity of sand. The reduction in the hydraulic conductivity of sand-stabilised specimens with fly ash was greater than it was with the lime treatment.

On the other hand, the obtained results revealed that the specimens with the maximum amount of dry density had a maximum reduction in hydraulic conductivity (i.e., the specimen with the combination of 3% lime and 15% fly ash). Furthermore, the hydraulic conductivity of other specimens with high dry density decreased noticeably. However, a direct and logical relationship could not be found between the dry density measurement and the hydraulic conductivity levels found in the sand.

It therefore appears that applying lime or fly ash or a combination of lime-fly ash to an earthen structure in permanent contact with water, such as dams, river levees and canals would be effective for improving the quality of structures.

5.4 A summary of one-dimensional consolidation results

Based on experimental research on seven specimens, divided into unstabilised samples (i.e., 0% lime) and lime stabilised samples (i.e., 0.5%, 1%, 1.5%,2%, 2.5%, and 3%) this study presents the laboratory investigation results of the consolidation and swelling properties of sand. The results indicate that the compressibility of all stabilised specimens improved in contrast with pure sand. All stabilised specimens were monitored to determine the effective role of lime in reducing the compression index of samples through the pozzolanic reaction occurring between the lime and the soil particles. The achieved results produced a compression index of between $4.98{*}10e^{-2}$ and $9.96{*}10e^{-3}$for the samples.

With regard to the relationship between the amount of lime and the compression index, it seems that more lime leads to a correlation between the reductions of the initial void ratio. The reduction of Cc occurred in all specimens. Investigations into the swelling properties of lime treated samples revealed a wide variation of results for the swelling index characteristics of the lime-treated sand. The obtained swelling index was in the range of $3.98{*}10e^{-2}$_ $5.81{*}10e^{-3}$.

Increases in the amount of additive were related to a reduction in the swelling index. The results illustrate that the addition of 0.5% lime to a pure specimen led to a reduction in the swelling index of a non-stabilised sample. Furthermore, stabilisation with more than 2% of lime had a remarkable effect on the Cs. The lowest amount related to samples with 3% lime. The initial void ratio in each combination reduced with increases in the amount of lime. The soil treatment with 3% lime had the least (minimum) initial void of all the mixtures.

The application of fly ash experimental research was conducted on nine samples, which were divided into unstabilised specimens (i.e., 0% fly ash) and fly ash stabilised combinations (i.e., 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5% and 20%). This research presents the results and conclusions of the laboratory investigation data regarding the consolidation and swelling properties of sand.

The results indicate that in contrast with pure sand, the compressibility of all stabilised specimens was developed. In all stabilised samples it was observed that fly ash plays a pivotal role in reducing the compression index of each sample, which could be due to the pozzolanic reaction between the fly ash and the soil particles.

It can be seen that increases in the dosage of fly ash related to decrements in the compression index of stabilised samples. However, it seems that utilisation of more than 17.5% fly ash in stabilised samples did not have a marked effect on the compression index in that it was the same as the compression index of the pervious mixture (i.e., 17.5%).

Study on the swelling properties of fly ash stabilised samples indicated a variation in the results for the swelling index characteristics of sand treated with fly ash. Overall, the results reported a downward tendency in the swelling index data of fly ash specimens. The lowest amount related to samples with 17.5% fly ash. Utilisation of 20% fly ash led to increments in the Cs of the specimen.

The initial void ratio of each combination was reduced with increases in the percentages of fly ash. A relationship was also observed between reductions in the compression index of samples, increments in the dosage of additives, and reduction of the initial void ratio, although this correlation changed for soil stabilised with 20% fly ash.

The data therefore suggests that fly ash could improve the compressibility and swelling properties of soil. Despite the various results of Cc and Cs in fly ash stabilised samples, one can draw a relationship between the ratio of increments in the amount of stabiliser and decrements in the soil compression index and swelling index. However, regarding the environmentally-friendly, cost-effective, and engineering property aspects, comparisons between the results of fly ash specimens show that soil stabilisation with 17.5% of fly ash is more efficient than other dosages of additives tested in this research.

In the context of the lime-fly ash application, regarding lime's ability to improve the composite's compressibility, the compression and swelling indices of the composite were slightly improved in contrast to fly ash stabilisation alone. Nevertheless, this amount is still less than the compressibility result of the lime mixtures.

5.5 A summary of direct shear results

On the other hand, based on the direct shear test results, the lime application was more effective than the fly ash treatment with regard to sand reinforcement. The utilisation of lime produced an upward trend in the shear stress amount at the failure point; the optimum effect was achieved by the addition of 3% lime. The polygonal structure of lime caused the generation of a reticular area in the lime composite. The creation of different sized particles led to increments in the composite's resistance. It was happening due to collect the particles with different structures.

In contrast to the lime, fly ash produced a different effect on the strength properties of sand which was efficient up to a particular point/specific dosage. The optimum effect of sand-stabilised fly ash occurred with 5% fly ash. However, for other percentages of fly ash, the failure point of composites showed a significant difference compared with pure sand. The cohesion ability and spherical structure of fly ash associated with sand particles caused the establishment of an area consisting of particles with the same structures as each other. Increments in the fly ash content caused the creation of a more globular particle; this particle showed the least resistance to the shear stress.

Further experimental tests on the lime-fly ash combinations showed some improvements in sand strength. However, by incrementing the content of additives, especially fly ash, this improvement was reduced. In fact, a reverse correlation occurred between the additive content and the shear stress properties of the sand.

The friction angle and cohesion characteristics of modified specimens were improved generally, as with the dilatancy properties of sand treated samples.

5.6 A summary of microanalytical results

Another factor that serves a pivotal role in sand treatment is the creation of the chemical components which led to improvements in the sand's compactibility and strength parameters. Further investigation into the effectiveness of additives on sand composites from a chemical viewpoint was conducted by X-ray diffraction. This explored the changes in the crystallinity of samples due to chemical interactions between the sand and the stabilisers. The XRD results confirmed the previous results, showing a minor shift in the position of the reflection peak by a lower 2θ

angle of a sand-stabilised sample. The XRD results also reveal the role of additive particles in generating chemical components. These created pozzolanic interactions, flocculation agglomerations, and finally, the polymerisation process which produced improved sand strength and compaction properties. Hence, the microscopic data and laboratory results confirmed the efficiency of lime and fly ash for modifying the compaction and strength characteristic of sand.

Based on the SEM micrographs, the calcium compound was produced by the inclusion of lime. The increments in the calcium compound caused an increase in the strength of the modified composite. From the SEM investigation, the creation of aluminosilicate components as the result of the application of hydrated lime and fly ash led to the establishment of a pozzolanic reaction, thereby forming a denser microstructure of the lime/fly ash-treated compound. The chance of a pozzolanic reaction increased due to incrementing the proportion of chemical elements in the composites and this was confirmed by the EDS results. Increases in the ratios of calcium (Ca), oxygen (O), silicon (Si), aluminium (Al), iron (Fe), and magnesium (Mg) in the lime/fly ash-modified mixture were directly associated with the adhesion of a greater number of soil atoms, and in this way a more uniform area was created between the micro-particles of the atoms in the composite.

The XRD revealed the existence of some key chemical compounds such as Aragonite and Calcite [$CaCO_3$], Periclase [MgO], Portlandite [Ca(OH)], Quartz [SiO_2], Diaspore [AlO(OH)], Magnetite [Fe_3O_4], Microcline, intermediate [$K(AlSi_3O_8)$], and Ettringite [$3CaO\text{-}Al_2O_3\text{-}3CaSO_4\text{-}32H_2O$]. The results confirmed that the specific mineral characteristics of lime and fly ash could lead to an interaction between the calcium and the composite's materials, along with the generation of calcium silicate and aluminium silicate hydrates as a part of the pozzolanic effect. Furthermore, the X-ray diffraction results demonstrated an improvement in the crystalline phase of stabilised specimens by a minor change in the position of 2θ angles to a lower degree.

Infrared spectroscopy technique results for the materials analysis of the presence of lime composite showed an increase in the formation of C–S–H, C–A–S–H gels. The existence of Quartz and some organic matter was identified by FTIR analysis. The main characteristic spectrums were represented at 3689, 3619, 1113, 1024, 911, and 788 cm^{-1}, and these were assigned to the O-H vibration, Si–O stretching vibration of C–S–H, and Al–OH group that showed OH deformation due to the presence of amorphous aluminosilicate. Moreover, the Ca-O-H group vibration was assigned 3642 cm^{-1}, the calcite was 1461 cm^{-1}, and Si-O was associated with a 1004 cm^{-1} peak, identified by the IR spectrum. It is evident from the investigation into the IR spectra, that the interaction among the lime or fly ash and composite's atoms might not create a massive change in the structure of the pure composite. However, a minor improvement in the position of the chemical bonds of the lime/fly ash treated mixture was achieved, when compared with the untreated compound. This confirms the efficiency of the effect of lime, fly ash and lime-fly ash on the chemical behaviour of lime composites that was previously identified by SEM, EDS, and XRD analysis.

5.7 Recommendation

The utilisation of chemical stabilisation as an economical and environmental friendly technique will be continued in geotechnical projects. The understanding of main chemical components of stabilisers using for improving the soil's geotechnical performance could be reduced the financial aspects and probable environmental side effects of construction projects.

This research study recommends that the application of geo-chemical/elemental examinations could provide the appropriate data about morphological, mineralogical, elemental, and chemical characteristics of soil and additives, thereby utilisation a more applicable modifier in soil treatment.

This research also suggests consideration to some other aspects including the importance of scale effect in soil's strength characteristic or the applied effort in compaction test, which are play main role in mechanical properties of soil, in the further studies. Moreover, the application of different types of soil and additives could be collected a more comprehensive and reliable results.

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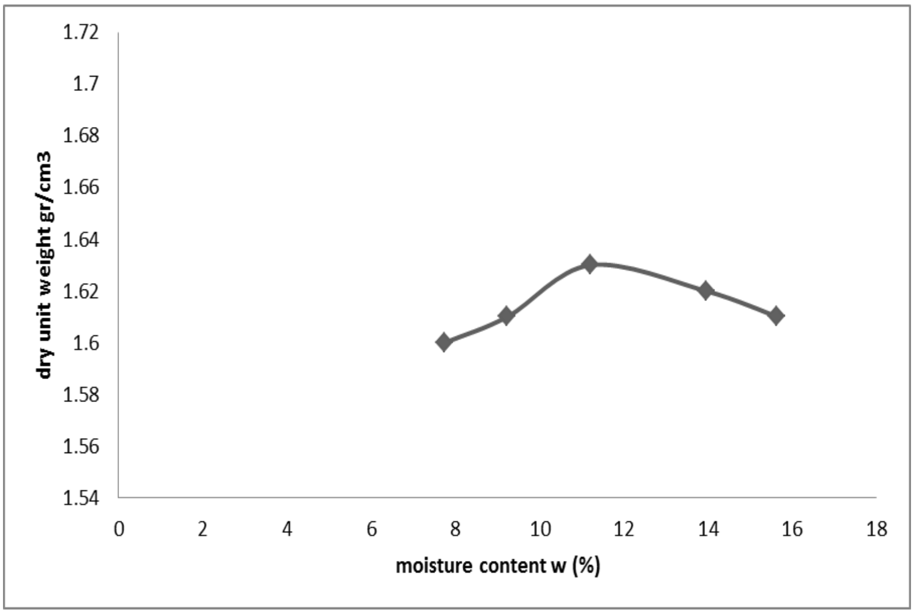
Appendix

Compaction results

Sand

Appendix 1. Pure sand

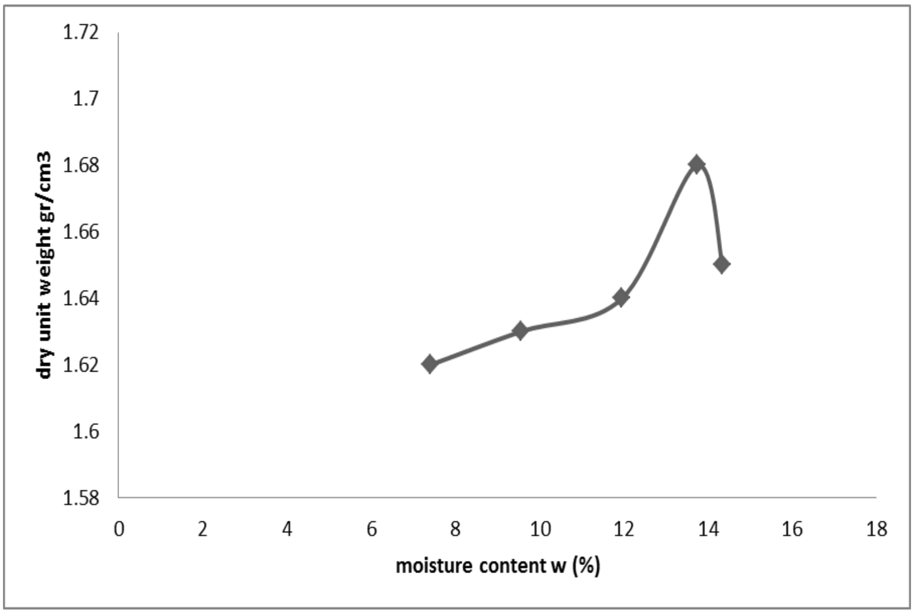
Assumed water content %.	%8	%10	%12	%14	%16
W2	6268	6303	6358	6387	6404
W3	22.4	22.8	23.24	22.97	23.1
W4	98.87	106.71	97.18	117.73	107.75
W5	93.37	99.62	89.73	106.73	96.3
w (%)	7.74	9.23	11.2	13.94	15.64
γ_d	1.6	1.61	1.63	1.62	1.61



Lime treated samples

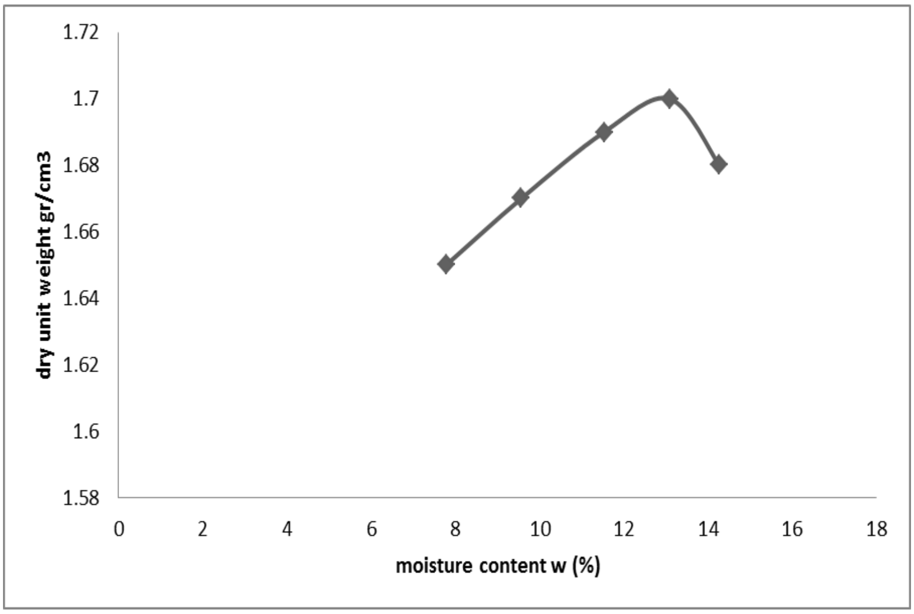
Appendix 2. 1% lime content

Assumed water content %.	%8	%10	%12	%14	%16
W2	6285	6330	6380	6455	6445
W3	23.2	22.26	23.4	22.4	23.78
W4	78.3	63.76	94.55	89.85	89.79
W5	74.5	60.15	86.95	81.70	81.51
w (%)	7.4	9.55	11.95	13.74	14.34
γ_d	1.62	1.63	1.64	1.68	1.65



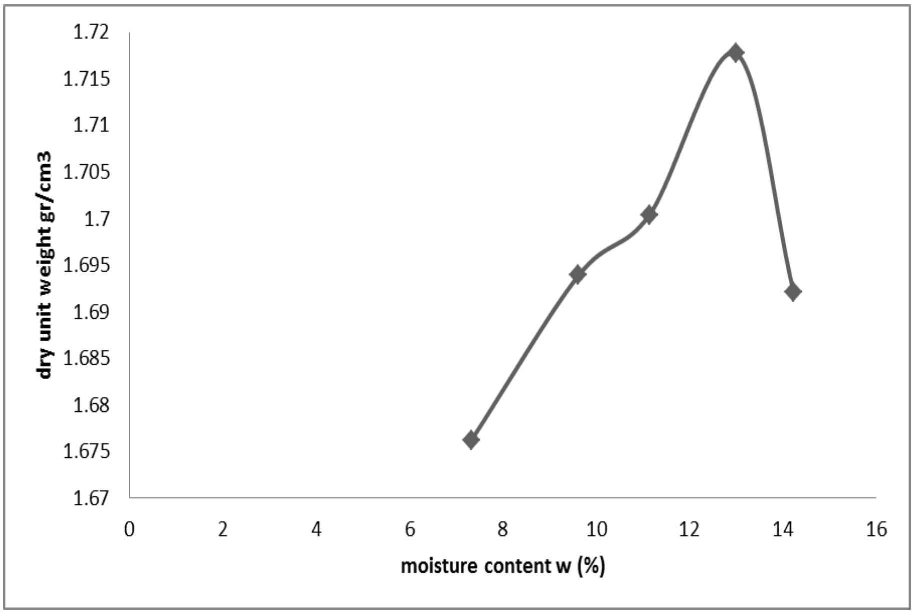
Appendix 3. 2% lime content

Assumed water content %.	%8	%10	%12	%14	%16
W2	6328	6375	6424	6464	6462
W3	23.2	23	23.1	23.8	23
W4	69.5	88.43	94	94.74	78.74
W5	66.16	82.72	86.67	86.53	71.78
w (%)	7.77	9.56	11.53	13.08	14.26
γ_d	1.65	1.67	1.69	1.7	1.68



Appendix 4. 3% lime content

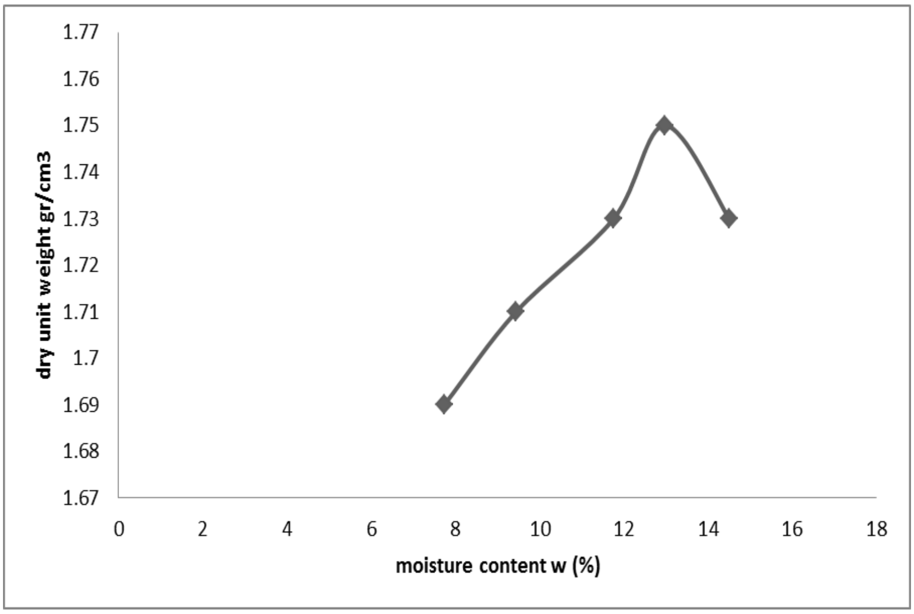
Assumed water content %.	%8	%10	%12	%14	%16
W2	6338	6396	6429	6480	6472
W3	23.2	23	23.1	23.8	23
W4	86.5	98.85	128.81	103.8	99.43
W5	81.9	92.19	118.21	94.6	89.75
w (%)	7.3253	9.6256	11.1449	12.9943	14.2322
γ_d	1.6762	1.6939	1.7004	1.7177	1.6921



Fly ash treated samples

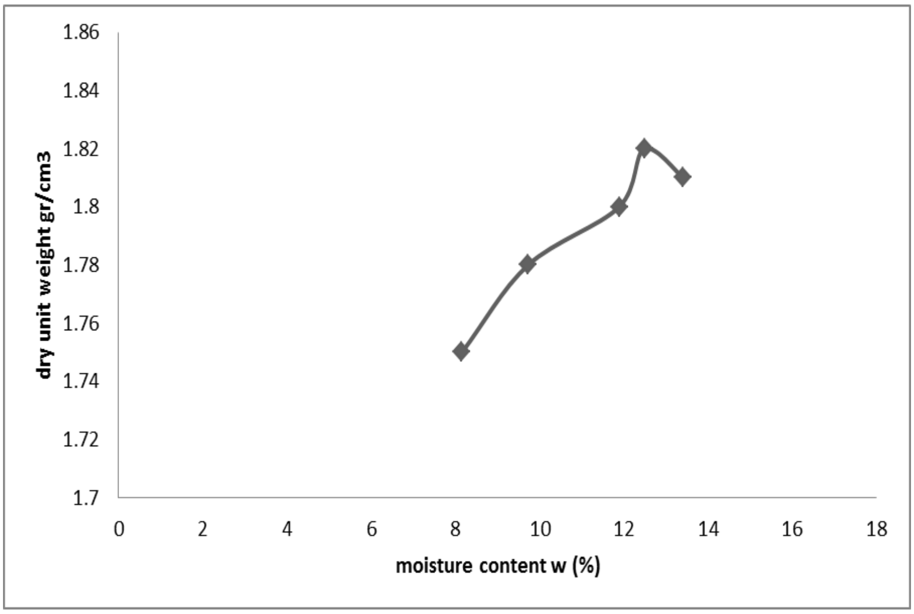
Appendix 5. 5% fly ash content

Assumed water content %.	%8	%10	%12	%14	%16
W2	6368	6418	6473	6522	6525
W3	23.2	22.36	23.4	22.4	23.78
W4	92.29	71.65	86.88	100.86	97.12
W5	87.33	67.4	80.2	91.84	87.83
w (%)	7.73	9.44	11.76	12.98	14.5
γ_d	1.69	1.71	1.73	1.75	1.73



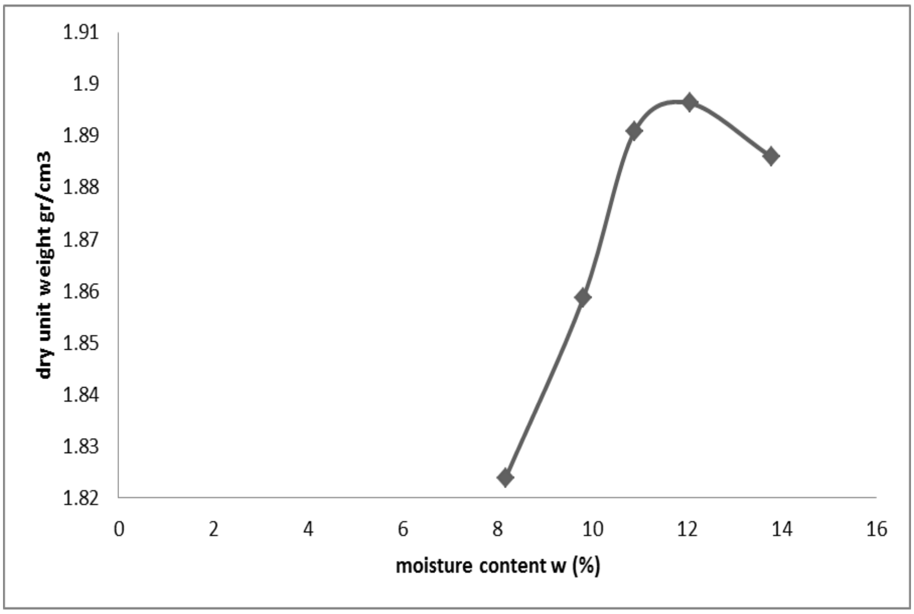
Appendix 6. 10% fly ash content

Assumed water content %.	%8	%10	%12	%14	%16
W2	6440	6494	6559	6597	6600
W3	23.2	22.36	23.4	22.4	23.78
W4	85.56	78.23	96.81	108.5	104.73
W5	80.86	73.28	89.01	98.94	95.16
w (%)	8.15	9.72	11.88	12.49	13.4
γ_d	1.75	1.78	1.8	1.82	1.81



Appendix 7. 15% fly ash continent

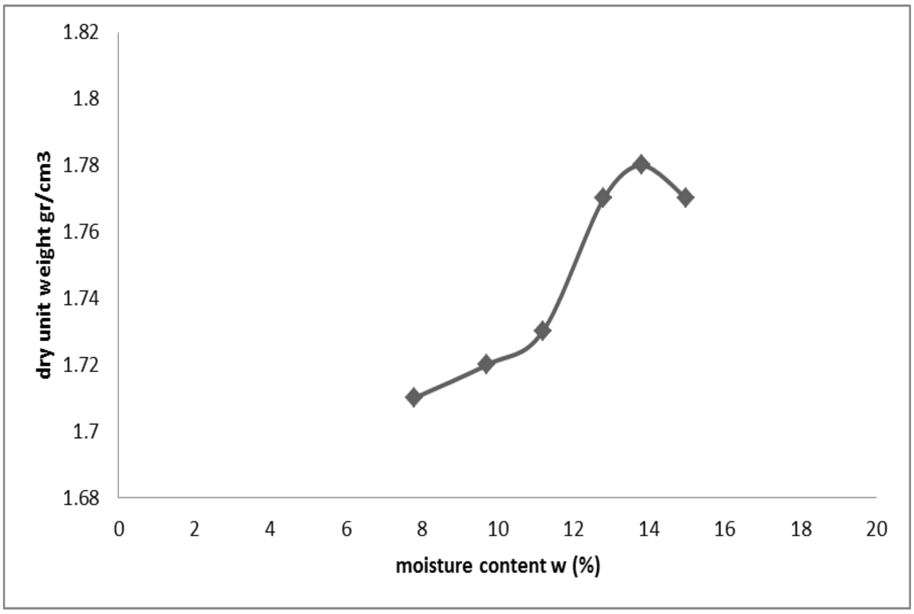
Assumed water content %.	%8	%10	%12	%14	%16
W2	6512	6580	6636	6664	6685
W3	23.2	23	23.1	23.8	23
W4	96	104.16	89.65	92.1	131.95
W5	90.5	96.91	83.11	84.75	118.75
w (%)	8.1723	9.8092	10.8981	12.059	13.7859
γ_d	1.8239	1.8586	1.8909	1.8963	1.8859



Lime-fly ash combination

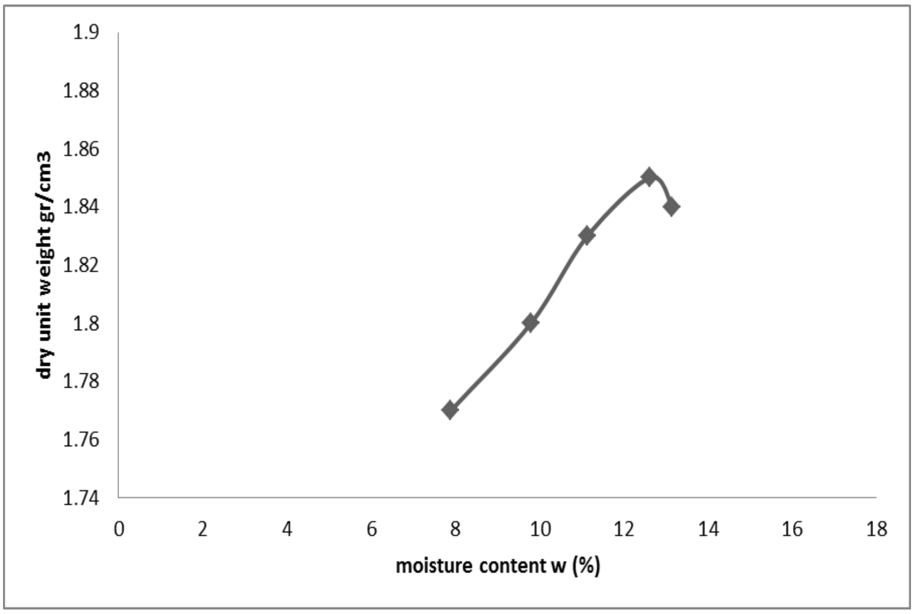
Appendix 8. 1% lime-5% fly ash

Assumed water content %.	%8	%10	%12	%14	%16	%18
W2	6390	6432	6477	6553	6565	6583
W3	23.2	23	23.1	23.8	23	23.23
W4	90.34	91.64	111.23	99.85	86.35	112.92
W5	85.48	85.56	102.36	91.22	78.66	101.23
w (%)	7.80	9.71	11.19	12.80	13.79	14.98
γ_d	1.71	1.72	1.73	1.77	1.78	1.77



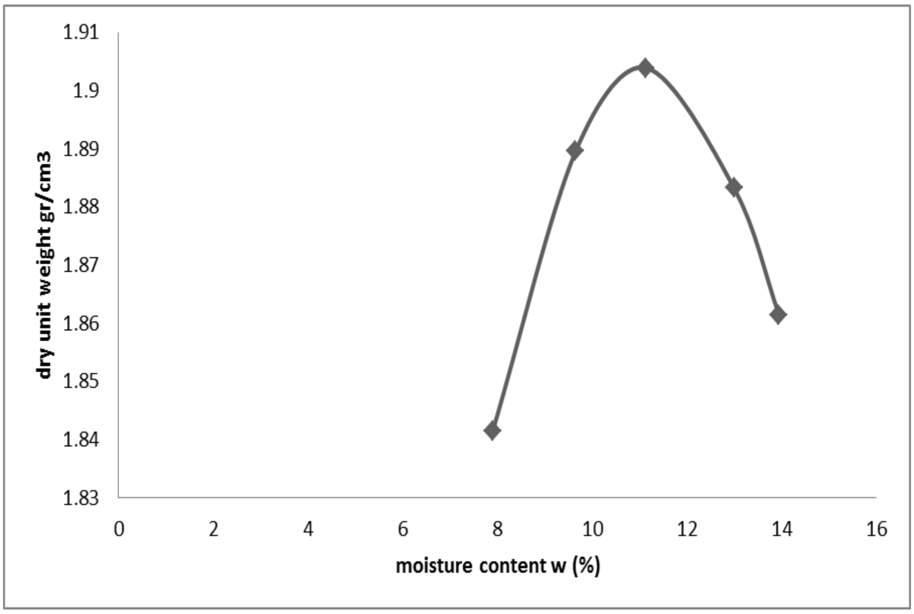
Appendix 9. 1% lime-10% fly ash

Assumed water content %.	%8	%10	%12	%14	%16
W2	6455	6517	6580	6623	6626
W3	23.2	23	23.1	23.8	23
W4	108.92	101.8	95.16	103.19	123.7
W5	102.65	94.77	87.94	94.29	112
w (%)	7.89	9.79	11.13	12.62	13.14
γ_d	1.77	1.80	1.83	1.85	1.84



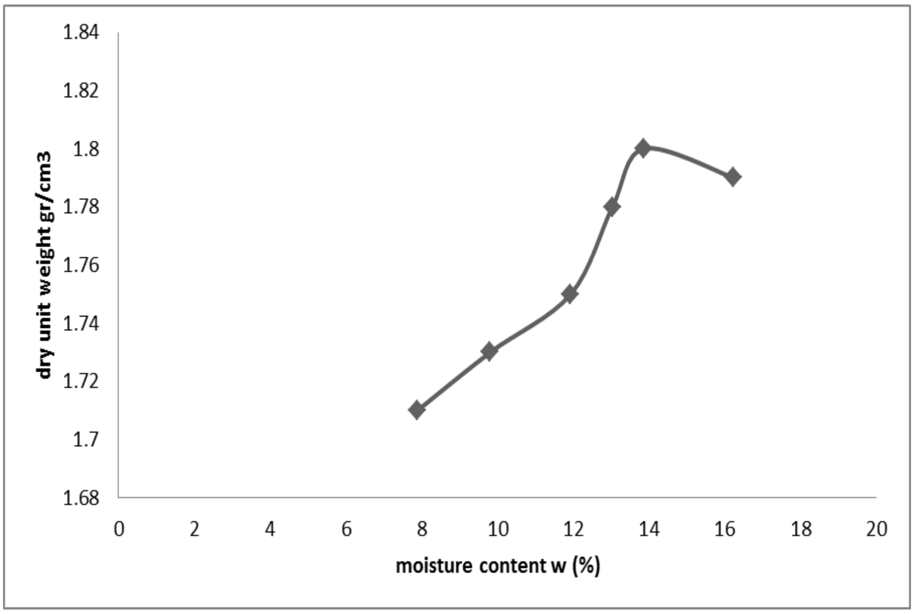
Appendix 10. 1% lime-15% fly ash

Assumed water content %.	%8	%10	%12	%14	%16
W2	6526	6611	6655	6667	6660
W3	23.2	22.3	23.4	22.4	23.78
W4	100.4	89.2	110.9	103.95	130
W5	94.75	83.4	102.13	94.57	117
w (%)	7.8965	9.6505	11.1393	12.997	13.9455
γ_d	1.8415	1.8896	1.9039	1.8832	1.8614



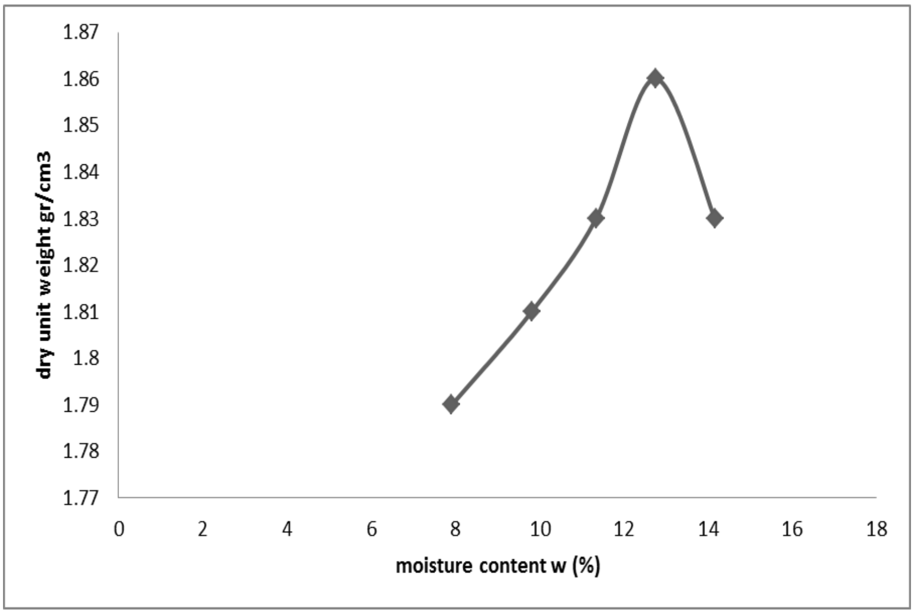
Appendix 11. 2% lime-5% fly ash

Assumed water content %.	%8	%10	%12	%14	%16	%18
W2	6392	6444	6505	6551	6595	6622
W3	23.2	22.36	23.4	22.4	23.78	23.23
W4	70.69	82.84	94.32	83.37	101.27	92.7
W5	67.22	77.44	86.76	76.34	91.83	83
w (%)	7.88	9.80	11.93	13.03	13.87	16.22
γ_d	1.71	1.73	1.75	1.78	1.8	1.79



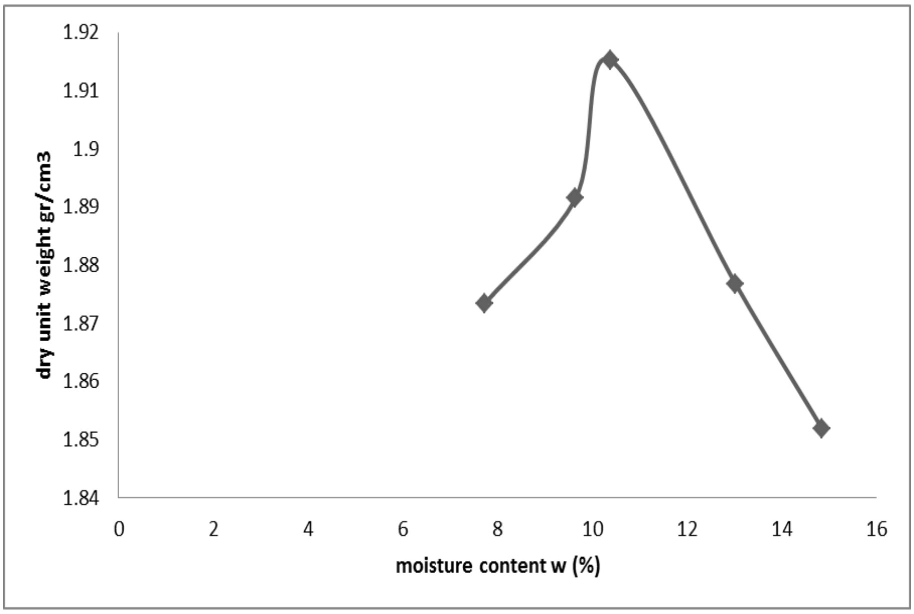
Appendix 12. 2% lime-10% fly ash

Assumed water content %.	%8	%10	%12	%14	%16
W2	6474	6535	6595	6636	6640
W3	23.2	23	23.1	23.8	23
W4	87.55	97.2	88.68	100.95	123.69
W5	82.83	90.57	82	92.22	111.2
w (%)	7.91	9.81	11.34	12.75	14.16
γ_d	1.79	1.81	1.83	1.86	1.83



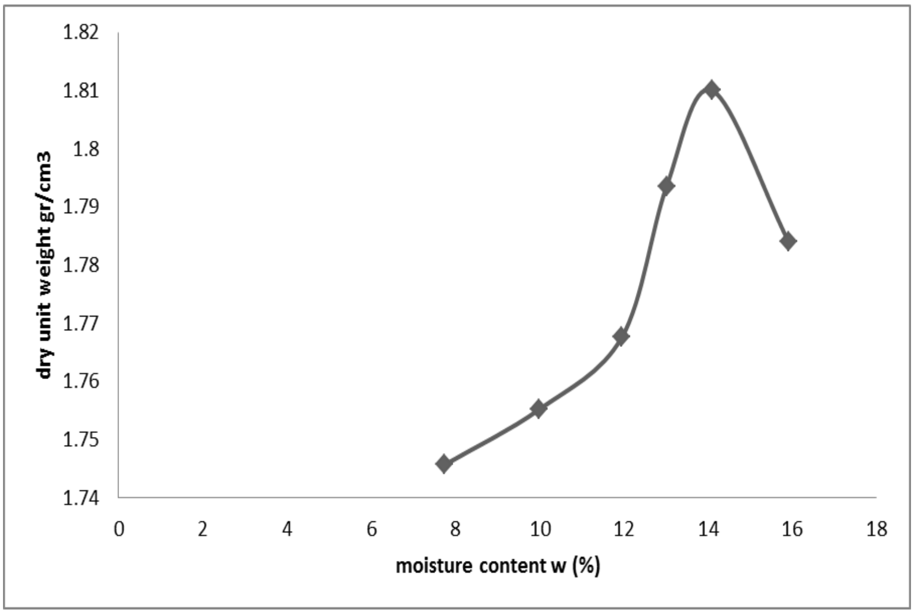
Appendix 13. 2% lime-15% fly ash

Assumed water content %.	%8	%10	%12	%14	%16
W2	6557	6613	6670	6660	6666
W3	23.2	23	23.1	23.8	23
W4	91.71	95.85	113.08	116.35	133.26
W5	86.8	89.44	104.02	105.68	119
w (%)	7.7201	9.6478	11.196	13.0312	14.8541
γ_d	1.8733	1.8915	1.9152	1.8767	1.8519



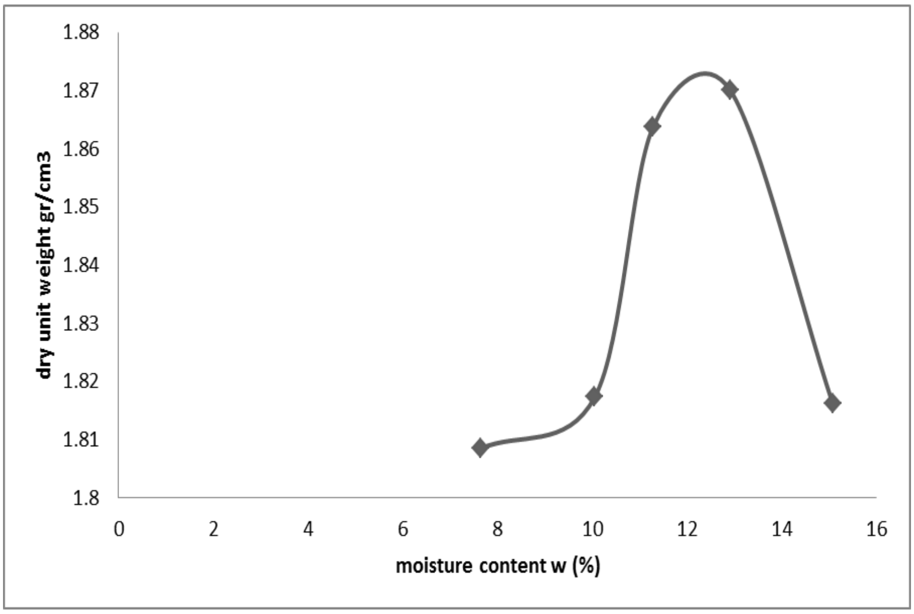
Appendix 14. 3% lime-5% fly ash

Assumed water content %.	%8	%10	%12	%14	%16	%18
W2	6420	6468	6518	6566	6604	6607
W3	23.2	23	23.1	23.8	23	23.24
W4	95.5	100.48	91.47	95	94.14	93.67
W5	90.3	93.5	84.17	86.8	85.35	84
w (%)	7.7496	9.99	11.9534	13.015	14.0978	15.915
γ_d	1.7457	1.7552	1.7676	1.7935	1.81	1.784



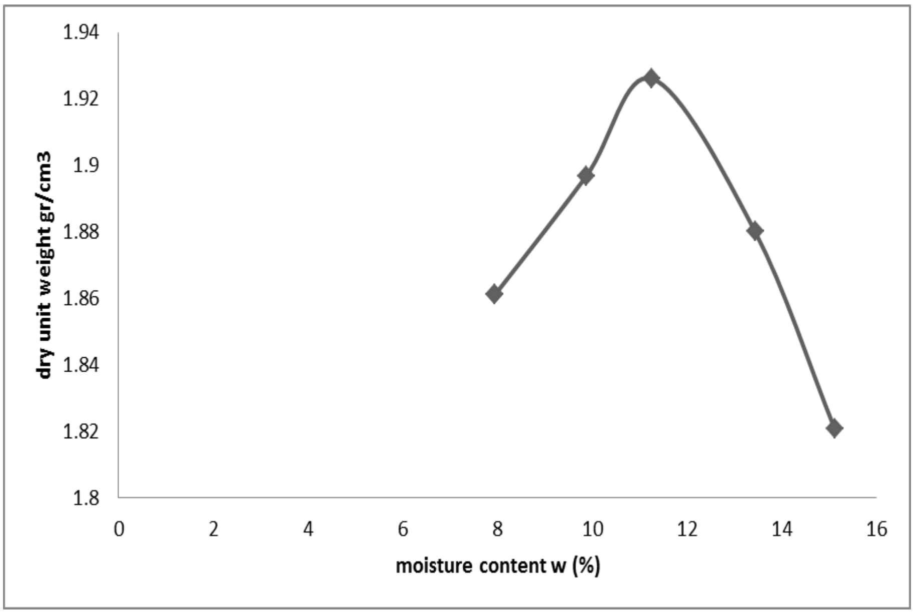
Appendix 15. 3% lime-10% fly ash

Assumed water content %.	%8	%10	%12	%14	%16
W2	6486	6539	6613	6650	6629
W3	23.2	22.36	23.4	22.4	23.78
W4	75.53	79.29	103.78	97.93	105.21
W5	71.81	74.09	95.63	89.29	94.54
w (%)	7.6527	10.0521	11.2834	12.9167	15.0791
γ_d	1.8085	1.8173	1.8637	1.87	1.81614



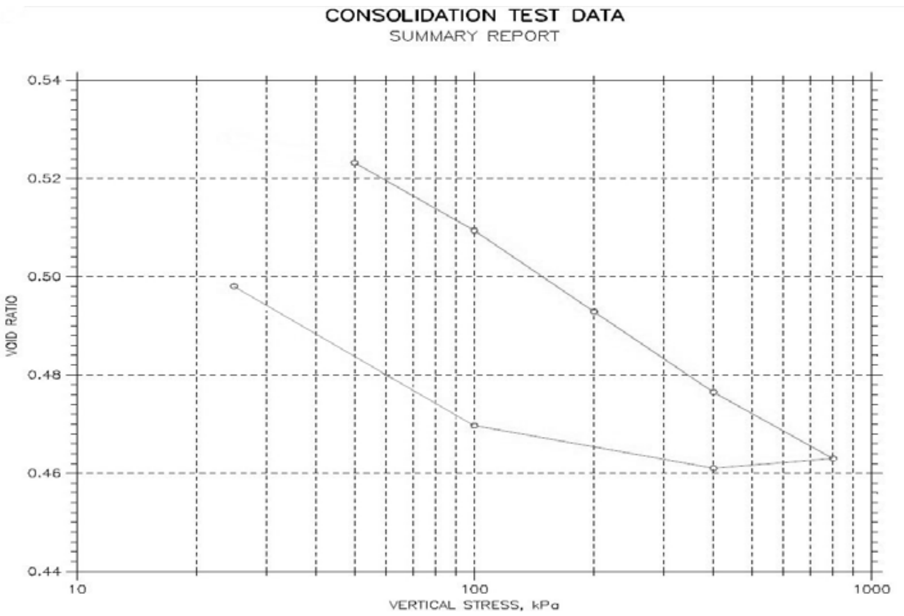
Appendix 16. 3% lime-15% fly ash

Assumed water content %.	%8	%10	%12	%14	%16
W2	6548	6623	6682	6672	6625
W3	23.2	22.36	23.4	22.4	23.78
W4	102.67	86.26	87.68	120.89	128.06
W5	96.82	80.52	81.17	109.16	114.36
w (%)	7.9462	9.8693	11.2688	13.4393	15.1247
γ_d	1.8611	1.8967	1.926	1.88	1.8206



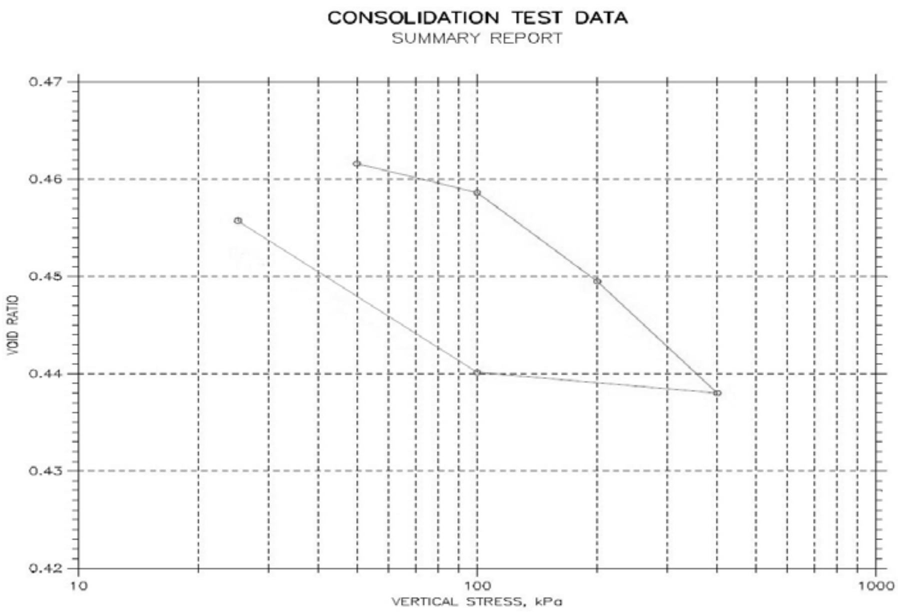
Consolidation curves

Sand-clay combination

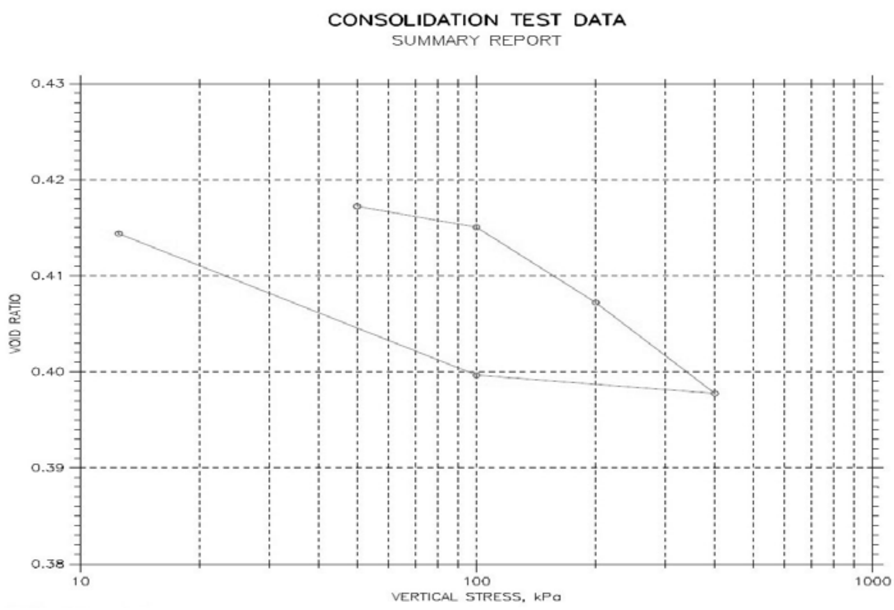


Appendix 17. sand-clay consolidation graph

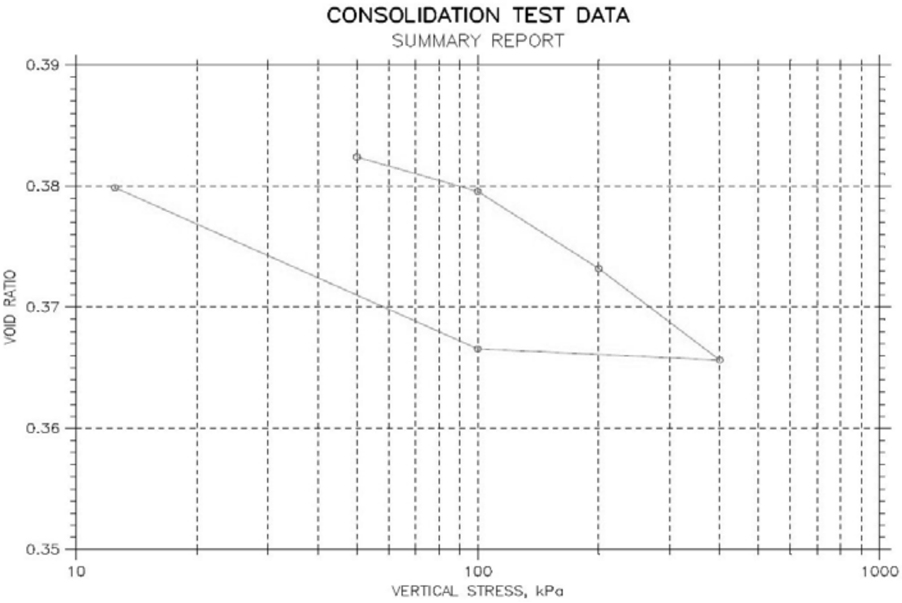
Lime treated sand-clay composites



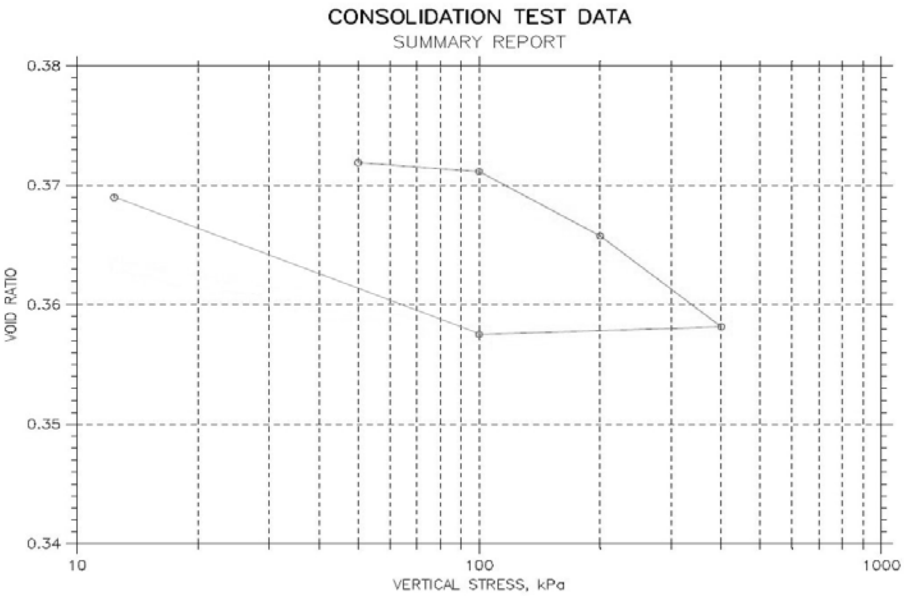
Appendix 18. 0.5% lime content



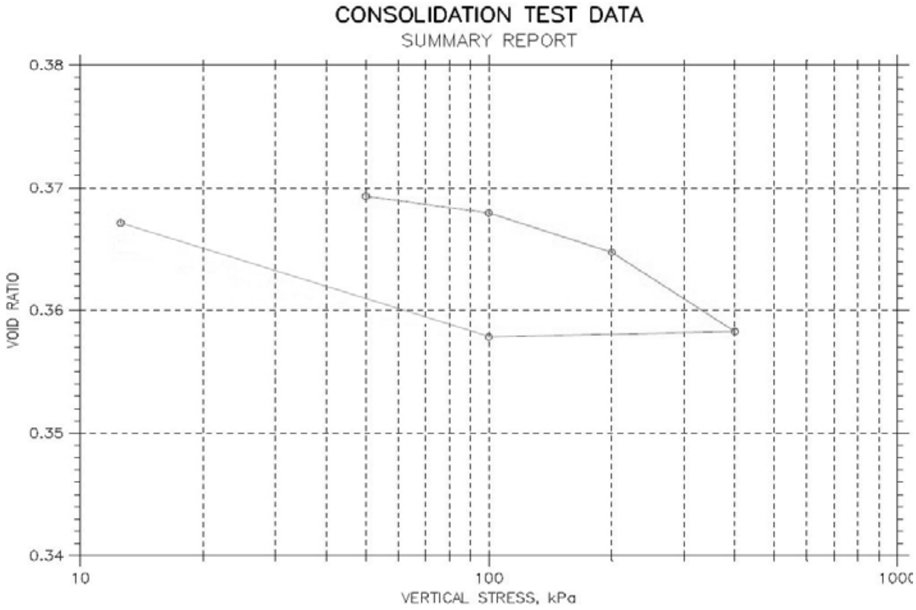
Appendix 19. 1% lime content



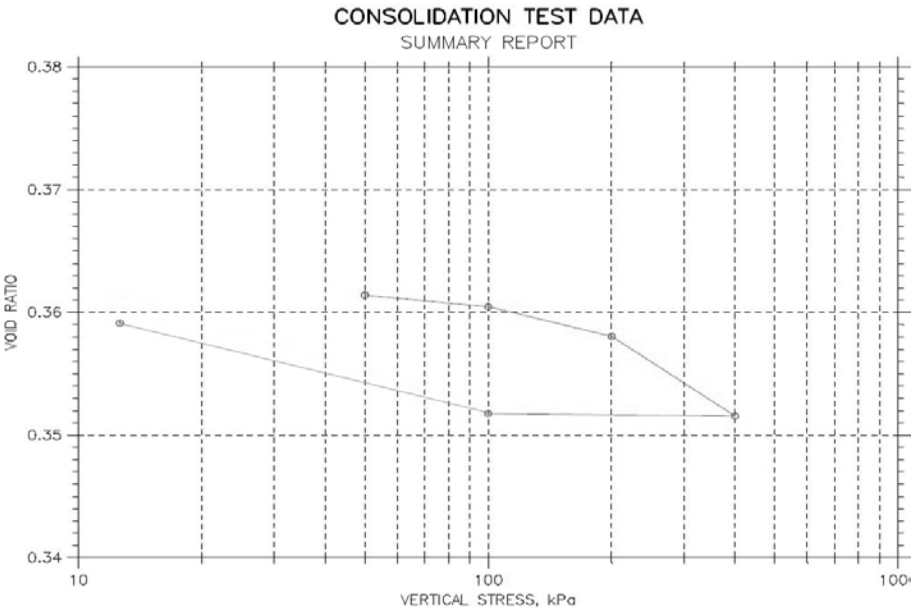
Appendix 20. 1.5% lime content



Appendix 21. 2% lime content

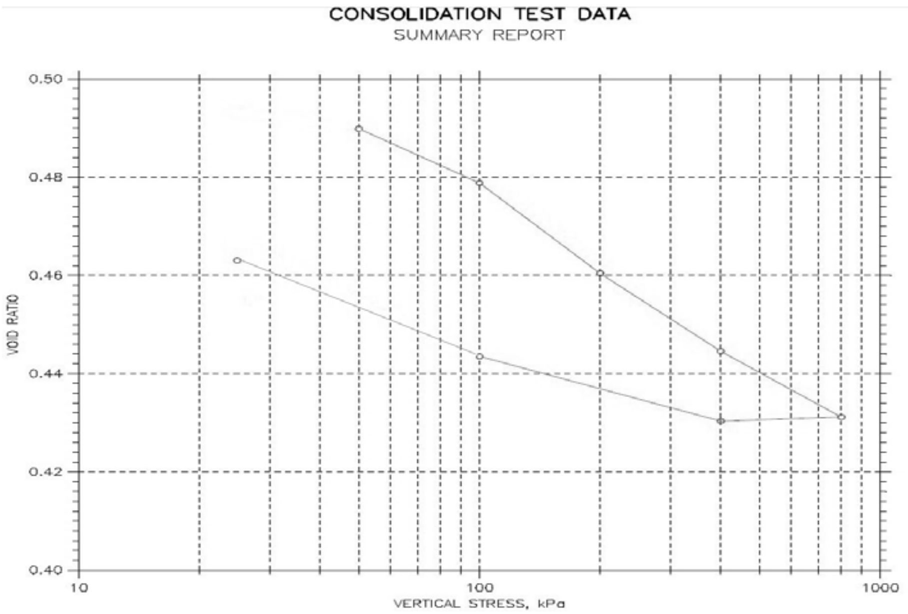


Appendix 22. 2.5% lime content

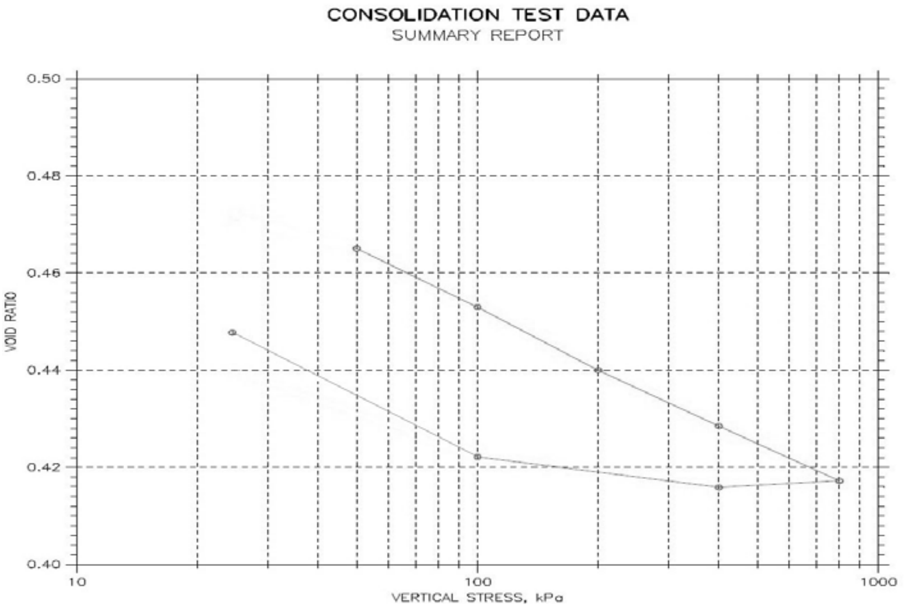


Appendix 23. 3% lime content

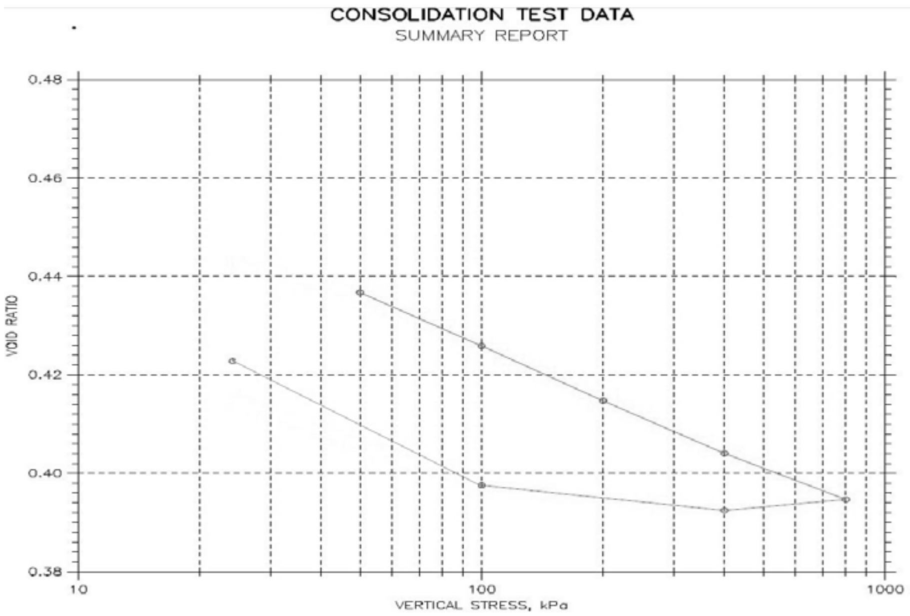
Fly ash treated sand-clay composites



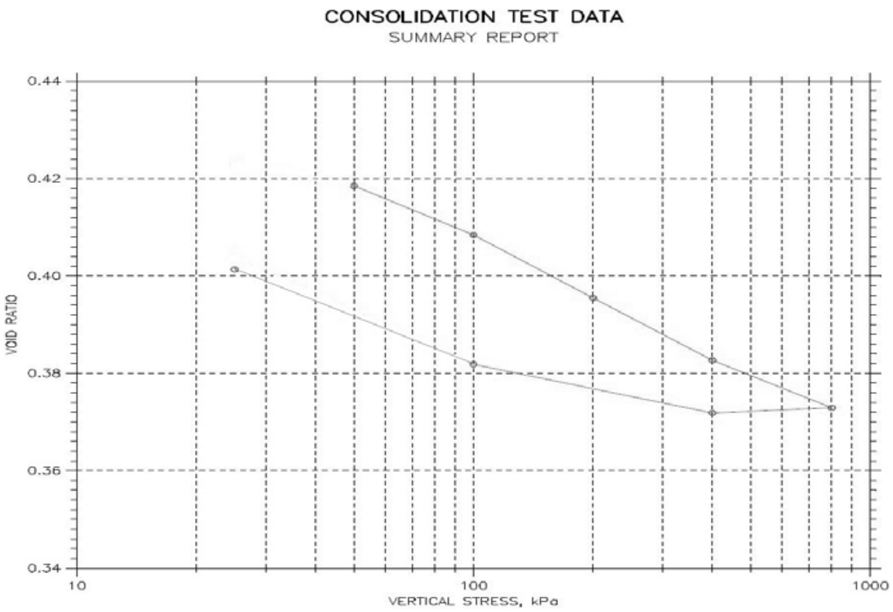
Appendix 24. 2.5% fly ash content



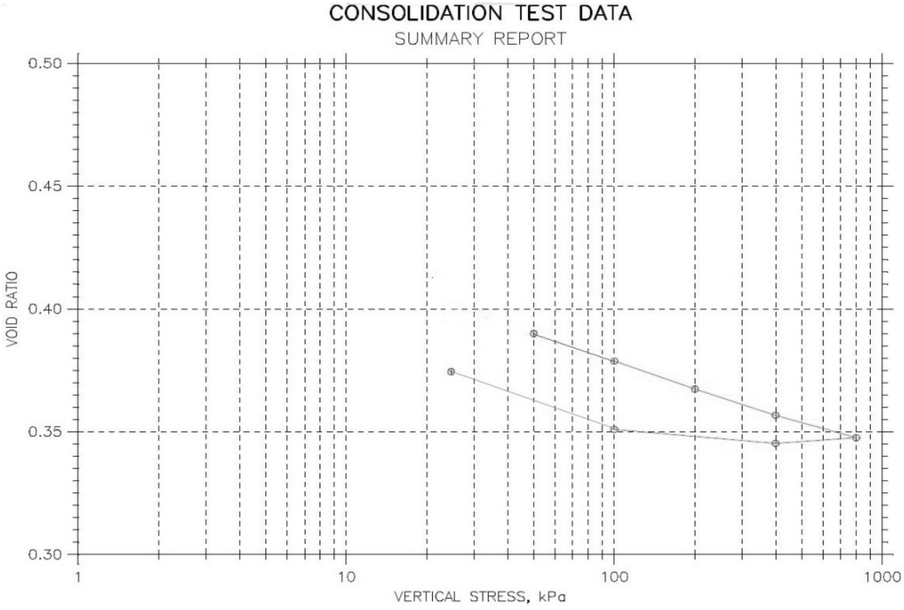
Appendix 25. 5% fly ash content



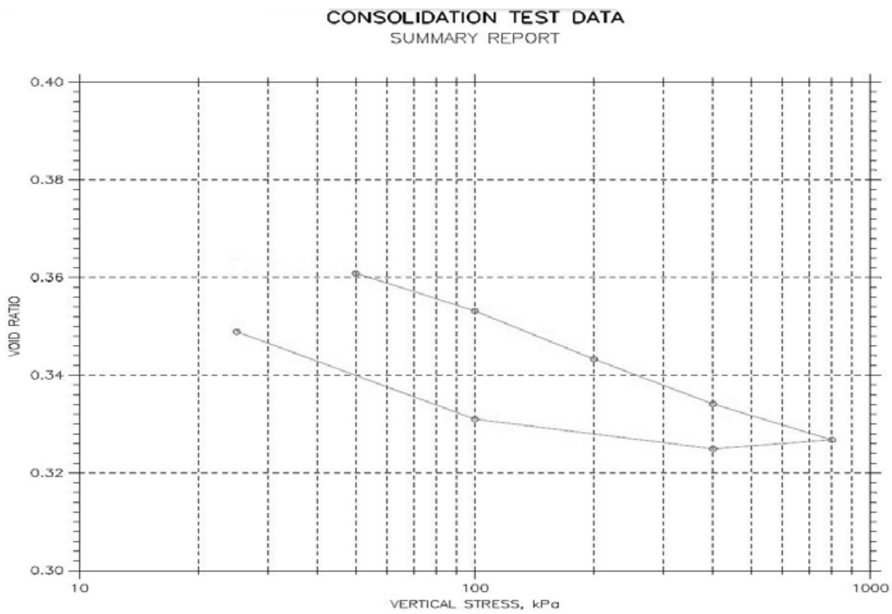
Appendix 26. 7.5% fly ash content



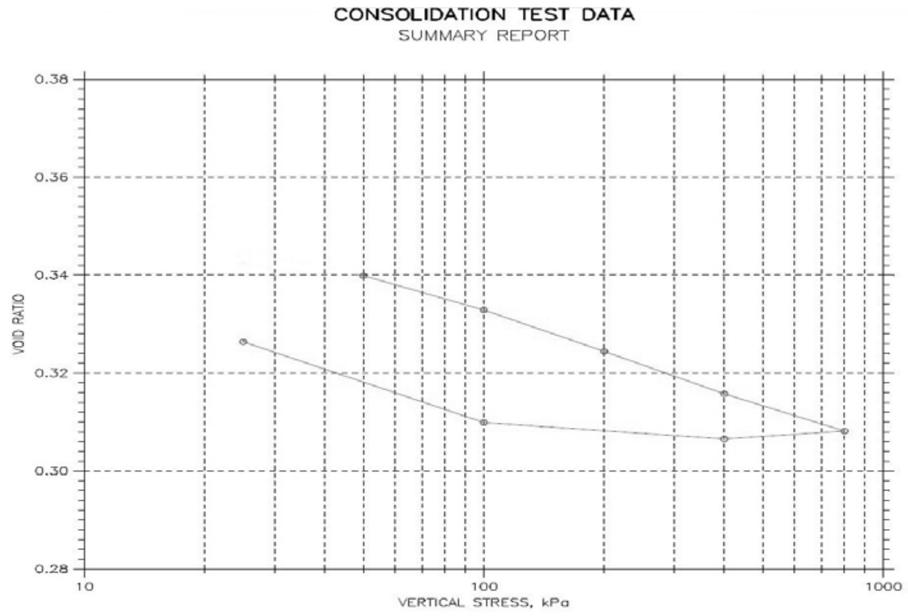
Appendix 27. 10% fly ash content



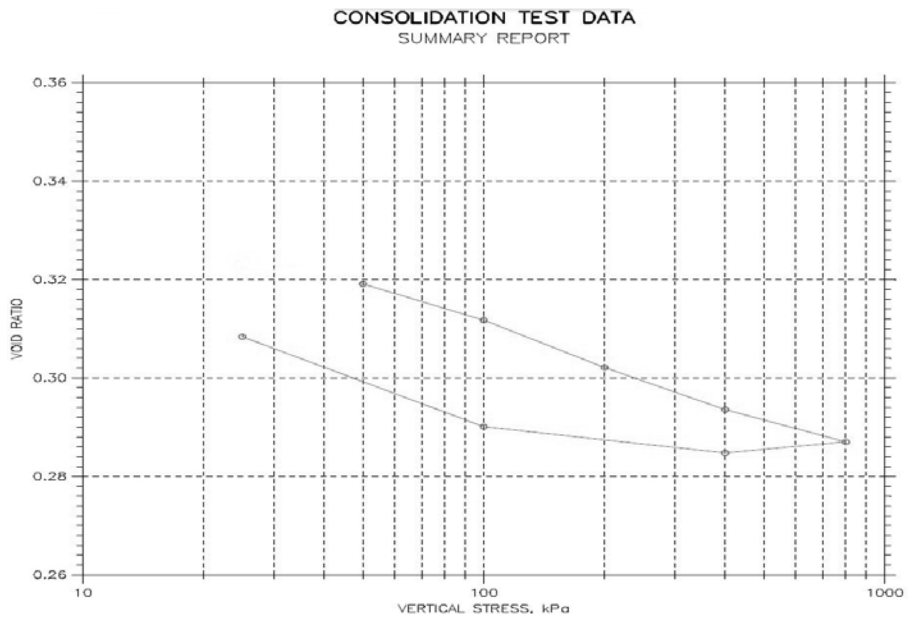
Appendix 28. 12.5% fly ash content



Appendix 29. 15% fly ash content

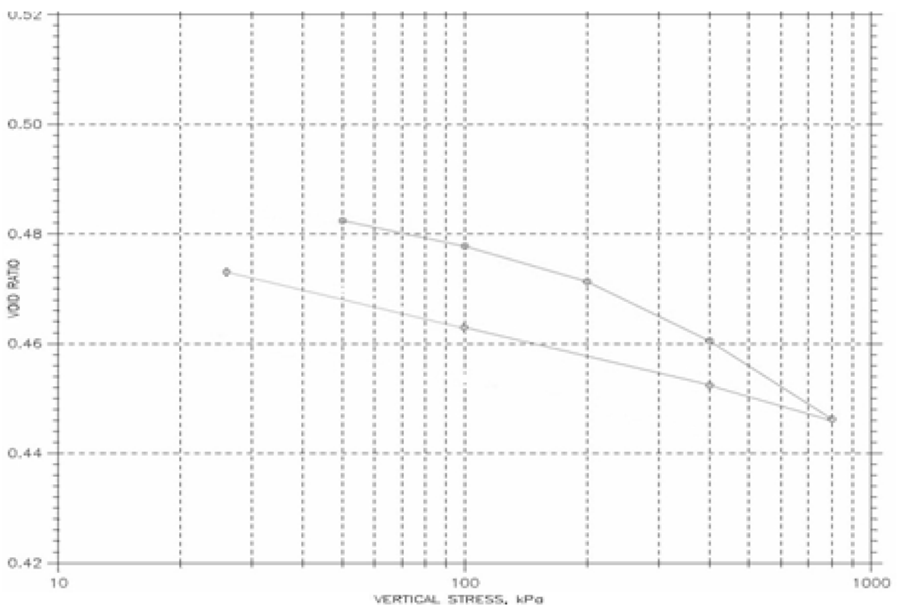


Appendix 30. 17.5% fly ash content

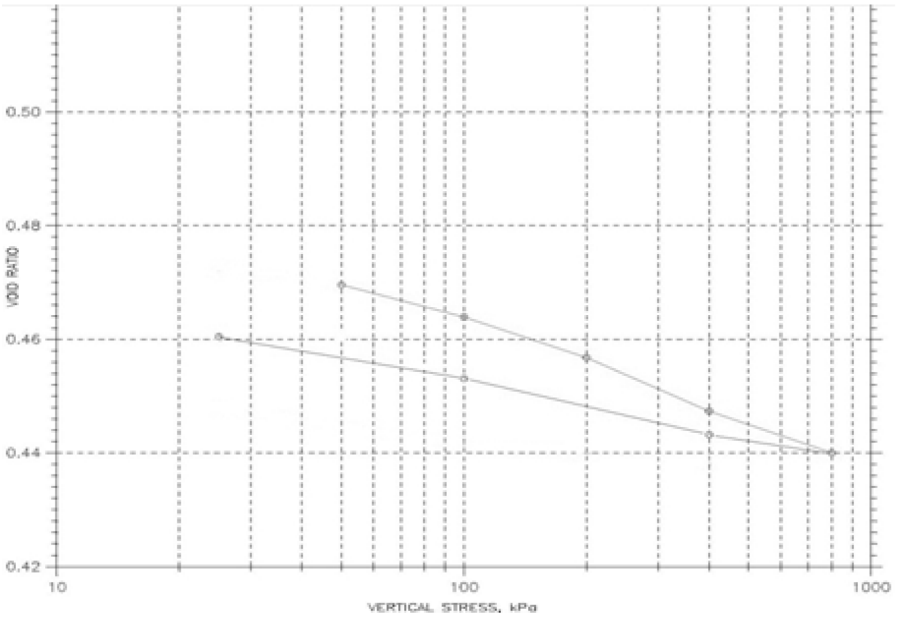


Appendix 31. 20% fly ash content

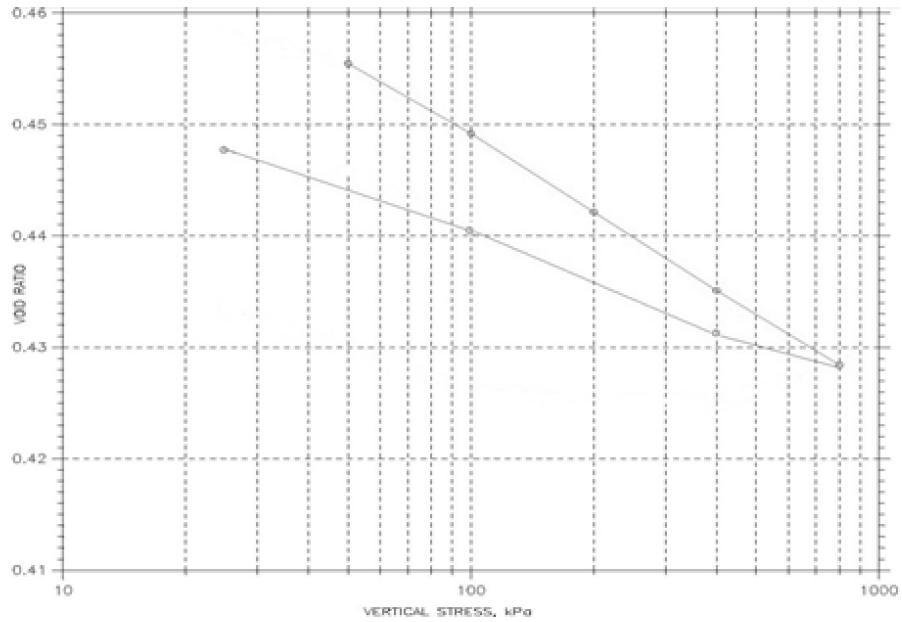
Lime-fly ash treated sand-clay composites



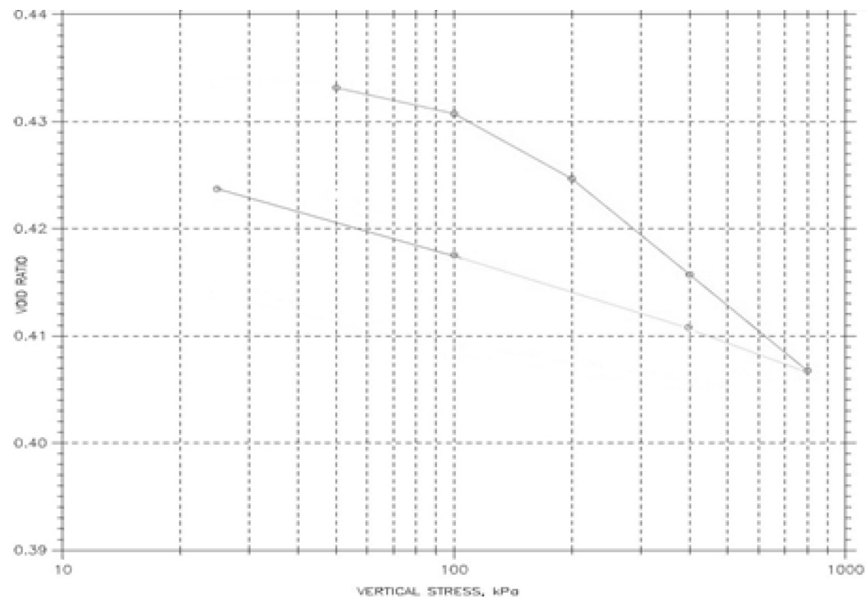
Appendix 32.1% lime-5%fly ash



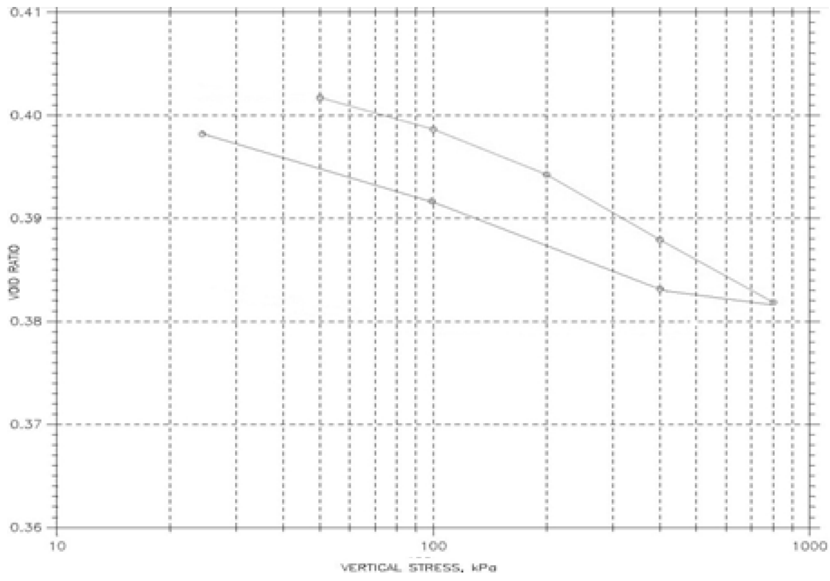
Appendix 33. 1% lime-10%fly ash



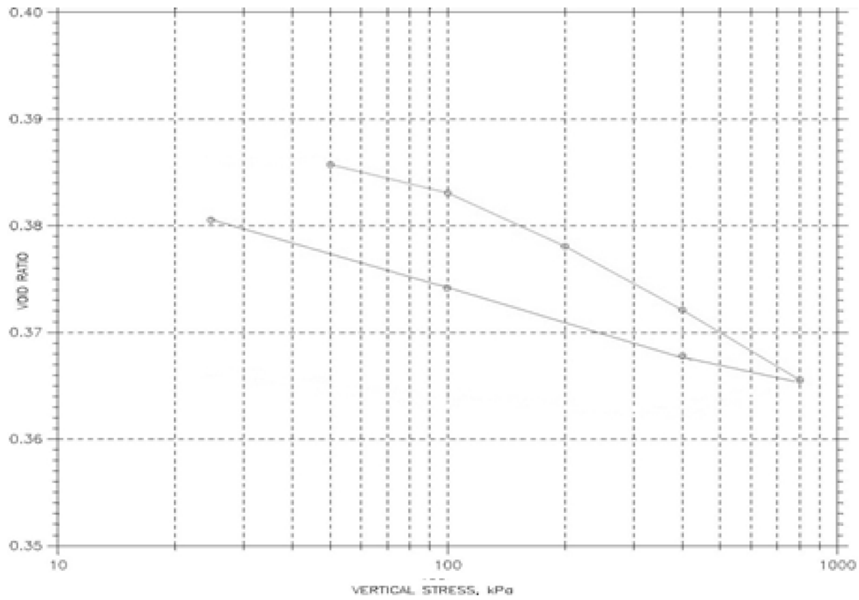
Appendix 34. 1% lime-15%fly ash



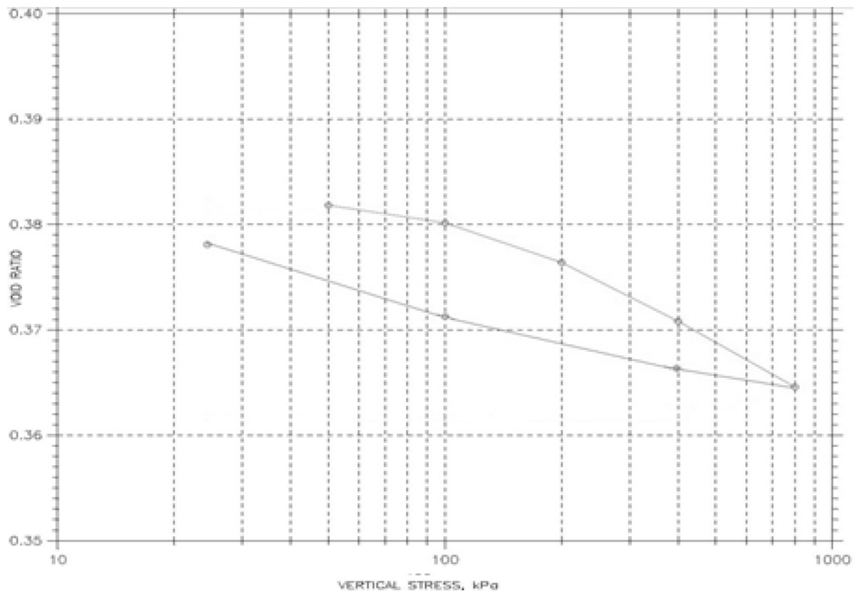
Appendix 35. 2% lime-5%fly ash



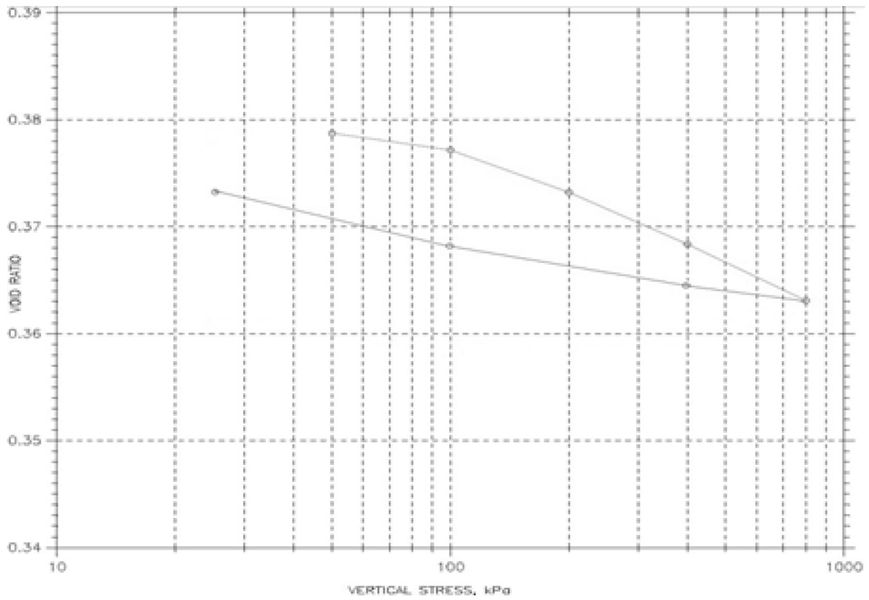
Appendix 36. 2% lime-10%fly ash



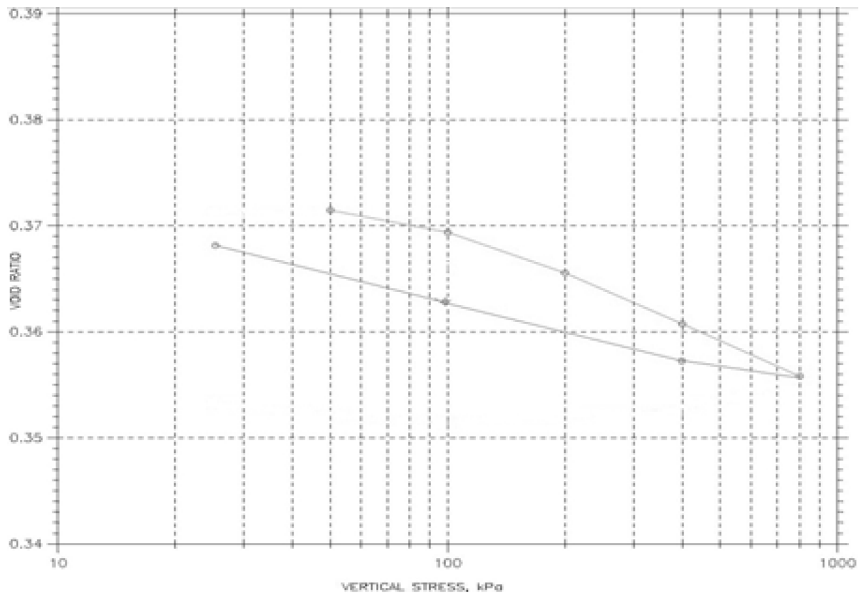
Appendix 37. 2% lime-15%fly ash



Appendix 38. 3% lime-5%fly ash



Appendix 39. 3% lime-10%fly ash



Appendix 40. . 3% lime-15%fly ash

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To: Saeid Amiralian

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- ‘Laboratory Investigation on the Compaction Properties of Lime and Fly Ash Composite’ International Conference on Civil and Architectural applications (ICCAA'2012) December 18-19, 2012 Phuket (Thailand)
- ‘Laboratory Investigation on the Effect of Fly Ash on the Compressibility of Soil’ International Conference on Civil and Architectural applications (ICCAA'2012) December 18-19, 2012 Phuket (Thailand)
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Saeid Amiralian

Saeid AmirAlian
MPhil candidate in Civil Engineering

Email : saeid.amiralian@postgrad.curtin.edu.au

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Yours sincerely
SaeidAmiralian

Regards,

Saeid

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