Using eggshell powder as a supplementary additive to lime stabilization in expansive soil

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Master by Research

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Certificate

I, Reem Alqaisi declare that this thesis, is submitted in fulfilment of the requirements for the award of Master of Engineering (Research), in the Civil and Environmental Engineering School / Faculty of Engineering and Information Technology (FEIT) at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

Expansive soils can be deemed as one of the poorest and most challenging soils frequently encountered around the world. Due to increased construction activities, particularly in underdeveloped countries, more regions of expansive soil deposits are being discovered.

Expansive soils, each with its own unique set of characteristics cause severe distress to the structures and is a major challenge for civil engineers around the world. Thus, it poses extreme difficulties in terms of its use in all construction and foundational works. One avenue for the management of such soils needs to be improved before stable and safe construction can be carried out on them. Furthermore, the suitability of expansive soils for engineering purposes involves a range of treatment processes.

This study involves the utilization of eggshell powder (ESP) as a supplementary additive to lime stabilization of the expansive soil in accordance with valuing its potential in augmenting the performance of lime mixed with expansive soil. Chicken eggshell is a waste material available from many sources such as hatcheries, fast food restaurants, poultry industry, egg product factories and domestic homes. This amount of eggshell waste material leads to an environmental issue and ends up in landfills. Challenges associated with disposals of eggshells include odour, costs, abrasiveness and availability of disposal sites. However, they can be processed into ESP and can play a role as a soil stabilizing agent. Calcium oxide is considered to be the main ingredient of the eggshell powder.

Due to some similar chemical composition of ESP to lime components, it can be used as a partial replacement of industrial lime if subjected to sufficient scrutiny. Therefore, a widespread experimental program has been carried out to quantify the properties of natural

and artificial expansive soils before and after treatment. Stage one involved an extensive analysis in determining the minimum lime required for modification of these problematic soils and it was found to be 5%. The pH values for the untreated and treated artificial expansive soil mixtures were determined after 0, 7, 14, and 28 days of curing.

The eggshell powder was used as an additive to 5% lime in four percentages of 5%, 10%, 15% and 20% by total dry weight of the soil mass in the second stage of the experimental program. In this stage, at the optimum moisture content of artificial expansive soil, which was approximately 29%, different percentages of additives were added. For each mixture, the maximum dry density of the artificial expansive soil was obtained, and it was used for performing all subsequent geotechnical tests. In the third stage of laboratory work, different percentages of ESP of 4%, 5% and 6% used as an additive to 5% of hydrated lime to investigate whether the target percentage (5%) of eggshell powder is the optimum value. In the third stage, all of the additives were added into the expansive soil at the optimum moisture content of the soil when mixed with 5% lime.

The outcomes of these experimental investigations showed that when the addition of eggshell powder into the expansive soils increased from 5% to 20%, the linear shrinkage reduced by 10% after 28 days of curing, the maximum dry density of the expansive soil decreased from 1.323 g/cm^3 to 1.293 g/cm^3 after adding eggshell powder. Similar results were obtained when the eggshell powder was added to the natural expansive soil. After conducting a series of pH and unconfined compressive strength (UCS) tests on untreated and treated expansive soil samples, it was noted that the improved geotechnical characteristics were more pronounced for 5% eggshell powder treated expansive soil. Therefore, the optimum percentage of eggshell powder believes to be around 5%. At this

optimum percentage, the compressive strength at failure and the corresponding strain increased slightly by 18% and 9%, respectively, compared to the untreated expansive soil after 28 days of curing. Meanwhile, the combination of eggshell powder and lime to stabilize soils when eggshell powder content increased up to 20% caused a further decrease in the linear shrinkage of 10.7% after 7 days of curing. Moreover, in comparison with lime (5%) only stabilized expansive soil, the combined lime (5%) and eggshell powder (5%), induced approximately 15% buildup in the compressive strength of samples.

On the other hand, the CBR value of the untreated soil increased from 2% to 56% when it was combined with the optimal values of additives. The utilization of eggshell powder for expansive soil stabilization without or with lime combination not only improved the geotechnical properties of expansive soil, but also assisted in minimizing the adverse effects of these domestic waste by-products on the environment. Finally, the effect of adding eggshell powder as a supplementary additive to lime stabilization of expansive soil has been investigated. It was observed that ESP led to a slight improvement in the geotechnical properties when it was added to the soil. However, the combined effect of eggshell powder and hydrated lime could be effective for stabilizing the expansive soil, where very high subgrade performance is neglected. Moreover, this combination could be used as a kind of fill material for road embankments to reduce energy consumption and contribute in conserving natural resources.

Keywords*:* Expansive Soils; Eggshell Powder; Hydrated Lime; Soil Stabilization; Linear Shrinkage; UCS Test.

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CHAPTER 1

Introduction

Notion of sustainable and eco-friendly infrastructures is gaining impetus in the geotechnical engineering research field. Nowadays, employing recycled or waste materials, obtained from the natural sources, are widely used as an alternative method in construction in recognition of the green concept. It is evident that transport infrastructure projects require a large amount of materials and natural resources and consume considerable quantities of energy. On the other hand, large volumes of wastes are produced daily. The beneficial effects of certain agricultural, domestic, industrial, construction, mineral and marine wastes in geotechnical applications, particularly in soil stabilization are discussed in this dissertation. Soil stabilization is highly recommended by engineers as a vital process to improve the performance of weak or marginal soils to achieve a higher level of stability. In particular, the use of eggshell powder in combination with hydrated lime for treatment of expansive soil is targeted in this study.

1.1 General

Soils are used in most construction activities; the most important challenge is how to deal with problematic soils such as expansive soils. In general, clays expand due to an increase in moisture and shrink due to decreased moisture. Expansive clays are those clays that exhibit behaviour that affects engineering structures (Nelson et al. 2015). Severe damages could occur to the structures like light buildings, pavements, retaining walls, canal beds and linings as evidenced by samples from many different countries such as

Australia, China, India, Israel, South Africa, the United Kingdom and the United States of America. The problems are particularly significant in Australia, where about 20% of Australia is covered with expansive soils (Karunarathne et al. 2013). It was reported by Considine (1984) that Over 50,000 houses are cracked every year in Australia, which accounts for approximately 80% of all housing insurance claims. Maintenance costs associated with the behaviour of expansive soil are estimated at billions of dollars a year worldwide. For example, in Britain over the past 10 years (2005-2015), the negative effects of shrinkage behaviour have cost £3 billion. The Association of British Insurers has estimated the cost of re-maintenance of building and infrastructures related to shrinking-swell subsidence to more than £400 million a year. Although there are no reliable accurate estimates in Australia, the damage caused by expansive soil is substantial. This leads to the necessity of determining the geotechnical properties of expansive soil in its natural state as well as when mixed with various proportions of selected waste materials, having beneficial effects on soil stabilization (Okagbue 2007; Phani Kumar & Sharma 2004; Rao, Jha & Misra 2007; Rao & Chittaranjan 2011).

Through the proposed approach, the focus of this study is on the presence of swollen clay minerals in the entire expansive soil strip; the clay minerals absorb water molecules and expand in the case of ambient humidity. In contrast, as they are exposed to dry conditions, they shrink leaving behind large voids in the soil. The process of shrinking and swelling becomes noticeable and is accompanied by an increase in the stress as a first stage followed by an increase in the strength capacity of highway subgrade surface or slab foundation. Therefore, swelling pressures can cause lifting or heaving of structures, whilst shrinkage can cause differential settlement as it exceeds the limit of subgrade bearing strength.

Indexing the swell potential of the expansive soil may significantly be influenced by either the soil type or its geotechnical properties, affecting the nature of the internal force in the field. Furthermore, there are other environmental or physical factors that stimulate the swell potential (Mokhtari & Dehghani 2012). Environmental factors, influencing the expansive soil behaviour, can include the initial moisture content, humidity changes, climate factors, groundwater level, drainage system, temperature variation, vegetation and permeability. Beside, physical factors, including the initial water content, the initial density, the amount and type of compaction, can also affect the swell potential and swell parameters of soils (Baser, 2009). On the other hand, delving into the effect of minerals contained in soil, including smectite, montmorillonite, bentonite, nontronite, vermiculite, illite and chlorite play a pivotal role in speeding up or slowing down the rate of swelling and shrinkage. Accordingly, the soil containing a large quantity of these minerals has the potential to expand. Montmorillonite, which contains clay minerals is considered to be one of the most profound swelling properties (Ramesh & Naik 2016). Conversely, kaolinite is considered as a less expansive minerals, which mitigates the phenomenon. Sand, as an auxiliary addendum reduces the swelling potential of the expansive soil. To facilitate the research into the complex behaviour of the expansive soil, one can visualize a mixed sample of three substances, containing montmoillonite, kaolinite and fine sand (Le, Fatahi & Khabbaz 2015).

Soil stabilization is highly recommended by engineers as a vital process to improve the performance of weak or marginal soil to achieve a higher level of stability. Numerous techniques are available for stabilization of such poor soils. Chemical stabilization is one of the most common ways of altering the physical properties of weak soils to enable them to meet the required engineering requirements. Chemical stabilization can be carried out either by the use of recycled wastes and by-product materials as a stabilizer by themselves, or they may be used in combination with primary conventional chemical agents, such as lime or cement. Both methods of treatment are applied to improve the engineering properties of soil to make it suitable for construction (Fatahi & Khabbaz 2012; Osinubi, Ijimdiya & Nmadu 2009). Chemical stabilization involves the use of chemical agents for initiating reactions within the soil. The majority of researchers dealt with cement and lime as conventional stabilizers (Bergado et al. 1996; Cokca 2001; Fatahi & Khabbaz 2012; Khabbaz & Fatahi 2012; Laguros & Cokca 2002).

Lime, cement, pozzolanic fly ash, blast furnace slag, expanded shale and potassium chloride can be used for stabilizing expansive high plasticity clayey soils to relatively shallow depths under footing and slabs for industrial foundations. One method of controlling the volume change is to stabilize the clay with an effective admixture to prevent the volume change (Amu et al., 2005).

Stabilization using waste materials is one of the techniques, employed to improve the engineering properties of expansive soils to make them suitable for construction (Ingles & Metcalf 1972; Sabat & Pati 2014). The waste materials concepts are mainly described as material by-products growing from all human activities, that have a non-renewable value (Maghool et al. 2017). An enormous amount of raw materials, which exist in the world are consumed immensely in transport infrastructure facilitates such as roads, highways, bridges, airports, railways, waterways canals and terminals. As a result, the non-renewable natural materials are quickly exhausted (Bolden IV 2013; Correia, Winter & Puppala 2016). However, the reuse of recycled materials in various types of infrastructure could profoundly reduce the need for natural materials, easing the pressure on landfills and stockpiles.

Department of the Environment and Energy in Australia issued a report on waste generation and resource recovery during the period of 2016-2017, as summarized in Figure 1.1. The report aimed to propose, investigate and analyze the data of solid wastes by concentrating on the waste generation by material category, stream and other related issues. According to this report, a significant amount of solid wastes are being produced in the Australian construction and agricultural sectors.

During the study period (Energy REC 2018), the total estimated Australian generated waste was 67 million tonnes, which was equivalent to 2.7 tonnes per capita. It was found that the highest amount of those wastes (17.1 Mt) came from masonry materials, including wastes as concrete, rubble and bricks. The second highest amount was associated with 12.3 Mt of ash followed by 6.3 Mt of hazardous wastes (mainly contaminated soil), 5.6 Mt of paper and cardboard and 5.5 Mt of metals. Then again, there was approximately 54 Mt of 'core waste' – that managed within the waste and resource recovery sector (2.2 tonnes per capita). The large amount of organic wastes that account for about 16.5% of the total wastes, which equals 11.5 Mt, could be an important reason to consider eggshell powder "which is one of the main classifications of organic waste materials" to be the focus of this study.

The core waste included 20.4 Mt from the industrial and commercial sector (I&C), 20.4 Mt from the demolition construction (D&C) sector and the rest originates from local government activities and households with 13.8 Mt (560 kg per capita) of municipal solid waste (MSW). It would be worth mentioning that the resource recovery rates for core waste plus ash was 58%, while it was 62% for the core waste only.

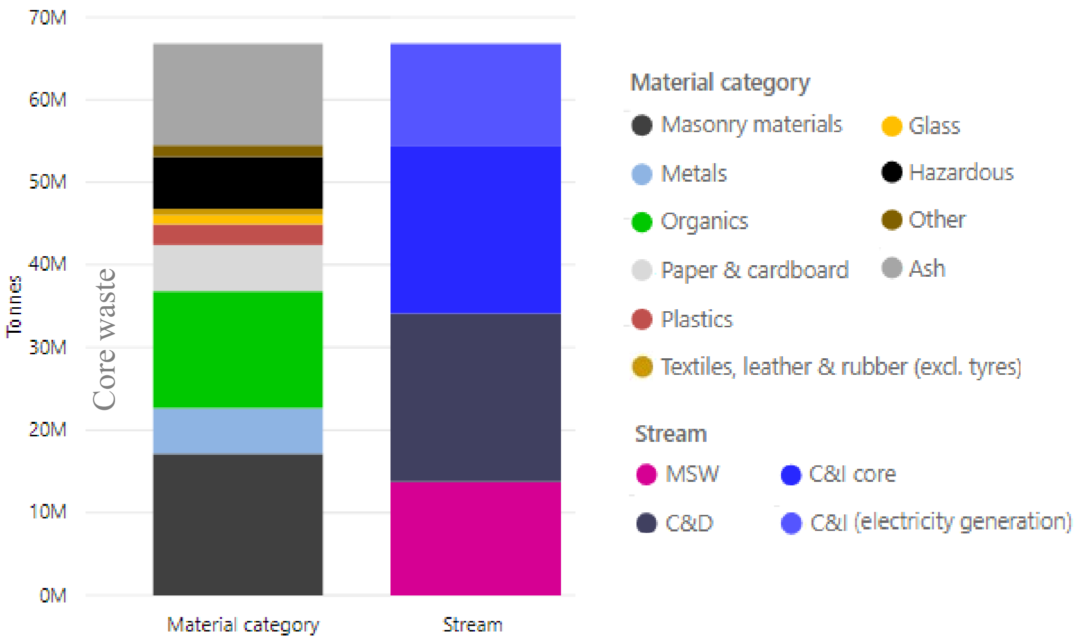


Figure 1.1 Australia's total waste generation by material category management in millions of tonnes in 2016-2017 (Energy REC 2018)

The environmental impacts of waste management was also an essential section of that report. The investigations have been carried out to utilize these waste materials in constructions to protect the environment from contamination. In addition, the prospective costs and benefits of such management were discussed, particularly those which generate energy from renewable resources. The report (Energy REC 2018) presents a clear vision for the importance of sustainability that the candidate aims to achieve in this study.

Most infrastructure activities leave behind significant environmental effects. For example, industries in the United States of America annually consumes over 40% of all raw stone, gravel and sand, 25% of all raw timber, 40% of energy, and 16% of the water, according to Chong et al. (2009).

As a result, the concept of sustainability must be applied in accordance with the conservation of energy and original materials. According to (Energy REC 2018), sustainability is a concept that originated from the direction of the world's attention towards better management of materials. The United Nations World Conference held in 1987 provided another definition of sustainability as follows: “management of resources such that current generations are able to meet their needs without affecting the ability of future generations to meet their needs”. This definition has stimulated many experts to increase the interest and the management of environmental resources (Hill & Bowen 1997; Horvath & Matthews 2004). In addition, one of the most important sustainability criteria in geotechnical applications is to reduce the use of concrete and soil by partially replacing recycled waste materials and improving their properties.

There are several recycled waste materials and by-products that are produced all over the world, which can be used in soil stabilization. A large series of wastes from domestic, industrial, agricultural, construction, mining and marine sectors are considered in the following sections. Industrial solid wastes including steel slag, fly ash, silica fume, red mud, and lignin from pulp and paper industry (Ahmaruzzaman 2010; Ashok & Sureshkumar 2014; Khan & Siddique 2011; Mazloom, Ramezanianpour & Brooks 2004; Najar P.A et al. 2012; Qasrawi, Shalabi & Asi 2009; Rathod, Suryawanshi & Memade 2013; Ribeiro, Labrincha & Morelli 2011; Sabat & Pati 2014; Samal, Ray & Bandopadhyay 2013; Siddique 2011; Singh, Upadhayay & Prasad 1996; Vaníček, Jirásko & Vaníček 2016). Meanwhile, the processing of various agricultural products, including sugarcane bagasse ash, rice husk ash, bagasse fibre, groundnut shells, whey, wood ash, burnt olive waste and coconut coir fibre generates agricultural solid wastes (Ahmaruzzaman 2010; Al-Khalaf & Yousif 1984; Ali et al. 2012; Balaji, Karthikeyan & Raj 2014; Ganesan, Rajagopal & Thangavel 2007; Hailu & Dinku 2012; NADGOUDA 2014; Rao & Chittaranjan 2011; Sabat & Pati 2014; Schettino & Holanda 2015; Srinivasan & Sathiya 2010). Furthermore, from post-consumer commercial and household waste, domestic solid wastes are generated. Tire rubber, carpet fibre, glass cullet, and eggshell powder are examples of domestic wastes (Boraste & Sharma 2014; Erfen & Yunus 2015; Hut 2014; Mirzababaei et al. 2009; Olufowobi et al. 2014; Pliya & Cree 2015; Wang 1999; Wang et al. 1994; Yerramala 2014a). In civil engineering, there are many examples of eggshells applications, for example, eggshells can be used as fine aggregate in concrete for sustainable construction (Raji & Samuel 2015a; Yerramala 2014b). The eggshell powder has been used to improve the properties of subgrade, as subgrade soil can exhibit a significant improvement in strength with the addition of eggshell powder in terms of California bearing ratio (CBR) under unsoaked conditions (Ahmed, Rahman & Das).

Eggshell is a waste material generated from domestic sources such as hatcheries, homes poultries, and fast food centres. Large amounts of eggshells pose a significant environmental concern if not recycled or discarded properly (Pliya & Cree 2015). Due to similar chemical composition to that of lime, the eggshell powder can be used as a partial replacement for industrial lime if subjected to proper examination (Rao & Chittaranjan 2011). As a result, the eggshell powder could be suitable for stabilizing the soil and producing a composition that could partially substitute for lime in soil stabilization (Leite et al. 2016).

The composition of shell membranes is approximately 69.2% protein, 2.7% fat, 1.5% moisture and 27.2% ash (Tsai et al. 2006). The eggshell and shell membranes form almost 10.2% of the total weight of the egg (Nakano, Ikawa & Ozimek 2003). Many investigations have been conducted in the utilization of eggshell wastes (ESW) in various civil engineering applications. Moreover, Different studies were implemented to discover the effects of adding eggshell powder (ESP) on different types of soils (Amu, Fajobi & Oke 2005; James & Pandian 2016a; Nyankson et al. 2013). The consumption of eggshell powder as an affluent source of calcium carbonate ($CaCO_3$) can efficiently solve both ecological and financial interest.

The key objective of this study is to study the geotechnical properties of the artificial expansive soil when the eggshell powder is added as a supplementary additive to the lime stabilized artificial expansive soil. The density Index, the consistency limits, the particle size indices, the compaction properties and the treated soil strength characteristics are some examples of the geotechnical properties, discussed in this study. A range of geotechnical tests were performed including linear shrinkage, Proctor compaction, pH determination, unconfined compressive strength, and California bearing ratio tests. The geotechnical properties of the natural expansive soil have also been studied to analyze the combined effects of eggshell powder and hydrated lime, when this combination blended with the natural expansive soil. It can be noted that the engineering properties of artificial expansive soil were studied extensively in this study due to its uniformity and abundance in the laboratory, whereas, the natural expansive soil has briefly been studied. Therefore, a comprehensive study on experiments was carried out on artificial expansive soil with the optimum hydrated lime content and different proportions of eggshell powder, after 7 and 28 days of curing. Furthermore, the geotechnical tests on these mixtures were carried out at different moisture contents. This combination of eggshell powder and hydrated lime can expectantly stabilize the expansive soil by reducing its swelling-shrinkage potential and could improve the mechanical properties of the expansive soil. The research implication shows the significance of utilization the domestic wastes, such as eggshell powder, to stabilize the expansive soil with hydrated lime for the construction of light foundations or road embankment on the top of this type of problematic soil.

1.2 Statement of Problem

In recent times, solid wastes reuse gained high momentum for achieving sustainable development of wastes (James & Pandian 2016b). Solid wastes can be categorized into agricultural, industrial, domestic and mineral wastes based on their origin or source of generation. There are several domestic wastes that are produced all over the world, which can be used in soil stabilization including tire rubber, eggshell powder, glass cullet, and carpet fibre (Anggraini et al. 2015; Basha, Hashim & Muntohar 2003; Sivakumar Babu, Vasudevan & Sayida 2008). On the same line, utilization of domestic wastes in soil stabilization is being heavily researched for their efficiency in modifying soil properties, and their use gained widespread acceptance in geotechnical applications.

For engineering purposes, such as road construction materials, reusing of solid waste materials requires an effective method. The application of solid wastes in soil stabilization can contribute in reducing the cost of pavement construction, which would be of economic importance in both underdeveloped and developing countries. Expansive soil and eggshell powder considered as quantities of waste materials which are formed continuously from industrial, agricultural and human activities.

Accordingly, different studies have been undertaken to address the issues related to stabilization of expansive soil with the utilization of eggshell powder, as mentioned in the previous section. It can be noted that few engineering properties of the expansive soil have been covered by other researchers. Although many studies have shown the effect of adding eggshell powder on the plasticity properties of expansive soils, only a few studies were conducted to investigate the effects of lime-eggshell powder combination on a wide range of geotechnical engineering properties of treated expansive soil. Based on the literature review, it has been revealed that the majority of researchers used small percentages of eggshell powder and the shrinkage potential and strength properties of expansive soil were not covered properly. In this experimental study, the innovative idea of blending eggshell powder and hydrated lime with an artificial expansive soil in high percentages of eggshell powder is investigated, which would be beneficial in geotechnical engineering applications. The shrinkage potential, Atterberg limits, compaction characteristics, unconfined compressive strength and California bearing ratio of expansive soils, treated with eggshell powder and hydrated, are investigated.

Brief procedures are followed to study the effect of adding eggshell powder into the natural expansive soil. The effect of eggshell powder on the geotechnical properties of natural expansive soil was tested by adding 5% and 20% content of eggshell powder into the untreated natural expansive soil. Linear shrinkage tests, proctor compaction tests, and unconfined compressive strength tests were conducted in purpose to estimate the effect of eggshell powder on the properties of natural expansive soil compared with the artificial one.

1.3 Project Scope and Objectives

Several objectives are expected to be achieved in this study. However, the main goal is to use eggshell powder as a supplementary additive to lime in the stabilization of expansive soil to enhance its performance. This combination can be effective in stabilization of expansive soil, where the high performance of the subgrade is not necessary. Moreover, it can be used as fill material in the embankments. Therefore, a green and low-cost method of ground modification technique can be introduced, using waste materials as a stabilizing agent in improving shrinkage and strength properties of expansive soils. The outputs of this experimental investigation are analyzed and discussed to obtain a better understanding of the effects of the hydrated lime, eggshell powder and their mixture on the shrink-swell behaviour of expansive soils.

Another aim of this study is to explore the effectiveness of employing eggshell powder as a partial replacement of lime in stabilization of expansive soil. To sum up, the specific objectives of this experimental investigation are outlined as follows:

- Determining the optimum lime content based on pH measurements of the expansive soils stabilized without or with hydrated lime and eggshell powder, as well as studying the effect of the addition of eggshell powder without or with the hydrated lime mixture on the compaction properties of treated soils.
- Finding the optimum ratio of eggshell powder, and hydrated lime to treat expansive soil in order to minimize damages caused by highly expansive soil underneath roads.
- Studying the influence of the additives (hydrated lime without or with eggshell powder combination) on the linear shrinkage behaviour and the unconfined compressive strength of treated soils, associated with different additive contents and curing periods.
- Quantifying the bearing capacity of untreated soil and soils treated with eggshell powder in combination with hydrated lime, using soaked California bearing ratio (CBR) tests when taking into account the effects of the stabilizers contents and curing time.
- Analyzing the data and results to figure out the effect of adding eggshell powder as a supplementary additive to lime stabilization of expansive soil.

1.4 Novelty and Significance

This research is a comprehensive study of many geotechnical and environmental properties of expansive soil when mixed with eggshell powder and hydrated lime.

Through an experimental program and analytical methods, these characteristics are examined. The innovation of this study by adding this sustainable material involves eliminating the pollution issues related to the disposal of eggshells. Due to the high percentage of calcium oxide in eggshell powder, it could be a reasonable supplement to lime stabilization of expansive soil by augmenting the pozzolanic reaction. Therefore, the benefits of adding the combination of eggshell powder and hydrated lime in the area of stabilization of expansive soil must be taken into account.

Moreover, the costs of maintenance and reconstruction of the building, particularly road embankments can be reduced. The amount of waste stockpiled in landfills can also gradually be reduced, and the carbon footprint resulting from the production of conventional stabilizers, such as lime, may decrease.

1.5 Gap Identification

Referring to Chapter 2 of this dissertation, an integrated literature review has been established for many wastes and by products, which could be used in the stabilization of problematic soils such as expansive soils. These soils are subject to volume change due to changing the moisture content. Thus, the expansive soil poses extreme difficulties in the construction of the foundation on them. In order to improve these soils, many ground improvement techniques have been adopted. Lime stabilization is one of the most common and effective techniques in the stabilization of such soils and mitigates swell potential. In recent years, several solid wastes have been probed by researchers for their effectiveness in soil stabilization. The available literature review has focused on the utilization of a large series of wastes. These wastes consisting of domestic wastes (eggshell powder, tyre rubber, carpet fibre, and glass cullet), industrial wastes (steel slag, fly ash, silica fume, red mud, and pulp paper) agricultural wastes (sugarcanes bagasse ash, rice husk ash, coconut coir fibre, whey, wood ash, and burnt olive waste), construction mining (recycled asphalt pavement) and marine sectors (seashells) in soil stabilization. In soil stabilization, the solid waste applications will not only reduce the cost of pavement construction, but can also be of economic importance in both underdeveloped and developing countries. Eggshell powder considered as one of the domestic solid wastes, which can be adapted to use in soil stabilization due to its high component of calcium carbonate. However, there are limited studies on the optimum content of eggshell powder and hydrated lime for improving the shrinkage and strength properties of expansive soil.

1.6 Thesis Organization

The thesis contains five chapters with the following outline:

- Chapter 1 gives an introduction with respect to the shrink-swell behaviour of expansive soil, the definition of the chemical stabilization without or with a combination of recycled waste materials. In addition, the statement of the project, the research objectives and scope of this investigation are provided.

- Chapter 2 provides an intensive literature review on the stabilization of expansive soil using different types of recycled waste materials, including industrial, agricultural and miscellaneous wastes and by-products. They consist of the unconfined compressive strength and its influencing factors, the pH variations, the bearing capacity, the linear shrinkage and compaction characteristics with various curing times and additive contents.

- Chapter 3 presents the detailed description of the adopted materials, sample preparation and laboratory testing procedures, employed in this investigation. It can also be noted that the test apparatus and devices are described in detail. All experimental tests used in this research were conducted at UTS Tech Lab in Botany.

- Chapter 4 gives an introduction on associated exiting studies and represents the results of the experimental program to evaluate the effect of eggshell powder and lime and their mixture on the properties of the treated soils. Numerous laboratory experiments were performed consisting of measuring pH, the swell pressure, the linear shrinkage, the unconfined compression strength and the California bearing ratio (CBR) on untreated and treated soil samples taking into account the effect of admixture contents and different treatment times.
- Chapter 5 presents a summary of the study and the conclusions derived from the experimental investigations. This chapter also highlights some recommendations for further investigations.

CHAPTER 2

Literature Review and Background

Recycled Waste materials and by-products that can be used in soil stabilization have enormous variations and are produced worldwide. A large series of wastes from domestic, industrial, agricultural, construction mining and marine sectors are considered in the following sections. There are many research works on various types of waste materials in different proportions with or without the presence of an activator (such as cement or lime). Researchers carried out many experiments such as unconfined compressive strength (UCS), compaction properties, swelling properties and California bearing ratio (CBR) to assess the physical properties of weak soil after treatment and ensure the stabilised soil would be suitable to achieve the desired engineering requirements.

2.1 Comparison of Industrial Waste Material for Soil Stabilization

Industrial solid wastes are usually generated by various industrial processes. They are usually placed in closed or open spaces to be disposed of around the perimeter of the plant. There are many industrial wastes that are used in soil stabilization.

2.1.1 Background

Table 2.1 illustrates 5 industrial wastes commonly used for soil stabilisation, including steel slag, fly ash, silica fume, red mud and lignin or pulp paper. It also shows the benefits and challenges of each sort of material referred to. As can be seen in Table 2.1, silica fume provides more advantages for stabilizing soil than other stabilizers in this comparison, while red mud appears as the least effective material. This might be due to the fact that adding the fume in the soil makes their mixture more elastic through high bond strength, hence enhancing its durability. On the other hand, it is more difficult to obtain this state for red mud because of its weaker bonding from complex composition and impurity.Furthermore, red mud is prone to be hazardous to the environment with their potential radioactive characteristics, while silica fume is harmful to expiration because it has a great amount of nano-sized particles. Referring to Table 2.1, each of the industrial waste materials has different characteristics and specifications suitable for use in soil stabilization. Silica smoke and fly ash are some examples, where their size and surface impacts can reduce the volume of ash deposited in the tailing dams. Pulp paper, nevertheless, is standing out with its sustainability when a great amount of paper waste can be used for engineering application. Fly ash and steel slag could be a partial replacement for aggregates, but their threat to groundwater quality can deter their stabilizing use in terms of environmental protection. Consequently, it is recommended to use silica fume due to its strength improvement in soil and fly ash for its low-cost options, while red mud can be used with its local availability in certain areas. Each industrial waste in Table 2.1 is reviewed in detail. Afterwards, their engineering properties in expansive soil stabilisation have been compared. The experiment tests, with or without the presence of an activator (e.g. cement or lime) include the unconfined compressive strength (UCS), the compaction properties, the swelling properties and the California bearing ratio (CBR). These tests are necessary to assess the physical properties of weak soil after treatment and ensure the stabilised soil would be suitable to achieve the desired engineering requirements.

2.1.2 Steel Slag

Steel slag is considered one of the most common industrial wastes, generated through either the steel-making process or by-product of the combustion process. This process produces different types of steel slag at different stages, such as electric arc furnace slag (EAFS) followed by ladle furnace slag (LFS). The high swelling potential is one of the main challenges appears to the slags applications (Hua-dong & Liu 2009; Maghool et al. 2017; Vaníček, Jirásko & Vaníček 2016; Vaníček & Vaníček 2013b).

Many investigators conducted different experimental programs to obtain the behaviour of stabilized soil using various types of steel slag. Poh, Ghataora & Ghazireh (2006) studied the use of basic oxygen steel (BOS) slag fines for soil stabilization. Experimental tests to treat English China clay and Mercia mudstone were conducted employing different BOS slag fines, collected from three different sites. Goodarzi & Salimi (2015) presented a comparison of using granulated blast furnace slag (GBFS) and basic oxygen furnace slag (BOFS) in dispersive soil stabilization. Both of these materials were separately added in the range of 2.5% – 30%. A set of tests were carried out to study the physicochemical, mechanical and microstructural changes of the stabilized soil. The results indicated that BOFS was very effective to overcome the problems associated with stabilizing dispersive soil, adding 10% of the stabilzer (BOFS), whereas GBFS had less impact on the soil engineering properties. They found a high percentage (20%-25%) was required to make a tangible change.

Activators such as lime and cement have a significant effect in improving the soil strength and stabilizations. Wild et al. (1998) delved into the positive impact of GBFS and its applications in soil durability enhancement, sulphate attack resistance, and chloride penetration resistance by partial replacement of lime in soil stabilization with GBFS. The treatment of flooded low capacity soil with lime and GBFS had investigated by Obuzor, Kinuthia & Robinson (2012). The results indicated increasing the strength of the flooded samples and a reduction in water absorption with the addition of GBFS. In a study conducted by Manso et al. (2013), the behaviour of clayey soil and its geotechnical properties such as the plasticity index, expansiveness, bearing capacity and durability were studied by adding Ladle Furnace Slag (LFS). It was found that the behaviour of this combination provided the same impact on the soil and lime mixture by significantly increasing the compressive strength and reducing the plasticity index (PI) and free swelling. On the other hand, this research found that the durability index of the soil and LFS slag mixtures is higher than the durability index of the soil and lime mixtures. Another type of steel slag was investigated to stabilize the soil through an electric arc furnace (EAF) steel slag (Akinwumi 2014). Many tests were conducted in this paper to confirm the applicability of soil stabilization. These tests were sieve analysis, consistency limits, specific gravity, compaction, California bearing ratio (CBR), unconfined compressive strength (UCS) and permeability. The results clarified that the optimal value of EAF was 8%, and by adding this value the unsoaked CBR increased by 40%, while the liquid limit, plastic limit and plasticity index were reduced by 6.3%, 4.0% and 2.3%, respectively. Using another conventional stabilizer, it was investigated the effect of slag as an additive to the bricks made of cement stabilized mud (Vijayaraghavan, James & Marithangam 2009).

2.1.3 Fly Ash

An industrial by-product, fly ash is considered as a pollutant waste material, as it is generated from the combustion of coal in coal-fired electric power and steam generating plants. Due to the negative impact of fly ash on the environment, much research has been conducted to minimize the volume of ash and use it in soil stabilization (Sabat & Pati 2014).

Various studies have been conducted to investigate the effects of adding fly ash and cement on different types of soil along with their geotechnical properties. Akinwumi (2014) found that the optimum percentage could approximately be 9% of cement and 3% of fly ash through which the maximum dry density (MDD), the optimum moisture content (OMC), CBR and shearing resistance were highly improved. In studying the potential of stabilizing expansive subgrade soil, Zumrawi (2015) used various values of fly ash up to 20% (i.e. 0, 5 10, 15 and 20%), mixed with a constant amount of cement (5%). He found a significant improvement in the geotechnical properties of soil, such as its strength, durability, reduction in swelling in addition to its plasticity.

These various properties were at their best when the dosage of fly ash and cement were 15% and 5% respectively. Moreover, he discussed the properties of treated and untreated soils, including consistency limits, compaction, CBR, the swell potential and the swell pressure. With respect to consistency, the liquid limit and the plasticity index decreased, while the plastic limit increased. It was observed that MDD increased by 7% compared to untreated soil, while there was a decrease in OMC by 15%. In treated soil, when fly ash was between 5% and 15%, CBR reached its highest value. This improvement was 90% compared with untreated soil.

Many researchers (Bhuvaneshwari, Robinson & Gandhi 2005; Bose 2012; Edil, Acosta & Benson 2006), however, found an improvement in the geotechnical properties after the utilization of fly ash even without adding cement into expansive soil. Wang, Abriak & Zentar (2013) examined the strength and deformation behaviour of Dunkirk marine sediments with cement, lime, and fly ash. As expected, they observed that the addition of activators increased the strength of stabilized sediments.

Many studies also carried out to investigate the addition of lime, another common conventional stabilizer. Sharma, Swain & Sahoo (2012) used the combination of lime and fly ash for stabilization of clayey soil and found that the best result was obtained when the soil stabilized by 20% fly ash and 8.5% lime, produced a sufficient strength for road subgrade. Mishra (2012) conducted another experiment on clayey soil by adopting fly ash as an additive to lime in soil stabilization; and he noticed that the optimum values for the additives lime and fly ash were 3% and 30%, respectively. It was recommended to use this mixture for stabilization of subgrades. As well as the results indicated that the addition of fly ash to lime stabilization, produced a significant improvement in soil strength. It can be stated that many researchers (Ahmaruzzaman 2010; Vaníček, Jirásko & Vaníček 2016; Vaníček & Vaníček 2013a) used lime or cement in combination with fly ash in soil stabilization.

Other studies, conducted on expansive and black cotton soils, indicated improvement in the geotechnical properties of these soils when fly ash and other materials were added. Radhakrishnan, Kumar & Raju (2014) investigated the swelling properties of Magnesium and Aluminum chloride with fly ash on expansive soil. It was found out that the swelling potential, swelling pressure (SP) and different free swell (FS) decreased to a certain extent. Sabat & Pradhan (2014) found that the optimum percentage and length of polypropylene fibre is 1% and 12mm and the optimum fly ash percentage is 20%. These percentages would result in improving the strength and swelling behavior of the soil. The study was investigated on the compaction properties, (UCS), soaked CBR, and (SP) of expansive soil. Pandian & Krishna (2003) added fly ash to black cotton soil gradually until it reached 100% of the treated soil. CBR values increased up to 20% and then decreased. The optimum value it reached was when fly ash was 70%. On the stabilization of organic soils, Tastan et al. (2011) added fly ash as a stabilizer to study the degree of stabilization that will be obtained. UCS and resilient modulus tests were carried out on the stabilized soil specimens. He found that the strength of organic soil depends on two parameters, the type of soil and the characteristics of fly ash.

Consequently, the UCS was increased by adding fly ash. In exploring the effect of Neyveli fly ash in stabilizing of shedi soil, Ramesh, Nanda & Manoj Krishna (2013) found that the maximum strength of the stabilized soil can be obtained by adding 20% of Neyveli fly ash. It was noticed that the strength for both soaked and unsoaked conditions increased by increasing the curing periods. The effect of adding sand, fly ash, and tile waste on the geotechnical properties of clay soil was investigated by Singh, Kumar & Sharma (2014). The CBR tests were determined for various blends. It was found that with the addition of sand, fly ash and tile waste both of soaked and unsoaked, CBR increased. It was revealed that the MDD decreased and OMC increased with the addition of fly ash to the combination, clay and sand while he noticed an initial increase followed by a decrease by adding tile waste. A combination of industrial waste from Phospho-gypsum and fly ash were intruded and studied for soil stabilization by Krishna et al (2014).

2.1.4 Silica Fume

An industrial by-product of producing silicon metal or ferrosilicon alloys. One of its applications is soil stabilization and improve its geotechnical properties (Uzal et al. 2010).

Different studies were conducted to investigate the geotechnical properties of different types of soil when adding silica fume. It was carried out two different studies on the effect of silica on two types of soil (Kalkan & Akbulut 2004) (Kalkan 2009). In the former study, many experiments were performed on the compacted soil to study the consistency limits, compaction properties, permeability, UCS and swelling pressure of soil. It was found that permeability and swelling pressure were reduced, while UCS increased after treatment. In the latter study, it was found that by adding silica fume to the fine-grain soil, the effects of freezing and thawing cycles would be reduced. There was an improvement in the soil properties. For instance, UCS, plastic limit and OMC increased. Furthermore, it was indicated a positive effect on decreasing the liquid limit, plasticity index, MDD and the permeability.

Kalhan (2012) conducted a comparison between the combinations of lime and silica fume and lime and fly ash on the stabilization of granular soils. It was shown that the combinations of lime and fly ash had produced high strength and significant values of CBR compared with the other mixture. Another experiment was performed by Moayed et al. (2012) on the stabilization of saline silty sand using lime and micro-silica.

CBR and UCS tests were performed to assess soil improvement, and it was found that the optimum dose of lime and micro-silica was 2,3%, respectively, to improve soil properties. To uncover the engineering properties of clayey soil, Abo-Hashema & El-Shourbagy (2004) blended lime with silica fume and found that by adding 5-9% lime mixed with 10% silica fume, CBR, friction angle and soil cohesion increased. However, the plasticity index, swell pressure and the value of the consolidation settlement decreased. Bagherpour & Choobbasti (2003) explored the difference between micro silica and lime or micro silica and cement on stabilization of silty clay of low plasticity. It was noticed a significant increase in the strength when adding micro-silica to lime compared to the addition of cement. Another study on black cotton soil carried out by Negi, Yadav & Singhai (2013) showed that by adding 20% silica fume, the unconfined compressive strength increased by 31% and the CBR increased by approximately 72%.

2.1.5 Red Mud

Red mud is a solid waste produced in the process of alumina production from bauxite following the Bayer process, and it is considered hazardous due to its high pH. Its major constituents are Fe_2O_3, Al_2O_3, SiO_2, Na_2O, and CaO (Ribeiro, Labrincha & Morelli 2011; Samal, Ray & Bandopadhyay 2013).

Several studies were conducted on the effects of using red mud in soil stabilization. By adding red mud and sodium silicate to the black cotton soil, Mane et al. (2017) concluded that in order to get the optimum stabilization results, there should be 30% of red mud replacement with 6% sodium silicate. A series of laboratory tests were conducted on the mix design such as UCS and CBR tests. The maximum point of UCS was 1.314 kg/cm^2. Furthermore, it was observed that the ultimate value of CBR was 3.9% with 8% of Sodium silicate. Kalkan (2006) analyzed the effects of adding red mud (RM) and cement-red mud (CRM) on the geotechnical properties of composite soil samples in addition to their possible utilization as compacted composite clay liners. After carrying out several tests such as UCS, permeability tests, and vertical swelling, he observed that there was a turn in the soil groups from high-plasticity soil group to low-plasticity soil group. There was an observable improvement in UCS, especially with composite samples containing cement red-mud. It was noticed that the values of vertical swelling and hydraulic conductivity decreased. As a result, RM and CRM could be used in several geotechnical applications, and the RM, particularly, may be used as a clay liners modifier. Gayathri (2016) investigated the addition of another binder, and delved into the possibility of using red mud as a stabilizing material and replacing the soil in the lime-soil treatment. The results showed that the optimum dosage is 2% of lime, 20% red mud in the soil at which the improvement was significant, compared to 15% red mud. Consequently, this confirms the possibility of replacing the soil by red mud when treating the soil with lime.

2.1.6 Pulp Paper

After being lightened, pulping wood is spread out into pieces in order to make paper. Then, it is processed through several chemical stages to give it certain properties such as turning paper into white colour through the bleaching stage and enabling it to be in various colours (Zavatta 1993).

In order to discover the effects of paper on the properties of various soils, tests on several soil mixtures were carried out. The expansive soil was treated with paper mill ash to test its UCS, CBR, Atterberg limits, MDD and OMC, all of which were improved (Byiringiro 2014). It was concluded that there was a similarity in properties between ash-soil treatment and lime treatment, and it was observed that paper mill ash from a multi-fuel boiler was a proper choice to be used for expansive soil treatment. Eroglu, Acar & Ucuncu (2012) found that lime mud from the paper industry enhances the geotechnical properties of soil used to stabilize forest road superstructures. The properties improved including Atterberg limits, the specific gravity, the cohesion, the slip strength angle, the slip strength coefficient, MDD and OMC.

Table 2.1 Industrial waste materials and their specifications

Material	Advantages	Challenges	References
Steel Slag	• Protection of natural aggregate.	• High swelling • Water pollution	(Maghool et al. 2017; Qasrawi, Shalabi & Asi 2009; Vaníček, Jirásko & Vaníček 2016; Vaníček & Vaníček 2013a; Yi et al. 2012)
Fly ash	• Decreased volume of ash deposited in tailing dams. • Decreased carbon footprint.	• Water pollution • Cost of transporting unit-value of coal fly ash. • Lack of knowledge of potential ash uses and its Sensitivity to surface erosion.	(Ahmaruzzaman 2010; Sabat & Pati 2014; Vaníček, Jirásko & Vaníček 2016, 2017)
Silica Fume	• High modulus of elasticity and Increased toughness • High bond strength and Enhanced durability • Superior resistance to chemical attack from chlorides, acids, nitrates and sulphates, etc. • High electrical resistivity and Low permeability	• Handling problem • Health hazards • High cost	(Khan & Siddique 2011; Mazloom, Ramezanianpour & Brooks 2004; Sabat & Pati 2014; Siddique 2011)
Red mud	• Improved soil properties • Reduced foundation and building cost.	• Difficulty in usage, due to its high alkalinity and water content • Complex composition and fine grained size. • Limited application due to the presence of sodium and radioactivity. • Environmental concerns	(Ashok & Sureshkumar 2014; Najar P.A et al. 2012; Rathod, Suryawanshi & Memade 2013; Ribeiro, Labrincha & Morelli 2011; Samal, Ray & Bandopadhyay 2013; Singh, Upadhayay & Prasad 1996; Soosan et al. 2005)
Lignin/pulp paper	• Sustained natural resources • Decreased environmental pollution	• Health hazards • Unendurable use	(Balwaik & Raut 2011; Seyyedalipour et al. 2014)

2.1.7 Engineering properties of treated expansive soils using industrial recycled waste materials

The improvements achieved of the unconfined compressive strength when the untreated soil stabilized by using some of the industrial wastes without any conventional stabilizer (lime/ cement) or with combinations of lime/ cement treated expansive soil are shown in Figure 2.1. The figure depicts that the addition of industrial solid wastes has resulted in improving the UCS as investigated by various researchers. At the optimum state, there is at least 29% increase in the UCS test result in the case of 30% silica fume. In addition, at the best state, it is clear that the addition of 20% Neyveli ash has the maximum improvement on UCS, as it is around 13.75 times more than the UCS before improvement. As for the mixtures of 8% steel slag, 30% silica fume, 20% silica fume, and 30% red mud) to soils, these materials have a relatively equal effect on soil improvement as shown in the UCS results. The improvement obtained due to the addition of industrial waste materials at the optimal dosage to lime/cement stabilization also shown in Figure 2.1. It can be seen that the addition of industrial waste produced better results than only using conventional stabilizers, such as lime or cement. Stabilization using granulated blast furnace slag (GBFS) produce excellent strength as well as swell control, and it was adopted with highly plastic, expansive clays. As shown in Figure 2.1, positive effects were generated, using combinations of lime/cement with industrial wastes at their optimal dosages.

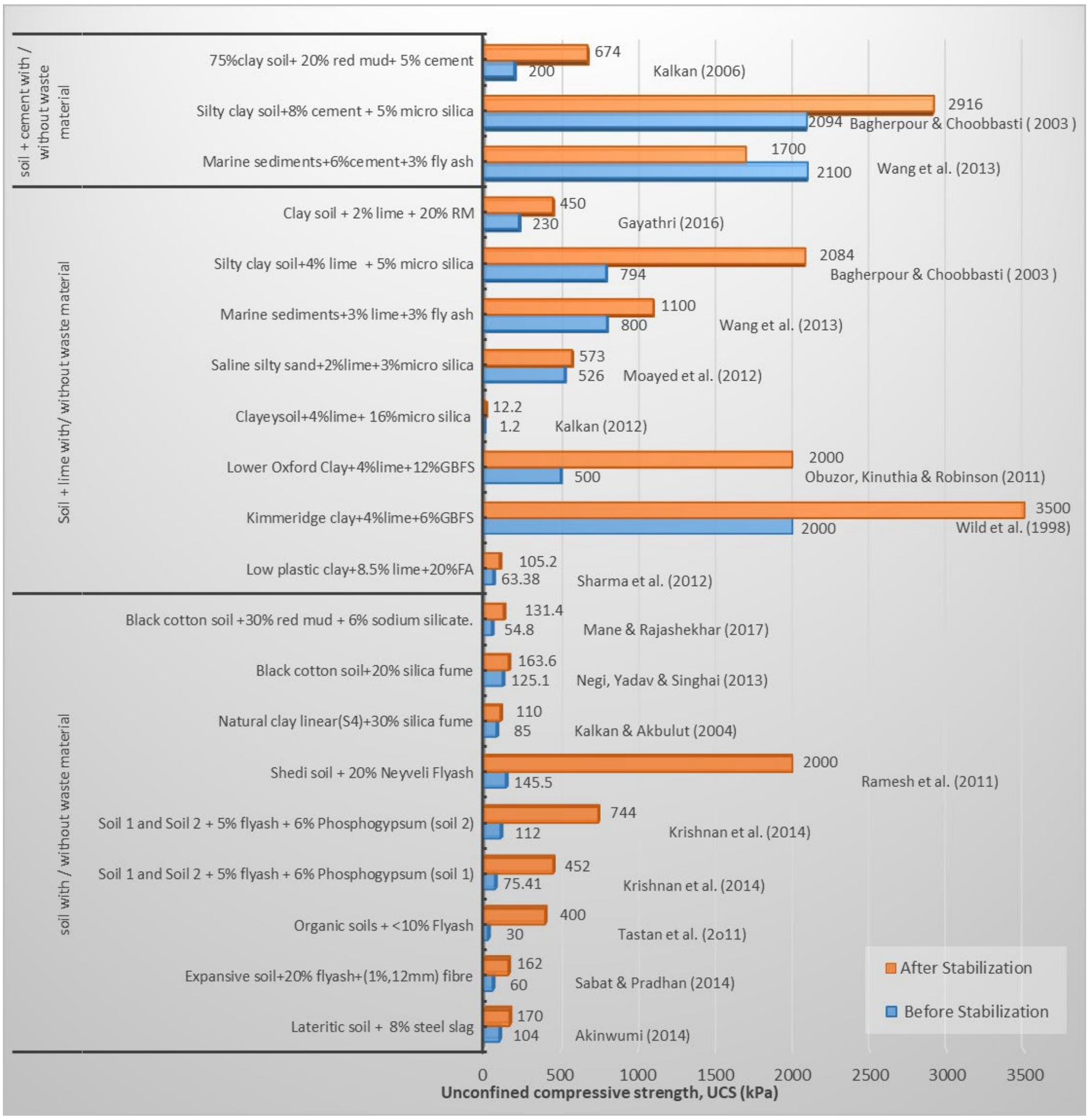


Figure 2.1 Comparison of UCS test results achieved by adding industrial wastes to the soil with or without a common stabilizer (lime or cement)

The improvements of soaked California bearing ratio (CBR) obtained when the untreated soil stabilized by using some industrial wastes material without any conventional stabilizer or with a combination of lime treated expansive soil are shown in Figure 2.2. In case of using 8% steel slag for stabilizing laterite soil, any increase in the steel slag content contributes in lowering CBR values as they are strongly correlated on soil because the value of the soaked CBR decreases. Figure 2.2 indicates that the combinations of 20% fly ash with 1% fibre in the length of 12 mm, different proportions of fly ash, 63, 27, and 10% with 9% tile waste, 20%

silica fume, and 30% red mud with 6% sodium silicate have relatively equal effects on increasing the CBR value 4%, 3%, 1% and 2%, respectively. In fact, paper mill ash has the most effect on growing the CBR from 2.8% to 64.4%. Consequently, there are instances of CBR rising in the case of paper mill ash and just by 1% in the case of silica fume. This indicates that the development of strength is influenced by the soil type and the nature of the industrial waste. Moreover, as shown in Figure 2.2, when the industrial wastes added to the lime-treated expansive soil, a noticeable increase in the CBR values were observed.

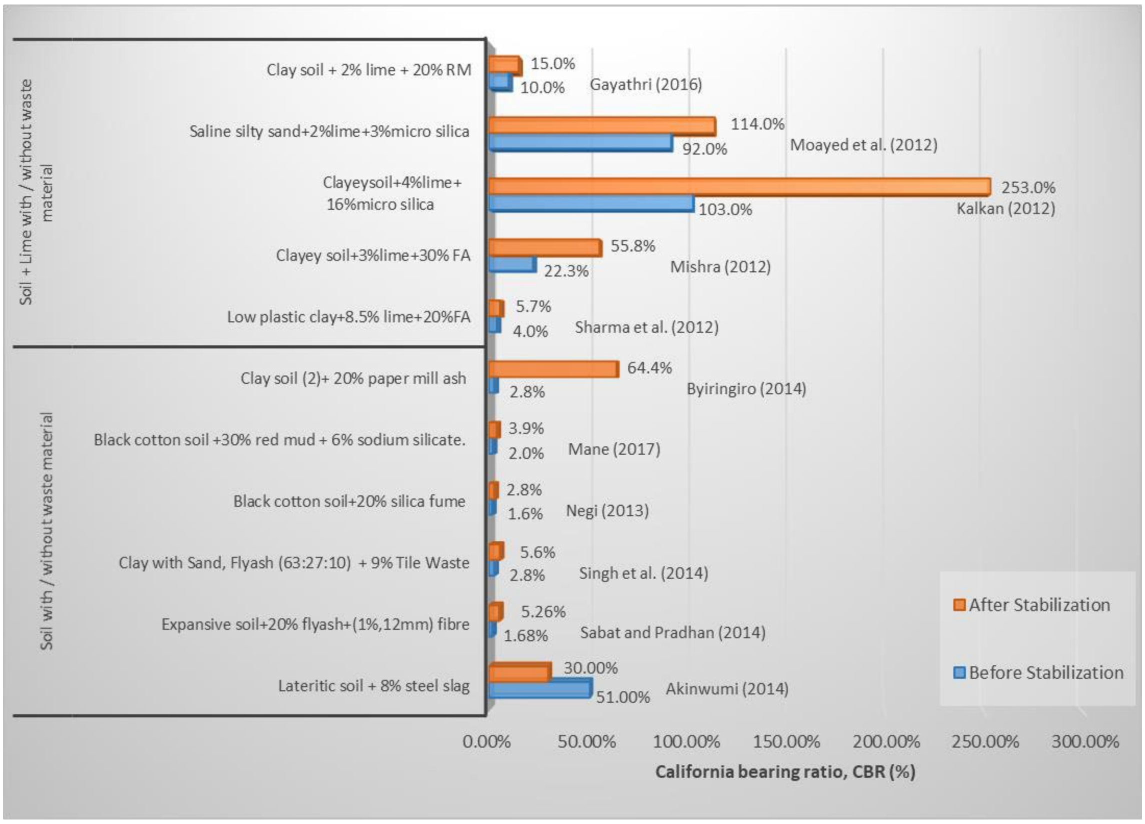


Figure 2.2 Comparison of soaked CBR achieved by adding industrial wastes to the untreated soil with/without lime treated soil

2.2 Comparison of Agricultural Waste Material in Soil Stabilization

Agricultural wastes are obtained from agricultural resources, produced by processing various agricultural products. A number of common agricultural wastes include sugarcane ash (bagasse ash), rice husk ash, sugarcane fibre, peanut husk, wood ash, burnt olive waste and coconut fibre. Table 2.2 illustrates 8 agricultural wastes that have been used in soil stabilization and it also shows the benefits and challenges for each sort of stabilizer. A number of investigations, conducted on the stabilization of soil using agricultural wastes, are described below.

As can be seen in this table, sugarcane bagasse ash, bagasse fibre, and rice husk ash have distinctive properties due to their high percentage of silica. The percentage of silica in bagasse ash is approximately 87%, while in rice husk ash is about 90-98%. This great amount of silica can enhance the engineering characteristic of expansive soils by improving the efficiency of the pozzolanic reaction. Meanwhile, peanut shell ash contains a small percentage of silica, which could limit its potential for meeting the criteria of the soil strength. Utilization of these agricultural wastes in soil stabilization can reduce the carbon footprint and energy consumption as well as solve its disposable problem. Particularly, coconut fibre proves to be a good reinforcement material due to it's resistant to fungi and rot and its excellent insulation against temperature and sound. Nevertheless, there is an inverse impact if exceeding the optimum percentage of coconut shell. The same impact on soil properties is noticed by adding a high percentage of olive wastes. Furthermore, for improving soil alkalinity, it was suggested to use wood ash as a stabilizer (Brown, Robbins & Freeborn 1998). In addition, it is recommended to employ rice husk ash in soil stabilisation due to its great amount of silica and agricultural fibres for soil strength reinforcement. However, despite the advantages of bagasse fibre in soil strength reinforcement, the durability of this mixture should be improved with fibre treatment (e.g. soaking fibres in sodium hydroxide before soil mixing).

Table 2.2 Agricultural waste materials and their specifications

Materials	Advantages	Challenges	References
Coconut coir fibre	• Low cost • Easy to use or handle • Resistant to fungi and rot • Excellent insulation against temperature and sound.	• Changed chemical composition of fibres because of immersion in water, saturated lime, and sodium hydroxide leading to loss of their strength.	(Ali et al. 2012; NADGOUDA 2014)
Sugarcane bagasse ash	• Low cost • Low co2 emission • Reduced energy consumption. • High silica content 87%	• Low impact on strength of soil • The problem of stocking raw material for an extended time.	(Ahmaruzzaman 2010; Balaji, Karthikeyan & Raj 2014; Hailu & Dinku 2012; Sabat & Pati 2014; Schettino & Holanda 2015; Srinivasan & Sathiya 2010)
Rice husk ash	• Reduced carbon footprint and energy consumption • High silica content	• A suitable incinerator and grinding method is needed to obtain good quality ash. • Transportation problem.	(Al-Khalaf & Yousif 1984; Ganesan, Rajagopal & Thangavel 2008; Rao & Chittaranjan 2011)
Bagasse fibre	• Solving its disposable problem	• Incompatibility between fibres. • Poor resistance to moisture. • High concentration of fibre defects. • Fibre degradation during processing	(Aggarwal 1995; Aziz, Paramasivam & Lee 1981; Ghazali et al. 2008; Venu & Rajalingam)
Peanut shells	• Low capital cost per tonne production compared to cement • reduced pollution and CO2 emission • conserved limestone deposits • Good Pozzolanic material, which reacts with calcium hydroxide.	• Little potential use • Not meeting the criteria for soil properties.	(Alabadan, Njoku & Yusuf 2006; Buari, Ademola & Ayegbokiki 2013; Mahmoud, Belel & Nwakaire 2012; Oriola & Moses 2010)

Materials	• Advantages	• Challenges	References
Wood ash	• Minimized energy consumption and carbon footprint. • Low cost. • Improved soil alkalinity as fertilizer. • Being able to capture several waterborne contaminants.	• Being prone to cracking, deforming or insects due to its low corrosion resistance. • poor stability	(Bohrn & Stampfer 2014; Cheah & Ramli 2011; Okagbue 2007; Rao, Reddy & Muttharam 2001)
Burnt olive waste	• Saving natural material. • Low cost Reduced environmental pollution.	Inverse impact on soil properties if exceeding the optimum percentage.	(Al-Akhras & Abdulwahid 2010; Attom & Al-Sharif 1998; Mo et al. 2016; Nalbantoglu & Tawfiq 2006; Rao & Chittaranjan 2011)

2.2.1 Coconut Coir Fibre

Coconut coir belongs to the hard-structural fibres group, and it is taken from coconut husk. It is an organic fibrous material containing 40% lignin and 54% cellulose. Because of its high lignin content, coir has the potential to be used as reinforcing the material in the soil (Khatri et al. 2016).

Many researchers have shown that coir fibre reinforcement can significantly improve the engineering properties of soil. The aim of Abhijith (2015) study was to research the effect of coir textiles on CBR strength of soil subgrade and to determine the ideal position to place the coir geotextiles. Coir fibres with various lengths and proportions, 5-30mm, 2-8% of the total weight of soil were added. The optimum fibre length and proportion were 15mm, 5% of the total weight of soil respectively. At this value, the CBR strength was enhanced. It was observed that the best position for placing the coir geotextiles at the top position of the subgrade while the least value obtained was at the lowest position. The effectiveness of adding coal ash and coconut coir fibre in local soil (silty sand) was explored by Singh & Arif (2014). Different proportions of coal ash, 20, 30, 40 and 50% were added to the soil. The maximum values of UCS and CBR were noticed to be at 20% coal ash content. The mixture of coal ash and soil 20% and 80%, respectively, was mixed with randomly coconut coir fibre. The optimum percentages of soil, coal ash and coir fibre mix were reached at 80:20:0.25 by dry weight of soil. At these values, all of the properties of the soil were greatly improved. Anggraini et al. (2015) investigated the effect of coir fibre content and curing time on the tensile and compressive strength of soft soil treated by lime. The test results indicated that compressive strength was less sensitive to lime and coir fibre stabilization compared to tensile strength. Another experimental study was conducted to investigate the compaction and strength behaviour of mixtures of clay-pond ash (PA) treated with cement- coir fibre. The soil was replaced by a different percentage of PA and it was found that the maximum UCS was reached at 1% coir fibre and 4% cement (Yadav & Tiwari 2016).

2.2.2 Sugarcane Bagasse Ash

Sugarcane bagasse is a fibrous waste product of the sugar refining industry. When the juice is extracted from the sugarcane, the solid waste material is known as bagasse. When this waste is burned, it gives ash called bagasse ash. Bagasse ash mainly contains aluminium and silica ions. It is a fibrous material with the presence of silica (SiO_2) can be used to improve the existing properties of black cotton soil (Sabat & Pati 2014; Srinivasan & Sathiya 2010).

Several studies were performed on the effects of bagasse ash (BA) mixed with lime and cement activators on the geotechnical properties of different types of soils. Many experiments were conducted on mixing BA with lime. Osinubi, Ijimdiya & Nmadu (2009) concluded that 8% lime and 4% BA on black cotton soil were the optimum values at which the peak CBR value was obtained 31%, and this value meets “the recommended criteria for subgrade materials”. However, the UCS on the seventh day was lower than 1034.25 kPa, an evaluation criterion for adequate lime stabilization. As a result, the black cotton soil could be stabilized for road construction. On the stabilization of compacted soil blocks, Alavéz-Ramírez et al. (2012) concluded that 10% lime with 10% BA enhanced the mechanical properties of compacted soil blocks. The results were obtained after 7, 14, and 28 days of conducting the experiment. Investigating the effects of adding this mixture of lime and BA to the lateritic soil by Sadeeq et al. (2015). In order to investigate “the effectiveness of lime and bagasse ash admixture in reinforcement the sub-grade of flexible pavement in the expansive soil, Sabat (2012c) concluded that 8% BA and 16% lime sludge were the optimum values at which the best stabilization could be obtained. Manikandan & Moganraj (2014) studied many properties of expansive soil and its consolidation characteristics. They observed that the combined effect of lime and BA were more effective than the effect of bagasse ash alone in controlling the consolidation characteristics.

Mu'Azu (2007) added up to 8% bagasse ash with up to 4% cement on the lateritic soil to investigate "the influence of British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) on the compactive effort". The results showed that MDD and OMC were dependent on the compactive energy. When the competitive effort increased from BSL, WAS and BSH, the value of MDD increased and OMC decreased. However, adding bagasse ash and cement to lateritic soil positively affected the shear strength properties; while there was a decrease in cohesion, and an increase in the angle of internal friction without any chemical or cementing material. Three different BA contents of 2%, 4%, and 8% were blended with two different cement contents in a study conducted by Lima et al. (2012). It was found that adding BA to a lesser amount of cement increased the compressive strength of compacted stabilized soil blocks. Kharade et al. (2014) added different amounts of BA to the black cotton soil (3%, 6%, 9% and 12%). The optimum value was 6% replacement of bagasse ash. Using the optimum stabilization dosage, MDD increased by 5.8%, CBR increased by 41.5% and UCS increased by 43.6%.

2.2.3 Rice Husk Ash

According to Rao and Chittaranjan (2011), after rice husk is obtained from paddy, it is disposed of by various methods, either "by dumping it in an open heap near the mill site or on the roadside to be burnt later". Burning rice husk produces 15-20% of its weighing as ash. Every 40 kN of rice, produces 10kN of husk. The ash is easily carried by the wind because of its lightweight. Being rich in siliceous material means that it has pozzolanic properties (Rao and Chittaranjan, 2011).

Many researchers studied the effect of using rice husk ash (RHA) with cement in stabilizing different types of soil. Alhassan and Mustapha (2007) added this mixture to lateritic soil, and they investigated many geotechnical properties of the treated soil, including CBR, UCS, MDD and OMC. A significant improvement was reported in the CBR and UCS with an increase in the RHA content. The peak values were reached at 6-8% cement and 4-6% RHA. Employing the same type of soil, Rahman (1987) used the same mixture of cement and RHA in order to investigate the potential of using that type of treatment in highway construction. He figured out that for the sub-base materials, the best result was found by mixing 6% RHA and 3% cement. For the base materials, it was concluded that the best result was associated with using 6% of both cement and RHA. For investigating the stabilization of residual soils, Basha et al. (2005) used cement and RHA. They conducted an array of tests, including compaction, CBR, UCS and X-ray diffraction. The optimum amount of cement and RHA were 6-8%, 10% respectively, at which the plasticity and the MDD were reduced, while CBR, OMC and UCS were increased and the CBR reached to its peak value of 60% at the combination of 6-8% cement and 10% RHA. The combination of cement and RHA would achieve a given strength with only a small amount of cement, compared to adding cement alone. In stabilization of high plasticity clay, Roy (2014) delved into the effect of RHA and cement mixture. The result revealed that 10% RHA with 4% cement was optimal to increase and improve the strength and CBR of the soil.

Other studies were carried out using RHA, lime and calcium chloride and polypropylene on certain types of soil. On clayey soil, Muntohar et al. (2000) added this mixture to find out its geotechnical properties. It was observed that when lime was 6-10% and RHA 10-12.5%, Plasticity index, CBR, shear strength parameters, swelling potential and specific gravity were significantly improved. Sabat (2012) analyses using polypropylene fibre in addition to the RHA and lime mixture to stabilize the expansive soil. The properties tested were compaction, UCS, soaked CBR, hydraulic conductivity and swelling potential all of which had improved at the optimum values of RHA: lime: fibre at 10:4:1:5, respectively. Sharma et al. (2008) implemented an experiment on the effects of adding calcium chloride, lime and RHA. The optimum values of lime, calcium and RHA were 4%, 1% and 12% at which UCS and CBR were enhanced. A slight improvement on the CBR, UCS, compaction characteristics was noticed after using RHA in soil stabilization. Al-Hassan (2008) added 2-12% RHA by weight of the dry soil. There is a little possibility of using RHA to improve the strength of soil depending on its maximum percent 6-8%. There was a clear difference in the values of UCS when comparing the treated soil and the soil treated with two ratios of RHA. The maximum UCS values were 293 kPa and 295 kPa at 6% and 8% RHA, respectively.

2.2.4 Bagasse Fibre

As a reinforcing component for expansive soil stabilization, bagasse fibre can be used although its degradation by time is an uncertain issue. Bagasse fibre is a by-product of the sugarcane industry. After the sugarcane is crushed for juice extraction, bagasse fibre is obtained (Onésippe et al. 2010).

A number of tests were conducted to uncover the effects of bagasse fibre on the geotechnical properties of stabilized expansive soils. A study by Oderah (2015) on sandy and clayey soils was conducted by adding different bagasse fibres content. He found out that there is a relation between bagasse fibre content and the shear strength parameters values of the soils, the more the bagasse content is, the more the shear strength parameters values are. The optimum content of bagasse fibre was 1.4%. The combination of hydrated lime and bagasse fibre proved to be more efficient to enhance soil properties than adding bagasse fibre by itself. This is what was emphasized by Dang, Fatahi & Khabbaz (2016), which is found that the optimum values are 0.5% bagasse fibre with 7% lime at which the expansive soil properties were improved. With increasing the curing time, bagasse fibre and hydrated lime, there was an observable decrease in the linear shrinkage of treated expansive soil.

2.2.5 Groundnut Shell Ash

Many researchers studied the feasibility of using Groundnut shell ash (GSA) to stabilize black cotton soil. The milling of groundnut results in groundnut shell which is considered as a waste. Because the accumulation of the groundnut shells has a negative impact on the environment and because of their low cost, they can be turned into ash in order to be utilized in stabilizing poor soil (Oriola & Moses 2010).

Several tests were conducted by Ijimdiya, Ashimiyu & Abubakar (2012); Otoko & Precious (2014) in order to check the geotechnical properties for black cotton soil blended with different content of GSA. They concluded that UCS depends on the curing period of the soil. Peak UCS at seven days “failed to meet the acceptable requirement for the base, sub-base and subgrade” while with longer curing time, they noticed a gradual strength development. From this observation, for better stabilization with Groundnut shell ash, it is recommended to mix it with a stronger stabilizer.

2.2.6 Whey

Many studies were conducted to investigate cottage cheese whey and straw to stabilize the soil by reducing soil erosion and increasing infiltration in narrow trench irrigation systems. Manufactured from cottage cheese through the phosphoric acid method, the liquid acid whey can be used to reduce sediment losses from furrow irrigation and stabilize soil aggregates (Lehrsch, Robbins & Brown 2008).

The acid whey with very high biochemical oxygen demand (BOD) can generally be used as an animal feed additive, reducing whey disposal problem (Brown, Robbins & Freeborn 1998). Whey and straw were used by Brown et al. (1998) to uncover their efficiency in reducing erosion and increasing infiltration. They found out that utilizing whey by itself effectively reduces sediment loss by 86% while mixing whey with straw was effective in significantly reducing erosion and increasing infiltration by 98%. Lehrsch et al. (2008) found out that sediment loss using whey was 75%. They used whey without any additives to check its efficiency in developing aggregate stability and soil erosion. It was observed that at 0–15 mm depth, the aggregate stability was 25% while at 15-30 mm, it was 14%.

2.2.7 Wood Ash

Whether burned in a home fireplace or an industrial power plant, the combustion of wood produces organic and inorganic powder known as wood ash. Being rich in potash make it useful for gardeners (Demeyer, Nkana & Verloo 2001).

Several tests have been made on different types of soils to investigate the effectiveness of wood ash in increasing soil strength. The stabilization of clay soil by using wood ash was evaluated by Okagbue (2007). The addition resulted in an increase in the strength and CBR of the soil and decreased the plasticity and dry density of the soil. Barazesh, Saba, Rad, et al. (2012) conducted an experiment to check the soils' Atterberg limits by adding different content of wood ash. The liquid limit decreases with increased wood ash weight except for soil type 4 in which the diagram followed a downtrend. Moreover, the plasticity index was reduced in soil type 3 and 4 and the diagram followed a downtrend. While Barazesh et al. (2012) conducted their experiment on a clay soil to check the Atterberg limit, Šķēls et al. (2016) implemented their experiment on the natural sand (SA) soil to check its load-bearing capacity. The test was also made to check wood fly ash potential as a good hydraulic binder with sand. Natural sand mixed with two different proportions of wood fly ash, 10% and 20% were compacted at optimal water content. After 96 hours of immersing the samples in water and after 7 days of sealing them, it was observed that the immediate bearing index was improved more than four times when compared to the untreated soil. The best results were obtained when there was 20% of wood fly ash. Bade et al. (2017) conducted an experiment to check the soil samples' plasticity index. They used ash derived from powdered wood shaving on the black cotton soil. Different percentages of wood shaving ash (i.e. 15%, 20% and 25%) were added to the soil sample mass. The optimum value was 25% of wood shaving ash at which the plasticity index comes down to 16.56%. As a result, adding more wood shaving ash would enhance the stabilization of the soil by reducing the plasticity index. By adding lime in addition to wood ash to stabilize lateritic soil, Amu et al (2005) conducted compaction and CBR tests to establish the analysis parameters needed for the study. It was observed that some of the geotechnical properties were enhanced more by adding lime by itself while others were improved when wood ash was added by itself. To obtain the best values for the CBR, it is preferred to stabilize it only with lime. However, in order to obtain the best values for the maximum dry density, it is preferred to use wood ash as a good stabilizer. The optimum percentage of stabilization was obtained at 6% for both lime and wood ash.

2.2.8 Burnt Olive Waste

After pressing olives and extracting them to produce oil, the by-product olive waste is left behind. The olive cake residue is continuously increasing in the Mediterranean countries, and it is predicted to double in an amount within 10-15 years. This quantity of the by-product olive cake could be beneficially used as a soil stabilizer (Nalbantoglu & Tawfiq 2006; Rao & Chittaranjan 2011).

Many researchers explored the effectiveness of using burnt olive waste in stabilizing expansive soils as a way to solve the problem associated with the increase of olive waste. Attom & Al-Sharif (1988) conducted a chemical analysis to recognize the elements constituting the olive waste after burning at 550 °C. However, this burning requires a significant amount of energy and generates considerable carbon emissions. The utilization of this by-product may cause more damage than the conventional stabilizers to the environment. They also carried out Atterberg Limits, UCS, Standard Proctor Density, and Swelling Pressure tests on soil samples. The UCS and the MDD were increased at 2.5% by weight of the burned olive waste. The swelling pressure of the soil was minimized at 7.5% of the olive ash by weigh. Consequently, there would be a potential to use this by-product as a soil stabilizer. Thus, this would help in solving its disposal problem.

On the expansive soils, Nalbantoglu and Tawfiq (2006) made several tests including Atterberg limits, compaction, swell, and UCS tests. They found that adding 3% burned olive waste into the soil causes a reduction in the plasticity and an increase in the UCS. Based on these results, the use of olive waste in soil stabilization is greatly beneficial for the environment as it achieves the concept of sustainability. After the olive waste was burned at 550 ∘ C, different proportions of this burned olive 1-10% were added by Mutman (2013) to the bentonite clay. The optimum value of olive waste was 1% at which the clay soil was enhanced. At this optimum value, the plasticity index decreased, and the UCS reached its maximum value.

2.2.9 Engineering Properties of Treated Expansive Soils Using Agricultural Waste Materials

Figure 2.3 illustrates the improvement achieved by unconfined compressive strength in which untreated soil stabilized using some agricultural wastes without the application of any conventional stabilizers such as lime and cement. This figure depicts that the addition of agricultural solid wastes has resulted in improving the UCS as investigated by various researchers. At the optimum state, there is at least 2% increase in the UCS test result in the case of 8% RHA. In addition, at the best state, it is clear that the addition of 20% coal ash with 0.25% coconut coir fibre to the silty sand soil and 3% groundnut shell ash to the clay soil has the maximum improvement on UCS, as it is approximately 3 times more than the UCS before improvement. If one considered 6% bagasse ash, 0.5% bagasse fibre, 3% burnt olive waste ash, or 1% burnt olive waste, these materials would have a relatively equal effect on soil improvement, as can be observed in the UCS results. Figure 2.3 also shows the improvement obtained due to the addition of agricultural waste materials at the optimal dosage compared to lime/cement stabilization. This figure depicts that the addition of agricultural waste can produce better results than that of conventional stabilizers. Stabilization using rice husk ash and bagasse ash produce excellent strength with both lime and cement stabilization as well as swell control. Consequently, RHA and BA were adopted frequently as an additive with lime and cement, based on proven results. These figures have been shown positive results by using combinations of lime/cement with agricultural wastes at its optimal dosage.

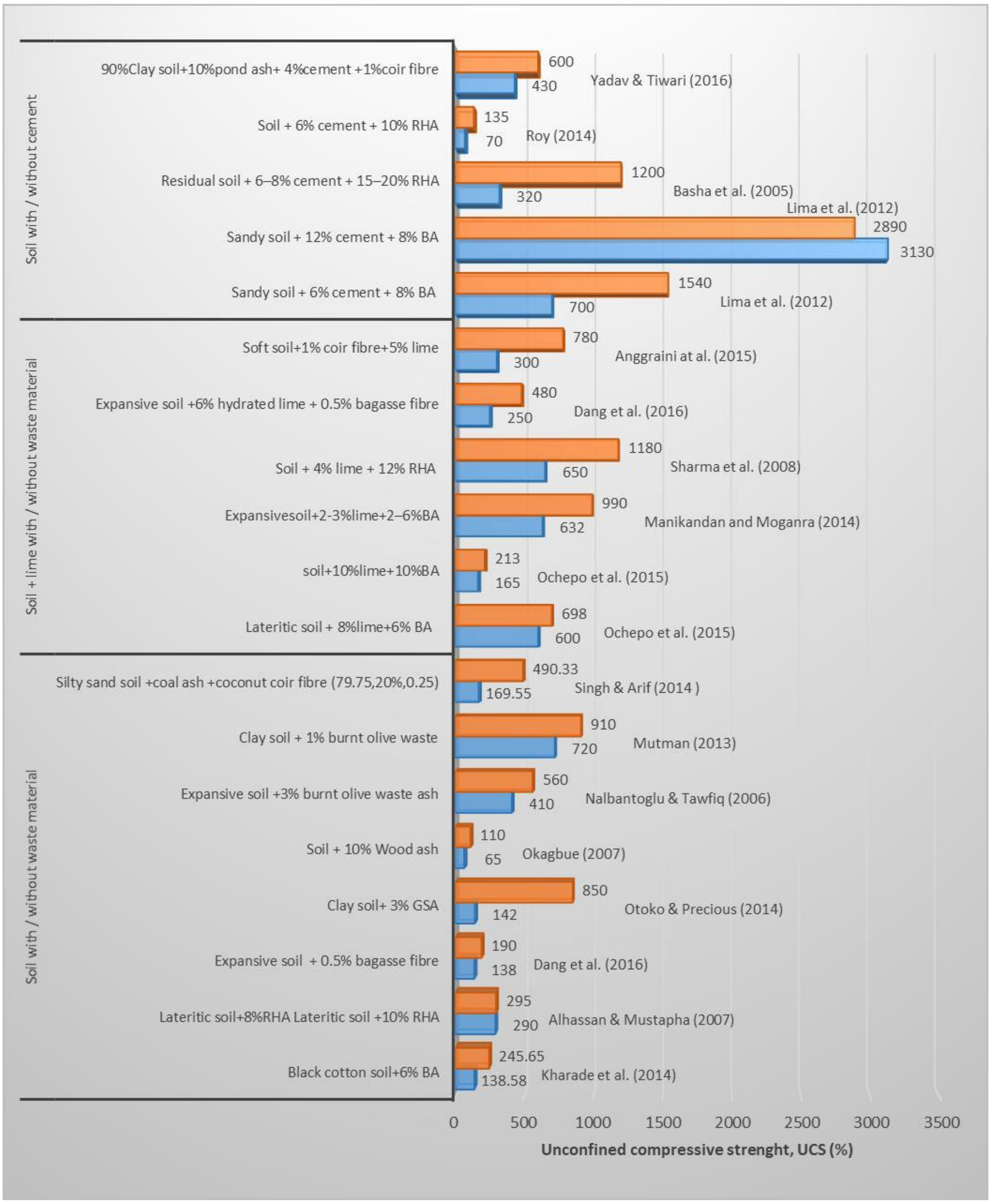


Figure 2.3 Comparison of UCS achieved by adding agricultural wastes to the untreated soil with/without lime or cement treated soil

A comparison in the improvement of soaked California bearing ratio obtained when stabilizing soil using different agricultural wastes materials is shown in Figure 2.4. Using 5% groundnut shell ash on stabilizing clay soil has the lowest effects on soil because the value of the soaked CBR increased by 1%. Figure 2.4 indicates that the soil with 6% bagasse ash to10% RHA has almost the same effect on increasing the CBR values (i.e. 9%, 7%, respectively). In fact, 20% of coal ash with 0.25 coconut coir fibre had the most significant effect on enhancing the CBR from 5.6% to 19.5%. Consequently, there were instances of CBR rising in the case of coal ash with coconut coir fibre and just by 1% in the case of groundnut shell ash. This indicates that the development of strength is influenced by soil type and the nature of agricultural waste.

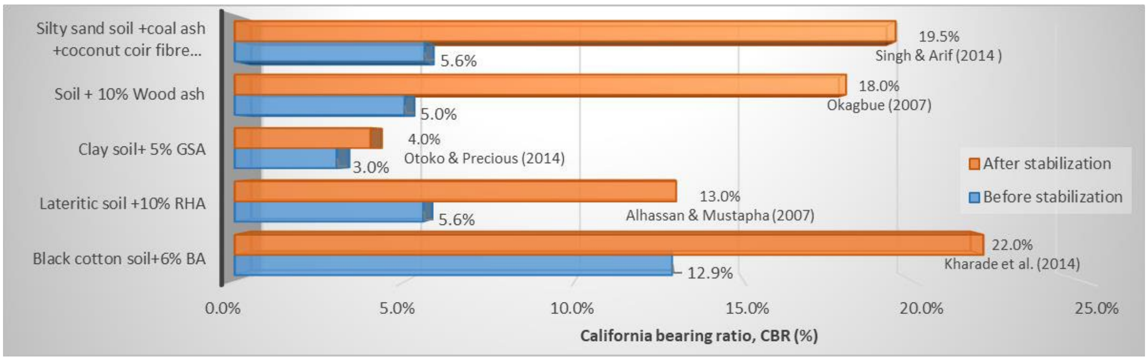


Figure 2.4 Comparison of soaked CBR achieved by adding agricultural wastes to the untreated soil

2.3 Comparison of Miscellaneous Waste Material Used in Soil Stabilization

Miscellaneous wastes originate from different sources such as construction and demolition, domestic wastes, marine deposits and mineral wastes. Table 2.3 illustrates 7 miscellaneous wastes that have been used in soil stabilization. In addition, it shows the benefits and challenges for each of the material listed in the table. Some studies, conducted on the stabilization of soil using miscellaneous wastes, are described below. As can be seen in Table 2.3, eggshell powder and seashell powder have a high percentage of CaO. Consequently, these materials can be used for increasing the efficiency of pozzolanic reaction as well as conserving the natural lime. An adverse impact was noticed by adding a high dosage of these powders to the soil. On the other hand, due to the granular properties of recycled asphalt pavement and the shredded tyre rubber, they can also be used as partial aggregate replacement in road construction materials such as road subgrade, subbase and embankment fill. Although tyre rubber has a negative impact on soil stabilization in case of tyre abrasion, a noticeable improvement in the properties of the stabilized soil can be observed by addition of quarry dust and glass cullet. Furthermore, the low cost of the process of obtaining fibres from carpet waste makes it a good choice for soil stabilization and increasing the internal cohesion of soil. However, limited types of fibres could be used in soil stabilization.

2.3.1 Construction Waste Materials (Recycled Asphalt Pavement)

Building and construction industry generates spoils, known as construction and demolition (C&D) wastes. Examples of these wastes include bricks, tiles, masonry, cement, timber, metals, plastics and cardboard. Much research has been conducted on the C&D wastes potential to be used in soil stabilization. One of the materials, which is commonly considered as a C&D waste is recycled asphalt pavement.

After recycling waste obtained from the end-of-life asphalt and concrete pavements into aggregate or pulverized, it is stabilized into full or partial depth reclamation bases by adding cement or other additives as hydraulic binders (Puppala, Saride & Williammee 2011). Maintenance works on asphalt pavements results in a significant amount of reclaimed asphalt, which is caused by "milling of asphalt road layers, through crushing of slabs ripped up from asphalt pavements, lumps from slabs, and asphalt from reject and surplus production"(De Bock & Gonçalves 2005).

The suitability of recycled asphalt pavement (RAP) stabilized with cementitious sawdust ash as pavement material was studied by Osinubi et al. (2011). An experimental investigation was carried out including CBR tests. It was found that 90% RAP blended with 10% sawdust ash increased the soaked CBR about 26% after 24 hours of soaking. The mix was recommended to be as a subbase material for pavement construction. Taha et al. (2002) delved into conducting a laboratory evaluation of cement stabilized RAP and RAP-virgin aggregate blends as base materials. Compaction and unconfined compressive strength tests were conducted on the following ratios of RAP/virgin aggregate mixtures: 100/0, 90/10, 80/20, 70/30, and 0/100%. Samples were prepared using 0, 3, 5, and 7% Type I Portland cement and were cured for 3, 7, and 28 days. It was found that employing RAP can enhance the engineering properties of treated soil. A 100% RAP aggregate is not recommended to be applied as a base material unless stabilized with cement. Cement stabilized RAP-virgin aggregate mixtures seem to be a viable alternative to dense-graded aggregate used in road base construction.

2.3.2 Tire Rubber

Significant environmental concerns will be associated with waste tires if they are not recycled properly. In civil engineering, there are many applications for recycled waste tyres such as asphalt paving mixtures and rubberized concrete (Bignozzi & Sandrolini 2006; Shu & Huang 2014).

Much research has been conducted on the stabilization of soil using domestic waste materials. Small particles of waste tire rubber were added to the expansive soil to figure out its swelling potential (Seda, Lee & Carraro 2007). It was noticed that adding this waste into the expansive soil significantly improved its engineering properties. Consequently, in the expansive soil-rubber mixture (ESR), the free swell and swelling pressure are greatly reduced. The optimum value was 20% rubber by weight of the soil. Because of the lower specific gravity of the rubber material, at this optimum value, the maximum dry density decreased. It was concluded that expansive soil-rubber mixture (ESR) is more compressible than the untreated soil. Hoan and Ming (2010) studied the mechanical and chemical properties of the cement-rubber chip to stabilize soft clay soil. The same amount of both materials were added. With randomly shredded rubber, 5% 10% and 15%, they focused on the strength and load-bearing capacity behaviour of soil. In order to achieve the maximum value of UCS of 250 kPa, at least 4% and 5% of cement and rubber chips were required, respectively. It was discovered that the shredded rubber can be a good soil reinforcement material, and the mixture of rubber and cement can be a proper and economic mix for improving soil strength. It was concluded that the efficiency of adding both rubber and cement to the soil is much higher than that of adding rubber by itself to the soil, as expected.

2.3.3 Carpet Fibre

Carpet fibres are recovered by shredding carpets, and they can act as tensile reinforcing elements in the soil when blended with conventional stabilizers. The shredded carpet waste fibres are proposed to be up to 70 mm long as shown by field trials. The low cost of the process of obtaining fibres from carpet waste makes it a suitable choice for soil stabilization (Wang 2006).

Many researchers investigated the effects of using carpet fibre to increase the strength of different types of soil. In the form of short strips of carpets, Ghiassian, Poorebrahim & Gray (2004) examined the effects of using recycled carpet waste on fine sandy soil. They conducted an array of triaxial compression tests. It was concluded that the shear strength of silty sands, compressive strength, Young's modulus, and ductility of sandy soil were improved. For reinforcing soil, another experiment was conducted by Wang (2006), using waste carpet fibres. Mixing the soil with carpet fibres up to 70 mm long increased the triaxial compressive strength and ductility of soil samples. It was reported that 3% of carpet fibre was the optimum value at which the peak stress value was reached to 34.5 kPa. Key geotechnical properties of cohesive soils were studied by Mirzababaei et al. (2009) using four different carpet fibre types. A number of quick undrained triaxial tests were conducted on specimens, reinforced with 1%, 5% and 10% fibre contents. The optimum value was 1% fibre at which the treated soil was reached to peak stress, of 681 kPa. However, once the fibre content exceeded 1%, the soil strength was negatively impacted.

2.3.4 Glass Cullet

An amorphous glass of non-crystalline material is usually brittle and optic transparent. In addition to using glass as a raw material to be recycled into glass containers, it may be used in some engineering applications. As being produced through super-cooling processes, it is composed mainly of silicon dioxide (sand) and sodium carbonate. Researchers found out that the crushed glass has many positive physical properties, high permeability, high crushing resistance, and small-strain stiffness. These properties enable the crushed glass to be used in soil stabilization (Rao & Chittaranjan 2011).

Many studies were conducted to investigate the effects of using recycled glass by itself and with cement on soil stabilization. Ikara et al. (2015) mixed different proportions of cement and recycled glass by dry weight of the expansive soil, 0, 2, 4, 6, 8% cement and 0, 5 10, 15, 20% recycled glass by weight of the dry soil. Several tests were conducted, including CBR, UCS, and compaction characteristics test to investigate the mechanical properties of the treated soil. The peak UCS after 7 days of curing was 1152 kPa, which was obtained at 8% cement and 20% waste glass. At the same percentage of the mix, the highest CBR was 53.8%. It was revealed that with increasing recycled glass content in all cement proportions, the MDD increased while the plasticity index (PI), liquid limit (LL) and plastic limit (PL) decreased. Consequently, the strength of black cotton soil was enhanced by using recycled glass. The same admixture was used by Olufowobi et al. (2014) to investigate its effects on stabilizing clay soil. Different proportions of glass powder were applied including 1%, 2%, 5%, 10% and 15% with 15% cement. In order to classify the clay soil, an array of tests was conducted, including the natural moisture content, the particle size distribution, specific gravity tests and Atterberg limits tests. In addition, compaction, CBR and direct shear tests were conducted to discover the effects of glass powder on the soil. The best percentage of the powdered glass, at which the soil properties were greatly enhanced, lies between 5% and 10% by the dry mass of soil. At 5% glass powder, the highest CBR was recorded, and at 10% of glass powder, the cohesion and the friction of angle increased. This led to the conclusion that powdered glass can be used as an admixture to strengthen clayey soil.

Unlike the previous two studies, Boraste & Sharma (2014) used various percentages of glass and fly ash. The study was carried out to assess the possibility of improving laterite soil and make it suitable for road embankment. CBR, UCS, direct shear and compaction tests were conducted on the treated soil. The optimum values for fly ash and recycled glass were 20% and 7%, respectively at which CBR for both soaked and un-soaked reached its maximum values, and the strength parameters reached their maximum values as well. By increasing WG and fly ash contents, the MDD increased and OMC decreased as noticed in the compaction test. Based on the results, the addition of recycled glass with fly ash had a significant improvement and this mix can be effectively used as a soil stabilizer.

2.3.5 Sea Shells

Calcareous mollusca shells, comprised a large amount of calcium carbonate, can easily be presented on the seashores. Seashells contain about 90% of calcium carbonate, which is a major component in lime (Mounika et al. 2014). A number of researchers (MohanChand & RameshBabu; Mounika et al. 2014) studied the effects of seashells as a stabilizing agent in the black cotton soil. Different proportions of seashells were applied to investigate the geotechnical properties of the soil. Based on the results, it was noticed that the UCS and CBR increased by increasing the seashells content. The optimum value of seashell content was 16%, as the treated sample UCS increased by 12%, compared to the UCS value of untreated soil sample.

Table 2.3 Miscellaneous waste materials and their specifications

Materials	Advantages	Challenges	References
		Construction Waste	
Recycled asphalt pavement	• Reduced landfill cost • Reduced carbon footprint Reduced demand for natural aggregate	• Lack of laboratory and field performance data. • Lack of proper standard Lack of located recycling facilities	(De Bock & Gonçalves 2005; Gomes Correia, Winter & Puppala 2016; Taha et al. 2002)
		Domestic waste	
Eggshell Powder	• Conserving natural lime • Low cost. • Reduced carbon footprint. • Increased soil density, cohesion and frictional resistance.	• Adverse Impact on soil properties if exceeding the optimum percentage.	(Erfen & Yunus 2015; Hut 2014; Pliya & Cree 2015; Raji & Samuel 2015b; Rao & Chittaranjan 2011; Yerramala 2014a)
Tyre rubber	• Reduced carbon footprint and energy. • Low cost of raw material.	• Negative impact on soil stabilization in case of tires abrasion	(Cairns & Kenny 2004; Huang, Bird & Heidrich 2007; Presti 2013; Vaníček, Jirásko & Vaníček 2017)
Glass Cullet	• Improved soil properties. • Reduced disposable wastes.	• Adverse Impact on soil properties if exceeding the optimum percentage.	(Boraste, ; Ikara, 2015 ;Olufowobi, 2014)
Carpet fibre	• Reduced needs for landfilling. • Reduced energy carbon footprint. • Increased in the internal cohesion of soil.	• Only limited types of fibres could be used in soil stabilization	(Mirzababaei et al. 2009; Wang 1999; Wang et al. 1994)

Materials	Advantages	Challenges	References
Marine waste			
Sea shells	• Conserving virgin materials. • Reduced pollution and energy. • Enhanced soil properties Being a rich source of several bioactive compounds and materials, such as calcium, chitin, pigments, and proteins.	Adverse Impact on soil properties if exceeding the optimum percentage.	(Hanif et al. 2014; Lertwattanaruk, Makul & Siripattarapravat 2012; Mounika et al. 2014; Muthusamy et al. 2016; Olivia, Mifshella & Darmayanti 2015; Othman et al. 2013)
Mineral waste			
Quarry dust	• Low cost.by Reducing the requirement of landfill area • Solving the problem of natural sand scarcity. • Improved soil properties Variation in water content does not seriously affect its desirable properties.	Difficulty in cutting grove in Casagrande's apparatus when applying the liquid limit test.	(Balamurugan & Perumal 2013; Chansoria et al. 2016; Chauhan & Bondre 2015; Kumar & Biradar 2014a; Shyam Prakash & Rao 2016; Soosan et al. 2005)

2.3.6 Quarry Dust

After crushing rubble, the quarry dust is obtained as an aggregate waste. Many researchers studied the effect of quarry duct on soil stabilization.

Kumar & Biradar (2014b) investigated the effect of adding quarry dust without any additives to soft soil subgrade and black cotton soil. On both unmodified and modified soil, Kumar and Biradar (2014) conducted several tests, including Atterberg limits, compaction and CBR tests. It was noticed that the optimum value for quarry dust was 40% at which the highest CBR was recorded. It was revealed that the addition of the quarry dust reduces the liquid limit and plasticity index. Consequently, soil-quarry dust mix could be used as a subgrade for flexible pavements. Regarding the engineering properties of black cotton soil, Chansoria et al. (2016) mixed 10%, 20%, 30% and 40% of quarry dust with black cotton soil. A series of laboratory tests conducted, including CBR, compaction parameters. The optimum value for the quarry dust was 40%. It was concluded that the utilization of quarry dust improved the soil properties and reduced the expansive behaviour of black cotton soil.

Sabat (2012b) blended lime and quarry dust with expansive soil. The effect of lime and quarry dust on some geotechnical properties of expansive soil was experimentally studied. A high percentage of quarry dust (40%) and different lime contents (2% to 7% at an increment of 1%) were added to the soil. Atterberg’s limits, compaction, consolidated undrained triaxial compression, and durability tests were conducted on these mixes. The effects of 7 and 28 days of curing were also studied on shear strength parameters. The results indicate that with an increase in the percentage of the addition of lime the plastic limit, the shrinkage limit, the cohesion, the angle of internal friction, and the optimum moisture content increased. Whereas, the liquid limit, the plasticity index, and the maximum dry density of the soil-quarry dust mix decreased. It was concluded that the addition of lime made the soil-quarry dust mixes more durable. The maximum positive effect on shear parameters at 28 days of curing was obtained when employing 5% of lime for soil-quarry dust mixes. Naranagowda et al. (2016) delved into the effect of quarry dust, and lime mixture on stabilization of black cotton soil. It was concluded that the optimal percentage of lime and quarry dust would be 8% and 20%, respectively. Sabat (2012a) came up with the idea of introducing statistical models for prediction of swelling pressure of a stabilized expansive soil (bentonite) with quarry dust and lime. Different percentages of lime and quarry dust were added to the soil (2% to 6% of lime at an increment of 1% and 0% to 50% of quarry dust in steps of 10% by dry weight of expansive soil). A model was developed by correlating the inputs including quarry dust (%), lime (%), the maximum dry density (kN/m^3), the optimum moisture content (%) and the curing period (days) with the swelling pressure as outputs. The Swelling pressure was calculated in stabilized expansive soil after 7 and 28 days of curing. On the other hand, the model was developed to predict the swelling pressure of stabilized expansive soil cured at 28 days from the swelling pressure of the stabilized expansive soil cured at 7 days. Sabat & Bose (2013) investigated the combined effect of fly ash-quarry dust mixes. An array of tests were conducted including compaction characteristics, UCS, CBR, shear strength parameters and swelling pressure. It was revealed that the addition of 45% fly ash quarry dust mix resulted in the maximum unconfined compressive strength, increased CBR and the angle of internal friction, while the cohesion and the swell pressure reduced. Consequently, the improvement that obtained from this stabilization resulted in a cost-saving of up to 11.5%.

2.3.7 Engineering Properties of Treated Expansive Soils Using Agricultural Waste Materials

A comparison in the improvement of the unconfined compressive strength obtained when the untreated soil stabilized by using some of the miscellaneous wastes without any conventional stabilizer or with combinations of lime/cement treated expansive soil are shown in Figure 2.5. This figure depicts that the addition of miscellaneous solid wastes has resulted in improving the UCS as investigated by various researchers. As shown in Figure 2.5, when a mixture of quarry dust (1: 2) with 45% fly ash added to the untreated soil, there were an increase at least 3 times in the UCS value compared to the UCS value for untreated soil. In addition, at the best state, it is clear that the addition of 16% micro silica had the maximum improvement on the UCS results, as it was around 7 times more than the UCS before improvement of the soil sample. The improvements obtained due to the addition of miscellaneous waste materials at the optimal dosage to lime/cement stabilization also shown in Figure 2.5. This figure depicts that the addition of miscellaneous wastes produced better results than the conventional stabilizer only. Furthermore, positive results were obtained by using combinations of lime/cement with miscellaneous wastes at its optimal dosage.

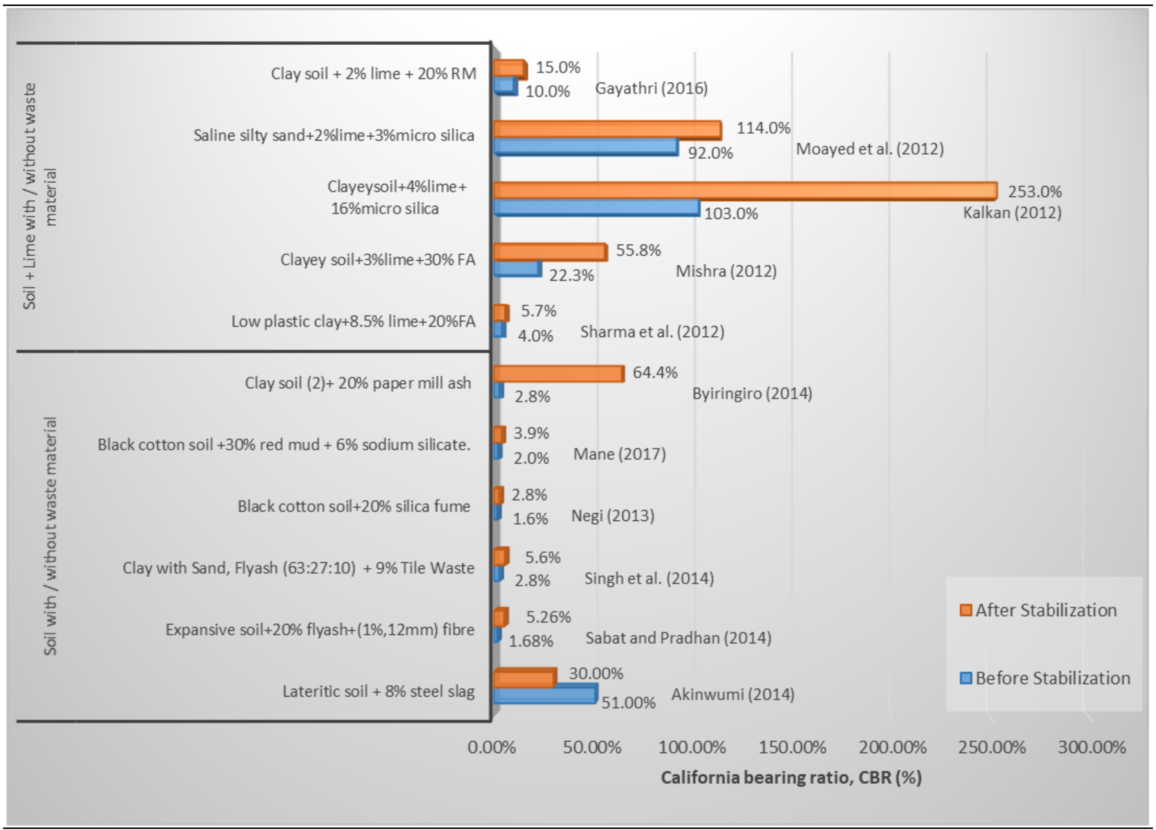


Figure 2.5 Comparison of UCS achieved by adding miscellaneous wastes to the untreated soil with/without lime or cement treated soil

A comparison regarding the improvement of soaked California bearing ratio is depicted in Figure 2.6 for soil specimens stabilized by some miscellaneous wastes materials. Using 40% quarry dust on stabilizing soil had an insignificant effect on soil because the value of the soaked CBR just increased by 2%. Figure 2.6 indicates that the combination of 90% RAP with 10% sawdust ash, 20% seashell powder, quarry dust (1:2) with 45% fly ash, and 40% quarry dust in the black cotton soil have a relatively equal effect on increasing the CBR value. In fact, 90% RAP with 10% sawdust ash had a better effect on enhancing CBR.

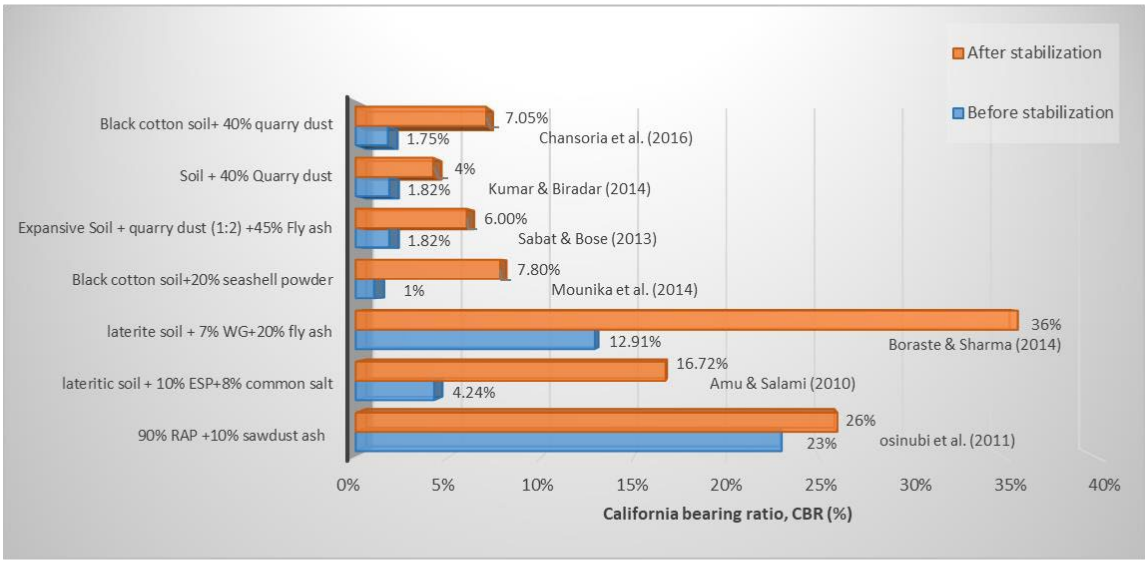


Figure 2.6 Comparison of soaked CBR achieved by adding miscellaneous wastes to the untreated soil

2.4 Previous Studies on Using Eggshell Powder in Soil Stabilization

Eggshell powder is one of the common waste materials produced from local sources such as pastry shops, cake and chocolate factories, poultries, hatcheries, and fast food centres. Large amounts of eggshells pose an environmental concern if not recycled or discarded properly (Pliya & Cree 2015). Due to its some similar chemical composition to that of lime, it can be used as a partial replacement for industrial lime if subjected to adequate scrutiny (Rao & Chittaranjan 2011). Thus, it can be presumed that the eggshell powder can be suitable and effective in stabilizing expansive soil (Leite et al. 2016). Consumption of eggshell as an affluent source of $CaCO_3$ could solve both ecological and financial interest.

Eggshell is mainly made up of 98.2% calcium carbonate (calcite), 0.9% magnesium, and 0.9% phosphorous (phosphate). The composition of shell membranes is approximately 69.2% protein, 2.7% fat, 1.5% moisture and 27.2% ash (Tsai et al. 2006). The eggshell and shell membranes form almost 10.2% of the total weight of a normal egg

(Nakano, Ikawa & Ozimek 2003). Many works have been conducted in utilization of eggshell wastes in various civil engineering applications (Abdelhadi & Gotoh 1998; Adogla et al. 2016; Ahmed, Rahman & Das; Amu, Fajobi & Oke 2005; Barazesh, Saba, Gharib, et al. 2012; James & Pandian 2013; Muthu Kumar & Tamilarasan 2014; Olufowobi et al. 2014; Paul et al. 2014; Soundara & Vilasini 2015; Walia & Singh 2015). This literature review provides insight into some research related to the use of eggshell wastes in expansive soils stabilization.

A number of studies carried out to discover the effects of adding eggshell powder (ESP) on soil properties. Amu, Fajobi & Oke (2005) and Barazesh et al. (2012) scrutinized the effects of using eggshell powder as partial replacement of lime on the stabilizing potential of the soil. Amu et al. (2005) found that the optimal percentage of lime was 7% used to stabilize the soil. It was gradually reduced and replaced by eggshell powder in the following ratios: 6% lime+1% ESP, 5%lime+2%ESP, 4%lime + 3%ESP, 3%lime+4%ESP, 2%lime +5%ESP and 1% lime + 6% ESP. An array of tests were conducted, including compaction, CBR, UCS and undrained triaxial shear strength tests. The results indicated that the optimum percentages of lime and ESP were 3% and 4%, respectively. However, the engineering properties of the soil, such as MDD, CBR and UCS were significantly improved when lime content was 7% without adding ESP. Barazesh et al. (2012) found that the optimum percentage of ESP is 16%. At this percentage, ESP contributes to improving the plasticity properties including the liquid and plasticity limits as well as the plasticity index of the expansive soil. In order to improve subgrade CBR value, Ahmad, Rahman & Das (2005) delved into finding the optimum percentage of ESP beyond which CBR value of soil decreased. James & Pandian (2013) investigated the effect of using a series of natural materials such as eggshell powder, tamarind kernel powder and jaggery on the performance of treated soil. Generally, the research revealed that ESP could improve soil properties. Nyankson et al. (2013) performed an experimental study on two different types of expansive soil. Different percentages of lime and eggshell powder were applied and their effects on swell-shrinkage enhancement were investigated. The samples were characterized by x-ray fluorescence (XRF), the free swell index, the plasticity index (PI) and pH tests. According to the results, the addition of lime induced a sharp decrease in the free swell index (FSI), whereas the reduction was marginal when ESP was applied. The optimum percentages were between 4% and 8% of ESP at which the swell-shrinkage behaviour was improved. It was observed that there was a decrease in the plasticity index in both samples. However, the eggshell-lime mixture did not show an appreciable decrease in FSI.

Olarewaju et al. (2011) investigated the ability of eggshell powder and cement to treat lateritic soil as subgrade materials for road construction. The engineering properties, such as Atterberg limits, CBR and compaction were highly improved at 8% ESP. The same improvement occurred when 2% of cement was added to the lateritic soil. It was concluded that eggshell powder can be used as a stabilizer for subgrade materials where very high performance is not necessary. However, it cannot be used as a stabilizer for base and subbase materials as they need much higher strength to meet their minimum requirements.

Paul et al. (2014) used a combination of quarry dust (QD) and ESP to stabilize clayey soil. Different percentages of eggshell powder were added by the dry weight of the soil and it was found that the optimum percentage of ESP is 20% at which the soil properties improved. Different percentage of QD was added to the optimum value of ESP. It was reported that with increasing the amount of eggshell powder and QD, there was an increase in the OMC, the shear strength, the permeability, the coefficient of consolidation and the angle of internal friction, while there was a decrease in MDD, the cohesion and the compression index. It was concluded that the optimum values were 30% quarry dust and 20% eggshell powder. Walia & Singh (2015) examined the effect of the combination of ESP and stone dust on the compaction characteristics and CBR of the clayey soil. It was found that with an increase in the percentage of eggshell powder and stone dust, MDD decreased and OMC increased significantly.

Muth Kumar & Tamilarasan (2014) also investigated the use of eggshell powder for soil stabilization. They found that the optimum percentage of ESP was 3% at which the maximum UCS reached 300 kN/m^2. Soundara & Vilasini (2015) looked into the effect of ESP on the engineering properties of clay soil. The suitability of ESP in enhancing the compressive strength of compressed lateritic earth blocks was investigated by Adogla et al. (2016). Another additive, called common salt, was used to study its effect on the properties of ESP stabilized lateritic soils (Amu & Salami 2010). Some engineering properties of stabilized lateritic soil were investigated such as consistency, CBR and compaction tests by adding different percentages of common salt (2, 4, 6, 8, and 10%) to the optimum content of the eggshell powder. A significant improvement was observed in all of the engineering properties at the optimum combination of 10% ESP with 2% common salt.

The efficiency of adding albumin and ESP on improving geotechnical properties of soil was investigated by Abdelhadi & Gotoh (1998). Different percentages of ESP and albumin were mixed separately by dry weight of the soil samples. An array of tests were performed such as direct shear, UCS, slaking and permeability tests. The findings exhibited that ESP did not make a positive impact on soil samples, while albumin was found to be a proper stabilizer with the maximum addition 1% by weight.

The combustion of ESP in a muffle furnace at elevated temperatures produces eggshell ash (ESA). Few experiments were conducted to detect the possibility of using ESA as an auxiliary addendum for stabilization of expansive soils. James et al. (2017) investigated the effect of adding ESA to lime stabilization of soil. They found that a mixture of 2% ESA with 4% lime resulted in a notable reduction in plasticity indices and enhancement in the strength. Another experiment was performed by James & Pandian (2016) to investigate the effect of ESA in enhancing the early strength of lime stabilized expansive soil. The performance of cement stabilized lateritic soil mixed with different doses of ESA was researched by Okonkwo et al. (2012). Extra increase in the strength and durability of cement stabilized soil was observed when ESA was introduced to the soil samples. To have an overall different study using eggshell either in the form of powder or ash, as well as their effects on the engineering properties of treated expansive soil, are tabulated in Table 2.4. It can be seen that the majority of researchers used small percentages of eggshell powder and the shrinkage potential and strength properties of expansive soil were not covered properly. In this experimental study, the innovative idea of blending eggshell powder and hydrated lime with expansive soil using a wide range of eggshell powder content is investigated, which would be beneficial in geotechnical engineering applications. The shrinkage potential, Atterberg limits, compaction characteristics, unconfined compressive strength and California bearing ratio of expansive soils, treated with various eggshell powder contents and hydrated lime, are investigated.

Table 2.4 Comparison between different studies on using the eggshell in the form of powder or ash as an Auxiliary Addendum in the stabilization of expansive soil.

Reference	Soil- lime /cement-optimum waste combination	Major geotechnical properties tested	Soil only	Soil with Lime and		Soil with ESP/ESA and		% Improvement before and after stabilization
				Only	ESP/ESA	Only	Other additives	
(Amu et al., 2005)	Clay soil+3% lime+4% ESP	Undrained shear strength	59.64 kPa	-	93.5 kPa	-	-	57%
		Unsoaked CBR	4.8%	-	4.1%	-	-	-0.7%
		Soaked CBR	4.4%	-	15.5%	-	-	11%
		Plasticity index	38%	17.3%	15.2%	-	-	-23%
(Barazesh et al., 2012)	Clay soil + 16% ESP	Plasticity index 35	35%	-	-	28%	-	-7%
(Ahmed, Rahman & Das)	Soil + 11 % ESP	CBR	6.47%	-	-	9.52%		3%
(Nyankson et al., 2013)	Clayey soil+8% lime+8% ESP	Plasticity index (DD sample)	16%	-	7%	-	-	-9%
(Paul et al., 2014).	Clay expansive soil+20 %ESP+ 30% Quarry dust	Plasticity	21.33%	-	-	9.13%	5.4%	-16%
		permeability	7.1 x 10-5 cm/s	-	-	5. 1 x 10-4 cm/s	9.1 x 10-4 cm/s	
(Walia and Singh, 2015)	Clayey soil+ 12% ESP+10% stone dust	Soaked CBR	3.94%	-	-	6.86%	21%	17%

(Muthu Kumar and Tamilarasan, 2014)	Expansive soil + 5.5% ESP	Plasticity index	18%	-		3%	-	-15%
	Expansive soil +3% ESP	UCS on 3 days	100.694 kPa	-	-	300 kPa	-	198%
(Soundara and vilasini, 2015)	Clay soil + 6% ESP	UCS	147.1 kPa	-	-	441.29kPa	-	200%
		Plasticity index	24.75%	-	-	13.2%	-	-12%
(Amu and salami, 2010)	Lateritic soil sample (C)+4% common salt + 10% ESP	Plasticity index	7.99%	-	-	6.5%	1.23%	-7%
	Lateritic soil sample (C)+ 8% common salt+10% ESP	Unsoaked CBR	2.49%	-	-	27.31%	34.20%	32%
		Soaked CBR	0.95%	-	-	8.38%	16.72%	16%
(James & Pandian 2013)	Expansive soil + 30% ESP	UCS	58.5 kPa	-	-	304 kPa	-	420%
	Expansive soil + 20% ESP	Free swell index	60%	-	-	42%	-	-18%
(James, Pandian & Switzer 2017)	Expansive soil+4% lime+ 2% ESA	Plasticity index	52.18%	21%	15%	-	-	-37%
		UCS on 28 days	60 kPa	171.87 kPa	213.86 kPa	-	-	256%
(James and Pandian, 2016)	Expansive soil + 3% lime + 2% ESA	Plasticity index	41%	-	-	-	-	
		UCS on 7 days	115.8 kPa	501 kPa	850 kPa	-	-	634%
	Expansive soil + 5.5 lime + 0.5 ESA	UCS on 7 days	115.8 kPa	980 kPa	1090 kPa	-	-	841%
(Okonkwo et al., 2012)	Lateriticsoil+8%cement+10% ESA	CBR	9%	82%	93%	-	-	84%
		UCS on 14 days	186 kPa	655 kPA	988KPA	-	-	431%

2.5 Effect of pH Values on the Compressive Strength during Lime Stabilization

Different experimental investigations were conducted to study the effect of using lime and other additives on the pH values of the problematic soils (Aldaood, Bouasker & Al-Mukhtar 2014a; Aldaood, Bouasker & Al-Mukhtar 2014b; Chen & Lin 2009; Chew, Kamruzzaman & Lee 2004; Jha & Sivapullaiah 2015; Solanki, Khoury & Zaman 2009). The long-term stability of lime stabilized gypseous soils known as problematic soils was studied by Aldaood et al. (2014b). Different gypseous contents (0, 5, 15 and 25%) were added to soil in combination with 3% lime to investigate the effect of wetting-drying cycles on the mechanical behaviour of fine-grained soils at various curing times of 2, 7 and 28 days. In order to investigate the mechanical behaviour and the long-term stability of lime stabilized gypseous soils, UCS tests were conducted. Approximately 20 g portion of every failed untreated and treated UCS sample was used to determine the pH value, after each UCS test. Therefore, the pH test conducted to study the effects of curing time and additive contents on the compressive strength as well as the development of reactions at the microstructural level. It was concluded that the addition of lime increased the pH values due to the cation exchange of lime stabilized gypseous soils.

In contrast, increasing the curing time resulted in a reduction of pH values, as can be seen in Figure 2.7. Furthermore, the increase in the pH values could be attributed to facilitate the dissolution of the silica and alumina from clay particles, and then such silica and alumina interact with calcium to form cementitious compounds (i.e. CSH, CAH and ettringite) that produced stronger soil samples. It was also confirmed that the pozzolanic reaction depends on the time and the temperature. Thus, the reactions between the soil, lime and gypsum resulted in forming the cementitious compounds which lead to a change in pH values. The most preferred environment for the dissolution, crystallization of ettringite (CASH) and the formation of new forms of hydrated silicates (CSH) and aluminates (CAH) is a high alkalinity environment. It was also noticed that with increasing the curing time, there was a reduction in the pH values due to reduction in calcium (Ca2+) and hydroxyls (OH-) ions. This reduction induced by the reaction between soil, lime and gypsum resulted in pozzolanic reaction and new formation of ettringite.

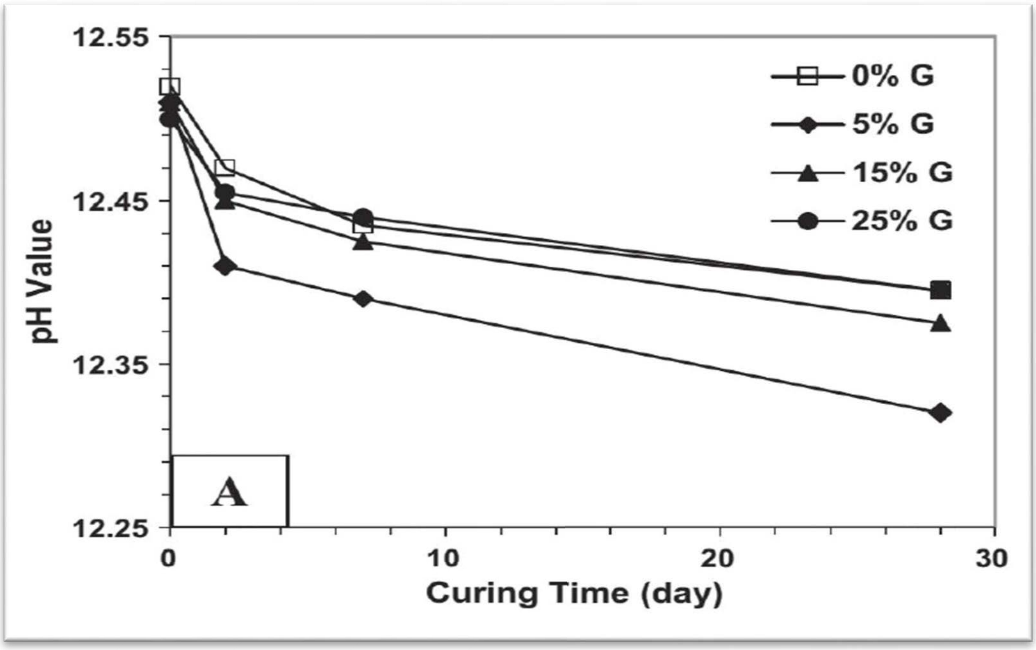


Figure 2.7 Variation of pH values of gypseous soil with curing time and additive content after (Aldaood et al. 2014b)

Similar test results were reported by Chen & Lin (2009). The variation of pH values with incinerated sewage sludge ash-cement contents was studied at a combination ratio of 4:1 and various curing times. This experiment emphasized that the pH values increased with increasing the content of sludge ash-cement content. The pH values for the untreated soil increased from 8.7 to 11.2 for 4% sewage sludge ash-cement combination-treated soft soil, as shown in Figure 2.8. A slight increase in the pH values on a certain extent for any sludge ash-cement admixture exceeded 4%. This increase could be caused by the calcium saturation principles of pH values and the mechanism of stabilization. However, the gradual decrease in the amount of calcium during the stabilization progress resulted in a decrease in the pH values of the soft soil with increasing the curing time.

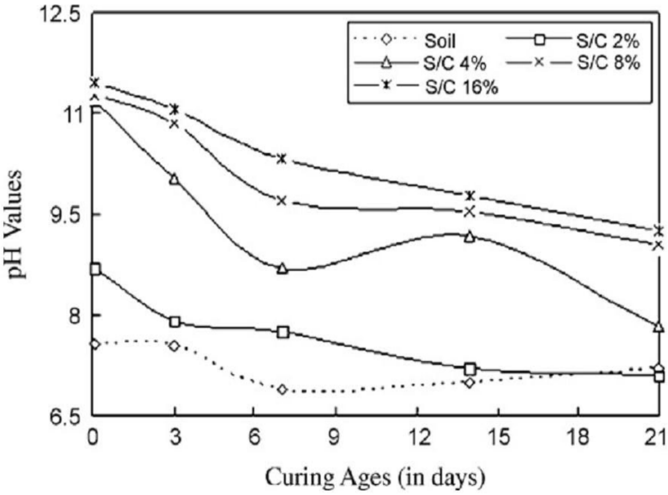


Figure 2.8 Relationship between pH values and curing ages with different amount of sludge ash-cement combination after (Chen & Lin 2009)

Furthermore, the effect of different content of lime, class C fly ash and cement kiln dust on the pH value of treated clay samples is shown in Figure 2.9. As can be seen from the figure, the pH value increased significantly at initial marginal content of additives. With 2% lime or 10% fly ash, as well as cement dust, a high pH was generated around 12.3 (Solanki, Khoury & Zaman 2009).

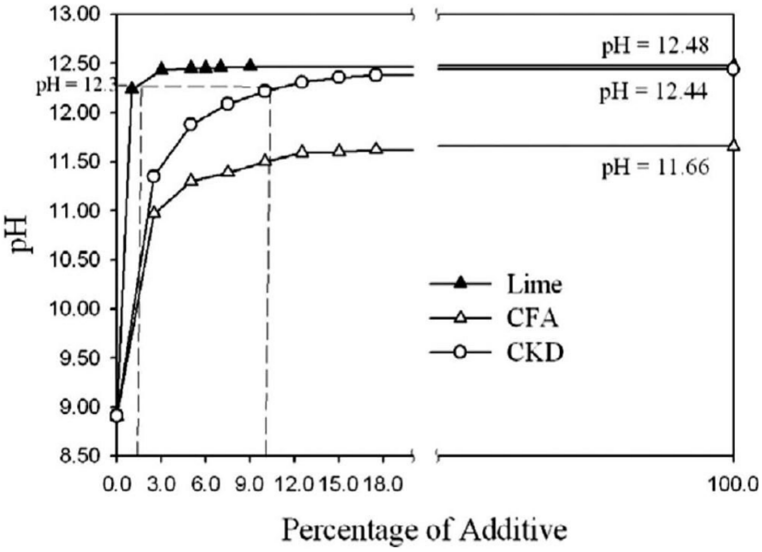


Figure 2.9 Variation of pH with the amount and types of additive after (Solanki et al. 2009)

2.6 Summary

Based on the integration of many investigations available in the literature and research on employing several types of waste materials in the stabilization of expansive soil, without or with the inclusion of conventional stabilizers, the following conclusions can be drawn:

- The stabilization of expansive soil using different types of wastes, whether by itself or with activators (lime or cement), improves the geotechnical properties of soil. In addition to the methodology of investigation, the performance of wastes depends on certain factors including the type of soil, the nature and amount of waste as well as the type and quantity of the conventional stabilizers.

- This literature review has attempted to provide a wide range of stabilizing effects using industrial, agricultural and miscellaneous wastes with weak soils. Industrial wastes consist of steel slag, fly ash, silica fume, red mud and pulp paper. Agricultural wastes include bagasse ash, rice husk ash, bagasse fibre, groundnut shell ash, wood ash, burnt olive waste and coconut coir fibre. In addition, miscellaneous wastes may comprise of construction wastes and different types of domestic wastes.

- Literature indicates that waste materials can increase the stability of soil similar to conventional stabilizers such as lime/cement. However, the combination of these two in soil stabilization generates even better results in many conditions. As a result, the amount of conventional stabilizers in the treatment of problematic soils will gradually be reduced. Accordingly, the carbon footprint of manufacturing of such materials will be reduced.

- Among industrial wastes, silica fume has been found to be a promising material for soil reinforcement. The UCS values increased three times compared to the UCS of lime treated soil. Fly ash is also considered as an effective reactive agent for soil stabilization, particularly when combined with lime. For class F fly ash an activator (either cement or lime) is essential. Referring to CBR results, micro silica has been the most effective by-product, added to lime treated soil. The same behaviour also noticed when fly ash and silica fume were blended with the cement stabilized the soil. Based on the literature, Nivel fly ash can provide the highest strength, as high as 2000 kPa. Other by-products such as steel slag, red mud and pulp paper produced less enhancement in soil strength.

- Regarding agricultural wastes, with the introduction of lime or cement, a significant improvement on soil strength and CBR were observed, when bagasse ash and rice husk ash mixed with the soil. Furthermore, coconut coir fibre and bagasse fibre have shown their effectiveness in soil reinforcement. Materials such as olive waste and groundnut shell ash have exhibited less enhancement effect on soil strength.

- Regarding miscellaneous wastes, it can be noted that limited studies were conducted on the effect of applying these wastes combined with lime or cement on treated soil properties. However, eggshell powder and seashell ash have been described as promising materials for enhancement of the soil strength or replacement of lime due to their high content of calcium oxide. Referring to UCS test results, quarry dust yielded better improvement compared to recycled asphalt pavement or glass cullet.
- By and large, studies on using wastes for soil stabilization offer an insight into their positive impacts on expansive soil treatment.
- Finally, the application of wastes and by-products in soil stabilization can significantly contribute in reducing the costs of pavement construction, which would be of economic importance in both underdeveloped and developing countries.

CHAPTER 3:

Materials and Laboratory Testing Program

This chapter highlights the materials employed in this research, which includes: artificial expansive soil, natural expansive soil, eggshell powder and hydrated lime. In this investigation, the sources of these materials were described in details. An array of geotechnical tests such as physical, chemical, mechanical and environmental tests were conducted on these mentioned materials. All of these tests, adopted in this investigation were conducted at the UTS Tech- Lab.

The particle size distribution, the coefficient of uniformity, and the coefficient of curvature were quantified by sieving and hydrometer tests. Meanwhile, the liquid limit, the plastic limit, and the plasticity index were identified by Atterberg limit tests. Furthermore, other characteristics of the soil such as the specific gravity, the shrinkage limit, and the optimum water content and the maximum dry density were determined. All of these tests fall under the concept of physical properties. These tests formed Stage one of the determinations of soil properties. Stage two involved determining the mechanical properties of treated soils including, unconfined compressive strength, modulus of elasticity, and CBR tests. In order to investigate the environmental properties, Stage three was performed to determine the pH values of treated and untreated samples plus the organic content of soil samples for assessing loss on ignition (LOI) values.

As stated in Chapter 2, the shrinkage potential, Atterberg limits, compaction characteristics, unconfined compressive strength and California bearing ratio of expansive soils, treated with different eggshell powder contents and hydrated lime, are investigated to find out the optimum amount of eggshell power in the lime-treated soil.

A wide range of tests have been conducted on soil samples created in the laboratory by mixing kaolinite, bentonite and fine sand to produce an artificial expansive soil. Also, brief experimental procedures have been followed to study the effect of adding eggshell powder into the natural expansive soil. The effect of eggshell powder on the geotechnical properties of natural expansive soil was assessed by adding 5% and 20% content of eggshell powder into the untreated natural expansive soil. Linear shrinkage tests, proctor compaction tests, and unconfined compressive strength tests were conducted in purpose to estimate the effect of eggshell powder on the properties of natural expansive soil compared to the artificial soil samples.

3.1 Materials

Several materials were used in the experimental program, conducted in accordance with the procedures laid down in the Australian standards. The four main substances employed in this research have been eggshell powder as a supplementary additive, hydrated lime as a conventional stabilizer, natural and artificial soil (a mixture of kaolin, bentonite and fine Sydney sand) as expansive soils.

3.1.1 Natural Expansive Soil

The natural soil adopted in this research was collected from a road construction site in Queensland, Australia. Soil samples were prepared by removing any plant residues and other foreign elements. Detailed properties of this soil were presented in the previous intensive studies conducted at UTS (Dang et al. 2015; Dang, Fatahi & Khabbaz 2016; Dang et al. 2016; Dang, Khabbaz & Fatahi 2017). Table 3.1 and Table 3.2 illustrate the physical and chemical properties of natural expansive soil to demonstrate the characteristics of this soil. The soil characterized as a highly expansive soil based on linear shrinkage and plasticity index values. Based on the chemical composition, it presumes that this natural soil has a high content of SiO_2 approximately 60%.

*Table 3.1 Mechanical and physical properties of natural expansive soil (after Dang et al., 2015) Note: * after (Dang et al. 2015)*

Property	Value
Gravel	0.06
Sand	10.97
Silt	78.00
Clay	10.97
Natural water content (%)	30.76
Liquid limit (%)	86
Plastic limit (%)	37
Plasticity index (%)	49
Linear shrinkage (%)	21.67
Swell potential (%)	9.80
Specific gravity	2.62-2.65
Specific surface area (m2/Kg)	1475
Soil classification	CH

Table 3.2 Chemical composition of natural expansive soil (after Dang et al., 2015)

Components	Content (%)
MgO	2.20
Al_2O_3	22.98
SiO_2	60.26
CaO	4.06
FeO	8.25
K_2O	0.60
Na_2O	0.39
TiO_2	1.26

Several samples of the natural expansive soil with different particle size distribution have been found in the UTS Tech Lab. In order to determine which of these samples were used in the previously mentioned experiments, particle size distribution test was conducted in accordance with the Austrian standard ('AS-1289.3.6.3-2003 2003'). The employed soil in this study is shown in

Figure 3.1. The corresponding particle size distribution is illustrated in Figure 3.2.

Figure 3.1 Selected natural expansive soil

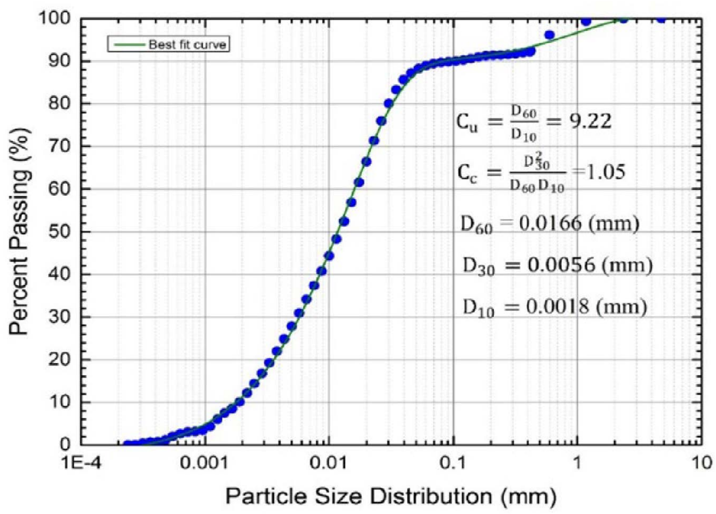


Figure 3.2 Particle size distribution curve for natural expansive

3.1.2 Artificial Expansive Soils

The experimental investigations commenced with the preparation of the artificial soil samples by mixing kaolinite Q38, Bentonite Active Bond 23 and Sydney fine sand (KBS). The artificial soil, employed in this investigation, is shown in Figure 3.3. The linear shrinkage (LS) for both kaolinite and bentonite was determined from the linear shrinkage test carried out in accordance with the Australia Standard ('(AS-1289.3.4.1-2008 2016)'). It was revealed that the kaolinite with white colour has a lower linear shrinkage (LS) comparing to the bentonite with darker grey colour (9% compared to 35%). Based on the Australian standard (*AS-1289.3.9.1:2015 (2015)*), the liquid limit values were reported for kaolinite and bentonite to be 50.5%, 340%, respectively. Table 3.3 illustrates the fundamental engineering properties of reconstructed artificial expansive soil.

In order to create soil samples similar to Queensland expansive soil (natural soil), a combination of artificial soils was mixed with a constant proportion of 30% bentonite, 65% kaolinite, and 5% fine sand by the total dry mass. The linear shrinkage value resulted from this arrangement was 21.7%, which was very close to that of the black cotton soil collected from a road construction site in Queensland. Once the linear shrinkage reached a value of 21.7%, the liquid limit of the blend was measured; and its average value was 155%.

The same amount of proportions and the mixing procedure was considered for all the subsequent expansive soil tests as shown in the following sections. Before achieving these final ratios for the target soil, many tests were conducted using different amounts of bentonite, kaolinite, and fine sand. For instance, 19.78% was the value of linear shrinkage that is obtained by mixing 65% kaolinite, 25% bentonite, 10% sand soil.

Figure 3.3 Selected artificial soil employed in this investigation

The first trial commenced by mixing 65% kaolinite, 25% bentonite, 10% sand and the LS, Liquid limit found to be as follow 19.78%, 119.54%. Another proportion was amended by mixing 65% kaolinite, 30% bentonite, and 5% sand by the total dry mass. The linear shrinkage was obtained to be 21.7%. These percentages of combination have been established for later use in all subsequent testing stages.

3.1.3 Eggshell Powder

The eggshell powder used in this study was obtained from the Food Supplies Restaurant, Commercial Store, New South Wales, Australia. It was washed to remove any organic matter then oven-dried at 110°C. In order to increase the efficiency of chemical reaction with larger surface areas, it was crushed by the grinder and sieved through 75 Mm BS sieve. The finely ground material of a uniform eggshell powder was used to conduct a series of geotechnical tests for the purpose of enhancing soil parameters stabilized with eggshell powder and lime. The eggshell powder had a natural moisture content of 1.7% on average. According to the Australian Standard, AS-1289.2.1.1 (2005), the specific gravity (G_s = 2.4) of eggshell powder was measured. The liquid limit was also determined in accordance with AS-1289.3.9.1:2015 (2015) standard. A photograph of this test is shown in Figure 3.4..

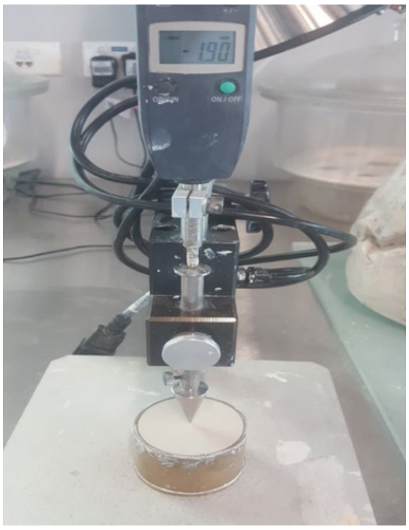


Figure 3.4 Determination of liquid limit for eggshell powder by cone penetrometer advice

(a)

(b)

Figure 3.5 Linear shrinkage of eggshell powder (a) preparation of the mould before shrinkage and (b) shrinkage limit of eggshell powder

Furthermore, the linear shrinkage of eggshell powder was determined. As expected, it was very low at approximately 1.5%, as illustrated in Figure 3.5. Moreover, from the result of sieving analysis with Cu=1.7 and Cc=0.96, the eggshell powder can be classified as SP-SM, in accordance with ASTM-D2487-11 (1998). Accordingly, it was observed that the values of the physical properties of the eggshell powder including specific gravity, linear shrinkage, and grain size distribution in this research, are consistent with previous studies except for the moisture content that is affected by the processes of preparing the eggshell powder in the laboratory.

A brief description of the chemical properties of eggshell powder is summarized in Table 3.3. It can be noted that the pozzolanic reaction begins when CaO is mixed with water and calcium silicate hydrate, calcium aluminate hydrate or calcium silicate aluminate hydrate can be formed in the soil. Thus, lime can play a pivotal role in enhancing the achieved stabilization and augmenting the calcium supply as the primary stabilizer.

Table 3.3 Chemical composition of eggshell powder

Mineral content	**ESP (%)**
CaO	50.7
SiO_2	9.0
Al_2O_3	3.0
MgO	1.0
Fe_2O_3	2.0
Na_2O	17.0
P_2O_5	2.3
SrO	1.2
NiO	1.0
SO_3	5.7
Cl	7.0

3.1.4 Hydrated Lime

Industrial hydrated lime was implemented in this investigation, which is the most commonly adopted stabilizer for stabilization of fine-grained soils. It was purchased from

Adelaide in Australia and used from packages provided by the Cement Australia. The lime chemical configuration reveals that it is of high quality with around 75-80% of the composition being calcium hydroxide. Lime powder was kept in tight bags to avoid coming into contact with the surrounding moisture. The detailed physical properties of the hydrated lime are as follows: The specific gravity of aqueous lime is 2.2-2.3, the bulk density is around 400-600 kg/m^3, and the pH value is 12.0. Furthermore, the main chemical components are SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and CO_2.

3.2 Experimental Method

In the present study, lime was used as a primary stabilizer, and the eggshell powder was used as a secondary additive to study their effects on the engineering properties of treated expansive soil samples. The use of eggshell powder, as a stabilizing agent to enhance the properties of expansive soil strength, might be a cost-effective solution for decreasing some waste materials ending up in landfills.

3.2.1 Mixing Designation

The program of work in this research involves the use of two types of expansive soils, namely the artificial soil and the natural soil.

The experimental investigation began with the preparation of artificial soil samples after removing gravel size particles. The minimum lime content required for modification of soil properties was found to be 5% after conducting many preliminary tests and reviewing the literature. The soil (with a maximum particle size of 2 mm) was mixed and stabilized with 5% lime, forming the control specimen for other combinations of lime and ESP. By the use of a mechanical mixer, the soil specimens were prepared by integration of the artificial soil, hydrated lime and different contents of ESP by the dry weight of the soil. The details are tabulated in Table 3.4.

Table 3.4 Summary of the combinations used in this study

Mix No.	Eggshell powder (%)	Hydrated lime (%)
1	0	0
2	5	0
3	10	0
4	15	0
5	20	0
6	0	5
7	5	5
8	10	5
9	15	5
10	20	5

3.2.2 Moisture Content Determination

According to Australian Standard, AS-1289.2.1.1 (2005), moisture content tests were performed on the artificial soil components including kaolinite Q38, Bentonite Active Bond 23 and Sydney sand (KBS). The percentages of the mix were established based on the dry mass of soil. Using a standard oven, three samples were taken from each component; and the results of moisture content were as follows: 1.2%, 11.5%, and 0.19, respectively as shown in Figure 3.6. Accordingly, these values were taken into consideration in the experimental tests and the sample preparation process to achieve proper moisture contents of specimens. Moreover, the moisture contents of eggshell powder and lime were determined, and they were as follows: 1.7%, 1.4%, respectively. The moisture content of natural expansive soil was also determined and it was 10.9% on average.

Figure 3.6 Moisture content determination

3.2.3 Liquid Limit Tests

To conduct liquid limit tests, about 250g from the mixture of dry kaolinite, bentonite and sand were used in the percentage of 65%, 25%, and 10%, respectively. The soil was sieved through the 425µm sieve for the purpose of determining the liquid limit using the static cone penetration test, in accordance with AS-1289.3.9.1:2015 (2015) standard. The value of liquid limit was 119.5%; this formed the first trial of the combination. It was found that the flow curve of liquid limit after many attempts of cone penetration between 15mm and 25mm. Furthermore, another combination of kaolinite, bentonite and fine sand was assumed as follows: 65%, 30%, and 5%, respectively. The liquid limit for this combination was 155%, and these ratios were adopted to carry out all subsequent tests.

3.2.4 Linear Shrinkage Tests

In accordance with standard procedures AS-1289.3.4.1-2008 (2016) A, the shrinkage limit tests were performed. The soil samples were prepared in accordance with the procedure prescribed in AS 1289.1.1 (AS 2001) for the preparation of disturbed soil samples for linear shrinkage tests. The shrinkage moulds were prepared by applying grease after that the wet soil placed in it. Then, all air bubbles were removed during overfill the mould by tapping the mould. The linear shrinkage tests were conducted on both untreated and treated artificial expansive soil with eggshell powder. The samples were cured for a period of 7 and 28 days.

Figure 3.7 and Figure 3.8 illustrate the process of linear shrinkage tests for the treated soil samples with ESP.

Figure 3.7 Linear shrinkage tests for the treated artificial expansive soil with 5% of the eggshell powder.

Figure 3.8 Linear shrinkage for the treated natural expansive soil with 5% of eggshell powder

3.2.5 Standard Compaction Tests

To determine the maximum dry density (MDD) and optimum moisture content (OMC), for both artificial and natural expansive soils, a series of standard compaction tests were performed on untreated and treated soil samples. Following the procedures prescribed in ('AS-1289.5.1.1—2003 2003'), varying percentages of water were added to the soil. In a distributed and organized manner, the water thoroughly mixed with the soil mixture. To decrease the effect of disturbance during extrusion, a thin layer of grease was applied on the inner wall of the mould before placing soil in the mould. Identical moulds with an internal diameter of 105 mm and a height of 115.5 mm were used for compaction tests. According to the procedures of AS 1289.5.1.1 (AS 2017), the soil samples were compacted in three layers by 25 uniformly distributed blows on the rammer falling freely from a height of 300 mm.

After that, the moisture contents and dry density of samples were calculated. After extruding the samples, each sample was divided into three parts to get three samples for moisture content determination. After conducting, a series of compaction tests on various samples with different water contents, the maximum dry density and the optimum moisture content were determined for the untreated soil. At the optimum moisture content of artificial expansive soil, different percentages of EPS were added. On the same techniques that were followed on the compaction of untreated soil, the blended mixtures were compacted. For each mixture, the dry density was obtained and it was used for performing all subsequent geotechnical tests. Figure 3.9 and Figure 3.10 provide photographs of the applied compaction tools and process.

Furthermore, another series of compaction tests were performed, on the soil samples treated with 5% of hydrated lime in order to find the optimum moisture content and the maximum dry density, as can be seen in Figure 3.11. At the optimum moisture content of artificial expansive soil treated with 5% of lime, various percentages of eggshell powder were added. Following the same technique applied for compacting the lime-treated soil, the blended mixtures were compacted. For each mixture, the dry density was obtained, and it was used for performing the unconfined compressive strength tests.

Figure 3.9 Compacted artificial soil sample by adding 5% of eggshell powder

(a)

(b)

Figure 3.10 Compaction test for natural expansive soil (a) preparation of a sample of natural expansive soil for compaction test ; (b) Compacted natural soil sample by adding 5% of eggshell powder

(a) (b)

Figure 3.11 Compaction test for treated artificial expansive soil with 5% of lime at various water content (a) the sample extruded from the mould; (b) compacted treated sample with 5% of hydrated lime

3.2.6 Unconfined Compressive Strength Tests

The unconfined compression tests of treated and untreated soil were conducted in accordance with AS 5101.4 (AS 2008a). The untreated and treated samples with hydrated lime and eggshell powder were compacted into a steel split mould of 50 mm in diameter and 100 mm in height, under static compaction load. Before compacting the soil in the mould, a thin layer of grease was evenly coated the inner wall of the mould. The reconstituted expansive soil was mixed with ESP, hydrated lime, or their combination before compacting in the mould.

After mixing the reconstituted soil with additives, all of the UCS samples were prepared depending on the value of OMC obtained from the compaction tests. On the other hand, the maximum dry densities of soils treated by additives were determined by an array of compaction tests before placing them in the mould. The tamping technique was performed to obtain the preferred dry density. Accordingly, to confirm that the specimens were uniformly compacted, the specimens were compacted in three layers in the cylindrical mould. Compaction conducted carefully ensuring to reach even distribution of compaction energy and proper connection between layers.

Meanwhile, plastic pieces were cut and placed at the base of the moulds to avoid any potential damage to soil sample (e.g. due to sticking the soil base to the laboratory bench). Furthermore, the samples were extruded, sealed in a plastic cover to prevent the loss of moisture throughout the curing period. The samples were kept in a temperature-controlled room at 25°C and with a relative humidity of 80%. The samples were unwrapped at certified testing dates for unconfined compression tests after the duration of curing reached. Before using the UCS loading frame, the samples were weighed and their dimensions were measured for calculating the sample dry density. Figure 3.13 shows some of the samples employed for measuring the unconfined compressive strength.

The loading frame Tritech that was employed in the UCS test consists of a linear variable differential transformer (LVDT) and S-shaped load cell. These two components joined with a computer via a data logger. The dial data was shown to users through the interface of Datacomm program. The data, which is including vertical displacement from LVDT and force from load cell saved in columns in separate, excel files. The data was transferred from the load cell and LVDT to an understandable output using the data logger. For converting the force into an electrical signal, S-shape load cell was employed as a transducer. In accordance with AS 5101.4 (AS 2008a), the apparatus with the capacity of 50 kN was adopted in the UCS test and a strain rate of 1 mm/min was applied during UCS tests. The strain of the samples was obtained from the LVDT reading. The unconfined compressive strength was calculated by division of force to the equivalent circular area of the samples. For every mixture, the unconfined compressive strength was reported at least 3 times at 7, and 28 days of curing. The final strength was obtained by measuring the average. Figure 3.13 illustrates the process of preparing UCS samples using natural expansive soil.

(a) (b)

Figure 3.12 unconfined compressive strength test: (a) selected artificial soil sample in conventional compression testing machine; (b) selected soil samples prepared and sealed in vinyl plastic wrap for curing

(a) (b)

Figure 3.13 preparation selected soil sample for conducting UCS (a) natural soil sample mixed with 5% eggshell powder; (b) processes of compacted the natural soil in the moulds

3.2.7 Loss on Ignition Tests

Adhering to AS 4489.7.1-1997 standard, loss on ignition tests were performed on three samples of eggshell powder. The purpose of the test was to determine the organic matter (OM) content of the eggshell powder. The OM was determined by comparing the weight of samples before and after the eggshell powder has been ignited. The difference in weight before and after ignition represents the amount of the OM that was present in the sample. The test involves using a muffle furnace without any chemicals. Three samples of eggshell powder were placed in the crucibles. These crucibles were placed in the oven at a temperature of 105°C to make it fully dry. After that, it was subjected to the furnace at two stages of high temperature for two hours. The first hour at 500°C and the second one at 750°C. Finally, the weight of burned ESP after two hours in the furnace was measured to obtain the value of loss on ignition percentage (LOI %).

3.2.8 pH Tests

In accordance with the procedure prescribed in ASTM D6276 (2006), the optimum lime content was obtained through the pH measurement of different percentages of lime blended with the untreated expansive soil (Eades & Grim 1966). The required amount of hydrated lime for stabilization of expansive soil was performed on the dry weight of the air-dried soil-eggshell powder-water mixtures in order of obtaining the pH values of the combinations. Using a pH meter with a proper probe, the pH tests were conducted as shown in Figure 3.14. At a controlled temperature room (25°C), the pH meter and its probe were calibrated with 4 and 7 buffer solutions. Samples were prepared at a solid-water ratio of 1:4. After the air-drying and passing the 425 μm sieve, 25g soil was mixed with various percentages of hydrated lime or eggshell powder combined with hydrated lime. They were dispersed in 100 ml distilled water, and the specimens were continuously stirred for the 30s at every 10 min for 1hour to ensure the soil mixtures were homogeneous. Subsequently, the pH values of the slurries after 1-hour of stirring were measured at a controlled temperature room (around 25°C).

Figure 3.14 pH meter and the probe

3.2.9 California Bearing Ratio Tests

The California bearing ratio (CBR) tests were performed on the artificial expansive soil treated with eggshell powder and hydrated lime according to the test method specified in AS 1289.6.1.1 (AS 2014). After mixing design, the treated soil samples were filled into a cylindrical metal mould with an internal diameter of 152 mm and a height of 178 mm. In order to ensure the uniformity of compacted samples in terms of OMC and MDD, each soil sample was compacted into five equal layers inside the mould by pressing the spacer disk of 61 mm in thickness with the help of a test machine. Afterwards, the prepared sample sealed in a plastic cover to prevent moisture loss. Then, the sample was kept for a curing period of 7 days in an environmentally controlled room with a temperature of 25°C and relative humidity of 80% as shown in Figure 3.15 (a). After 7 days of curing, the sample was subjected to a soaking condition by keeping the sample in water for 7 days prior to testing in case of soaked CBR tests or an annular surcharge of 4.5 kg placed on the top as prescribed in AS 1289.6.1.1 (AS 2014) and shown in Figure 3.15 (b).

The machine was set for a uniform loading of 1mm/min. The LVDT and load cell readings were used to draw the load-penetration curve for use in calculating CBR values. The CBR values were calculated and selected from the higher ratio of applied force to 13.2 and 19.8 kN at the penetration of 2.5 mm and 5 mm, respectively.

(a)

(b)

Figure 3.15 CBR sample (a) under the curing condition (b) under the soaking condition

3.3 Summary

This chapter has proposed a full description of the experimental program, including the employed materials, sample preparation, and the implemented tests. The physical and chemical properties of the artificial and natural expansive soils used in experimental work were studied and analyzed in detail. Different laboratory tests were executed throughout this study namely, linear shrinkage tests, pH tests, compaction tests, unconfined compressive strength tests, CBR tests, and loss on ignition tests. These tests not only illustrate the effect of adding the eggshell power on the engineering properties of the expansive soil but also demonstrates the effect of the eggshell powder as a supplementary additive to lime stabilized soil. Untreated and treated artificial expansive soil samples were utilized with the earlier mentioned tests at different curing times. In this study, the curing days were varied as 7 and 28 days with the addition of eggshell powder and lime to the soil by the dry weight of the soil. A small percentage of eggshell powder has been blended with the natural expansive soil to investigate the effect of this addition on the geotechnical properties of natural expansive soil. The results of the tests were also compared with the artificial expansive soil results.

CHAPTER 4:

Experimental Results and Discussions

Geotechnical test results are presented in this chapter based on intensive laboratory experiments. The progress of the study was commenced by a comprehensive literature review to investigate the problem and define the gap in the literature. The laboratory tests conducted in this chapter have been implemented according to the procedures prescribed in the previous chapter. The main purpose of this chapter is to investigate the combined effect of the eggshell powder and hydrated lime on the behaviour of treated soil and its shrink-swell potential. The soil was stabilized by mixing with 5% lime, which is formed the control specimen in this study. The eggshell powder was used as an additive to 5% lime in four dosages 5%, 10%, 15%, and 20% based on the dry weight of expansive soil. The second series of tests were conducted around the optimum eggshell powder content (i.e. 4%, 5% and 6%). An array of the physical and chemical tests were performed on untreated and treated soil specimens. These tests include linear shrinkage tests (LS), compaction tests, pH tests, unconfined compressive strength (UCS), California bearing ratio tests, and loss on ignition tests. The LS tests, pH tests and UCS tests were conducted at two different curing times of 7 and 28 days. In addition, the compaction and UCS tests were conducted at different moisture contents. In order to recognize the combined effect of eggshell powder and hydrated lime, the results of the experimental tests were discussed, analyzed and figured out.

4.1 Geotechnical Characteristic of Expansive Soil Stabilized with Lime and Eggshell Powder

The soil mixtures were tested by conducting linear shrinkage, compaction and UCS tests and the results obtained are summarized in Table 4.1 and Table 4.2. In addition, the soil mixtures, tested using natural soil, are tabulated in Table 4.3.

Table 4.1 Soil mixtures and results for all of the tests conducted on untreated soil with a moisture content around 29.04%

Sample	Linear shrinkage with different liquid limit (%)				UCS (kPa)	
	7 days	**28 days**	**OMC (%)**	**MDD (g/cm^3)**	**7 days**	**28 days**
Untreated soil (KBS)	21.23 %	21.23	29.04	1.323	285	285
			Compaction MC (%)	**Dry Density (g/cm^3)**		
KBS+5ESP	16.96	16.78	28.5	1.319	320	335
KBS+10ESP	14.99	13.92	28.8	1.315	306	326
KBS+15ESP	14.15	13.01	29.1	1.308	222	268
KBS+20ESP	12.32	11.24	29	1.293	224	255
KBS+5L	15%	-	29	1.121	455	540
KBS+5L+5ESP	13.52	-	28.5	1.219	500	620
KBS+5L+10ESP	12.35	-	28.5	1.228	330	385
KBS+5L+15ESP	10.98	-	28.5	1.265	270	351
KBS+5L+20ESP	10.50	-	28.5	1.228	260	329

Table 4.2 Soil mixtures and results for all of the tests conducted on untreated soil with a moisture content around 32.31%

Sample	OMC (%)	MDD (g/cm^3)	UCS (kPa)	
			7 days	28 days
KBS+5L	32.31	1.298	433.33	525.8
	Compaction MC (%)	**Dry Density (g/cm^3)**		
KBS+5L+4ESP	32.33	1.24	460.7	556.7
KBS+5L+5ESP	31.37	1.237	520.9	606.8
KBS+5L+6ESP	31.49	1.234	320.5	420.3

Table 4.3 Soil mixtures and results for all of the tests conducted on natural expansive soil

Sample	MDD (g/cm^3)	OMC (%)	Linear shrinkage (%) at 7 days of curing	UCS (kPa) at 7 days of curing
Untreated natural expansive soil	1.29	36.5	21.67	242
	Compaction MC (%)	**Dry Density (g/cm^3)**		
Natural soil +5% eggshell powder	1.217	36.5	16.4	252
Natural soil+20% eggshell powder	1.12	35.8	-	230

4.1.1 Linear Shrinkage Tests

The effect of adding different proportions of eggshell powder on untreated expansive soil and the lime stabilized artificial soil is presented in Figure 4.1 and Figure 4.2. The eggshell powder was added based on the total dry weight of the soil, and the results were obtained after 7 and 28 curing days. The addition of 5% eggshell powder into highly plastic clay at the same liquid limit showed a slight reduction in the linear shrinkage. The same value of liquid limit was applied for all soil-eggshell powder specimens for conducting the linear shrinkage tests. An adverse impact on the shrinkage limit was observed after adding higher proportions of eggshell powder. It was noticed that a further increase in eggshell powder content powder resulted in a marginal increase in the linear shrinkage. This leads to the fact that the liquid limit of eggshell powder-soil admixture decreased with an increase in the eggshell powder content (Barazesh, Saba, Gharib, et al. 2012; Nyankson et al. 2013). Therefore, the excess water spills outsides the voids and negatively effect on the values of linear shrinkage. The same behaviour was observed at 28 curing days. As a result, the water content was adjusted to meet the required amount of liquid limit for each sample of eggshell powder and soil.

Figure 4.1 illustrates a gradual decreasing in linear shrinkage values by adding different ESP content. The linear shrinkage reduced by 4.27%, 6.24%, 7.08%, and 8.91%

by adding 5%, 10%, 15%, and 20% eggshell powder, respectively, at 7 curing of days. A further marginal decreasing caused by adding eggshell powder at 28 curing of days. Thereby, by adding different eggshell powder contents, including 5%, 10%, 15%, and 20%, the linear shrinkage values were reduced by 4.45%, 7.31%, 8.22%, and 10%, respectively, at 28 curing of days. In other words, further addition of ESP decreased the linear shrinkage of artificial expansive soil. This is basically because of the replacement of monovalent ions in soil by divalent calcium ions from eggshell powder (Bhuvaneswari et al. 2010; Little 1995). Another reason is the reduction in the diffused double layer (DDL) with an increase in electrolyte concentration in the pore fluid (Sivapullaiah & Jha 2014). It may also be due to an increase in viscosity of the pore fluid due to the adsorption of calcium ions. The addition of ESP augments the supply of calcium ions available for ion exchange, an increase in electrolyte concentration and increase in viscosity of pore fluid.

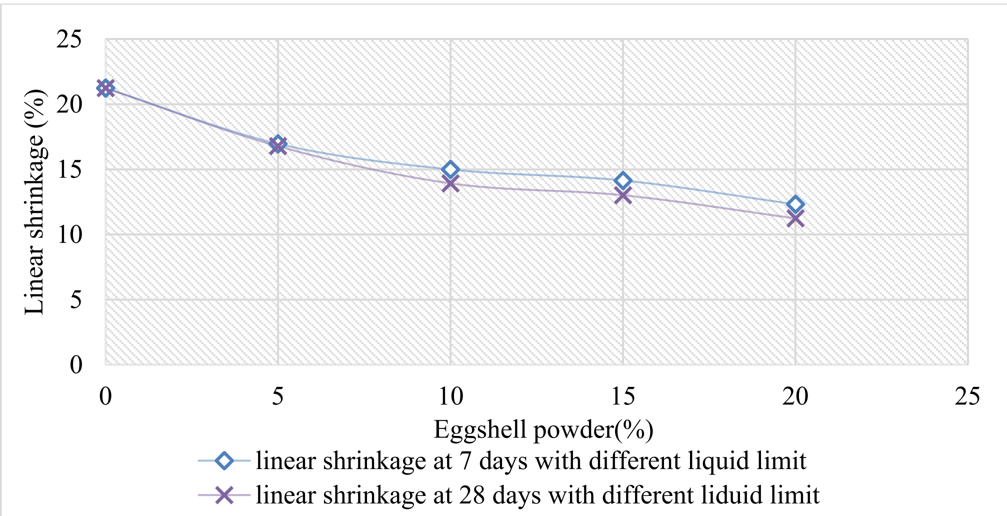


Figure 4.1 Linear shrinkage of different content of eggshell powder on the treated expansive soil at 7and 28 days of curing

A further reduction in linear shrinkage was observed upon addition of 5% lime into the stabilized soil. The lime is rich in calcium, thereby the supply of calcium ions can be augmented. Therefore, adding 5% of hydrated lime resulted in a significant decreasing in LS from 21% to 16% (about 6.2% reduction). Furthermore, at a different liquid limit, different doses of eggshell powder amended with the lime stabilized expansive soil by total dry weight of the mass. The results of LS revealed that eggshell powder played a pivotal role in enhancing the shrinkage properties of lime stabilized expansive soil at 7 curing days as shown in Figure 4.2. The LS shrinkage reduced from 15% to 10.50% when the eggshell powder added from 5% to 20% to the lime stabilized the soil. The combination of eggshell powder and hydrated lime in soil achieved a higher reduction in LS compared to those when lime or ESP were used separately for soil stabilization. The eggshell powder as an admixture causes the aggregation and flocculation of clay particles. Therefore, a reduction in clay surface area induced by this phenomenon. These phenomena contribute to form a coarse, less clayey, and less plastic soil admixture. This explains the marked decline in linear shrinkage when increasing the additive content during specified curing times.

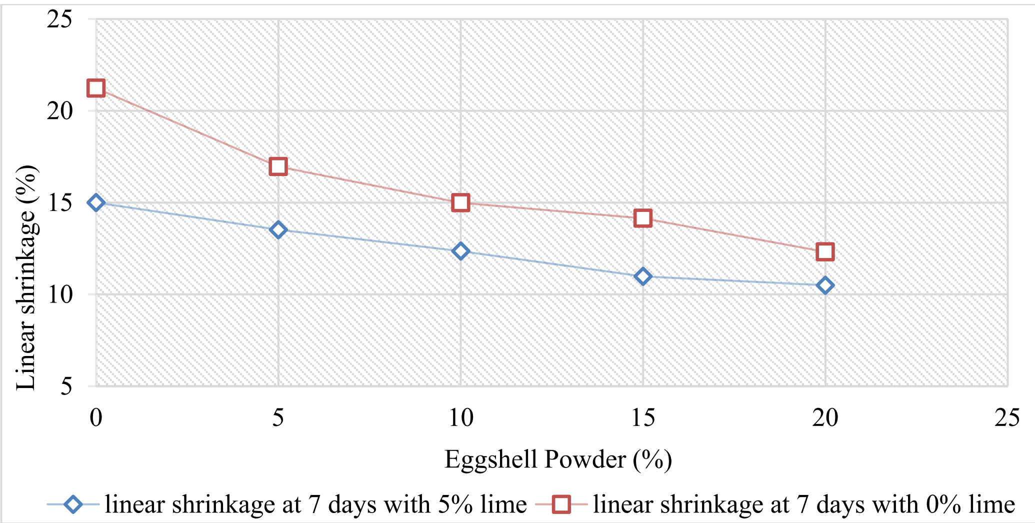


Figure 4.2 Linear shrinkage of different content of eggshell powder treated 5% lime stabilized expansive soil at 7 curing days

On the other hand, when 5% content of eggshell powder added to the natural expansive soil, the linear shrinkage decreased from 21.7% to 16.4%. In comparison with the tests conducted on artificial expansive soil, the results appear to be close.

4.1.2 Standard Compaction Tests

As a preliminary step, the maximum dry density (MDD) and the optimum moisture content (OMC) were determined in accordance with the procedures prescribed in the preceding chapter. It can be inferred from Figure 4.3 that the achieved MDD was 13.23 kN/m^3 and the OMC was 29.04%, for the untreated expansive soil. In order to evaluate the effect of additive content and the so-called maximum dry density of the treated soil mixtures, the value of optimum moisture content of 29.04% was applied to other additives and soil mixtures. It is worth mentioning that the OMC and the MDD of mixtures may differ significantly compared to those obtained by testing the untreated samples.

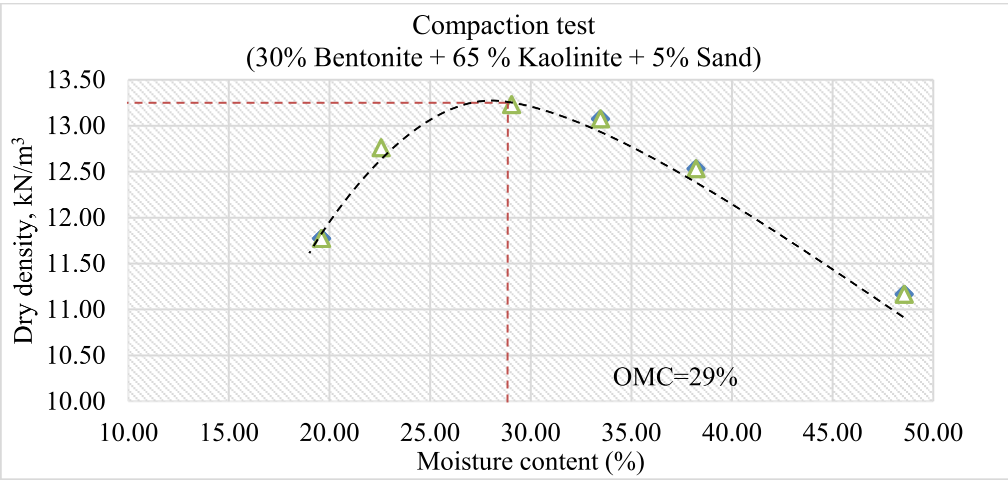


Figure 4.3 Compaction test results for the untreated artificial expansive soil

Figure 4.4 depicts the effect of adding different contents of eggshell powder on the dry unit weight of treated expansive soil after applying the standard compaction tests. It was revealed that the dry density decreased with increasing the content of Eggshell powder. A significant decrease was observed in the dry density, from 13.23 kN/m^3 to 12.93 kN/m^3, when the eggshell powder content increased from 5% to 20%.

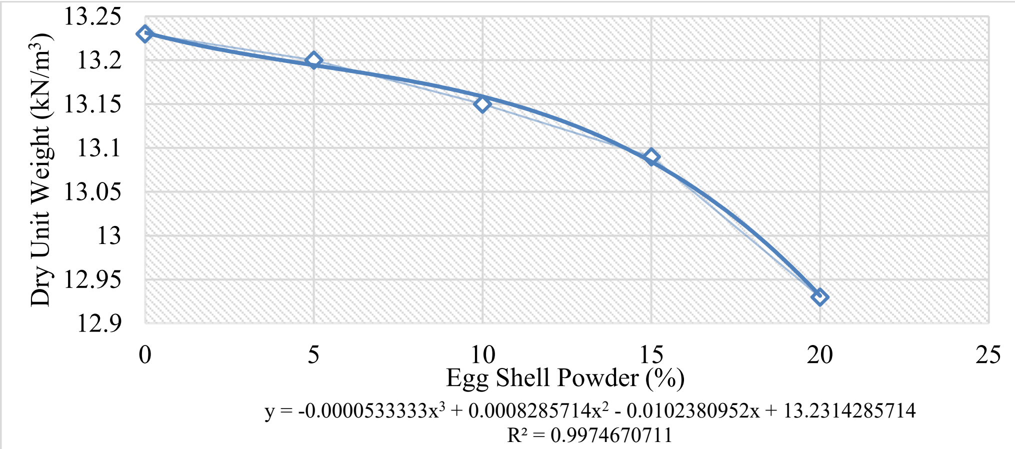


Figure 4.4 Variation of dry density by adding different contents of eggshell powder on the treated expansive soil

The decrease in the dry density can be attributed to the replacement of the soil by the eggshell powder, having a relatively lower specific gravity (i.e. 2.4) compared to that of the artificial expansive soil which is 2.65. In other words, the decrease in dry density can be due to the fact that OMC mixtures may not necessarily be identical to the treated soils. The standard compaction test results, when different percentages of eggshell powder mixed with the lime stabilized expansive soil, are depicted in Figure 4.5. As can be seen, all dry unit weights of treated soils are less than that of untreated soil.

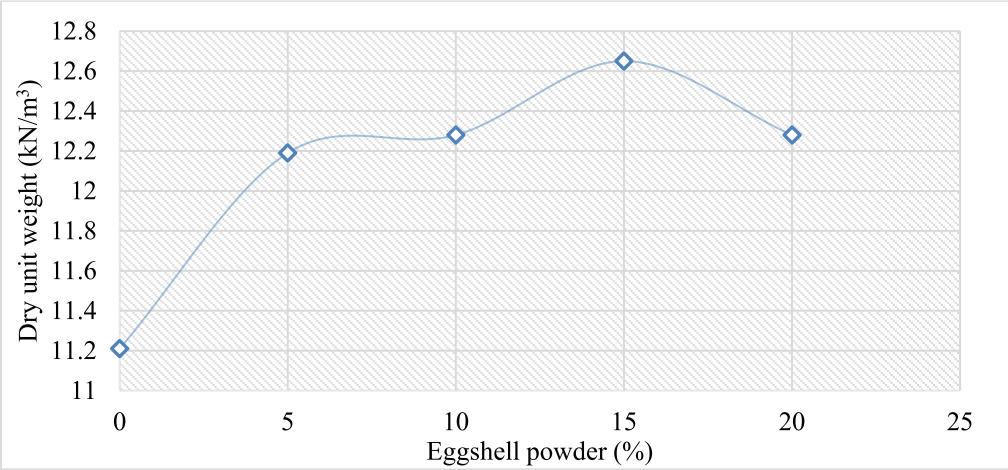


Figure 4.5 Variation of dry density by adding different content of eggshell powder with 5% lime treated expansive soil

A slight increase was observed in the dry density compared to the soil-lime mixture when the eggshell powder was added. As can be seen in Figure 4.5, the addition of eggshell powder to 5% lime stabilized expansive soil increased its dry density because the specific gravity of eggshell powder is higher than the hydrated lime, which is 2.2. This explains that the marginal increase in the dry density when the eggshell powder content increased from 5% to 15% into 5% lime stabilized expansive soil. It should be noted that uncertainties about the uniform distribution of moisture in all soil samples can be another reason for this increase. It can be seen that all values of dry densities of treated soil were less than the MDD of untreated expansive soil. According to Rahman (1987), the reduction of the dry density of the treated soil mixtures may be explained by several reasons among them the lower specific gravity of the additives compared to the untreated artificial expansive soil. Another reason is associated with the creation of coarser particles, which is caused by the cation exchange process between clay particles and additives. Therefore, the void volume increased due to the coarser particles, which is occupying the large spaces. These processes called flocculation and agglomeration (Kinuthia, Wild &

Jones 1999; Millogo et al. 2012). Generally, the higher the dry density, the better the soil for construction works, but for expansive soil, the higher dry density usually indicates also the higher swelling potential (Surjandari, Djarwanti & Ukoi 2017).

On the other hand, when 5% and 20% of eggshell powder were added into the natural expansive soil, the dry density decreased from 1.35 g/cm^3 to 1.29 g/cm^3 and 1.21 g/cm^3, respectively. This effect of reduction was recorded when a different percentage of eggshell powder was added to the artificial expansive soil. This again emphasizes that the specific gravity of eggshell powder is lower than the specific gravity of both artificial and natural expansive soils.

Figure 4.6 shows the results of the experiment were conducted to obtain the maximum dry density versus the optimum moisture content of the artificial expansive soil treated with 5% of hydrated lime at different ESP contents. As can be seen, the achieved MDD was 12.98 kN/m^3 and the corresponding OMC was 32.31%, for the treated expansive soil with 5% hydrated lime.

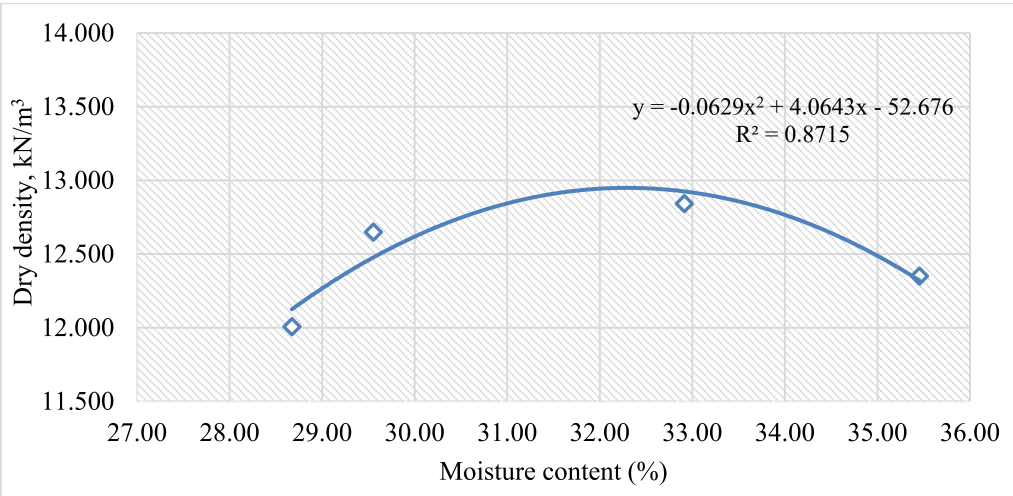


Figure 4.6 Variation of maximum dry density of 5% lime treated expansive soil

In order to evaluate the effect of the additive content and the dry densities of the treated soil mixtures, the value of optimum moisture content of 32.31% was applied to other ESP percentages as shown in Figure 4.7. Referring to this figure, adding different percentages of ESP (2%, 4%, 5% and 6%) into 5% lime stabilized expansive soil, the dry density decreased from 12.98 kN/m^3 to 12.34 kN/m^3 with increasing the content of the eggshell powder.

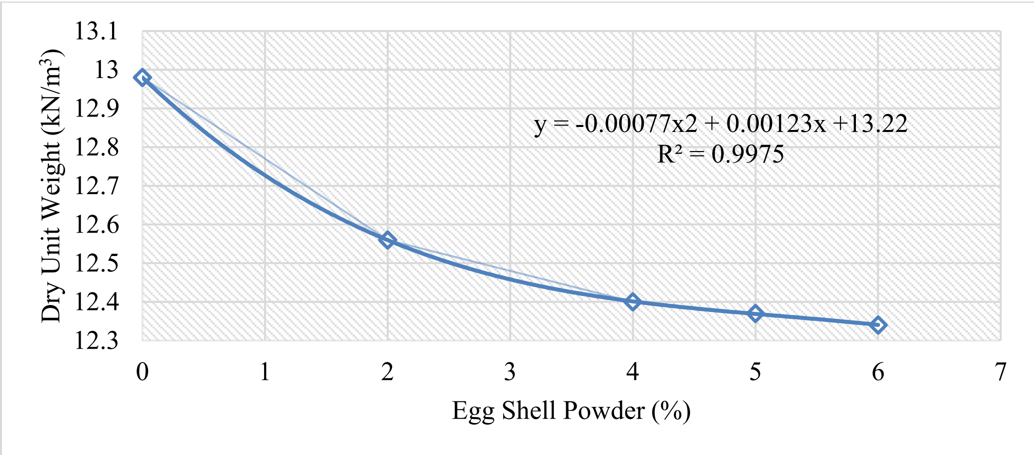


Figure 4.7 Compaction tests results for dry density of the treated artificial expansive soil with 5% hydrated lime and different percentages of ESP

4.1.3 Stress-Strain Behaviour

From unconfined compressive strength tests, the typical curves of stress-strain were obtained for eggshell powder treated expansive soil samples after 28 days of curing. Figure 4.8 illustrates the stress-strain behaviour of artificial expansive soil treated with different eggshell powder contents. Each curve represents the average results of three specimens for the untreated soil samples and the soil samples treated with the addition of eggshell powder. As can be observed in Figure 4.8, in all cases whether for untreated or treated expansive soil, after the ultimate load was gained, the specimens still deformed, and fine cracks could be seen in the surface of the specimens. It seems that the stress-strain relationships were non-linear for all the test series. For the untreated expansive soil, the peak stress reached 285 kPa at an axial strain of 3.82%. Furthermore, in tests on treated soil with eggshell powder, the ultimate stress and strain increased gradually with the increasing eggshell powder content up to 10%. In contrast, a slight reduction was noted when eggshell powder content increased from 10% up to 20%. Referring to Figure 4.8, the peak stress and corresponding axial strain at 5% dosage of eggshell powder were 335 kPa and 3.91%, respectively. In comparison with UCS results of untreated expansive soil, the stress and strain increased by 18% and 9%, respectively. It can be concluded that the compressive strength and material ductility were improved with the addition of this dosage of eggshell powder. This may be explained by considering the redistribution of internal force between the soil matrix and eggshell powder due to the pozzolanic reaction, which is formed a cementitious bond. After the final failure, the soil – eggshell powder composite was not disintegrated totally (Ghavami, Toledo Filho & Barbosa 1999). Samples mixed with eggshell powder achieved the highest stress and strain at 5% content and this percentage could be the optimum amount of addition. In general, notable improvement in the mechanical properties of the artificial expansive soil can be observed when soil is blended with eggshell powder.

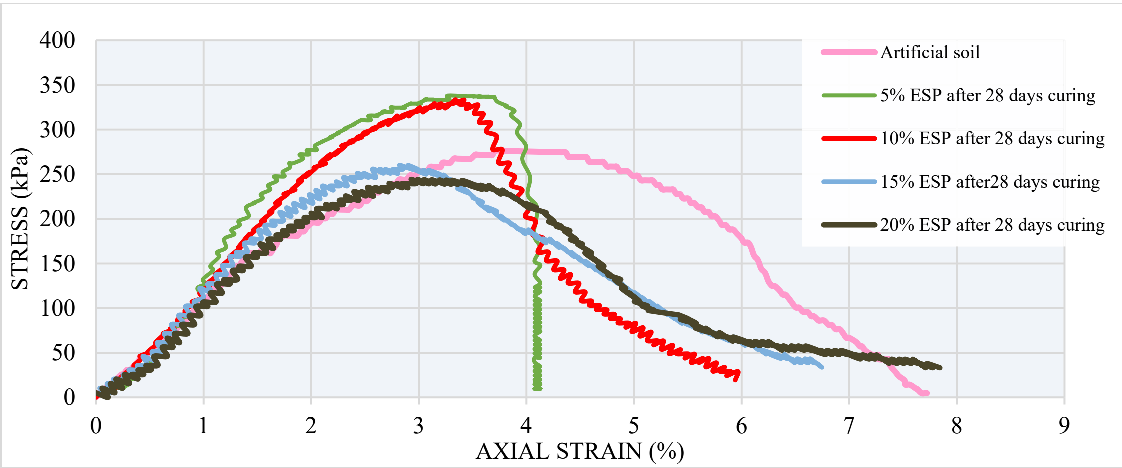


Figure 4.8 Influence of different eggshell powder content on stress-strain behaviour of expansive soil

The effect of adding various percentages of eggshell powder to the lime-treated expansive soil on stress-strain behaviour of expansive soil after 28 days is shown in Figure 4.9. As can be observed in Figure 4.9, after adding 5% eggshell powder to the lime treated soil, a noteworthy increase occurred in the stress from 540 kPa to 620 kPa. Therefore, a 15% improvement was achieved at this dosage, compared with the lime-treated expansive soil. This improvement was a clear reflection on the stabilized expansive soil in terms of the brittleness and stiffness. For example, the axial strain value of the untreated expansive soil was 3.82%, when the 5% content of eggshell powder added to 5% lime treated expansive soil, the value of axial strain was 2.02%, which shows a significant reduction in the axial strain about 47% compared with the value of untreated artificial expansive soil. On the other hand, as shown in Figure 4.9, when the expansive soil treated with 5% of hydrated lime, the value of ultimate strain was 1.2%, the addition of 5% hydrated lime –eggshell powder combined resulted in an increase in the axial strain from 1.2% to 2.02%, the axial strain increased by approximately 68%. This lead to the fact that the combination of hydrated lime and eggshell powder displays more ductile behaviour than lime treated expansive soil alone.

Moreover, the failure strain values of the soil treated with hydrated lime-eggshell powder combination achieved in this research varying from 2.02% to 2.4%. Thereby, this range considers as a noteworthy enhancement in ductility because it is significantly higher than the frequent failure strain for lime/cement-treated clay soil, which is varying from 0.5% the 0.75% according to previous investigations (Cai et al. 2006; Fatahi & Khabbaz 2013; Tang et al. 2007). This indicates that the compressibility characteristics of the treated expansive soil were also reduced in the early stages of the loading.

According to Figure 4.9, the combination of hydrated lime and eggshell powder yielded a notable increase with adding 5% content of the eggshell powder. However, it is not effective beyond adding 10% of eggshell powder, the stress dramatically decreased, and the corresponding axial strain increased, with the addition of eggshell powder up to 20% content of the eggshell powder. In order to explain this finding, it was assumed that the chemical reaction between the expansive soil and the additives (hydrated lime and eggshell powder) consists of several forms of interactions including pozzolanic reaction, cation exchange, carbonation and cementation. The flocculation of clay particles phenomena due to the cation exchange process, which forms coarser particles, plays a pivotal role in enhancing the compressive strength. The agglomeration into coarse particles resulted in a higher UCS value compared with that of the untreated expansive soil. This could clarify the increase in compressive strength with a combination of 5% hydrated lime and eggshell powder. Moreover, the load cell is too strong for such small loads required in the UCS tests. That can explain the fluctuations in stress-strain curves.

Furthermore, the cementation process resulted in an increase the compressive strength due to the binding between clay particles together. The initial increase in the UCS value was because of the gradual formation of cementitious compounds (calcium silicate hydrate). However, it seems that after addition of 10% eggshell powder that eggshell powder lacks cementitious properties, the excess eggshell powder was occupied spaces within the soil to form weak bonds between the soil and the cementitious compounds, hence, an adverse effect was observed on the cohesive nature of the soil and this could interrupt the steady decrease in compressive strength. Thus, the accumulation of excess eggshell powder decreases the strength of the soil. However, the value of stress with an addition 10%, 15%, and 20% of eggshell powder reached as follows: 385, 351, and 329 kPa, respectively. These values of stress were higher than the value of stress of the untreated artificial expansive soil which was 285 kPa. This gives a promotion in the possibility of utilization of eggshell powder in the field of soil stabilization.

As stated earlier, the eggshell powder can be used as a supplementary additive to lime stabilization and it is not effective as a replacement of lime totally. This result is consistent with several previous research on the possibility of utilization eggshell powder in soil stabilization (Ahmed, Rahman & Das; Amu, Fajobi & Oke 2005; Anoop et al.; Muthu Kumar & Tamilarasan 2014; Paul et al. 2014; Soundara & Vilasini 2015).

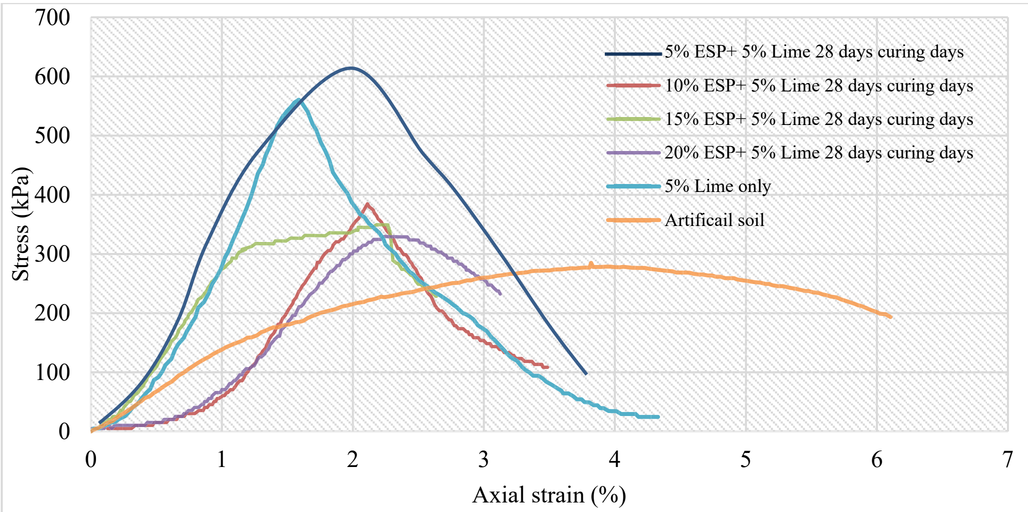


Figure 4.9 Influence of different hydrated lime-eggshell powder content on stress-strain behaviour of expansive soil after 28 days of curing

4.1.4 Modulus of Elasticity ($E_{50\%}$)

$E_{50\%}$ values were derived from the UCS tests conducted earlier. Each specimen was subjected to loading. The straight lines are drawn through the first two loading curves (secant modulus) and the average slopes in these lines are the $E_{50\%}$ of the stabilized expansive soil.

The variation in $E_{50\%}$ resulting from adding different proportions of eggshell power is shown in Figure 4.10. As can be seen, the secant $E_{50\%}$ increased from 10.58 MPa for untreated soil to 14.44 MPa when adding 5% eggshell powder. On the contrary, any additional doses of eggshell powder will reduce the value of the elastic modulus.

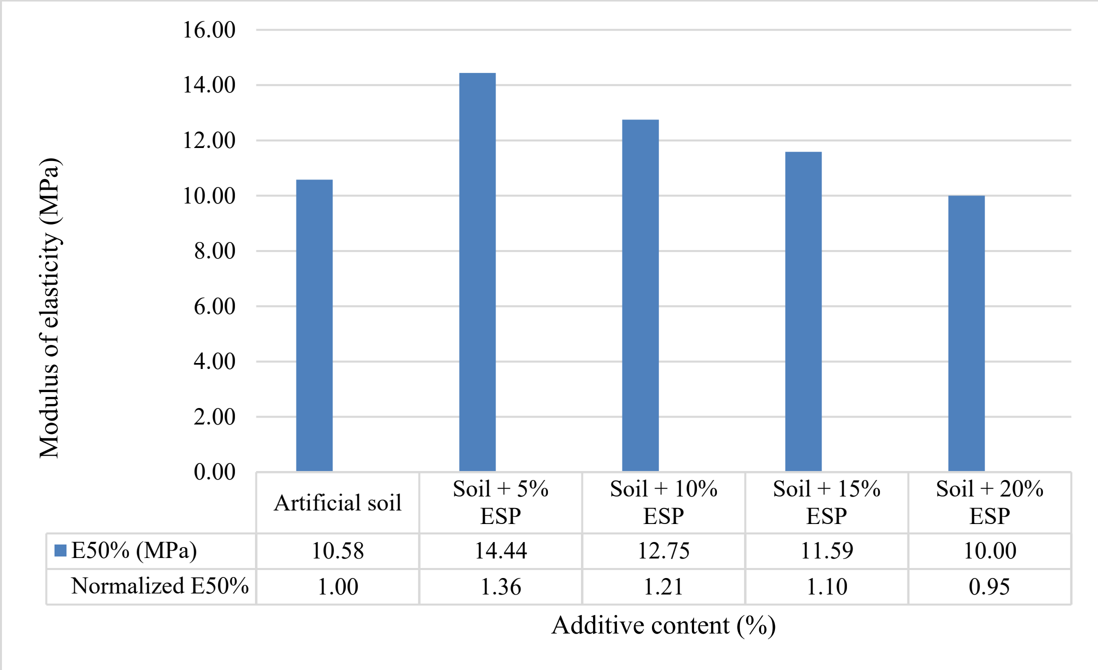
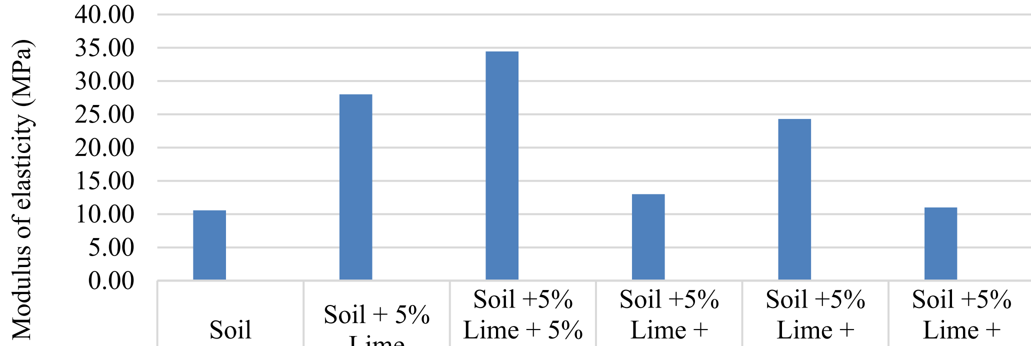


Figure 4.10 Variation of $E_{50\%}$ values with adding different percentages of eggshell powder

Attempts have been made to monitor the effect of adding different proportions of eggshell powder to 5% lime treated soil on the $E_{50\%}$ as shown in Figure 4.11. It is clear that the normalization factor for the elasticity value increases with increasing eggshell powder - lime content compared to the untreated soil. It was observed that the optimum improvement in $E_{50\%}$ was achieved by adding 5% of ESP to 5% of the lime treated soil. This mixture has the highest pH value of 12.6 produced the highest modulus value. This trend is consistent with the behaviour investigated by other researchers (Amu, Fajobi & Oke 2005; Barazesh, Saba, Gharib, et al. 2012).



	Soil	Soil + 5% Lime	Soil +5% Lime + 5% ESP	Soil +5% Lime + 10% ESP	Soil +5% Lime + 15% ESP	Soil +5% Lime + 20% ESP
E50% (MPa)	10.58	28.00	34.44	13.00	24.29	11.00
Normalized E50%	1.00	2.65	3.26	1.23	2.30	1.04

Additive content (%)

Figure 4.11 Variation of $E_{50\%}$ values by adding different percentages of eggshell powder to 5% of lime treated expansive soil

4.1.5 Unconfined Compressive Strength (UCS)

The effect of eggshell powder content on unconfined compressive strength of treated artificial expansive soil after 7 and 28 days of curing is depicted in Figure 4.12. It was noticed that the strength of the soil increased approximately by 12% with addition 5% eggshell powder by dry weight of the soil at 7 days of curing, though, the increase is marginal. A sudden decrease was observed at 10% addition of eggshell powder compared with its value at 5% dosage into the soil. The strength value at 10% dosage reached 306 kPa; however, it was still higher than the strength value of untreated expansive soil. Furthermore, the strength of the stabilized expansive soil reduced by 26%, 25% with the addition of 15%, 20%, of eggshell powder, respectively. Hence, there is a reduction in the unconfined compressive strength due to the excessive usage of the content of the eggshell powder. At 28 days of curing, a further increase in the unconfined compressive strength was obtained at 5% dosage of eggshell powder.

The improvement in the unconfined compressive strength by adding this dosage could be attributed to cation exchange, pozzolanic reactions due to a high amount of alumina, silica in the expansive soil and lime available in eggshell powder. A chemical reaction occurred in the presence of water when minerals such as alumina, silica interact with the available CaO in eggshell powder forming a cementitious compound, which is scattered among clay particles. This dosage resulted in a clear increase in the strength of about 18% and then followed by a slight drop to 20% eggshell powder inclusion at 28 days of curing. Thus, it can be seen that 5% dosage of eggshell powder stabilized soil could be the optimal dosage for the artificial expansive soil under investigation. Moreover, above this level of increase, the strength was found to decline. It seems that the addition of a small dosage of eggshell powder improves the strength of soil by augmenting the rate of pozzolanic and hence gives a higher strength reaction. Anoop et al. (2019) also reported that by increasing the percentage of ESP in the mixture, the strength begins to fall (Anoop et al.).

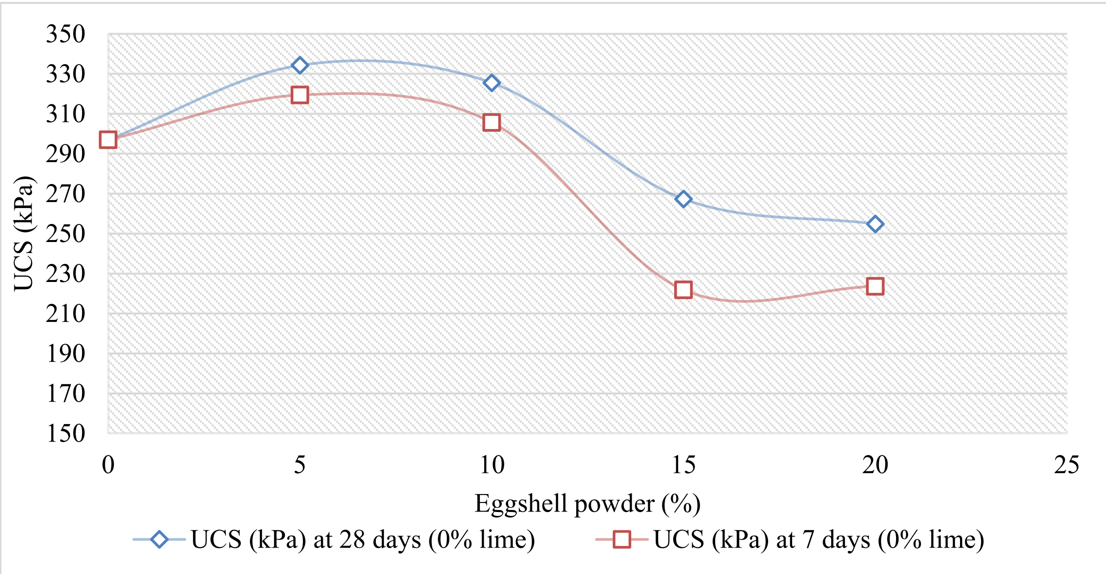


Figure 4.12 Effect of eggshell powder on UCS expansive soil after 7 and 28 days of curing

The variation of UCS with the addition of eggshell powder to the lime stabilized expansive soil is shown in Figure 4.13. A quantity of 5% hydrated lime was added to the ESP-soil samples in order to explain the effect of lime-ESP admixture on the enhancing of soil strength. Referring to Figure 4.13, the addition of lime into the expansive soil gives rise to the strength of the stabilized soil from 285 kPa to 455 kPa at 7 days of curing. The addition of hydrated lime plays a pivotal role in accelerating the reactivity of the pozzolanic reaction. However, adding 5% of eggshell powder as a secondary additive to lime in the stabilization of soil resulted in a further increase in the strength of the stabilized soil from 455 kPa to 500 kPa. It was noticed that the strength increased by about 10% when 5% content of ESP added compared with 5% percentage of lime stabilized the expansive soil. Although the increase was marginal, small dosages of ESP are capable of enhancing the strength of limed-soil. Hence, the rate of pozzolanic reaction occurring increases by the addition of small dosages of eggshell powder and can lead to a higher strength. As the percentage of eggshell powder increased, the strength started to fall, as illustrated in Figure 4.13. Thus, the values of unconfined strength with the addition of 10%, 15%, and 20% of ESP to the lime stabilized soil were close to the values of strength with the addition of ESP by itself at 7 days of curing. This leads to conclude that eggshell powder is not as compatible and effective material as hydrated lime. In other words, the lime usage will not be reduced if the percentage of ESP is greater than 10%.

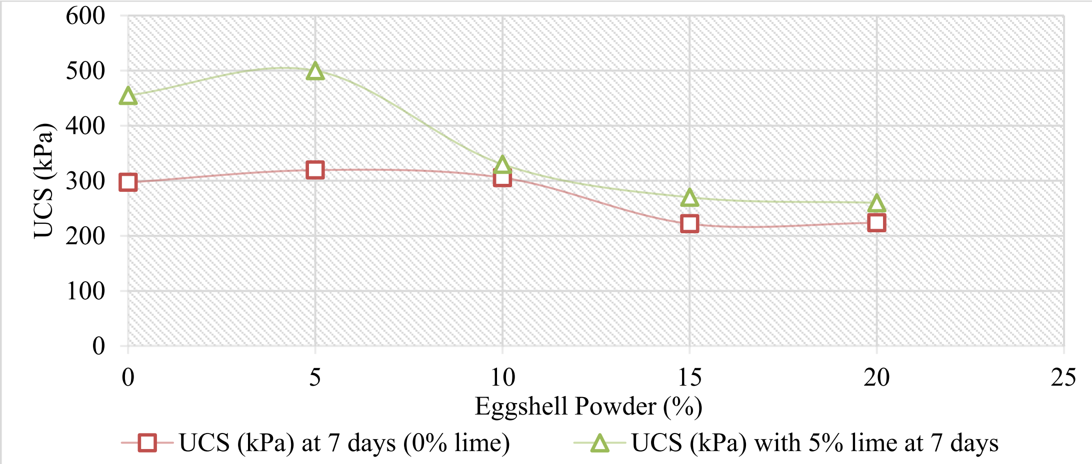


Figure 4.13 Effect of eggshell powder and hydrated lime on UCS of expansive soil after 7 days of curing

The results of the unconfined compressive strength revealed that the combination of 5% hydrated lime plus 5% eggshell powder was more effective in enhancing the strength of stabilized expansive soil than that of eggshell powder used alone. Hence, 5% ESP and 5% hydrated lime selected as target percentage. Furthermore, the soil strength could not be improved by adding large quantities of eggshell powder at 7 and 28 days of curing. These results are consistent with previous studies, used eggshell powder in the stabilization of expansive soils (Amu, Fajobi & Oke 2005; Anoop et al. ; James, Pandian & Switzer 2017; Muthu Kumar & Tamilarasan 2014).

The effect of curing time on the contribution of eggshell powder in developing the strength of the untreated soil and lime-treated soil is represented in Figure 4.14. This figure depicts the variation of unconfined compressive strength with 7 and 28 curing days for eggshell powder treated soil samples with or without hydrated lime admixture. Figure 4.14 reveals the fact that provision longer curing times for lime-eggshell powder-soil mixtures gave a higher UCS value, especially, in case of addition 5% ESP. For example, the UCS increased by 5% for 5% content of eggshell powder treated soil samples when curing times increased from 7 to 28 days. As the addition of eggshell powder increased to 10%, the strength increased by 7%, when the curing increased from 7 days to higher curing of 28 days. Beyond this addition, the strength remains stable and not affected by the curing time.

Finally, when the eggshell powder content increased from 5% to 20 % with increasing the curing time from 7 to 28 days, a slight increase in the UCS was observed. However, the value of UCS was lower than that of untreated soil. For instance, at 7 days of curing, when 15% of eggshell powder added into the untreated soil, the UCS value was 221 kPa. Nevertheless, at higher curing time (28 days), the strength value reached 268 kPa. This portrays the effect of curing time in augmenting the pozzolanic reaction. As discussed earlier, it is still below the value of UCS compared with the untreated soil. An adverse effect was noticed when eggshell powder content increased from 5% to 20%. Consequently, these higher percentages did not produce any enhancement in the UCS values.

The effect of curing time, for different contents of eggshell powder added to lime treated expansive soil, are shown in Figure 4.14. As can be seen, the strength increased by 15% by adding 5% eggshell power compared to 5% lime treated expansive soil. At 28 days of curing, a remarkable improvement in the UCS was noticed, by adding 5%, 10%, 15%, and 20% of eggshell powder to the lime stabilized expansive soil, the strength increased by 24%, 17%, 30%, and 27%, respectively, compared to the result of lime-eggshell powder mixes at 7 days of curing. Many cementitious linkages formed by the reaction between lime-eggshell powder-soil mixtures. As expected, the strength increased with longer curing time. It is clear that the unconfined compressive strength increased from 540 kPa to 620 kPa, corresponding with increasing the curing time from 7 to 28 days. A sudden reduction was obtained at 10% content of eggshell powder about 385 kPa. This reduction continues gradually up to 20% content of eggshell powder, which is treated lime stabilized expansive soil after 28 days of curing. However, it is evident that the addition of small dosages of eggshell powder plays a secondary role in stimulating the behaviour of the lime-stabilized soil. This role is developed with increasing the curing time. Another illustration of the data is shown in Figure 4.15.

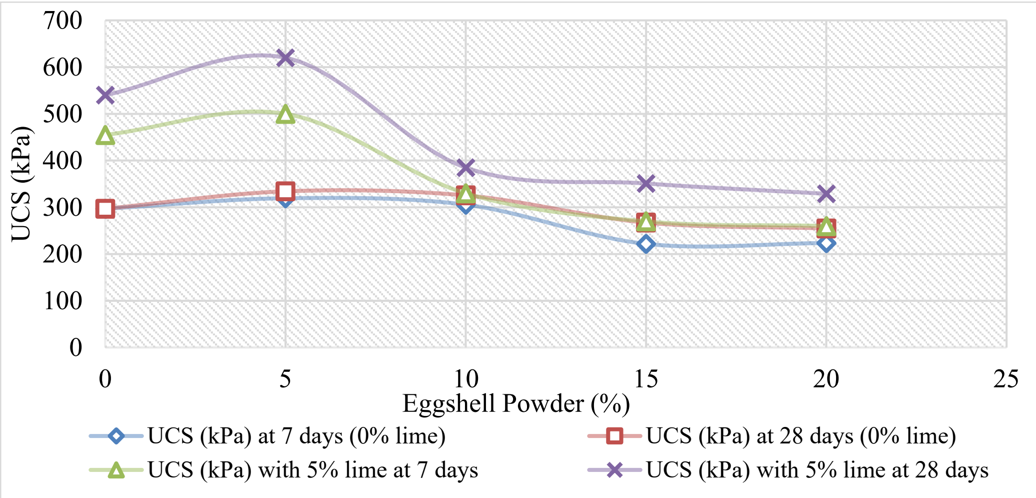
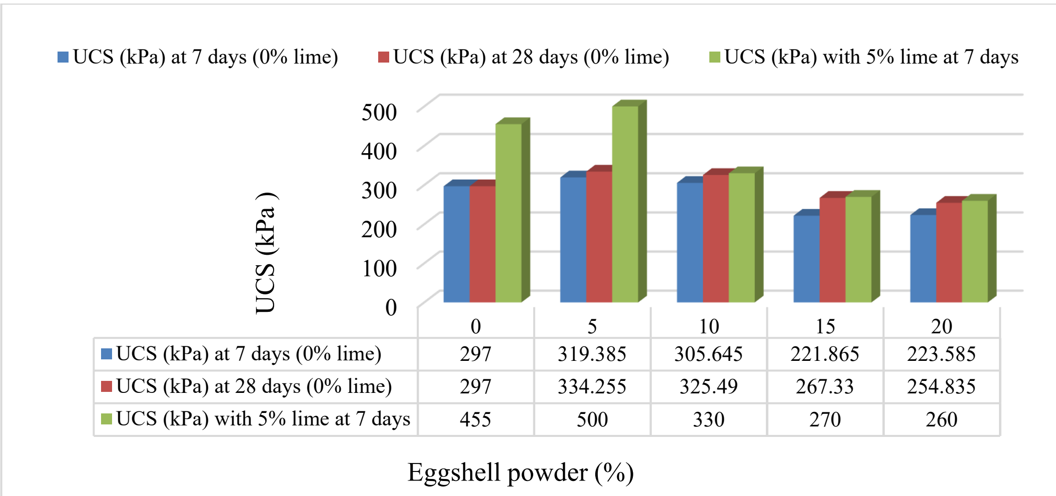


Figure 4.14 Effect of eggshell powder and lime on UCS of treated expansive soil at 7and 28 days of curing



	0	5	10	15	20
UCS (kPa) at 7 days (0% lime)	297	319.385	305.645	221.865	223.585
UCS (kPa) at 28 days (0% lime)	297	334.255	325.49	267.33	254.835
UCS (kPa) with 5% lime at 7 days	455	500	330	270	260

Figure 4.15 Effect of eggshell powder and lime on UCS of treated expansive soil at 7and 28 days of curing

Based on the experimental findings, it is possible to understand the effect of adding the eggshell powder as a supplementary additive to lime stabilization in expansive soil. A lower linear shrinkage was obtained when the eggshell powder was added to the untreated soil. Further reduction in linear shrinkage was observed by adding an extra dosage of eggshell powder to the lime stabilized expansive soil. The mixture of eggshell powder and lime-treated expansive soil was yield a higher strength compared with eggshell powder by itself, but with only small contents of eggshell powder. This indicates the possibility of using eggshell powder as a supplementary additive to lime for improving soil properties.

On the other hand, the eggshell powder could be used as a partial replacement of the costly lime (Zaman et al. 2018). Using eggshell powder in road subgrade stabilization can solve the disposing problem of eggshell waste and make the stabilization work more economically and sustainable by reducing the required lime dosage. Thus, the carbon footprint of manufacturing of such materials will be reduced. Based on the strength behaviour of expansive soil treated with different eggshell powder contents, it can be seen that eggshell powder in a right proportion can lead to a proper stabilizer for the subgrade when high performance is not essential. As previously mentioned regarding the effect of eggshell powder on linear shrinkage and strength properties of expansive soil, the utilization of eggshell powder for many purposes will be an acceptable development (Ahmed, Rahman & Das; Nyankson et al. 2013; Paul et al. 2014; Soundara & Vilasini 2015; Walia & Singh 2015).

Another experiment was conducted, using the OMC (32.31%) value, obtained from the compaction tests of the treated expansive soil with 5% of lime, and its value was then applied to all samples used for UCS tests. Figure 4.16 shows the effect of adding different percentages of ESP into 5% lime stabilized expansive soil on the UCS values after 7 and

28 days of curing. After 7 days of curing, the strength increased from 433.3 kPa to 520.9 kPa when 5% content of eggshell powder added as a secondary additive to lime in the stabilization of soil. Moreover, it was noticed that the strength increased by about 15% when 5% content of ESP added compared with 5% percentage of lime stabilized the expansive soil after 28 days of curing.

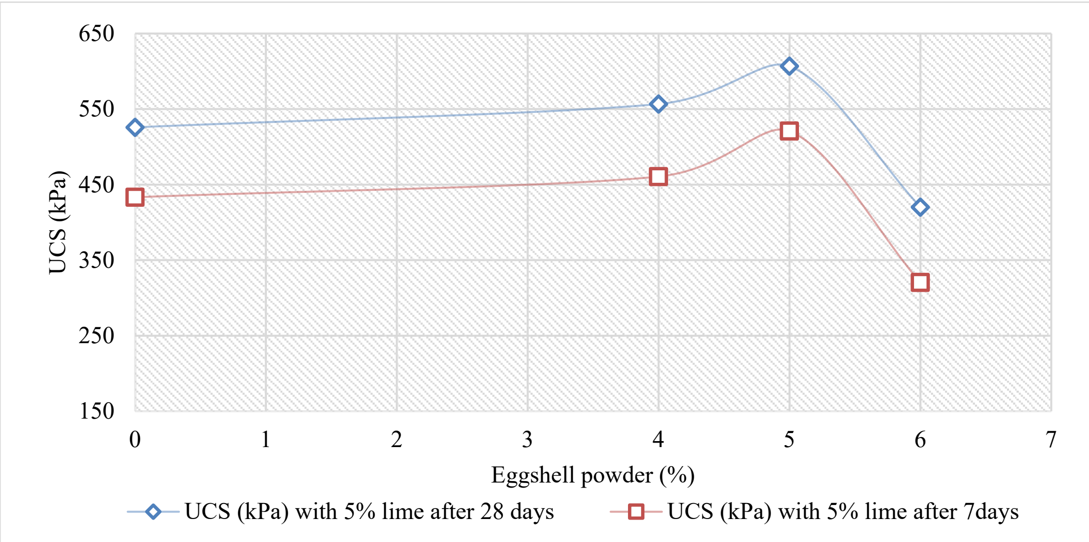


Figure 4.16 Effect of eggshell powder and lime on UCS of treated expansive soil at 7and 28 days of curing

Thus, it can be concluded that the combination of 5% of hydrated lime and 5% of eggshell powder resulted in the optimum UCS value. This was also emphasized by testing this combination at different moisture contents, and both of the results were close to each other. Furthermore, ESP can improve the performance of expansive soil in terms of shrinkage properties, compaction characteristics, and strength aspects.

4.1.6 Loss of Ignition Tests (LOI)

In order to estimate the organic matter content in eggshell powder, loss on ignition tests were performed on three samples of eggshell powder, as displayed in Figure 4.17. As shown in Figure 4.17, the average of loss on ignition for all of the samples was approximately 3%, and this value gives a clear indication that the proportion of organic matter in the eggshell powder is negligible. Thus, the effect of organic matter in eggshell powder is not important when the eggshell powder is added to the expansive soil and does not affect the physical properties of the combination. This result has been confirmed by some studies (Jayasankar, Mahindran & Ilangovan 2010; Nasif 2015).

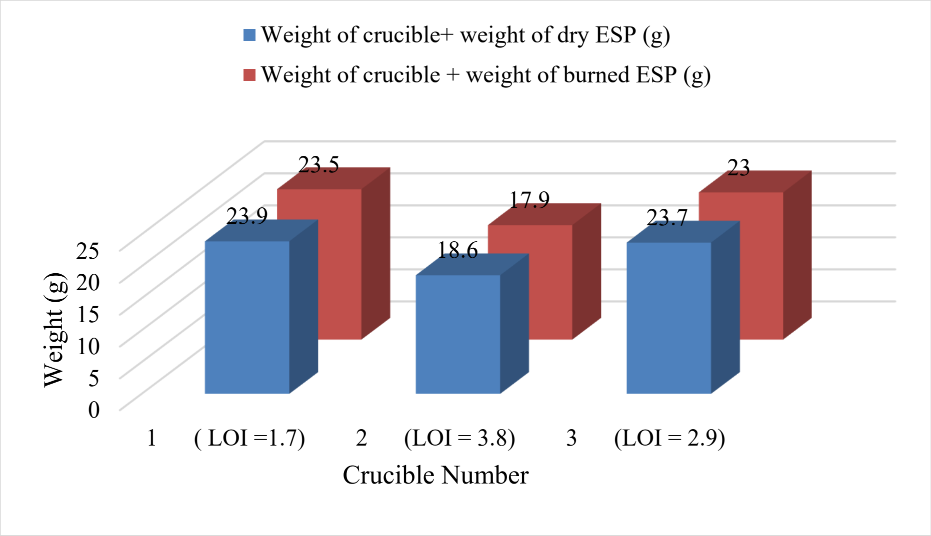


Figure 4.17 Loss on Ignition test results for many samples of eggshell powder

4.1.7 Influence of Additives on the pH Values of the Treated Expansive Soil

Figure 4.18 illustrates the variation in pH values by increasing lime alone. It should be noted that the pH values in this study were determined using the test method proposed by Eades & Grim (1966). Based on the pH values analyzed, it was found that about 5% of hydrated lime can be considered the optimum lime content for soil stability. The value of pH increased from 7.07 for untreated soil to 12.03 for treated soil with 5% of lime and beyond this value, remained constant.

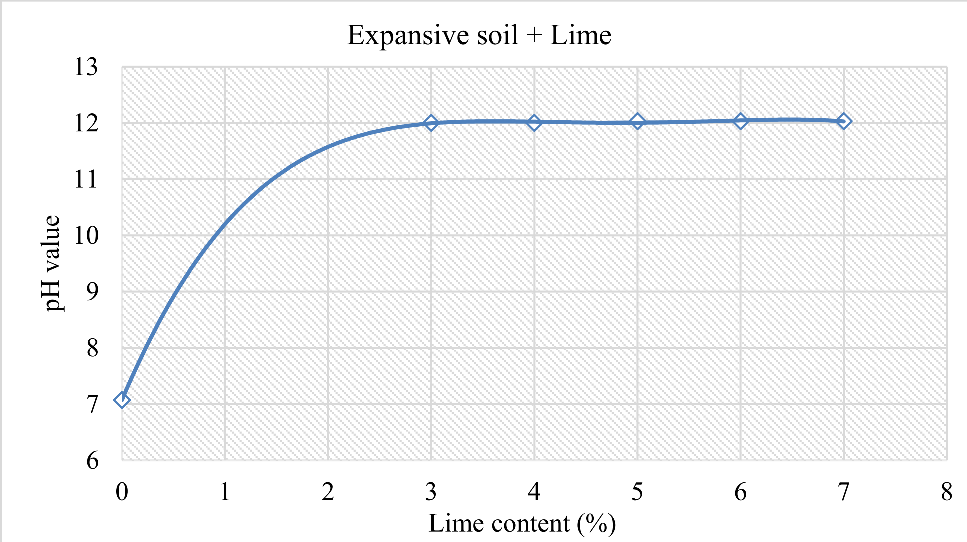


Figure 4.18 pH values of lime stabilized expansive soil after 1hour of mixing

Differences in pH values along with an increase in eggshell powder content in mixtures are illustrated in Figure 4.19 and Figure 4.20. These figures provided a comparison in the pH values when different percentages of eggshell powder were added in firstly into 5% lime stabilized expansive soil, then the same ESP contents were added to 4% of lime at various curing times. Referring to Figure 4.19 and Figure 4.20, pH values for lime and eggshell powder have been reported to decrease with increasing the curing time. This decrease may be attributed to a decrease in calcium (Ca^{2+}) and hydroxyl (OH^-) ions due to pozzolanic reactions and the new formation of ettringite caused by the interactions between soil, lime and eggshell powder.

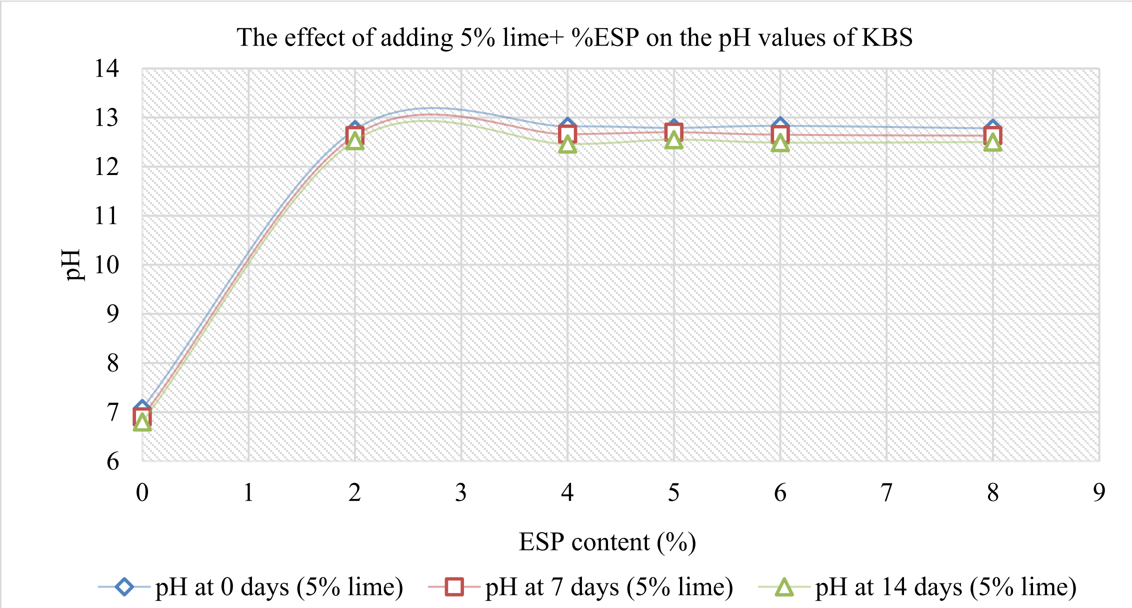


Figure 4.19 pH values of eggshell powder-5% lime (ESP+L) treated expansive soil at different curing times.

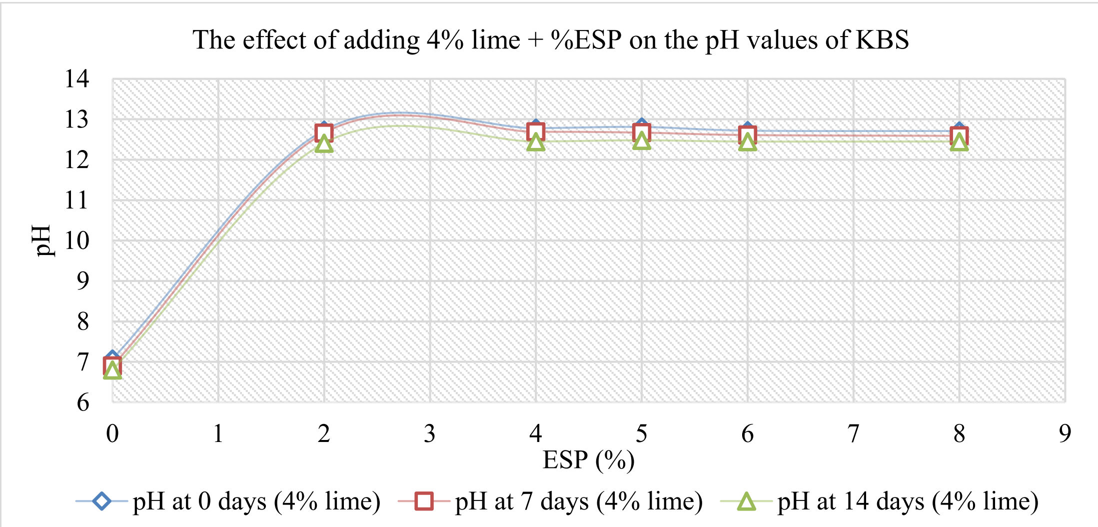


Figure 4.20 pH values of eggshell powder-4% lime (ESP+L) treated expansive soil at different curing times.

As can be seen in Figure 4.20, the combination of (4% hydrated lime + 5% eggshell powder) recorded the highest value of pH after 14 days of curing. This has led to the fact that approximately 5% eggshell powder-hydrated lime combination (containing 5% lime in the mixture) could be considered the optimal additional content of hydrated lime with eggshell powder to stabilize the expansive soil. However, it can be noted that the increase in the pH value (>9) of stabilized soils may sometimes create a corrosive environment for infrastructure. Therefore, special attention should be paid during the design phase of the chemical treatment of the expansive soil with lime.

4.1.8 Influence of Optimum Additives on CBR Value of Expansive Soil

California bearing ratio (CBR) is a penetration test used to find the strength of soil layers beneath the ground surface. It is the most common test to assess the quality of the base and subgrade materials for highway and road construction and design purposes. The soaked CBR tests were performed on the soil samples treated with 5% eggshell powder and 5% hydrated lime. Figure 4.21 represents variations of the CBR values of untreated expansive soil specimen stabilized with 5% of hydrated lime alone/ or with (5% of hydrated lime + 5% eggshell powder) at 7 days of curing. As shown in this figure, an appreciable improvement in CBR value was observed with the optimum additives. As can be seen, in comparison with the untreated soil, the CBR value of eggshell powder and hydrated lime stabilized expansive soil after 7 days of curing increased from 2% to 56%.

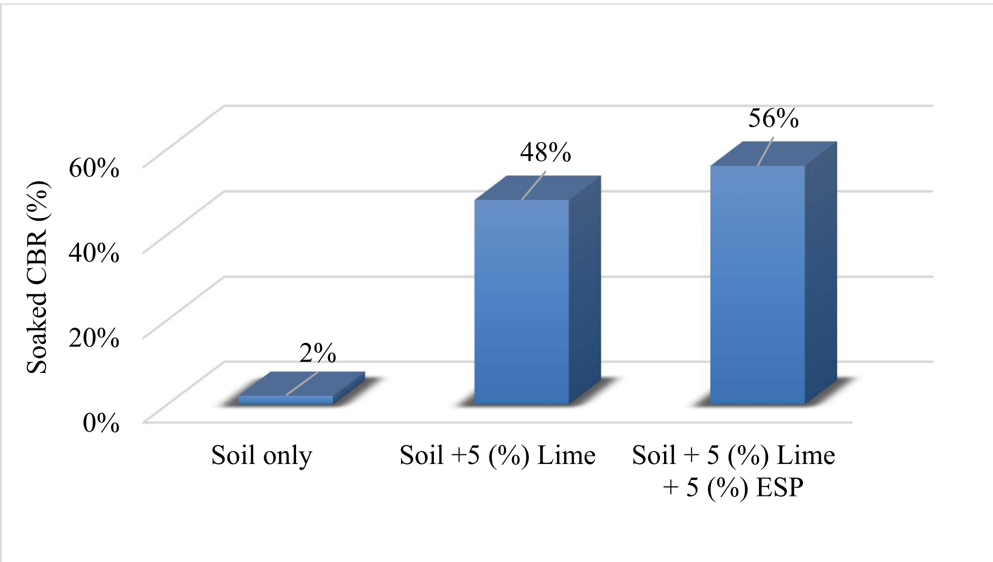


Figure 4.21 Variation of CBR values for expansive specimens stabilized with (Lime) or (Lime and ESP) after 7 days of curing

It was noticed that the CBR value increased from 48% to 56% when eggshell powder added to lime stabilized the expansive soil. The increase in CBR value may be due to hydration and pozzolanic reactions inducing the improvement in strength contributed from the combination of eggshell powder and hydrated lime, which is in good agreement with the number of researchers observations (Amu, Fajobi & Oke 2005; Walia & Singh 2015). This increase in CBR value indicates that selecting the eggshell powder-lime combination is required to achieve a higher bearing capacity of subgrade and maximize the use of available eggshell powder designed in road construction projects. The CBR value of this combination could easily meet the minimum of 15% CBR requirement adopted by most of the design guidelines for subgrades (Muntohar et al. 2012).

4.2 Summary

In this chapter, the effects of eggshells, collected from a commercial restaurant in Sydney, on properties of lime treated soil samples have been presented. A set of stages to achieve a uniform powder from the collected eggshells were applied, including washing, drying, grinding and sieving. Furthermore, the effects of adding eggshell powder, without hydrated lime, and in combination with hydrated lime on the physical and mechanical properties of expansive soil samples were presented in this chapter.

Referring to previous investigations conducted at UTS (Dang et al. 2015; Dang, Fatahi & Khabbaz 2016), an effective lime content was selected to stabilize expansive soil. Through pH measurements, it was found that approximately 5% hydrated lime content is an appropriate content for the short period reactions (i.e. cation exchanges between soil particles and lime) to occur. A laboratory program has been followed through conducting a series of experimental tests including linear shrinkage, compaction, unconfined compressive strength, pH, and loss on ignition tests on the untreated and treated expansive soil samples. The linear shrinkage and unconfined compressive strength tests were conducted in accordance with the Australian standards (AS-1289.3.4.1-2008 2016) and (AS-5101.4 2008), respectively. These tests were conducted at various curing times. With the high percentage of CaO in the eggshell powder and the small value of its linear shrinkage (approximately 1.5%), it was expected that the shrinkage potential of tested soil to be reduced by adding eggshell powder. A further reduction was achieved when the combination of eggshell powder and hydrated lime added into the soil samples. Based on the experimental results, a slight increase was observed in the sample strength by adding 5% eggshell powder into the soil. Further increasing obtained with the combination of 5% hydrated lime and eggshell powder. Then, a steady decrease was noticed bt increasing the eggshell powder content. In addition, samples treated with a combination of lime and eggshell powder exhibited more ductility behaviour compared to those samples treated with lime alone. All results compared with the untreated expansive soil used as control samples. Following the Australian testing standard, AS-1289.5.1.1 (2003), the maximum dry density (MDD) and the optimum moisture content (OMC) of each sample were determined by conducting compaction tests at different moisture contents. With the addition of eggshell powder in different contents into the expansive soil, the maximum dry density decreased gradually. This was due to the fact that the specific gravity (Gs) of the expansive soil (2.65) was higher compared to other additives. The specific gravity of eggshell powder and hydrated lime were 2.4 and 2.2, respectively. Therefore, by increasing the percentage of these additives, the soil proportion might be eliminated from the blend.

Based on this experimental study, 5% of eggshell powder was found to be the most effective content to produce the maximum strength in combination with lime to stabilize expansive soil. Addition of 5% ESP contributed to 15% strength gain, compared to the strength of soil samples stabilized with lime alone at 28 days of curing at a moisture content of 29%.

Generally, it can be expressed that the eggshell powder can be used as a supplement in conjunction with traditional stabilizers such as industrial hydrated lime, and can serve as an effective additive in the stabilization of expansive soil when combined with lime. The utilization of this lightweight material can reduce the disposal problem of eggshell waste.

CHAPTER 5:

Conclusions and Recommendations

Expansive soils arise from decaying rocks, containing mainly fine-grained particles. They exhibit a dramatic change in volume upon fluctuations in moisture content. Evaporation, rainwater, dewatering, waste and supply of water pipe leak phenomena, to name a few, are primarily responsible for changes in moisture content. Soil contraction and expansion can occur near the surface of the earth, where it is immediately exposed to seasonal and environmental changes.

5.1 Summary

Lime stabilization is the most commonly used method for controlling the shrink-swell behaviour of expansive soil. The lime reacts with the expansive clay in the presence of water and alters the physical and chemical properties of the extended soil, which in turn changes the physical and chemical properties of the treated soil. Furthermore, soil enhancement using lime associated with agricultural or industrial waste products such as fly ash, eggshell powder, rice husk ash, bagasse fibre, recycled coconut fibre, and silica fume, to name a few, can prolong the effectiveness of lime stabilized soil in terms of improved compressive strength, shear strength, ductility and bearing capacity. Furthermore, the widespread application of lime and waste products for soil stabilization can reduce construction costs by limiting the use of lime, while at the same time effectively facilitating the reduction of potential environmental impacts for sustainable development and economic growth.

In this experimental research, an attempt has been made to study the possibility of using eggshell powder without or with a lime mixture to enhance the shrink-swell behaviour, and other geotechnical properties of expansive soils. At the same time, two other key objectives of this study are reducing the domestic wastes and reduction of lime content for stabilizing expansive soils. Several laboratory experiments were conducted consisting of compaction, linear shrinkage, pH tests, unconfined compressive strength, and California bearing ratio (CBR). The main conclusions of this study and recommendations for further research are summarized in this chapter.

5.2 Conclusions

The major conclusions of this experimental investigation are summarized as follows:

1. The literature suggests that waste materials can significantly contribute in stabilization of problematic soils, particularly as partial replacement of conventional stabilizers such as lime or cement. Generally, the combination of these two groups in soil stabilization generates better results in many conditions. As a result, the amount of conventional stabilizers in the treatment of problematic soils will be reduced. Accordingly, the carbon footprint of manufacturing of such materials will also be reduced.

2. The results of the experimental study indicated that the addition of eggshell powder (ESP) alone to soil had a marginal effect on the geotechnical properties of stabilized expansive soils. However, the combination of hydrated lime and ESP had a significant influence on the main engineering properties of expansive soils. Based on the results of pH measurements, it was found that about 5% of hydrated lime could be the target lime content for the stabilization of expansive soils, required for cation exchanges between soil particles and lime to take place. Meanwhile, the

combination of 5% hydrated lime plus 5% eggshell powder was experimentally determined as the optimum additive mixture for expansive soil stabilization.

3. The standard compaction results showed that the maximum dry density (MDD) of soil samples, stabilized with eggshell powder (ESP) and hydrated lime (L) combination, decreased as the additive content increased when compared with untreated soil samples. These results can be valid as the specific gravities of lime and ESP are less than the expansive soil samples used in the experimental program. The results revealed that the MDD of soil samples treated with ESP gradually decreased as the eggshell powder content increased from 5% to 20%. The MDD of eggshell powder treated soils combined with hydrated lime decreased further as the hydrated lime content was 5%. The lower specific gravity of eggshell powder together with the larger spaces occupied in the soil matrix, due to the flocculation and agglomeration of soil stabilization with lime, could be the main reasons leading to a reduction on the MDD of stabilized soils when additive content increased. The small air gaps trapped into the powder surface could also cause a decrease in MDD of L-ESP-soil mixtures.

4. The linear shrinkage of ESP+L stabilized soils were considerably enhanced in comparison with that of soils stabilized with eggshell powder or hydrated lime alone. The evolution in the linear shrinkage behaviour of stabilized soils can be due to flocculation and aggregation of treated clay particles in the short period together with the new cementitious products associated with eggshell powder and clay particles due to the pozzolanic reactions. Such modification and pozzolanic reactions changed the soil particles to be coarser and stronger, reduced the plasticity

of the specific surface of soil particles, and ultimately enhanced the strength of the treated soil. In other words, the finer clay particles were replaced by relatively stronger and coarser particles that can be the main factors leading to a significant reduction in shrinkage of the treated soil samples over time.

5. The unconfined compressive strength (UCS) of treated soils increased with curing time increased. The strength development of soils treated with ESP+L was higher than those of eggshell powder, or hydrated lime alone stabilized soils. In addition, soils stabilized with ESP+L mixture exhibited more ductile behaviour than hydrated lime alone treated soils. A study of the UCS results of treated soils with curing time revealed that the strength increased marginally and reached to its maximum when the content of eggshell powder was 5% blended with 5% of hydrated lime followed by a gradual decrease in strength during the first 7 days of curing.

6. It is important to note that after 28 days of curing, at the optimum percentage of the combination, the strength of ESP+L treated soils continued to develop. The low quantity of employed stabilizers at the optimum state had a noticeable effect on the strength gain of stabilized soil after 28 days of curing. The decrease in the compressive strength gain after this optimum percentage of the ESP+L might be due to inadequate free lime available in eggshell powder or ESP+L admixtures necessarily to accelerate the activity of pozzolan to form cementitious compounds that play a key role in binding clay aggregates together as well as improving the strength of stabilized soils. However, all of the UCS values after the optimum

combination value were still higher than the UCS values of the untreated soils and higher than the soil samples treated with lime alone.

7. A remarkable improvement was observed in soil stiffness (secant modulus) after 7 days of curing when adding ESP+L into the stabilized soil samples. With the further increase in curing time up to 28 days, the increment of the secant modulus was more notable compared with the first days of curing.

8. The obtained CBR values increased with the addition of the optimal value for the eggshell powder and hydrated lime up to 50%. Consequently, the maximum allowable CBR of the subgrade (typically 15%) can be used for pavement design, resulting in a significantly thinner pavement structure and hence a significant saving in construction costs.

9. In the case of embankments and pavements that are built over expansive soil, foundation columns that originate from lime and eggshell powder mixture can be considered as one of the recommended practical applications to avoid pavement distress. These deformations are caused by additional stresses from the traffic volume or the processes of widening the embankments. Although the experimental results accomplished in this study confirm the efficiency of the proposed combination of hydrated lime and eggshell powder, it is highly recommended to determine the feasibility and long-term performance of the proposed combination using the foundation columns technique with actual highway construction projects.

10. Based on the findings of this experimental investigation, it can be concluded that the utilization of hydrated lime-eggshell powder combination in expansive soil stabilization could not only improve the engineering properties of expansive soil

but also minimize the environmental impact of domestic waste (e.g. eggshell powder) and the construction costs, because of reduction of lime usage. This experimental study has provided a detailed insight into promoting the applications of domestic waste (ESP) as a stabilizer component in the stabilization of road subgrade, which the high performance is not necessary. By and large, ESP may be used as a partial replacement of lime in soil stabilization practice. Furthermore, the combination of eggshell powder and hydrated lime can be effective as construction fill materials for sustainable development in the area of infrastructure foundations or pavements.

5.3 Recommendations of Future Research

From analyzing the results of the conducted experimental study, several recommendations are highlighted below for future investigations.

1. Another intensive series of experimental tests can be conducted to examine and analyze the possibility of applying this combination (eggshell powder and hydrated lime) to determine the geotechnical properties of treated soils after a long period of curing time (e.g. 56 days and 90 days). These tests may include UCS, CBR plus plasticity properties of the treated soil, specific surface area and pore size distribution. Moreover, it is recommended to study the mineralogical changes of lime treated expansive soil without or with eggshell powder. This will enable us to gain a better understanding as well as provide possible options for utilizing ESP+L for expansive soil stabilization.

2. Further experimental investigations, subjected to convert the eggshell powder into eggshell ash to investigate the behaviour of lime treated soils with eggshell ash

and compare the new results with the corresponding measured test results based on the eggshell powder treatment.

3. Improve the geotechnical engineering properties of expansive soil through studying the effect of mixing the eggshell powder with a number of agricultural wastes, such as bagasse ash or rice husk ash rich in silicon. In other words, the combined effect of eggshell powder, bagasse ash and hydrated lime can be investigated in detail.

4. Using different advanced constitutive models implemented in PLAXIS to simulate the behaviour of eggshell powder and hydrated lime treated expansive soils. This simulation may enable in understanding the meticulous behaviour of eggshell powder and lime treated expansive soil.

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