# EXPLORING THE IMPACTS OF ABUNDANTLY AVAILABLE SUSTAINABLE BY-PRODUCT MATERIALS IN AUSTRALIA ON STABILIZING EXPANSIVE SOILS

**Hadi Khabbaz[1] and Behzad Fatahi[2]**

[1]*School of Civil and Environmental Engineering, University of Technology Sydney, hadi.khabbaz@uts.edu.au*
[2]*School of Civil and Environmental Engineering, University of Technology Sydney, behzad.fatahi@uts.edu.au*

## ABSTRACT

This paper aims to examine the effects of utilizing readily available sustainable by-product materials in Australia for the purpose of stabilizing expansive soils. Some waste by-products, commonly found in Australia that can be employed for soil stabilisation are cement kiln dust, blast furnace slag, quarry dust, bagasse ash and fibre, rice husk ash, fly ash and bottom ash.

With support of industry a number of materials have been selected for characterisation. Extensive experimental tests utilizing bagasse fibre, bagasse ash, bottom ash, fly ash, and eggshell powder have been conducted at the University of Technology Sydney (UTS) to enhance the engineering properties of expansive soils. These tests have been supplemented by microstructural tests, numerical analysis, and comprehensive discussions. These pozzolanic materials are characterized by significant levels of calcium carbonate, silica, and alumina. Numerous tests have been performed using these by-products to investigate the impact of their composition in conjunction with lime or cement, the curing time, the particle size, the optimal blending ratios, on both treated and untreated soil properties.

Based on research and laboratory investigations, sustainable by-product materials have demonstrated substantial potential for enhanced durability, cost savings and long-term environmental benefits, compared to traditional cementitious agents in treating expansive soils. These materials offer improved soil strength, reduced swelling potential, enhanced soil ductility, and controlled deformation over time. However, the implementation of these sustainable materials in practice is not yet widespread among construction companies and road authorities in Australia. This paper addresses this concern and provides practical recommendations for adoption of these sustainable by-products in weak subgrade of roads.

## 1 INTRODUCTION

Soils containing expansive minerals can undergo volume changes, either expansion or contraction, based on variations in the availability of free water for absorption or evaporation. This phenomenon is referred to as swelling and shrinking, respectively. Expansive soils refer to fine-grained soil or weathered rocks that undergo significant volume fluctuations when exposed to changes in moisture content (Nelson and Nelson, 2013; Dang and Khabbaz, 2018). This swelling and shrinkage behavior typically occurs near the ground surface, where it is directly influenced by seasonal and environmental fluctuations. According to Fityus and Buzzi (2008) expansive soils are often unsaturated and contain clay minerals of the smectite group (Table 1). The extent of damage associated with expansive soils primarily depends on the level of monovalent cations absorbed by these clay minerals as expressed by Dang et al., 2017).

**Table 1: Main expansive clay minerals (modified after Mitchell, 2001)**

| **Expansive Clay (Smectite Group)** | **Swelling Capacity** (Greater than original volume) | **Clay Activity** $A_c = \frac{PI}{Clay\ content(\%)}$ |
|---|---|---|
| Bentonite (Sodium) | Up to 15 times | 3 - 7.2 |
| Montmorillonite (Sodium) | Up to 10 times | 2.5 - 7 |
| Bentonite (Calcium) | Up to 2 times | 1.6 in average |
| Montmorillonite (Calcium) | Up to 2 times | 1.5 in average |

The distinction between expansive and non-expansive soils lacks a precise definition. Several guidelines are available for defining expansive soil based on its physical and chemical properties (e.g., AASHTO T 258-81, 2018; Australian Standard AS 2870, 2011; ASTM D4546-21). Some of the most common criteria for high potential movement include:

- Linear shrinkage (LS): Expansive soils typically exhibit a linear shrinkage exceeding 18%.
- Liquid limit (LL): Expansive soils typically have a liquid limit greater than 60%.
- Plasticity index (PI): Expansive soils usually have a PI higher than 35%.
- Soil activity (Ac): Expansive soils tend to have a soil activity exceeding 1.25.
- Soil suction: Expansive soils generally possess a natural soil suction at the time of construction exceeding 380 kPa (this is not a general rule for all expansive soils and depends on clayey soil type, natural moisture content, and climate conditions).
- Swell pressure: According to ASTM D4546-21, a soil is classified as highly expansive if its swell pressure is greater than 200 kPa.

It is important to note that these guidelines are general rules of thumb. Some expansive soils may not meet all of these criteria, while some non-expansive soils may meet some of them. Therefore, a comprehensive geotechnical investigation is essential to determine soil expansiveness. In addition to the physical and chemical properties mentioned above, various other factors can contribute to soil expansiveness, including:

- Climate: Expansive soils are more prevalent in arid and semi-arid climates, where there is significant moisture content variation.
- Topography: Expansive soils are commonly found in areas with flat or gently sloping topography, facilitating water pooling and soil infiltration.
- Vegetation: Expansive soils are less common in areas with dense vegetation cover, which helps regulate soil moisture content.

The aim of this paper is to portray the consequences of employing sustainable by-product materials readily accessible in Australia to stabilize expansive soils. These waste by-products, which are commonly found in Australia and can be utilized for the purpose of soil stabilisation, include: cement kiln dust (a by-product derived from cement manufacturing), blast furnace slag (originates from iron and steel manufacturing processes), quarry dust (a by-product of crushing stones in quarries), bagasse ash (obtained from burning sugarcane bagasse), rice husk ash (a residue of burned rice husks), fly ash (generated by coal combustion in power plants), and bottom ash (collected at the bottom of the furnace during coal combustion, which does not undergo burning). The production of the last two materials mentioned, namely fly ash and bottom ash, is expected to be limited in the near future due to the Australian government's decision to close most of the coal-fired power plants. Nevertheless, there will still be a significant quantity of fly ash and, notably, a substantial amount of bottom ash that will remain available for utilization in road construction for a couple of decades to come.

An extensive experimental program was conducted at the University of Technology Sydney using bagasse fibre, bagasse ash, bottom ash, fly ash, and eggshell powder in combination with hydrated lime or cement to improve the engineering characteristics of expansive soils. These laboratory tests were complemented by microscopic examinations, numerical analyses, and in-depth discussions. These pozzolanic materials contain significant levels of calcium carbonate, silica, and alumina. Multiple tests were carried out with these waste by-products to investigate their influence when combined with lime or cement, such as effect of curing time, wetting and drying cycles, particle sizes of bagasse ash, and the optimal blending ratios on treated soil properties. These tests included assessments of soil consistency, linear shrinkage, compaction factors, friction angle, cohesion, California bearing ratio (CBR), unconfined compressive strength (UCS), permeability, soil water characteristic curve (SWCC), tensile stress, Young's modulus, shear wave velocity, and microstructural properties. Rather than presenting an extensive set of results and lengthy discussions, this paper focuses on the key findings and typical results. Proper references are provided to access the original data and discoveries. To promote the use of waste materials available in Australia for mitigating the adverse effects of expansive soil, this paper also offers a list of recommendations.

## 2 WASTE MATERIALS IN AUSTRALIA

The National Waste Report, prepared by Pickin et al. (2022), clearly conveys that Australia produced an approximate total of 75.8 million metric tons of waste in the fiscal year 2020-21. This amount incorporates 25.2 million tonnes of building and demolition materials, 14.4 Mt of organic waste, 12.0 Mt of ash, 7.4 Mt of hazardous waste, primarily contaminated soil, 5.8 Mt of paper and cardboard, 5.7 Mt of metals, and 2.6 Mt of plastics. To put this in perspective, it averages out to 2.95 tonnes per person. As circular economy principles gain widespread acceptance among Australian state governments, the focus has shifted towards the practical application of these policies. This requires the ongoing practice of reusing and recycling materials, thereby diminishing the necessity for extracting new resources and minimising the volume of waste sent to landfills. Figure 1 displays the distribution of waste generation in Australia categorized by material type, presented as percentages.

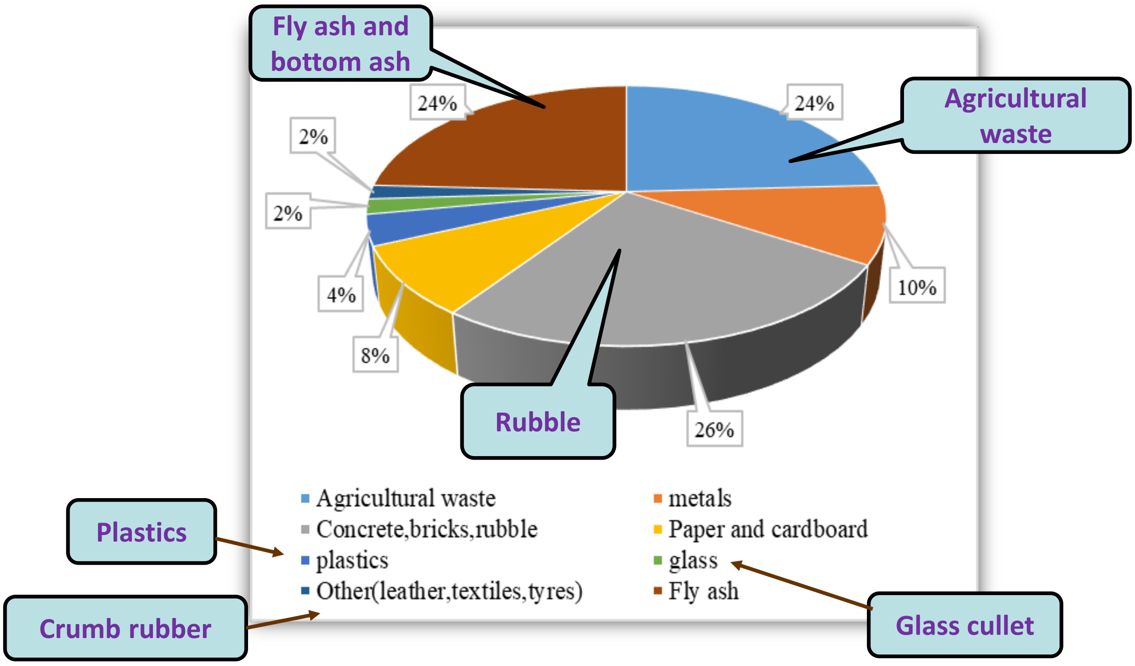



**Figure 1: Generation of total waste in Australia by material category management in percentages (modified after Pickin et al. 2022)**

# 3 USING DIFFERENT PROCEDURES FOR EXPANSIVE SOIL STABILISATION

## 3.1 ABUNDANTLY AVAILABLE BY-PRODUCT MATERIALS IN AUSTRALIA

In Australia, several common agricultural and industrial waste materials can readily be used to reduce the usage of lime and cement for soil treatment. Many of them are rich in silica and alumina with pozzolanic or cementitious characteristics. Some common waste materials that can be used in Australia for modification of weak soils are listed below:

- ✓ Sugarcane wastes (bagasse ash, bagasse fibre)
- ✓ Rice husk ash
- ✓ Coal fly ash, bottom ash, run ash
- ✓ Blast furnace slag
- ✓ Crushed waste glass
- ✓ Recycled tyre rubber, crumb rubber,
- ✓ Plastics
- ✓ Recycled construction and demolition waste
- ✓ Eggshell powder, eggshell ash
- ✓ Certain organic materials, such as palm oil ash, rice straw or coconut coir
- ✓ Cement kiln dust and quarry dust

It is important to note that the effectiveness of these waste materials may vary depending on the specific properties of the expansive soil and the intended application. Prior to using any of these materials for soil stabilisation, a detailed geotechnical analysis and laboratory testing should be conducted to determine the appropriate mix proportions and treatment methods.

## 3.2 SOIL STABILISATION APPROACHES

There are many methods available to curtail expansive soil swelling and shrinkage. There approached are summarised in Figure 2. Chemical stabilisation of expansive soils, particularly lime stabilisation in combination with waste materials, which adopted in the study, primarily involves the process of immobilising clay particles by cementing them in a manner that prevents them from expanding in volume.

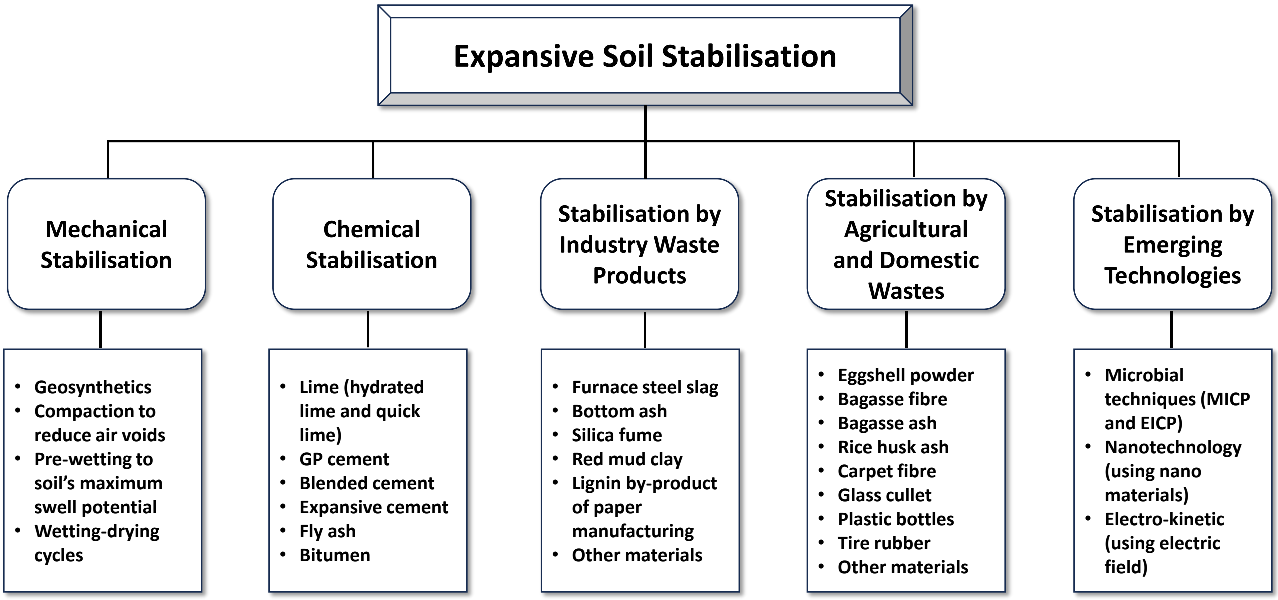



**Figure 2: Various methods to improve expansive soil**

Lime-soil stabilisation is a process of improving the properties of soil by adding lime. Lime reacts with the clay and silt particles in the soil to form cementitious bonds, which makes the soil stronger and more stable. Lime-treated soil was studied extensively in the literature (Firoozi et al., 2017; Little and Nair, 2009; Texas DoT, 2008). Many field and laboratory studies were conducted to evaluate the improvement of geotechnical properties of soil by addition of lime. The mechanism of treatment comprised hydration, cation exchange, flocculation agglomeration of soil particles and pozzolanic reaction to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). The key factors affecting lime treated soil are type of lime, lime content, curing time, curing temperature and soil mineralogy. Soil-lime mixtures have advantages and disadvantages. Its advantages comprise significantly increase soil strength, reduce plasticity (increase workability) and increases soil durability. In addition, a considerable reduction in consolidation settlement and improve compressibility characteristics were observed.

However, there are some potential long-term problems associated with lime soil stabilisation. Leachate of lime over time, raising pH level of soil impacting on plant growth and soil microorganisms, sulfate attack when lime reacts with sulfates in the soil and forming ettringite, cracking potential as limed soil is more brittle, and environment impact such as reduced soil fertility and generating a lot of dust are a number of the disadvantages of lime-treated soil.

Several research studies have been carried out to offer recommendations for mitigating the negative impacts of these challenges. For example, strategies such as managing moisture levels, incorporating additives like fly ash or slag, or exploring alternative binding agents have been explored. Magnesium oxide and hydroxide can be considered as viable alternatives to lime due to their chemical properties, which make them promising candidates for addressing the drawbacks. Furthermore, some studies have shown substantial enhancements in soil strength, workability, and durability when using magnesium-based additives for soil stabilisation. Therefore, it is worthwhile to investigate the effectiveness of these materials in soil stabilisation through further research.

# 4 MATERIALS AND METHODS

The summary of materials and methods used by research team at the University of Technology Sydny (UTS) is given in Figure 3. The detailed material properties can be found in previously published papers and thesis by the researchers, conducted comprehensive investigations at UTS (e.g., Liet and Khabbaz, 2018, 2019; Liet et al., 2019; Le et al., 2023; Hasan et al., 2018; Alqaisi et al., 2020; Le, 2021).

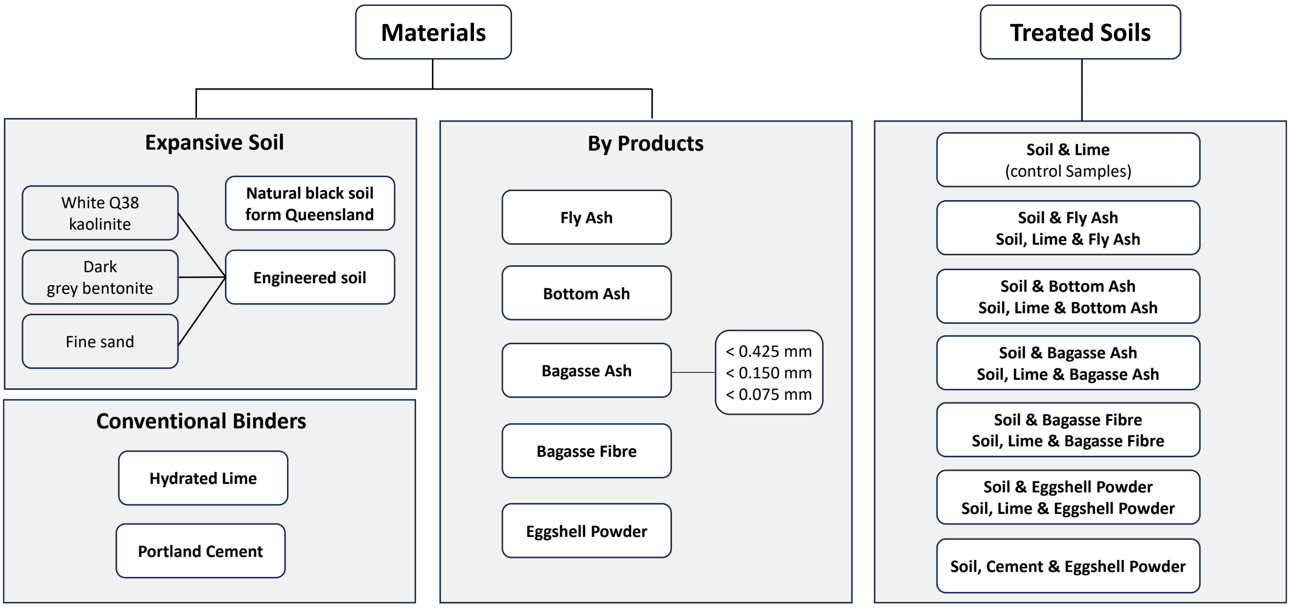



**Figure 3: A simplified diagram representing the materials employed in the study**

The main conventional binder, used for treatment of expansive soil has been hydrated lime. According to Adelaide Brighton Cement Ltd, the loss of ignition (LoI) of hydrated lime is around 24%. The specific gravity of hydrated lime is between 2.2 and 2.3. The pH level of hydrated lime is approximately 12, indicating its high alkalinity. Table 2 summarises the compositions of hydrated lime.

**Table 2: Composition of hydrated lime**

| Composition | Chemical Formula | Value |
|---|---|---|
| Calcium Oxide | Cao | < 72% |
| Magnesium Oxide | MgO | < 1 |
| Silicon Dioxide | $SiO_2$ | < 2% |
| Aluminium Oxide | $Al_2O_3$ | < 0.5% |
| Ferric Oxide | $Fe_2O_3$ | < 0.6% |
| Calcium sulfate | $CaSO_4$ | < 0.2 |

Incorporating hydrated lime into the soil results in an elevation of both soil pH and cation exchange capacity. The pH enhancement in clay supports time-dependent and temperature-related pozzolanic reactions.

In the experimental program at UTS, two different soil types have been used, including natural black soil, taken from Queensland (Figure 4), and engineered expansive soil. The properties of these soils are presented in Tables 3 and 4, respectively. The manufactured expansive soil examined in this research comprises three constituents: bentonite Active Bond 35, Kaolinite Q38, and Sydney fine sand. This soil is classified as a synthesized material, offering the advantage of precise control over the proportions of each component in every sample. Consequently, the soil samples are consistent and possess identical compositions, simplifying the process of comparing results.

**Table 3: Properties of natural black soil taken from a road construction site in Queensland**

| Soil Characteristics | Average Value |
|---|---|
| Gravel (%) | < 0.1 |
| Sand (%) | 18.30 |
| Silt/Clay (%) | 81.65 |
| Natural water content (%) | 30.8 |
| Liquid limit (%) | 86 |
| Plastic limit (%) | 37 |
| Plasticity index (%) | 49 |
| Linear Shrinkage (%) | 21.7 |
| Specific gravity | 2.62-2.65 |
| USCS classification | CH |

To minimise the variations in soil properties and the presence of impurities typically found in in-situ soil, an engineered artificial soil was created for the experimental testing program. This artificial soil comprises bentonite (30%), kaolinite (65%), and Sydney fine sand (5%). The manufactured soil characteristics are detailed in Table 4.

**Table 4: Properties of the engineered expansive soil**

| Soil Characteristics | Average Value |
|---|---|
| Plastic Limit (%) | 30.9 |
| Liquid Limit (%) | 155 |
| Plasticity Index (%) | 124 |
| Linear Shrinkage (%) | 21.2 |
| USCS Classification | CH |
| Maximum Dry Density (t/m$^3$) | 1.34 |
| Optimum Moisture Content (%) | 28.8 |

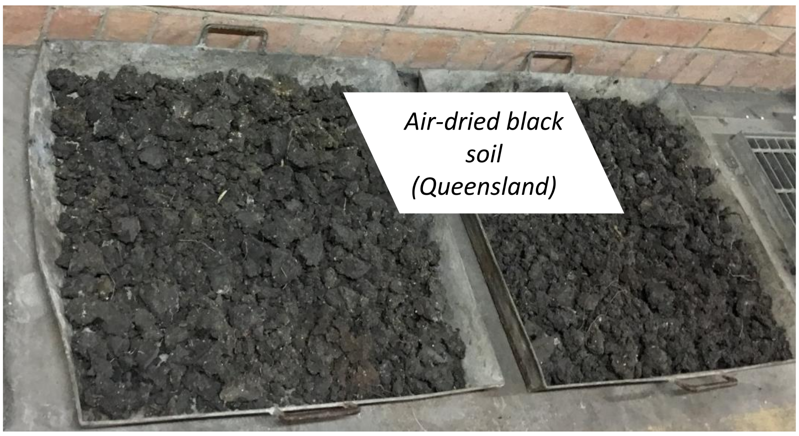



**Figure 4: Air dried eexpansive black soil in the soil laboratory at UTS**

The study utilized bagasse ash with the following physical characteristics: a pH of 8.64, and a specific gravity of 2.32. The percentage of silica was 78.3% (Dang et al., 2016). The chemical compositions of bagasse ash collected from Australian Sugar Milling Council (ASMC) are summarised in Table 5.

**Table 5: Chemical compositions of bagasse ash (after Dang et al., 2016)**

| Components | Content (%) |
|---|---|
| MgO | 1.98 |
| $Al_2O_3$ | 5.95 |
| $SiO_2$ | 78.30 |
| CaO | 2.43 |
| FeO | 5.25 |
| $SO_3$ | 0.89 |
| $K_2O$ | 3.27 |
| $Na_2O$ | 0.54 |
| $TiO_2$ | 0.36 |
| $P_2O_5$ | 1.03 |

The pH measurements indicated that about 5% hydrated lime content was sufficient for the short-term reactions (i.e., cation exchanges between soil particles and lime) to take place, defined as the optimum lime content to stabilise expansive soils as shown in Figure 5. while 18% (Bagasse Ash and %5 Hydrated Lime) combination was experimentally determined as the optimum additive combination for expansive soil stabilisation. Inspection of the UCS results of treated soils with curing time reveals that the strength development of soils mixed with lime and bagasse ash continued smoothly increasing after a long time of curing, meanwhile the compressive strength remained almost constant for lime treated soils as the curing time increased beyond 28 days. It is important to note that the low quantity of employed stabilisers has an insignificant effect on the strength gain of stabilised soils with time.

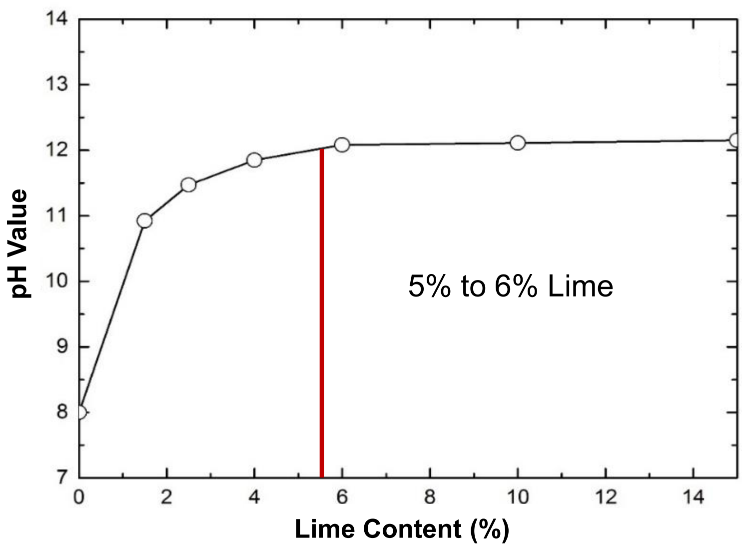



**Figure 5: Variation in pH values when different amounts of lime are introduced into expansive soil after 1 hour of mixing (modified after Dang and Khabbaz, 2018)**

The experimental program of the study can be categorized into several groups, as illustrated in Figure 6. An array of pH and electrical conductivity tests were conducted. Physical tests included the specific gravity, the particle size distribution, Atterberg limits and compaction tests. Meanwhile, mechanical tests in this study comprised linear shrinkage, free-swelling, consolidation, unconfined compressive strength (UCS), indirect shear strength (IDS), California bearing ratio (CBR), consolidation undrained (CU) shear triaxial, bender element, and suction measurements using filter paper method. Finally, the micro-structural analysis on samples from previous tests, consisting of four experiments :X-ray Diffraction, microscopic imaging and Scanning Electron Microscopy (SEM) tests followed by Energy Dispersive X-ray spectroscopy (EDX) analysis.

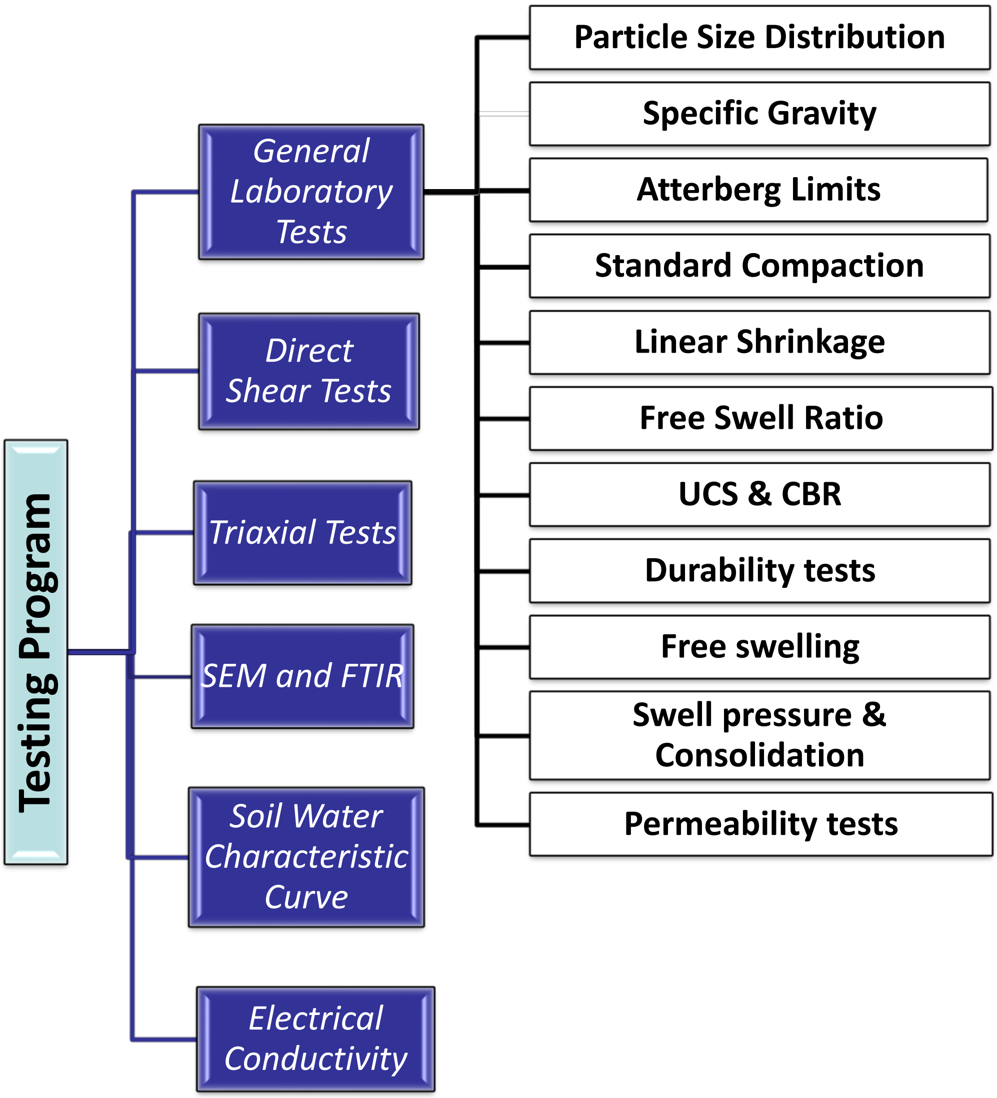



**Figure 6: Summary of the testing program**

# 5 RESULTS AND DISCUSSION

## 5.1 BAGASSE ASH AND HYDRATED LIME STABILISATION

An effective chemical stabilisation is a treatment method characterised by its convenient application, quick modification of soil characteristics, and enhancements in key soil properties, including moisture restraint, improved strength, and enhanced workability.

Bagasse ash is rich in silica and calcium oxide, both of which are recognized for their pozzolanic characteristics. When incorporated into expansive soil, bagasse ash undergoes a reaction with the soil, forming a cement-like substance that binds the soil particles together. This binding effect reduces the soil's capacity to expand and contract in response to fluctuations in moisture content. Research studies conducted by Le et al. (2019), Dang et al. (2019), and Hasan et al. (2018) have demonstrated that the inclusion of bagasse ash can enhance the strength and rigidity of expansive soils, diminish their plasticity and tendency to swell, and heighten their resistance to erosion. Moreover, bagasse ash stands as an environmentally friendly material, given that it is a by-product that would otherwise be discarded as waste. Its utilization in soil stabilisation can also curtail the demand for virgin materials, further lessening the environmental impact associated with construction projects.

Generally, the incorporation of hydrated lime and bagasse ash can alter the state of expansive soil from highly plasticity clay (CH) to elastic silt (MH) by reducing the liquid limit and increasing the plastic limit. Mixing hydrated lime and bagasse ash with expansive soil can lead to a decrease in both the maximum dry density and the optimum moisture content in the treated mixtures.

The linear shrinkage for black soil before treatment was 21.6%. The impact of adding bagasse ash and hydrated lime on the linear shrinkage of expansive soil at various curing times have been explored. As can be seen in Figure 7, the linear shrinkage of 13.5% bagasse ash (BA) plus 4.5% hydrated lime (L) was lower than employing 4.5 using hydrated lime only.

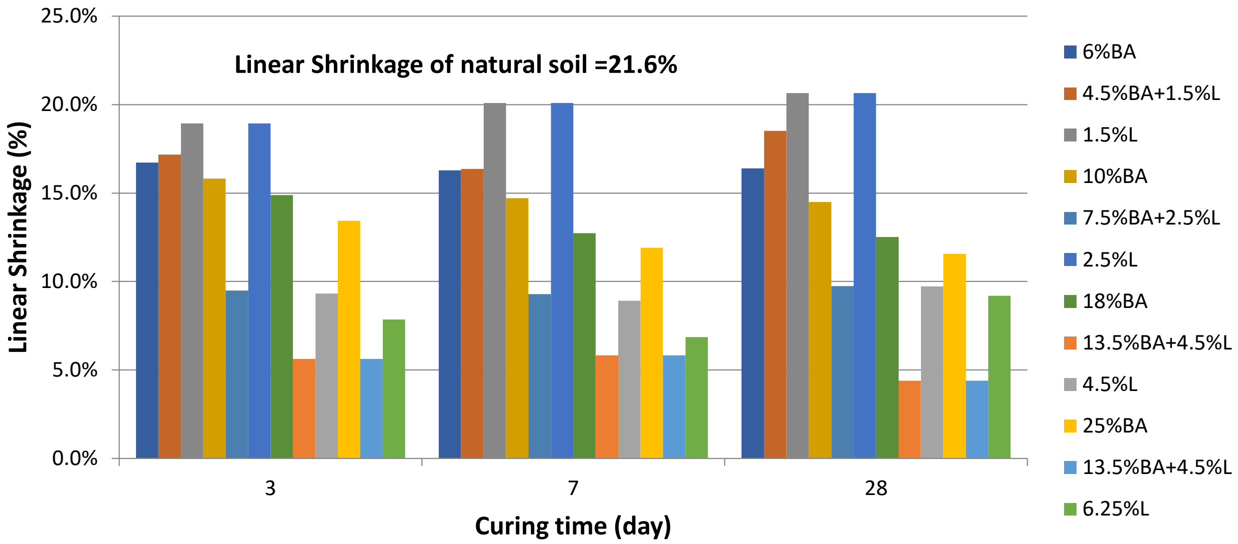



**Figure 7: Effect of bagasse ash and lime on linear shrinkage of expansive soil at different curing time**

The study revealed an effective lime content ranging from approximately 5% to 6%. One of the primary objectives of the experiments was to maximize the utilization of bagasse ash for lime stabilisation. As depicted in Figure 8, a ratio of 1 part lime to 3 parts bagasse ash proved to be optimal. A comprehensive series of tests was conducted to assess soil stabilisation outcomes, involving the removing bagasse ash particles larger than 425 microns before their introduction into the limed soil. The results of the unconfined compressive strength (UCS) tests are illustrated in Figure 9, clearly demonstrating that the addition of 15% bagasse ash significantly enhances the unconfined compressive strength of the samples.

The addition of hydrated lime stabilised expansive soil combined with bagasse ash resulted in a remarkable influence on the unconfined compressive strength and the compression curve and compression index of stabilised soil. The SEM results indicated the formation of cementitious products (i.e., CSH, CAH or CASH) as a result of the time-dependent pozzolanic reactions between clay or bagasse ash particles together with hydrated lime could be primarily responsible for the strength development and the stiffness improvement as well as the enhanced other geotechnical properties of treated soils.

The research team made a hypothesis that using finer bagasse ash can improve the strength of limed soil. Hence, in a study conducted by Le et al. (2023), the objective was to assess the use of bagasse ash with different particle sizes in combination with hydrated lime to stabilize expansive soils. The main findings from the tests conducted on bagasse ash in various maximum sizes of 75, 150 and 425 microns are as follows:

This study was part of an ongoing research program at UTS, focusing on mitigating the negative impact of expansive soils on pavements using sugarcane bagasse ash. The investigation involved testing for changes in shrinkage and strength properties of the soil mixture, including Atterberg limits, linear shrinkage (LS), and unconfined compressive strength (UCS) tests. The test results were correlated with three different maximum particle sizes of bagasse ash (i.e., 75, 150, and 425 microns).

The study found that the liquid limit of the mixture moderately decreased with a reduction in the maximum size of the bagasse ash particles, indicating that a reduction in the maximum particle size led to a decrease in the liquid limit. However, samples with larger bagasse ash particles (up to 425 microns) exhibited reduced linear shrinkage. When assessing the strength of lime-treated expansive soil with varying maximum bagasse ash particle sizes, it was observed that samples with a larger particle size (maximum 425 microns) outperformed mixtures with bagasse ash of smaller particle sizes. In other words, reducing the maximum particle size of bagasse ash below 425 microns did not result in an improvement in the unconfined compressive strength of ash-lime-treated soils.

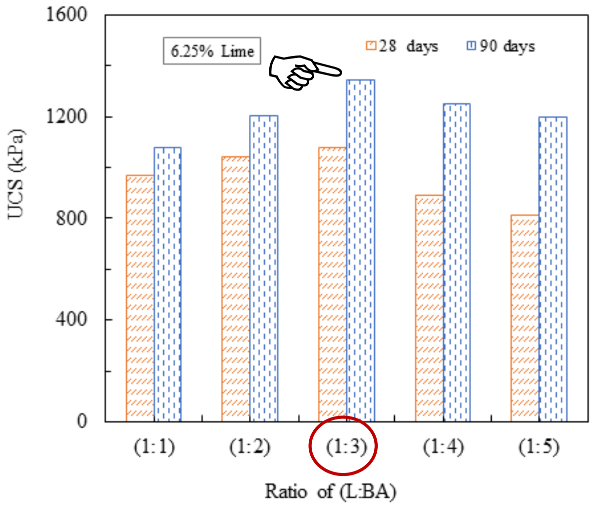



**Figure 8: Unconfined compressive strength against lime (L) to bagasse ash (BA) ratio of Soil treated with 6.25% L and different BA contents ranging from 6.25% up to 31.25% (after Hasan et al., 2018)**

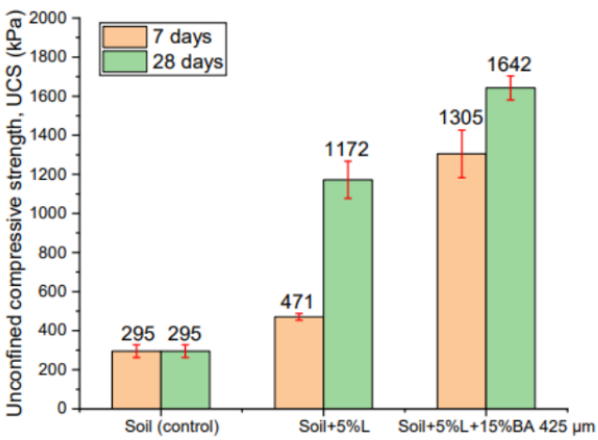



**Figure 9: Unconfined compressive strength results for samples cured 7 and 28 days (after Dang and Khabbaz, 2018)**

## 5.2 BAGASSE FIBRE AND HYDRATED LIME STABILISATION

A series of tests was conducted to investigate the engineering properties of expansive soil after being reinforced with randomly dispersed bagasse fibres and hydrated lime, in accordance with the testing methodologies and procedures detailed in Section 4 of this paper. Figure 10 illustrates the impact of incorporating bagasse fibres on the failure characteristics of lime-treated soils with varying fibre contents, ranging from 0% to 2%. It is evident that the inclusion of fibres enhances the ductility of the specimens. In this study, bagasse fibres with an average diameter of 3 mm were employed. Figure 11(a) displays a scanning electron microscopy (SEM) image of bagasse fibres, while Figure 11(b) provides a photograph of bagasse fibres used in the tests for being mixed with soil and lime at different volumes.

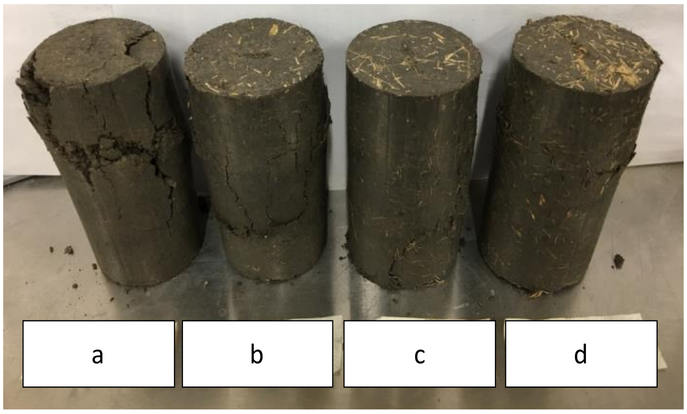
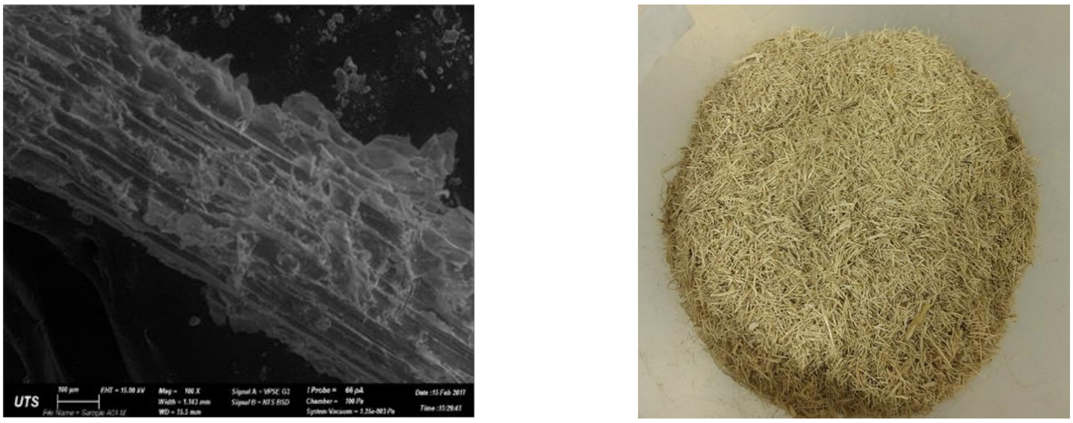



**Figure 10: Effect of adding bagasse fibre (BF) on failure characteristics of 4% lime treated soils with: (a) 0% BF; (b) 0.5% BF; (a) 1% BF; (d) 2% BF**




(a) Bagasse fibre (Dia: 0.3 mm to 3 mm) (b) Bagasse fibre (length: 0.3 mm to 13.8)

**Figure 11: Bagasse fibre used in this investigation (a) SEM image, (b) photograph of bagasse fibre used in the test (modified after Dang and Khabbaz, 2019)**

The following concluding statements have been excerpted from Liet and Khabbaz (2016), regarding the utilization of bagasse fibre in combination with lime for stabilisation of expansive soil samples.

- The results from standard compaction tests indicated a gradual decrease in the maximum dry density of soil samples as the content of bagasse fibre increased from 0% to 2%. When bagasse fibre was introduced in expansive soils, with or without lime treatment, there was a significant reduction in linear shrinkage as the additive content and curing time increased. The incorporation of bagasse fibre had a notable effect on the ductility of lime-treated soils, shifting the behavior of the stabilised soil from brittle to more ductile.
- When a higher lime content (i.e., 6% lime) was used for soil stabilisation, the addition of bagasse fibre to the limed soils enhanced tensile strength. However, the stiffness of the stabilised soil remained nearly unchanged when compared to soils treated with 6% lime without fibre reinforcement. It was observed that the California Bearing Ratio (CBR) showed a more noticeable increase in soil samples treated with the lime-bagasse fibre combination compared to samples reinforced with bagasse fibre or hydrated lime alone. The swelling behavior of expansive soil treated with a combination of bagasse fibre and lime was significantly improved, as lime stabilisation altered the physical and chemical properties of clay particles through cation exchange with lime. Furthermore, the compressibility properties of soils treated with lime initially decreased as the bagasse fibre content increased from 0% to 1%, but they increased when the bagasse fibre content exceeded 1%. The presence

of bagasse fibre reinforcement had a slight adverse effect on the water retention capacity of stabilised soils, though this effect was not significant. The improvement in air entry suction of stabilised soils was mainly attributed to changes in a small fraction of clay particles and enhanced pore size distribution resulting from lime stabilisation.

- As a result, the utilization of a combination of hydrated lime and bagasse fibre in expansive soil stabilisation not only improved the engineering properties of the soil but also reduced the environmental impact of agricultural waste by-products such as bagasse fibre. This combination also helped minimize construction costs by reducing the amount of lime needed.

## 5.3 BOTTOM ASH AND HYDRATED LIME STABILISATION

The UTS team conducted a comprehensive experimental study aimed at enhancing the geotechnical characteristics of limed soil and mitigating pressure on tailings dams by the use of bottom ash (Le, 2021). This readily available waste by-product, abundant in silica, was sourced from Eraring Power Station in New South Wales, Australia. Various proportions of bottom ash were mixed with hydrated lime to stabilize expansive soils. The research encompassed a wide range of experiments examining electrical conductivity, physical attributes, mechanical properties, and the microstructure of stabilised soils. It was followed by a numerical analysis of an embankment constructed on soft soils in Australia.

An innovative method for assessing electrical conductivity was employed to identify the optimal ash-to-lime ratio in the treatments, based on the pozzolanic reactivity of the ash mixtures. The test results revealed that when using 5% hydrated lime, the ideal proportion of bottom ash was 25%. However, when both bottom ash and bagasse ash were utilized, the respective ratios were 17.5% and 7.5%. When utilizing a bottom ash content exceeding 25%, it results in a reduction in the shear strength of the treated material as shown in Figure 12. This could be attributed to the surplus of bottom ash, which causes an imbalance between pozzolan and hydrated lime, consequently lowering the unconfined compressive strength (UCS) and California bearing ratio (CBR) after a 28-day curing period.

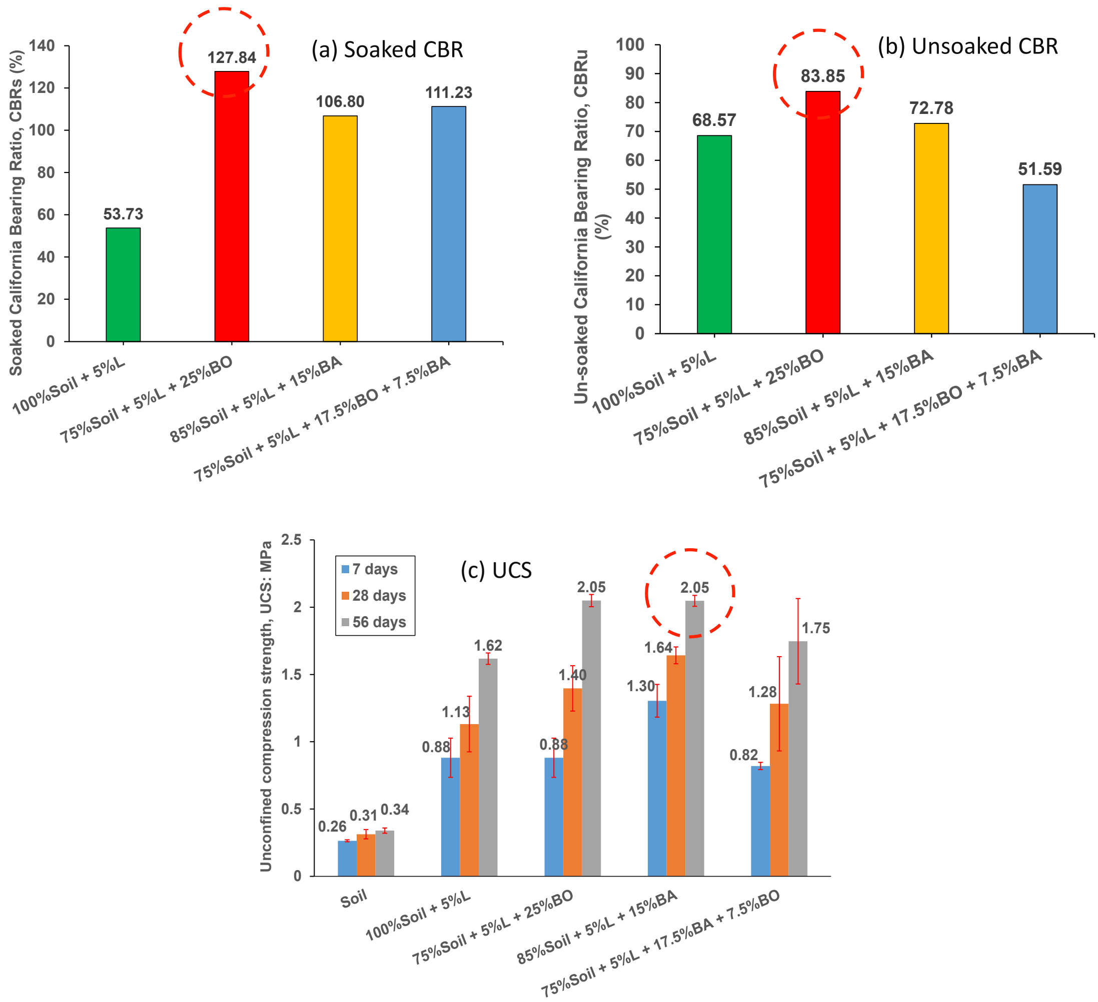



**Figure 12: Characterization of treated soil using bottom ash, bagasse ash and hydrated lime**

### 5.4 EGGSHELL POWDER AND HYDRATED LIME STABILISATION

Eggs, which are both nutritious and delicious, have become an essential part of the daily diet for many Australians. According to Safe Food (2022), to meet this demand, Australian egg producers generate approximately 17 million eggs on a daily basis, amounting to a total of 6.2 billion eggs annually. Given this the average Australian consumes around 240 eggs per person per year. Consequently, a substantial volume of eggshells is produced as waste material.

Eggshells are a readily available waste product generated by various sources, including hatcheries, fast-food establishments, poultry industries, egg product factories, and households. The accumulation of eggshell waste poses environmental concerns and often results in landfill sites. These eggshells can be transformed into eggshell powder (ESP) and serve as a soil stabilisation agent, as the primary component of eggshell powder is recognized to be calcium oxide.

A comprehensive experimental study at UTS revealed that incorporating eggshell powder (ESP) into clayey soil by itself had only a minor improvement on the geotechnical characteristics of expansive soils. However, when hydrated lime and ESP were combined, it had a substantial effect on the primary engineering properties of expansive soils. After conducting pH measurements, it was determined that around 5% of hydrated lime was the proper lime content for the stabilisation of expansive soils, facilitating cation exchanges between soil particles and lime. In addition, through experimentation, it was established that the optimal additive mixture for the stabilisation of expansive soil was 5% hydrated lime and 5% eggshell powder. More eggshell powder content did not increase the strength of limed soil.

In a separate investigation conducted at the University of Technology Sydney (UTS), eggshell powder and cement were utilized as stabilizing agents for expansive soil. This represents a promising methodology with the potential to enhance soil strength and mitigate linear shrinkage. Cement plays a pivotal role in expediting the pozzolanic reaction, thus leading to heightened strength. Augmenting the cement with 6% eggshell powder as a secondary additive to expansive soil resulted in a more pronounced enhancement of the stabilised soil's strength. Specifically, the Unconfined Compressive Strength (UCS) of soil specimens treated with both 6% eggshell powder and 6% cement exceeded that of samples treated solely with 6% cement by a noteworthy 25% as shown in Figure 13. Nevertheless, an examination of Figure 13 highlights the existence of a threshold for the quantity of eggshell powder that can be introduced, as an increment in the eggshell powder percentage initiated a reduction in the soil strength.

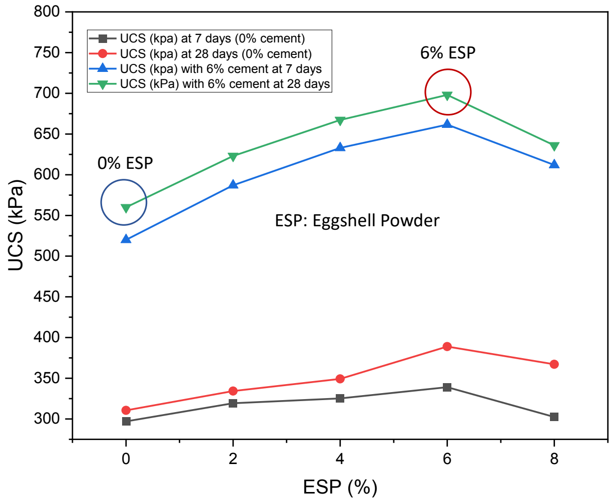



**Figure 13: Effect of eggshell powder and cement on UCS of treated expansive soil at 7 and 28 days of curing**

## 6 LESSONS LEARNT AND RECOMMENDATIONS

Practical recommendations for stabilizing expansive soil with lime, either with or without the addition of by-products, come with several lessons learned.

- One of the most effective strategies for mitigating the effects of expansive soils is to control the moisture content of the soil. This can be achieved through a range of techniques, such as the use of drainage systems to remove excess water from the soil, the use of moisture barriers to prevent moisture from reaching the soil, or the use of vegetation to absorb excess water.
- The application of lime should be executed with care to prevent the generation of dust and runoff.

- The best technique for stabilising expansive soil depends on the specific soil conditions and the desired outcome. For example, if the goal is to reduce the soil swell-shrink potential, lime stabilisation may be a better option. However, if the goal is to increase the strength of soil, cement stabilisation may be a better choice.
- Lime-Soil stabilised mix are useful to construct sub-base and base course for pavement. Lime treated soil is more suitable for warm regions where temperature is very high and for colder regions it is not suitable.
- Lime soil stabilisation is suitable for soils like clay, silty clay, clayey gravel and so on. However, it is not suitable for granular soils with some clay contents.
- A critical consideration when choosing the appropriate stabiliser is the amount of organic matter within the soil. Organic content can potentially interfere with the processes responsible for enhancing strength. If the organic content even exceeds 1%, supplementary additives may be required to counterbalance the cation exchange capacity of the organic material, as recommended by the Texas Department of Transportation (2008).
- Given the differences in physical and chemical interactions between the soil and the stabilizing agents, it is imperative to contemplate customized treatment strategies for the particular site. These strategies should be substantiated by evaluating soil-stabilizer combinations in simulated field conditions, as suggested by Little and Nair (2009).
- Although lime stabilisation is effective in improving the volume and strength characteristics of expansive soils, it is not without its constraints. According to Firoozi et al. (2017), these limitations are primarily associated with the presence of organic carbon and soluble sulfates. Research has shown that an excess of one percent organic carbon can disrupt pozzolanic reactions, leading to restricted strength enhancements. Conversely, the existence of sulfates raises more significant concerns because lime treatment in soils containing sulfate minerals such as gypsum ($CaSO_4$) and sodium sulfate ($Na_2SO_4$) can result in excessive swelling and pavement failures. These unfavorable reactions occur due to the formation of expansive minerals, notably ettringite, a mineral due to sulfate ions reaction with calcium and aluminum ions.
- Quicklime (CaO) is more effective than hydrated lime ($Ca(OH)_2$) for soil stabilisation; however, there is only a slight difference in the final results. If quick lime is applied, care should be taken otherwise dust and even burns may occur. Hence, in most of the cases hydrated lime is used either in dry powder form or by mixing water.
- Magnesium oxide soil stabilisation advantages: it can exhibit higher compressive strength, higher cementitious ability, and superior resistance to sulfate attacks than calcium-based systems. Generally, magnesium oxide (MgO) is more costly than calcium oxide (Cao), but it can exhibit higher compressive strength, higher cementitious ability, and superior resistance to sulfate attacks than calcium-based agents, which may reduce the maintenance cost and increase the durability of the stabilised soil.
- Cement can be utilized for soil stabilisation in a wide range of soil types, with the exception of soils containing more than 2% organic content or having a pH lower than 5.3, as specified in ACI 230.1R-90 (2009).
- Cement undergoes rapid hydration, leading to immediate strength development. Consequently, there is no requirement for a waiting period when using cement for stabilisation, and compaction of soil-cement samples is usually carried out within 2 hours of the initial mixing. However, cement-treated soils can become relatively brittle, leading to the potential for cracking and reduced flexibility. Lime-treated soils tend to exhibit greater flexibility and resilience.
- In order to prevent or reduce the risk of sulfate attack, it is advisable to conduct a sulfate content assessment on the soil prior to lime application. When high sulfate levels are detected in the soil, lime stabilisation may not be the most suitable option, or it may necessitate specific precautions. Potential measures to address this issue include reducing the lime dosage, incorporating a sulfate-resistant additive such as fly ash or slag, or considering alternative stabilisers such as cement or bitumen.
- Introducing 5% or more lime to expansive soil enhances its compressive strength and diminishes expansion by altering the structure of soil through processes such as cation exchange, soil particle flocculation, and the initiation of pozzolanic reactions (Le et al., 2018; Dang et al., 2016; Alqaisi et al., 2021).
- When sulfate is present in the soil, lime treatment can result in increased strength, but it can also lead to significant expansion due to the excessive formation of ettringite.
- Soils exhibiting sulfate levels exceeding 3,000 ppm, as suggested by Little and Nair (2009), should be regarded as potentially problematic. These soils necessitate special attention, starting from the choice of additives and extending through the entire process of mix design and construction.
- The stabilisation of acidic soil using lime, resulted in lower compressive strength than that of alkaline soil.
- There are significant challenges associated with managing treated expansive soils over the long term. Expansive soils can continue to undergo cycles of swelling and shrinkage for many years, and the properties of the soil can change over time due to weathering and other factors. As a result, it is important to monitor the behavior of expansive soils over the long term and to develop strategies for managing the soil behaviour as it changes over time.

- Only with careful assessment of the soil properties under traffic load in long term and the development of effective mitigation strategies, it is possible to design and build infrastructure that can withstand the challenges posed by expansive soils.
- Bagasse ash is generated as a combustion by-product from boiler of sugar factories comprises silica and can be employed as an admixture for treatment of expansice soil. It is considered pozzolanic and non-expansive material. Based on the results of pH measurements, it was found that about 5% hydrated lime was the optimum lime content to stabilise expansive soil, which required for cation exchanges between soil particles and lime to take place, meanwhile 18% hydrated lime-bagasse ash combination (1 lime to 3 bagasse ash) were experimentally determined as the optimum additive combination for expansive soil stabilisation.
- The unconfined compressive strength (UCS) of treated soils notably increased when additive content and curing time increased. The strength development of soils treated with bagasse ash and lime was higher than that of bagasse ash, or hydrated lime alone treated soils.
- The addition of hydrated lime stabilised expansive soil combined with bagasse ash resulted in a remarkable influence on the compression curve and compression index of stabilised soil.
- Bagasse ash can reduce the formation of ettringite in soil containing some sulfate. Bagasse ash contains silica, which can bind with the sulfate ions and prevent them from forming ettringite. Bagasse ash was more effective at reducing the swelling of soil caused by ettringite. Bagasse ash also contains aluminum ions, which can compete with calcium ions for the sulfate ions. This further reduces the amount of ettringite that can form.
- Bagasse ash can also improve the drainage of soil, which can assist to reduce the amount of water available for ettringite formation. the usage of sugarcane bagasse ash in treated soil assists in increasing the resistivity towards sulfate attack.
- Additives are the materials which are added to improve lime-soil mix to improve its strength. Some additives generally used are fly ash, slag, bagasse ash, bagasse fibre, rice husk ash, etc.
- Proper curing of the lime-soil blend is necessary to avert lime leaching into water sources. The lime-soil layer must harmonize with the surrounding vegetation and wildlife, considering its elevated pH levels.
- Inclusion of bagasse fibres in soil increases the strain at failure, and therefore makes the reinforced soil matrix more ductile.
- Class F fly ash is abundantly available in Australia, but it requires the inclusion of an activator such as lime or cement to create pozzolanic stabilised mixtures since it lacks self-cementing properties. When combined with lime, fly ash can be effectively employed for soil stabilisation purposes. According to Fatahi and Khabbaz (2013), the ratio of 1 part lime to 3 parts fly ash can effectively be used in soil stabilisation.

# 7 CONCLUSIONS

The performance of expansive soil after treatment with various eco-friendly waste materials, such as bagasse ash, bottom ash, and eggshell powder, both with and without conventional binders like lime and cement, has been examined. These materials offer potential for sustainable infrastructure development, reducing the need for traditional stabilizers in expansive soil treatment. The findings suggest that when combined with hydrated lime, these by-products not only improve the geotechnical properties of expansive soils but also address the impending environmental challenges associated with waste material disposal. Through research and laboratory studies, it has become evident that sustainable by-product materials show significant promise in terms of increased longevity, cost-efficiency, and long-lasting environmental benefits compared to conventional lime or cement-based agents for addressing expansive soil issues. These materials enhance soil strength, reduce swelling potential, improve soil ductility, and control deformation over time. However, the implementation of these sustainable materials in practice is not yet widespread among construction companies and road authorities in Australia.

Lime stabilisation for expansive soil, whether used alone or in combination with marginal materials, may not be the most effective approach in regions where wetting and drying cycles have a significant impact. Another concern arises from the presence of sulfates in the soil. When lime reacts with these existing sulfates in the soil or groundwater, it can lead to the formation of ettringite. Sulfate attack can result in soil expansion, cracking, and structural deterioration, thereby diminishing the soil's strength and durability. The influence of cyclic loading needs to be carefully considered, especially when addressing shrinkage effects on roads using lime. The use of ashes, fibres, and other waste materials helps alleviate the pressure on landfills. However, a thorough investigation into the long-term performance and durability of stabilisation is needed. The practical application of by-products as road construction materials should be assessed through field tests. Collaboration with road authorities is undoubtedly essential for effectively incorporating agricultural and industrial waste materials into road foundations.

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