An experimental study on engineering behaviour of lime and bagasse fibre reinforced expansive soils

Une étude expérimentale sur le comportement d'ingénierie des sols expansifs renforcés de fibre de chaux et de bagasse

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ABSTRACT: This investigation exhibits a series of laboratory tests conducted to evaluate the influences of bagasse fibre and hydrated lime addition on the engineering properties and swelling behaviour of stabilised expansive soils. Bagasse fibre is industrial waste by-product left after crushing of sugar-cane for juice extraction, used in this study as a reinforcing component for expansive soil stabilisation. The expansive soils used in this investigation were collected from Queensland, Australia. Varying proportions of randomly distributed bagasse fibre of 0.5%, 1.0%, and 2.0% were added to expansive soil and lime-treated expansive soil to investigate the influences of bagasse fibre on the engineering characteristics of stabilised soil. Results of California bearing capacity (CBR), swell potential and one-dimensional consolidation tests after various curing time are presented and discussed in detail. The findings of this experimental investigation indicate that expansive soil reinforcement, blended with bagasse fibre and lime leads to a significant increase in the compressive strength and the bearing capacity of expansive soil. Meanwhile, the swell potential and compressibility of stabilised expansive soils decreased with increasing lime and bagasse fibre contents.

RÉSUMÉ: Cette étude présente une série d 'essais en laboratoire visant à évaluer les influences de la fibre de bagasse et de l' addition de chaux hydratée sur les propriétés d 'ingénierie et le comportement de gonflement des sols expansifs stabilisés. La fibre de bagasse est le sous-produit des déchets industriels qui a été laissé après le broyage de la canne à sucre pour l'extraction du jus, a été utilisé dans cette étude comme composant de renforcement pour la stabilisation du sol expansif. Les sols expansifs utilisés dans cette étude ont été recueillis auprès du Queensland, en Australie. Des proportions variables de fibres de bagasse distribuées au hasard de 0,5%, 1,0% et 2,0% ont été ajoutées aux sols expansifs et au sol expansé traité à la chaux pour étudier les influences de la fibre de bagasse sur les caractéristiques techniques du sol stabilisé. Les résultats de la capacité portante de la Californie, du potentiel de gonflement et des essais de consolidation unidimensionnelle après divers temps de durcissement sont présentés et discutés en détail. Les résultats de cette étude expérimentale indiquent que le renforcement du sol expansif, mélangé à la fibre de bagasse et à la chaux, entraîne une augmentation significative de la résistance à la compression et de la capacité portante du sol expansif. Pendant ce temps, le potentiel de gonflement et la compressibilité des sols expansifs stabilisés ont diminué avec l'augmentation de la teneur en fibre de chaux et de bagasse.

KEYWORDS: Expansive soils; Lime; Bagasse fibre; Swell potential; CBR; Compressibility and Sustainable development.

1 INTRODUCTION

Expansive soils are fine grained soil or decomposed rocks that show huge volume change when exposed to the fluctuations of moisture content. Swelling-shrinkage behaviour is likely to take place near ground surface where it is directly subjected to seasonal and environmental variations. The expansive soils are most likely to be unsaturated and have dominantly montmorillonite clay minerals. Most of severe damage of residential buildings and other civil engineering structures built on top of expansive soils is dependent on the amount of monovalent cations absorbed onto clay minerals. The average annual cost of damage to structures due to shrinkage and swelling is estimated about £400 million in the UK, $15 billion in the USA, and many billions of dollars worldwide (Jones & Jefferson 2012) .

Many efforts have been applied in practice to overcome the adverse effects of expansive soil including replacement of existing expansive soil with non-expansive soil, maintaining a constant moisture content, expansive soil stabilisation and so on. Each method of expansive soil modification has its own benefits and drawbacks based on different site conditions. However, this investigation is mainly concerned with chemical stabilisation technique, using lime and natural fibre to improve expansive soil behaviour.

Lime stabilisation is the most commonly used method for controlling shrink-swell behaviour of expansive soil due to seasonal variations. Lime reacts with expansive clay in the presence of water and changes the physico-chemical properties of expansive soil, which in turn alters the engineering properties of treated soil (Bell 1996). Moreover, soil improvement and reinforcement using lime combined with industrial waste by-products such as fly ash, bagasse ash, rice husk ash, coconut coir fibre, recycled carpet fibre (Fatahi et al. 2012, 2013) and bagasse fibre (Dang et al. 2016a), just to name a few, have become a focus of research interest in recent years.

Bagasse fibre is an abundant fibrous waste by-product of the sugar industry, left after the crushing of sugar-cane for juice extraction. Bagasse fibre has been used for many purposes as a combustible material for energy supply in sugar factories, a pulp raw material in paper industries, and building materials like treated bagasse fibre reinforced biodegradable composites (Cao et al. 2006) and green cementitious composites (Dang et al. 2016c, 2018) for sustainable infrastructure development. Bagasse fibres are environmentally friendly, low density and low-cost materials. They have similar physical and mechanical properties of other natural fibre such as jute, sisal, pineapple and coir fibre. Bagasse fibre has several potential applications in the area of construction, such as building materials and reinforcing component for soil reinforcement in support of subgrade beneath pavements and roads (Dang et al. 2016a,c; 2018). However, very few studies have been carried out on bagasse fibre reinforced problematic soil so far. Hence, more investigations are required to comprehend the engineering properties of bagasse fibre reinforced expansive soil either with or without combination with hydrated lime adopted in ground improvement methods.

In this paper, an array of laboratory experiments including CBR, swell potential and one-dimensional consolidation tests were conducted on untreated and treated expansive soil samples with different hydrated lime contents and various proportions of randomly distributed bagasse fibre after short curing periods of 3 and 7 days. The findings of this experimental investigation were analysed and discussed for better understanding of the impacts of bagasse fibre alone or hydrated lime-bagasse fibre combination on the swell potential, bearing capacity and compression characteristics of treated expansive soils.

2 MATERIALS AND EXPERIMENT PROGRAM

2 .1 *Materials*

2.1.1 *Soil*

The soil samples used in this study for current experimental tests were collected from Queensland, Australia. The soil was air-dried and broken into pieces in the laboratory. In term of sizes of particles, the soil was classified as high plasticity clay (CH) according to the Unified Soil Classification System (USCS). The specific gravity of soil solids (G_s) was 2.64±0.02. The grain size distribution showed that 0.1% of particles were in the range of gravel, 18.3% in the range of sand and 81.6% were fine-grained material (silt/clay). Atterberg limits of the fine portion of material were about 86% liquid limit (LL) and 37% plastic limit (PL), which yielded to a plasticity index (PI) of 49%. The average linear shrinkage and natural moisture content of the samples was 21.7% and 30.8%, respectively. Based on the high linear shrinkage and plasticity index, the soil can be classified as highly expansive soil.

2.1.2 *Lime*

Hydrated lime used in this investigation has high quality and quantity of calcium hydroxide (>85%). The hydrated lime was locally purchased in Sydney, Australia.

2.1.3 *Bagasse fibre*

Bagasse fibre used in this study was obtained from ISIS Central Sugar Mill Company Ltd., Queensland, Australia. The bagasse fibre, as depicted in Figure 1, had a diameter ranging from 0.3 mm to 3.1 mm and a length ranging from 0.3 mm to 13.8 mm. The specific gravity of bagasse fibre (G_f) was about 1.25-1.55 and their average tensile strength was 96.24 ± 29.95 MPa. The obtained fibre was air dried at a controlled room environment with a temperature of 25°C and a relative humidity of 80% until its mass remained constant. Then, the dried fibre were carefully sieved and passed through 9.5 mm aperture sieve and retained on 300 μm aperture sieve, which were selected for this investigation.

Figure 1. Bagasse fibre used in this investigation

2 .2 *Experimental program*

2.2.1 *Mixing of materials*

Soil samples with particles size smaller than 2.36 mm were prepared by mixing bagasse fibre or hydrated lime combined with bagasse fibre. Following this preparation, the specimens were mixed thoroughly. A mechanical mixer was used for the mixing of the expansive soil with hydrated lime and bagasse fibre. After mixing of the materials, the specimens were prepared for the conventional geotechnical experiments, including compaction and California Bearing Ratio (CBR), swell potential and consolidation tests.

2.2.2 *California bearing ratio test*

CBR tests were conducted on untreated and treated expansive soils in accordance with the method specified in AS 1289.6.1.1 (2014) in order to examine the strength and bearing capacity of expansive soil as the subgrade materials in support of road and highway systems. Right after conducting the process of mixing expansive soil with bagasse fibre and lime, untreated and treated samples were compacted in a cylindrical metal mould of a known volume, with an internal diameter of 152 mm and a height of 178 mm, at the maximum dry density (MDD) and the optimum moisture content (OMC). Then, the prepared samples were sealed using plastic wrap to prevent moisture change, cured for 7 days at a controlled room environment; and followed by soaking for another 7 days prior to testing. After that, the samples were tested using conventional compression apparatus in accordance with the method specified in AS 1289.6.1.1 (2014). The CBR values of untreated and treated expansive soil specimens were calculated based on the greater CBR value calculated at 2.5 mm and 5.0 mm penetration. For each type of mixtures, the CBR value was obtained as the average of three CBR tests.

2.2.3 *Swell potential test*

Swell potential tests were conducted on untreated and treated samples using a similar set up for CBR tests in order to examine the free swell potential and swelling versus elapsed time in addition to estimating the vertical ground surface heave of expansive soil due to full wetting. After sample preparation and 3 days of curing, samples were soaked in water to swell. The soil samples were subjected to an initial seating load of 1 kPa put on the top of sample. The soil samples commenced swelling immediately after submersion and were allowed to undergo freely swelling. Swell deformations were measured using a dial gauge. Readings were taken at regular time intervals until swelling stopped (i.e. less than 0.1% change). The final swelling readings were used to determine the total swell (ΔH). Accordingly, the free swell potential of each soil sample ($\Delta H/H$) was determined. It should be noted that the free swell potential values reported were obtained as the average of duplicate swell tests. If the test results had significant variability, additional swell tests were carried out before averaging.

2.2.4 *One-dimensional consolidation test*

To evaluate the effects of bagasse fibre and lime treated expansive soil, a series of one-dimensional consolidation tests were carried out on untreated and treated specimens using conventional odometer apparatuses. The expansive soil samples stabilised with 0.5% bagasse fibre and different percentage of lime and cured for 3 days. For sample preparation, soil specimens were compacted in a cylindrical metal ring, 20 mm in internal diameter and 17 mm in height, at the maximum dry density and the optimum moisture content. After specimen preparation and 3 days of curing, the compacted soil was placed into the Oedometer, while placing dry filter papers and air-dried porous stones on the top and bottom of the soil specimen. Then, vertical deformation measuring device was adjusted to zero reading and an initial seating load of 1 kPa was applied. Once proper loading contact was obtained, the test setup was inundated with distilled water from the top on the specimen for 4 days to get full saturation prior to compression. After completion of saturation, the soil specimens were subjected to additional pressures in time increments in accordance with the standard consolidation test procedures stated in AS 1289.6.6.1 (1998). At any level of pressure, the applied pressure was kept on the specimens for 24 hours to ensure the completion of consolidation was reached and the express pore water pressure was almost zero or negligible. For each type of mixtures, at least two samples were tested and average results were presented.

3 RESULTS AND DISCUSSIONS

3.1 *Effects on the California Bearing Ratio (CBR)*

Figure 2 represents the variation of soaked CBR values of randomly distributed bagasse fibre reinforced expansive soil after 7 days of curing and 7 days of soaking. As can been seen in Figure 2, the smallest CBR value of 3.5% is associated with untreated expansive soil. Then the CBR values increases slightly from 3.5% to 4.7% with an increase in bagasse fibre content from 0 to 2.0%. The increase in CBR values of bagasse fibre reinforced expansive soil could be attributed to the interaction and interlocking mechanism between clay particles and fibres developed during specimen preparation process by compactive effort and with the curing age. The increase in fibre content resulted in an increase in the fibre surface area, exposed to soil matrix, which facilitated better resistance to penetration load.

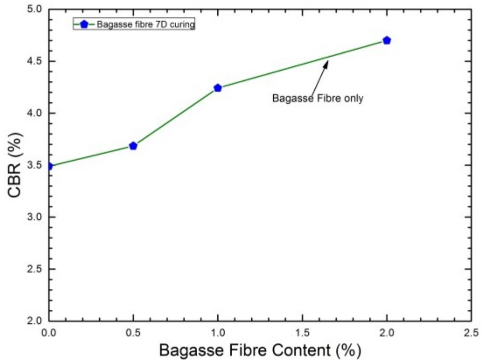

Figure 2. Variation of the soaked CBR of randomly distributed bagasse fibre reinforced expansive soil after 7 days of curing

Figure 3 displays the influence of various contents of bagasse fibre and hydrated lime treated expansive soil after 7 days of curing and 7 days of soaking. As illustrated in Figure 3, the CBR values of treated expansive soil increased steadily with increasing bagasse fibre content from 0.5% to 2.0% in combination with increasing lime content from 4% to 6% (based on dry mass of soil). To illustrate this, the increase in bagasse fibre content from 0.5% to 2.0% added to 4% lime treated expansive soil caused the soaked CBR values increased by approximately 40%. Likewise, a significant increase in amount of 39% for soaked CBR values were found by an increase in bagasse fibre content from 0.5% to 2.0% added to 6% lime treated expansive soil. As expected, the increase in CBR values was more noticeable for the 6% lime combined with different percentages of bagasse fibre treated expansive soil. It can be explained that the significant improvement in CBR value could be attributed to the cation exchange between calcium ions in lime and metal ions on surfaces of clay particles. Then, such physical effects and chemical reactions form agglomeration and flocculation of clay particles, make the clay particles to be coarser, more brittle and less plastic, which facilitate to promote friction resistance of soil matrix. The next justification is associated with the time dependent pozzolanic reactions. Such pozzolanic reactions take place quite slowly and are facilitated by high alkaline soil. The pH value around 12.4, produced by lime-soil mixtures, gives rise to the dissolution of silica and alumina from clay mineral lattice. The dissolved silica and alumina from the lattice of clay minerals react with calcium available in the lime in order to establish new cementitious compounds, calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These cementitious compounds crystallize with time and give rise to compressive strength of treated expansive soil. The addition of bagasse fibre reinforcement, moreover, contributed to the development of interaction between bagasse fibre surface and soil matrix with time, which could be essentially beneficial of fibre reinforcement with lime treated expansive soil. Similar behavior was reported by other researchers (e.g. Bell 1996; Dang et al. 2016a,b).

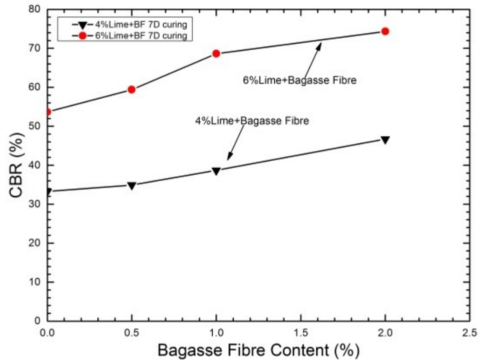

Figure 3. Variation of the soaked CBR of randomly distributed bagasse fibre and lime reinforced expansive soil after curing period of 7 days

3.2 *Effects of bagasse fibre and lime on the swell potential*

Figures 4 and 5 exhibit the fluctuation of swell potential of randomly distributed bagasse fibre reinforced expansive soil and bagasse fibre-lime treated expansive soil, respectively, after 3 days of curing. Overall, swell potential decreased with increasing bagasse fibre and lime contents. To be more specific, Figure 4 shows reduction of swell potential of only bagasse fibre reinforced expansive soil was rapid up to 1.0%. For example, the swell potential reduction of 0.5% bagasse fibre reinforced expansive soil was about 48% in comparison with the swell potential of untreated expansive soil. Then, with increasing bagasse fibre content greater than 1.0% up to 2.0%, the value of swell potential showed a slight increase of swelling. However, the amount of swell potential measured was lower than that of untreated expansive soil. It is of interest to note that the reduction of swell potential of reinforced expansive soil indicated the enhancement of bagasse fibre in heaving resistance.

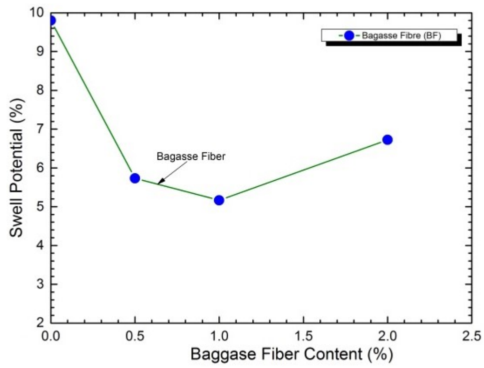

Figure 4. Variation of swell potential of randomly distributed bagasse fibre reinforced expansive soil

Furthermore, Figure 5 presents the enhancement of 0.5% and 2.0% bagasse fibre combined with different hydrated lime treated expansive soil. Observation of the results of swell potential plotted in Figure 5 depicts that bagasse fibre-lime combination treated soil results in a significant reduction of swell potential of treated soil. For example, the amount of swell potential significantly reduced from 9.8% to less than 0.5% with merely adding 2.5% lime plus 0.5% bagasse fibre to the soil samples. Further increase of bagasse fibre and lime content gave rise to the swell potential of reinforced soil down to almost zero.

The significant improvement in swell potential could be attributed to cation exchange between calcium ions in lime and metal ions on surfaces of clay particles. As discussed earlier, when lime adopted to treat expansive soil, some physical and chemical changes take place to form agglomeration and flocculation of clay particles, make the clay particles become coarser, more brittle and less plastic, which facilitate to promote better resistance to swelling behaviour. More importantly, with addition of bagasse fibre to lime-soil mixtures, expansive clay replaced with non-expansive bagasse fibre and development of interaction and interlocking mechanism between clay particles and fibre could provide the effective resistance to swell potential of lime-bagasse fibre-soil mixtures.

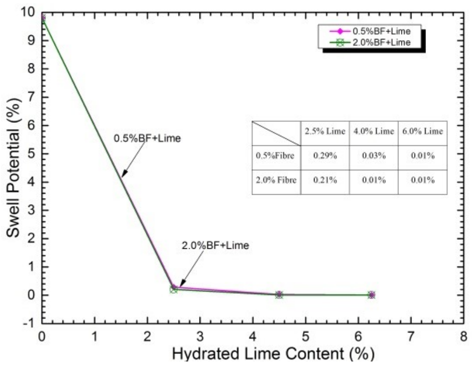

Figure 5. Variation of swell potential of various percentages of randomly distributed bagasse fibre and lime reinforced expansive soil

3.3 *Effects on the compression characteristics*

To investigate the influence of hydrated lime and bagasse fibre inclusion on the compressibility characteristics of stabilised expansive soil, a series of one-dimensional (1D) consolidation tests were undertaken on treated expansive soil with only 0.5% bagasse fibre combined with various percentages of lime from 2.5% to 6%.

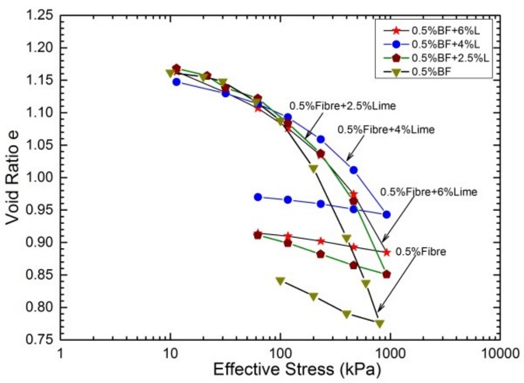

Figure 6. Variation of effective stress-void ratio curves of randomly distributed bagasse fibre and lime reinforced expansive soil

Figure 6 exhibits that the relationship of void ratio against effective compression pressure, obtained from the 1D consolidation tests after 3 days of curing. The test results indicated that the bagasse fibre and lime treated soil tended to decrease the compression characteristics of treated expansive soil with increasing lime content from 0 to 4% and then followed by a light increase in the compressibility with higher lime inclusion. A decrease in the slope of the virgin curves was obviously observed for all combined additive admixtures of treated expansive soil. However, the reduction of virgin curve was more noticeable for 4% lime-0.5% bagasse fibre combination treated soil. The improvement of compressibility of combined lime-bagasse fibre reinforced expansive soil might be attributed to cation exchange reactions between calcium ions in lime and metal ions on surfaces of clay particles and contribution of interaction between bagasse fibre surface and lime-soil matrix with curing time. An increase in lime content results in an increase in the flocculation and aggregation as a result of cation exchange reactions between calcium cations and other exchangeable cations including sodium, magnesium and so forth, which are responsible for the improvement of compressibility characteristics of treated expansive soil.

4 CONCLUSIONS

The key conclusions that can be drawn, based on the experimental results, are as follows:

The CBR values of treated expansive soil increased with the increase in bagasse fibre and lime-bagasse fibre percentages. The increase in CBR values was surely more pronounced for the combined lime-bagasse fibre reinforced expansive soil. From the outcomes of swell potential tests, it is noteworthy to state that modifying expansive soil with bagasse fibre in combination of and lime has significant effect on minimising the swell potential of soil. The addition of a relatively small amount of 2.5% lime-0.5% bagasse fibre could result in non-swelling of treated soil. Refering to the 1D consoliation test results, It is clearly observed that the compression characteristics of lime-bagasse fibre reinforced expansive soil decreased with increasing the additve content. The smallest compressiblity was observed with 0.5% bagasse fibre-4% lime treated soil.

The findings of this experimental investigation demonstrate the combination of lime-bagasse fibre can successully stabilise expansive soil. More importantly, this investigation explores an interesting potential for making use of agricultural and industrial waste by-products such as bagasse fibre as construction fill materials for sustainable development in the area of infrastructure foundations.

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