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Experimental Investigation on the Compaction and Compressible Properties of Expansive Soil Reinforced with Bagasse Fibre and Lime

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ABSTRACT: This paper presents a laboratory investigation into the mechanical characteristics of expansive soil reinforced with randomly distributed bagasse fibre and lime combination. Bagasse fibre, an agricultural waste by-product left after crushing of sugar-cane for juice extraction, was employed in this investigation as a reinforcing component for expansive soil reinforcement. Several series of laboratory experiments including standard compaction and consolidation tests were carried out on untreated soil and soil samples mixed with various contents of bagasse fibre in a wide range from 0% to 2% and a certain amount of 2.5% lime. The experimental results were used to comprehend the effects of adding bagasse fibre on the compaction and compressible properties of fibre reinforced soils with lime stabilisation. The compaction test results indicate that the addition of bagasse fibre, hydrated lime, and their combination decreased the dry density of stabilised soils. Moreover, the obtained results of the consolidation tests reveal that the reinforcement of expansive soil with bagasse fibre improved the pre-consolidation pressure, meanwhile tended to reduce the compression characteristics of the lime stabilised soils as bagasse fibre content increased from 0% to 1%. However, an excessive increase in bagasse fibre content beyond 1% to 2% was found to result in a slight reduction of the compressibility of lime-soil mixtures reinforced with bagasse fibre. The findings of this research provide a deeper insight into promoting applications of an agricultural waste by-product of bagasse fibre as a low-cost and eco-friendly material for treatment of expansive soils and fill materials for sustainable construction development in the field of civil infrastructure foundations.

INTRODUCTION

Expansive soils are fine-grained soil or decomposed rocks, showing significant volume change when exposed to variations of moisture content. Swelling and shrinkage behaviour is most likely to take place near the ground surface where it is directly prone to environmental and seasonal fluctuations. The expansive soils are usually at unsaturated state and have dominantly montmorillonite clay minerals. Most of the severe damage to residential buildings and other civil engineering structures built on top of expansive soils is dependent on the amount of monovalent cations absorbed into 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).

Stabilisation of expansive soil using chemical stabilisers (e.g. lime or cement) is commonly used as the most effective improvement method to overcome the adverse impacts of shrinkage and expansion behaviour of expansive soil because of its volume change again moisture variation. When lime is added into expansive soil, some physical and chemical changes between lime and expansive clay particles taking place in the presence of water alter the physico-chemical properties of expansive soil, which in turn changes the engineering characteristics of stabilised soil (Bell 1996; Dang et al. 2016c). Moreover, according to many researchers (Anggraini et al. 2016; Dang 2018; Dang et al. 2015a; Dang et al. 2015b; Dang & Khabbaz 2018a, 2018b, 2018c; Dang et al. 2017b; Fatahi & Khabbaz 2013, 2015; Fatahi et al. 2012; Kampala & Horpibulsuk 2013), soil stabilisation using lime or cement combined with waste by-products (fly ash, bagasse ash, rice husk ash, coconut coir fibre, recycled carpet fibre and bagasse fibre, just to name a few) can extend the effectiveness of lime stabilisation of clayey soils in terms of compressive strength, shear strength, permeability, and ductility. Thus, the utilisation of combined lime and waste by-products was identified as an eco-friendly alternative solution in improving the engineering properties of clay expansive soils and it has increasingly become an extensive research interest in recent years. Moreover, it is interesting to state that as well-documented in the literature, lime stabilisation of clay expansive soil with fibre reinforcement can be used as an alternative earth load transfer platform in support of highway and railway embankments constructed on columns improved soft grounds (Dang et al. 2016a; Dang et al. 2017a, 2018a, 2018b, 2018c).

The experimental investigation by Chen & Indraratna (2014), however, indicated that conventional chemical stabilisers (e.g. lime, cement) for soil stabilisation are not always acceptable in Australia since they may cause adverse effects on the environment by changing the pH level of treated soil and its surrounding areas. As a result, the quality of ground-water and the normal growth of vegetation can be affected because of the pH change. On top on that, the increasing use of conventional chemical agents to stabilise soil can produce high compressive strength, but also increase the brittleness behaviour of stabilised soil, which influences the soil stability when subjected to cyclic traffic loading under road and railway embankments. Therefore, an environmentally friendly alternative solution such as bagasse fibre reinforcement of soils combined with lime stabilisation is necessary to improve the strength, the ductility and the durability of stabilised soils, meanwhile minimises the negative effects on the environment.

Recently, Dang et al. (2016b) examined the performance of bagasse fibre in enhancing the linear shrinkage and the compressive strength of compacted expansive soils by changing bagasse fibre content from 0% to 2% along with increasing curing time from 3 to 28 days. The test results indicated that as the curing time increased up to 7 days, the introduction of bagasse fibre reinforcement from 0% to 2% improved both the linear shrinkage and the compressive strength of expansive soil and then they remained most likely unchanged with a longer curing time. They concluded that the improvement in the shrinkage and the strength of soils reinforced with bagasse fibre might be due to the development of interaction and interlocking mechanism between fibre surface and soil matrix by compaction energy and with time. Viswanadham et al. (2009) studied the swelling behaviour of geofibre reinforced expansive soil by mixing various polypropylene fibre content from 0.25% to 0.5% and different aspect ratios of 15, 30 and 45. Based on the favourable results obtained, they concluded that polypropylene fibre effectively improved the heave and swelling pressure of expansive soil. The maximum reduction of the heave and the swelling pressure was found at the fibre content of 0.25% and the lower aspect ratio between 15 and 30. According to Mohamed (2013), the shear strength and tensile strength of expansive clay soil reinforced with Hay fibre increased as the fibre content added into soil mixtures increased up to 1%. Meanwhile, the shrinkage limit and the swelling potential decreased up to 1% Hay fibre insertion to the soil matrix followed by an increase with higher fibre addition up to 1.5%. Although those aforementioned experimental investigations indicated that both natural and synthetic fibre could be beneficial for the engineering property improvement of expansive soil with or without chemical stabilisation as fibre content increased from 0% to 1.5%. However, the influence of a combination of natural fibres such as bagasse fibre and lime for expansive soil treatment on the other engineering properties such as compaction and compressibility have not fully been investigated and well reported in the literature.

To have a comprehensive understanding of the potential utilisation of natural fibre for expansive soil reinforcement, several series of laboratory experiments, including standard compaction and consolidation tests, were performed on natural expansive soil and treated soil samples with different contents of randomly distributed bagasse fibre ranging from 0 and 2% and a fixed lime content after 7 days of curing and soaking. The test results of this experimental investigation are analysed and discussed to comprehend the influence of bagasse fibre reinforcement and lime stabilisation on the compaction and compression characteristics of expansive soil. It should be noted that the only results obtained from the compaction and consolidation tests are presented in this paper, which are part of an ongoing research project of characterisation and treatment of expansive soils using agricultural waste by-products (bagasse ash and fibre). Further experimental evaluations of the influence of bagasse fibre inclusions on the shrink-swell behaviour of reinforced expansive soils could be found in Dang et al. (2016b) and Dang et al. (2017c). Moreover, as known that natural fibre reinforcement is biodegradable with time, it is indispensable to improve the durability of natural fibre such as bagasse fibre by applying chemical treatment (i.e. sodium hydroxide, sodium silica, sodium sulphite) and/or coating (asphalt emulsion, rosin-alcohol, acrylic, polystyrene, and silane) to prevent water absorption. However, the results of those tests, which are beyond the scope of this paper, were identified as a follow-up publication.

MATERIALS

Natural soil

Soil samples collected from Queensland, Australia, was used in this experimental investigation. After removal of visible organic matters such as tree roots and leaves, the soil was air-dried and broken into pieces in the laboratory. The specific gravity of soil solids (G_s) was 2.64 ± 0.02. The grain size distribution illustrated that there were 0.1% of particles in the range of gravel, 18.3% in the range of sand and 81.6% of fine-grained material (i.e. silt/clay). Atterberg limits of the fine-grained 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. In term of sizes of particles, the soil was classified as high plasticity clay (CH) according to the Unified Soil Classification System (USCS) (AS 1993). Based on the high linear shrinkage and plasticity index, the soil can be classified as highly expansive soil.

Bagasse fibre

Bagasse fibre used in this study was obtained from ISIS Central Sugar Mill Co., Ltd, Queensland in Australia. The bagasse fibre, as depicted in FIG. 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 in a controlled room environment with a temperature of 25°C and a relative humidity of 80% until its mass remained constant. Then, the dried fibres were carefully sieved and passed through 9.5 mm aperture sieve and retained on 300 μm aperture sieve, which were selected for this investigation.

FIG. 1. Bagasse fibre used in this investigation

Table 1. Chemical composition and physical properties of hydrated lime

Physical properties		Chemical Composition	
Property	**Value**	**Components**	**Content (%)**
Specific gravity	2.2-2.3	Ignition loss	24%
Bulk density (kg/m^3)	400-600	SiO_2	1.8
pH	12.0	Al_2O_3	0.5
		Fe_2O_3	0.6
		CaO	72.0
		MgO	1.0
		CO_2	2.5

Hydrated lime

Hydrated lime utilised in this study (FIG. 2) has about 90% of calcium hydroxide. The hydrated lime was locally purchased in Sydney. Table 1 shows the physical and chemical properties of hydrated lime provided by the producer.

FIG. 2. Hydrated lime used in this investigation

SAMPLE PREPARATION AND EXPERIMENTAL PROGRAM

Mixing of materials

Soil samples were prepared by thoroughly mixing the pulverized natural soil with individual hydrated lime, bagasse fibre or their combination, as shown in Table 2, to become homogeneous mixtures before tap water was added at the target water content. It can be noted that in this investigation, the additive and water contents were calculated based on the total dry weight of each mixture. Following this preparation, the mixtures were mixed thoroughly using a mechanical mixer. After mixing of the materials, soil specimens (FIG. 3) were prepared for many conventional geotechnical experiments.

Table 2. Summary of mixtures employed in this investigation

Mix No.	Bagasse Fibre content (%)	Hydrated Lime (%)	Notes
1	0	0	Natural soil
2	0.5	0	Bagasse fibre and soil
3	1.0	0	
4	2.0	0	
5	0.5	2.5	Lime, bagasse fibre and soil
6	1.0	2.5	
7	2.0	2.5	

FIG. 3. Additives and soil mixing

Standard Compaction Test

Standard compaction test was carried out to determine the maximum dry density (MDD) and the optimum water content (OMC) for untreated and treated soils in accordance with the procedures prescribed in AS 1289.5.1.1 (AS 2017). Different water contents were added to the pulverised soils and thoroughly mixed to make them uniformly distributed through the soil mixtures. Then, the soil mixtures were placed in a cylindrical metal mould, with an internal diameter of 105 mm and height of 115.5 mm and compacted in three equal layers by 25 uniformly distributed blows on the rammer falling freely from a height of 300 mm in accordance with the procedure of AS 1289.5.1.1 (AS 2017). The specimens (FIG. 4) were extruded, measured and weighed, and their moisture contents were determined. The dry density and water content of untreated soil for each specimen were calculated and recorded in accordance with AS 1289.5.1.1 (AS 2017). A total of eleven tests on samples with different water contents were conducted to determine the MDD and the OMC of untreated soil. After that, different amounts of additives, as shown in Table 2, were added to the pulverised soil at the optimum moisture content of untreated soil. The blended mixtures were compacted in the same procedure applied to the untreated soil. The dry density of each mixture was achieved and used for carrying out other geotechnical engineering tests.

FIG. 4. Compacted soil sample

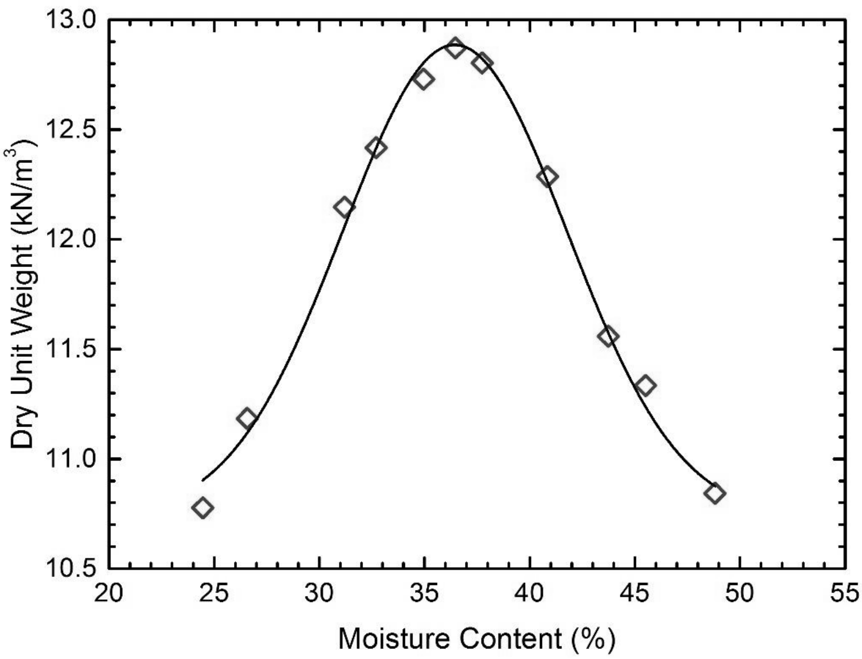
One-dimensional (1D) Consolidation Tests

A series of one-dimensional swelling consolidation tests were carried out on untreated and treated soil specimens after 3 days of curing using conventional Oedometer apparatus following the testing procedure in accordance with AS 1289.6.6.1 (AS 1998). For sample preparation, soil specimens were compacted in a cylindrical metal ring, with an internal diameter of 50 mm and height of 17 mm, at the MDD and OMC. After specimen preparation and curing for 3 days, the compacted soil was extruded and put into the Oedometer ring of the same diameter and then the standard Oedometer testing setup was followed (two-way drained setup). An initial seating load of 3 kPa was applied. Once proper loading contact was achieved, the sample was inundated with distilled water and remained for 4 days to get full saturation prior to compression. During the saturation stage of the consolidation tests, vertical swell deformations were measured using a dial gauge. After completion of this stage, the soil specimens were subjected to additional pressure incrementally in accordance with the standard consolidation test procedure AS 1289.6.6.1 (AS 1998). At any level of pressure, the applied pressure was kept on the specimens for 24 hours to ensure the completion of consolidation. For each type of mixtures, at least two samples were tested and then the average of the compression test results was presented.

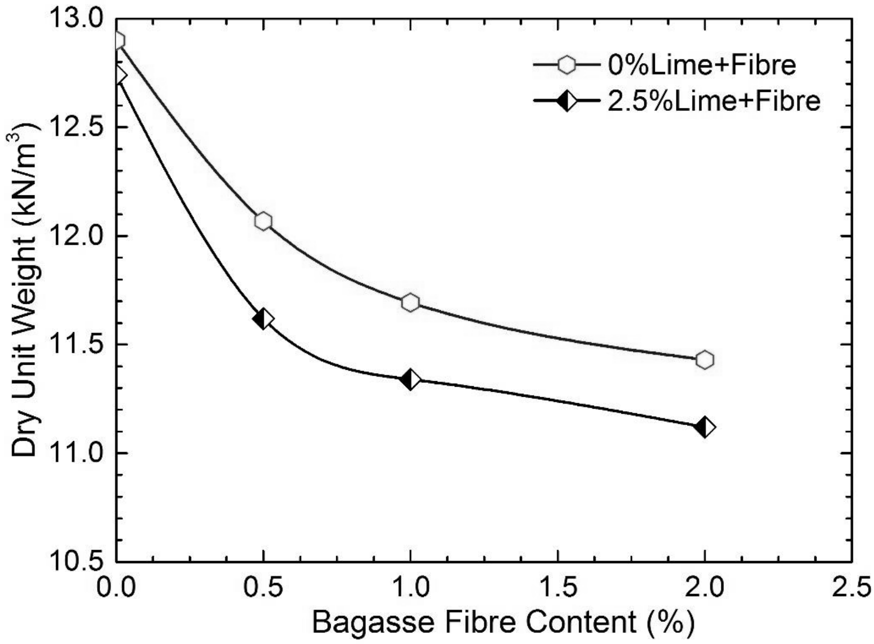
RESULTS AND DISCUSSION

Influence of Additive Content on Compaction Characteristics of Expansive Soil

The standard compaction curve of untreated expansive soil as a preliminary step to determine the maximum dry density (MDD) and the optimum moisture content (OMC) of the soil only is presented in FIG. 5a. Analysis of the compaction results of natural soil found the MDD and the OMC to be 12.9 kN/m^3 and 36.5%, respectively. Subsequently, several series of soil samples mixed soils with different contents of bagasse fibre and lime were prepared at the OMC of the untreated soil (36.5%) to investigate the influence of the additive content on the so-called maximum dry density of the treated soil mixtures. The obtained results of the standard compaction tests for expansive soil reinforced with various contents of bagasse fibre reinforcement and lime are depicted in FIG. 5b. It is observed that with inclusion of bagasse fibre into soils without lime treatment, the MDD of the reinforced soil mixtures gradually decreased from 12.9 kN/m^3 to 11.4 kN/m^3 as bagasse fibre content increased from 0% to 2%. The MDD reduction could be due to the lower specific gravity of bagasse fibre in comparison with that of untreated soil. Furthermore, addition of 2.5% hydrated lime into bagasse fibre reinforced soil mixtures as observed in FIG. 5b shows that the MDD of stabilised soils decreased further. It is noted that the MDD of each lime-bagasse fibre-soil mixture was obviously lower than that of the bagasse fibre reinforced soils without lime treatment. The MDD decrease of lime treated soils with bagasse fibre might be attributed to the lower specific gravity of bagasse fibre together with the flocculation and agglomeration because of cation exchange processes between clay particles and lime that changed the soil particles to be coarser particles. As mentioned earlier, the formation of the coarser particles occupying the larger spaces in the soil matrix, increased the void volume and hence reduced the dry density of the treated soil mixtures. In addition, tiny air gaps trapped into fibre surface could be another possible reason that explains the reduction of the MDD of lime-fibre-mixtures. An increase in bagasse fibre content led to the increase in the tiny air gaps and hence reduced the MDD of stabilised soil composite. Results of this investigation are consistent with other researcher observations (Ayeldeen & Kitazume 2017; Kinuthia et al. 1999).



(a) Compaction curve of natural expansive soil



(b) Compaction curves of lime treated expansive soil with bagasse fibre reinforcement

FIG. 5. Compaction curves of expansive soil reinforced with different contents of bagasse fibre and hydrated lime

Effects on the compression characteristics

The previous investigation by the authors revealed that for only bagasse fibre reinforcement of expansive soil, when bagasse fibre content increased from 0% to 2%, the unconfined compressive strength, the California bearing capacity, and the linear shrinkage of reinforced soils, compared to non-reinforced soil, were found to significantly improve by approximately 40%, 34% and 40%, respectively. However, the swelling potential was observed to reduce by a great amount of 48% as bagasse fibre content increased from 0% to 1% and this was followed a small increase in the swelling potential as an additional increase in bagasse fibre exceeded 1%. These findings confirmed the effectiveness of adding bagasse fibre alone in improving the shrink-swell behaviour and the other mechanical characteristics of reinforced expansive soils. Further details of the experimental investigations could be found in Dang et al. (2016b) and Dang et al. (2017c).

In this study, a series of Oedometer tests was undertaken on expansive soils treated with combinations of a fixed lime content with different contents of bagasse fibre after 3 days of curing and 4 days soaking (so-called 7 days of curing). As it can be found in FIG. 6 that when the bagasse fibre content was varied from 0% to 2%, only 2.5% hydrated lime were added to bagasse fibre-soil mixtures to study the effect of adding bagasse fibre on the compressible property of lime treated expansive soil. Moreover, to have a better comparison of the compressibility between untreated soil and lime treated soils with bagasse fibre reinforcement, the test results obtained from untreated soil sample is also depicted in FIG. 6. Observation of the experimental results in FIG. 6 reveals that adding bagasse fibre into lime treated soil mixtures was found to reduce the compression characteristics of reinforced soils as bagasse fibre content increased from 0% to 1%. Subsequently, the compressibility of lime treated soils reinforced with bagasse fibre indicated a slight increase when the addition of bagasse fibre exceeded 1%. When compared with the compression curves of untreated soil and 2.5% lime treated soil, the lower slope reduction of the virgin compression curves was found for soil samples treated with 2.5% lime in combination of bagasse fibre reinforcement. Referring to FIG. 6, the combination 2.5% lime and 1% bagasse fibre caused the most notable improvement in the virgin curve of reinforced soils.

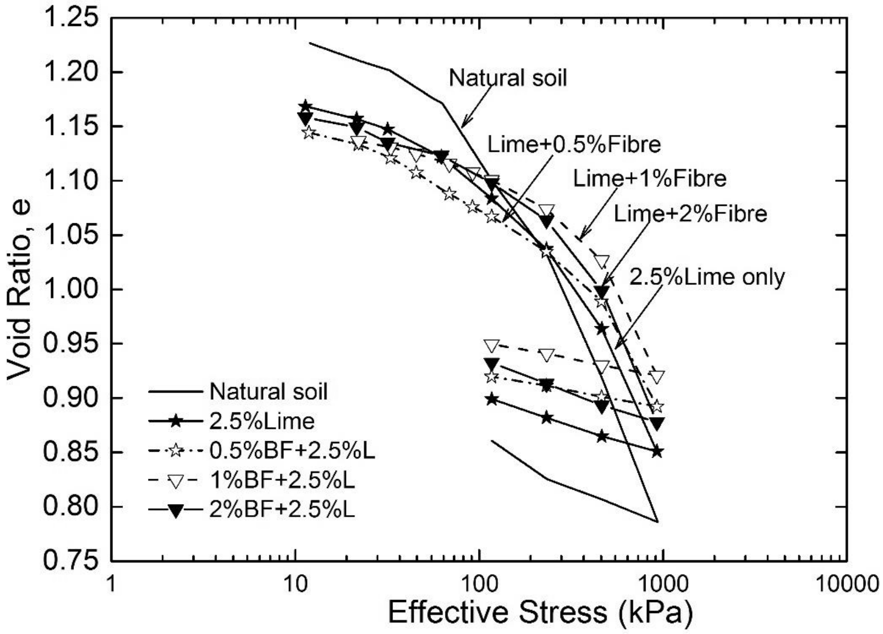


FIG. 6. Compression curves of expansive soil reinforced with different contents of bagasse fibre and 2.5% lime

The compressibility decrease of expansive soil stabilised with lime-bagasse fibre combination could be attributed to replacement of exchangeable ions on the clay surface with calcium ions in lime as a result of cation exchange. This phenomenon transformed the clay particles in the lime-soil matrix to become coarser, stronger and less plastic, which consequently promoted the improvement in the compressibility of treated soils. In addition, when bagasse fibre was introduced into the lime-soil mixture, interactions between bagasse fibre surface and lime-soil matrix with curing time might contribute to additional improvement in the compressible property of stabilised soils. As expected, when bagasse fibre content increased, the fibre surface area that was exposed to soil matrix also increased, which facilitated the better resistance to the compression pressure. However, the excessive addition of fibre bagasse content into lime-soil mixtures was about to increase the compressibility of stabilised soils to a certain extent due to the relatively high compressibility of natural bagasse fibre compared with soil particles.

The influence of bagasse fibre reinforcement on the preconsolidation pressure of lime treated expansive soil is illustrated in FIG. 7. It is noted that the preconsolidation pressures of 2.5% lime treated soils with various bagasse fibre contents were deprived from FIG. 6 using a proposed method of Boone (2010). Observation of the preconsolidation pressures presented in FIG. 7 notes that the increase in bagasse fibre content from 0% to 1% to reinforce soils with 2.5% lime resulted in the corresponding increase in the pre-consolidation pressure from 165 kPa to around 240 kPa (approximately 45% improvement). When additional increase in bagasse fibre content beyond 1% exhibited a marginal decrease in the preconsolidation pressure of reinforced soils to a certain value of 215 kPa. However, by comparing with untreated soil and only 2.5% lime treated soils, the preconsolidation pressure of 2.5% lime treated soil with 2% bagasse fibre reinforcement significantly increased by 38% and 30%, respectively. This behaviour reveals that bagasse fibre reinforcement was very effective in improving the preconsolidation pressure of lime-soil mixture, whereas an excessive inclusion of bagasse fibre content exceeded 1% tented to reduce its positive impact on the improvement in the preconsolidation pressure of reinforced soils with lime.

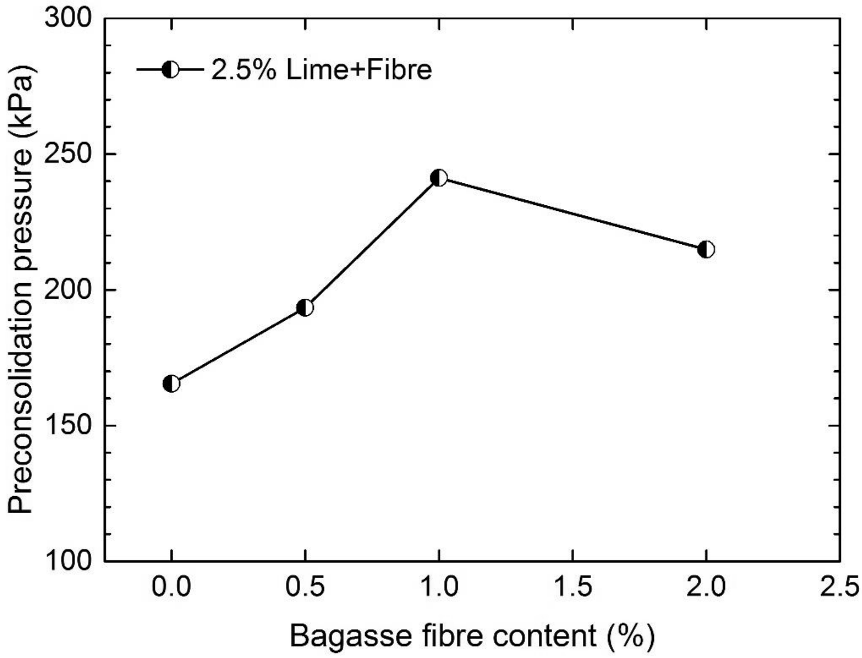


FIG. 7. Variation of preconsolidation pressure of expansive soil reinforced with various contents of bagasse fibre and 2.5% lime

FIG. 8 indicates the influence of bagasse fibre reinforcement on the variation of compression index (Cc) and swelling index (Cs) of 2.5% lime-soil mixtures after curing and soaking for 7 days. It can be noted that Cc is defined as the slope of the straight line portion (virgin compression portion) of the effective stress-void ratio curve, meanwhile Cs is the slope of the unloading compression curve. As can be seen in FIG. 8, the value of Cc appeared to reduce with increasing bagasse fibre inclusion from 0% to 1%.

However, an increasing trend of the compression index was observed when the bagasse fibre inclusion into the lime-soil mixture increased beyond 1%. A similar behaviour can be found the swelling index of lime treated soils with bagasse fibre reinforcement as bagasse fibre content increased up to 2%. As observed in FIG. 8, the change of Cc was more pronounced than the Cs variation of reinforced soils with lime stabilisation. The reduction of both the Cc and Cs indices confirms that the addition of bagasse fibre can effectively reduce the compressibility of lime treated soils. As noted earlier, the improvement of lime treated soils reinforced with bagasse fibre might be due to the interlocking mechanism and interaction between lime-soil matrix and bagasse fibre surface that play an important role in improving the mechanical properties of reinforced soils. As bagasse fibre content increased to a certain amount, the lime-soil mixtures with bagasse fibre reinforcement would promote the better resistance to the applied compression pressure, and consequently facilitate the lower compressibility of reinforced soils.

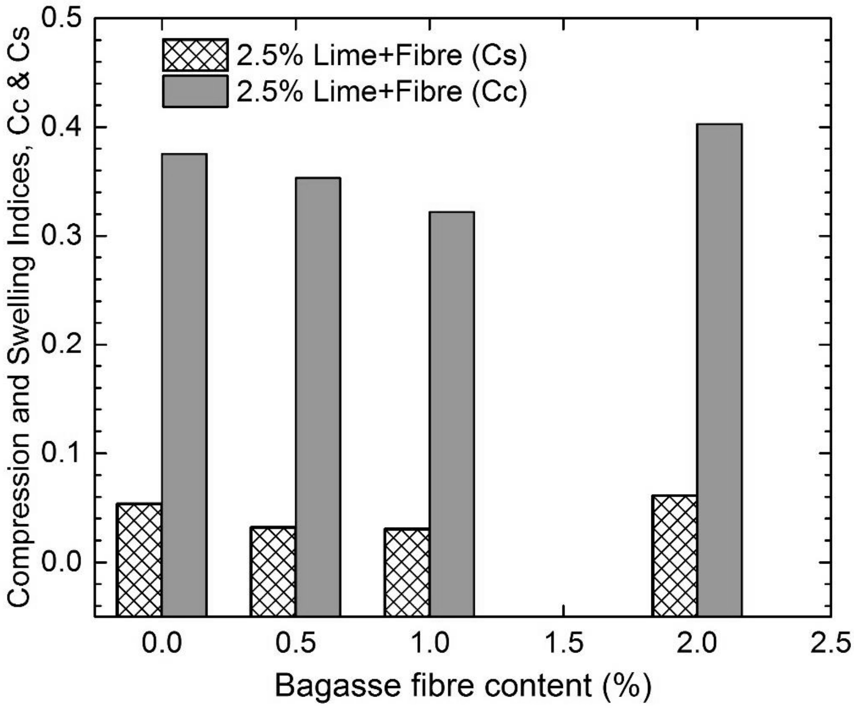


FIG. 8. Variations of compression and swelling indices of expansive soil reinforced with various contents of bagasse fibre and 2.5% lime

CONCLUSIONS

This paper shows an experimental investigation, conducted on expansive soils stabilised with different contents of lime and bagasse fibre reinforcement, in order to evaluate the compaction and compressibility characteristics of stabilised soils. The key findings of this investigation are summarised as follows:

- In comparison with untreated soil, the maximum dry density (MDD) of soils reinforced with only bagasse fibre was found to gradually decrease with increasing the bagasse fibre content from 0% to 2%. With the addition of hydrated lime into the bagasse fibre-soil mixtures, the MDD of combined hydrated lime-bagasse fibre reinforced soils decreased further.

- From the one-dimensional consolidation test results, it is concluded that the addition of bagasse fibre into soils stabilised with lime was found to result in a remarkable influence on the compressible properties of reinforced soils. The compression curve, the compression and swelling indices reduced, meanwhile the preconsolidation pressure of stabilised soils improved, as bagasse fibre content increased from 0% to 1%. However, the improvement was observed to reduce when bagasse fibre inclusion increased further to 2%. This finding corroborates that adding a certain amount of bagasse fibre into lime-soil mixtures was proved to promote the most effective improvement in the compressibility characteristics of treated soil.
- This investigation indicated that the utilisation of hydrated lime-bagasse fibre combination for expansive soil treatment could highly be effective in not only improving the geotechnical properties of expansive soil but also minimising the environmental impacts of an agricultural waste by-product of bagasse fibre. This study also revealed that bagasse fibre reinforcement had the potential use as a recycled, environmentally friendly and cost-effective additive in combination of with lime for sustainable civil infrastructure construction development because of reducing the consumption of conventional stabilisers such as lime or cement, commonly adopted in treatment of expansive soil.

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