A Practical Application Using Industrial Waste for Enhancing the Mechanical Properties of Expansive Soil

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Abstract. In this study, a series of laboratory tests was conducted to investigate the possibility of enhancing the mechanical properties of expansive soil using bagasse fibre (BF, a waste by-product of sugar industry) integrated without or with lime stabilisation as a novel, practical application of reuse of industrial waste materials for sustainability. Soil samples reinforced with three different contents of bagasse fibre ranging from 0% to 2% without or with lime combination in a range of 0–6%, were systematically prepared to assess their effect on improved engineering mechanism of expansive soil. The results revealed that BF reinforcement produced the shear strength development of reinforced soils. Moreover, a lime-BF combination provided better improvement in the shrink-swell behaviour and the compressibility of reinforced soils as compared to soils treated with lime or bagasse fibre alone. The findings also indicated that adding BF into lime-soil mixtures reduced the compressible properties of lime-treated soils. Meanwhile, excessively increasing bagasse fibre content greater than 1% caused a minor decrease in the compressibility improvement of reinforced soils. Hence, an appropriate combination of lime and BF should be determined and used as an environmental-friendly, cost-effective and green solution for stabilisation of expansive soil to facilitate sustainable civil infrastructure development.

Keywords: Expansive soil · Soil stabilisation · Bagasse fibre · Industrial waste recycling · Fibre reinforcement · Sustainable civil infrastructure

1 Introduction

Bagasse fibre is an abundant fibrous waste of the sugar-cane 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-cane factories, a pulp raw material in paper industries and building materials. Besides, BF waste is used as fuel in the cogeneration boiler to generate steam for the production of sugar as well as electricity, while producing bagasse ash. Nonetheless, due to increasing sugar production

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worldwide, a huge amount of bagasse fibre and its ash are simply disposed in a landfill and now becoming an environmental burden. It is noted that bagasse fibre is a renewable, environmentally friendly, low density and low-cost material that has physical and mechanical properties similar to other natural fibres such as jute, sisal, pineapple and coir fibres. Hence, BF has a highly potential application in the area of construction as reinforced building materials and reinforcing components for soil reinforcement in support of subgrade and subbase beneath pavement and road systems.

Expansive soil is classified as a type of problematic soil, showing significant volume change when exposed to the fluctuations of moisture content. Frequent soil movements due to the moisture change can generate cracks and the damage of superstructures, freeways, seaports, airports and other civil constructions directly placed on this type of problematic soil. The average annual cost of structural destruction associated with light structures and footings constructed on expansive soils was estimated about £400 million in the UK, $15 billion in the USA, and many billions of dollars worldwide [1]. There are many ground modification methods that have been applied in construction practice to minimise the adverse effects of expansive soils. Among them, special attention has been paid to stabilisation of expansive soil utilising agricultural and industrial wastes because it has been identified to be effective in curtailing the negative impacts of shrinkage and expansion behaviour of expansive soils, while minimising the environmental impacts of industrial wastes [2–9]. Moreover, it is worth mentioning that fibre reinforcement of cemented clays could be useful for various construction practices such as fibre-reinforced load-transfer platform (FRLTP) to support highway embankments over soft grounds [10–19]. This has increasingly become a focused research interest in recent years.

This research aimed to evaluate the potential use of recycled BF waste for expansive soil reinforcement. An array of comprehensive laboratory experiments was conducted on non-reinforced expansive soil, and three different contents (e.g. 0.5%, 1% and 2%) of BF reinforced expansive soils together with various contents of lime stabilisation ranging between 0% and 6% after various curing times. The experimental results were presented and analysed to comprehend the mechanical characteristics of BF reinforcement of expansive soil without or with lime combination for sustainability.

2 Materials and Experimental Programs

2.1 Materials

The soil samples used in this investigation were collected from a road construction site in Queensland, Australia, which was thoroughly described in previous studies [6, 8, 20]. According to the high swell potential, linear shrinkage, and plasticity index, the collected soil can be categorised as highly expansive soil (CH) in accordance with the Unified Soil Classification System (USCS), AS 1726 [21]. It should be noted that for preparation of soil samples, particles larger than 2.36 mm were removed resulting in more consistent samples. Hydrated lime has high quality and quantity of calcium hydroxide (>85%) that was used in this investigation. The hydrated lime is locally purchased in Sydney, Australia.

Bagasse fibre adopted in this research was obtained from ISIS Central Sugar Mill Co., Ltd, Queensland in Australia [22–24]. The BF, as depicted in Fig. 1, had a diameter ranging from 0.3–3.1 mm and a length ranging from 0.3–13.8 mm. The specific gravity of BF (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 60% until its mass remained constant. Then, the dried fibre was carefully sieved and passed through 9.5 mm aperture sieve and retained on 300 μm aperture sieve, which was selected for this research. It is known that natural fibres are biodegradable with time. Hence, the durability of natural fibres such as coir fibre and BF, can be improved by chemical treatment using sodium sulphite, sodium hydroxide, or silane coating [25] to prevent the decay of natural fibres from water absorption. Yet, these experimental results were identified as future studies, which are beyond the scope of this paper.

Fig. 1. Photograph of BF used in this investigation

2.2 Experimental Programs

Soil samples were prepared by thoroughly mixing the pulverised natural soil with individual hydrated lime, BF or their combination in the examined ranges to become homogeneous mixtures before tap water was added at the target water content by the dry mass of each mixture. In case of untreated soil specimens, air-dried soils were thoroughly mixed with distilled water to obtain the optimum moisture content of 36.5%. A mechanical blender was used for the mixing of the expansive soil with BF, lime and water. After mixing of the materials, fibre-lime-soil specimens were prepared for both the conventional and comprehensive geotechnical experiments. To investigate the shear strength properties of BF reinforced soils, isotropically consolidated-undrained (CU) tests were conducted on soil samples after 7 days of curing using triaxial compression apparatus following the standard procedure of Australian Standard, AS 1289.6.4.2 [26]. Meanwhile, swelling and consolidation tests were carried out on untreated and treated soil specimens after 3 days of curing using conventional oedometer apparatus following the testing procedure, AS 1289.6.6.1 [27]. The details of testing can be found in previous research by Dang et al. [5, 22]. It should be noted that soil specimens were compacted at the optimum moisture content and maximum dry unit weight [5, 22–24, 28]. For each type of mixtures, the reported test value was obtained as the average of three experimental tests and should not deviate by more than 10% from the mean strength.

3 Test Results and Discussion

3.1 Ultimate Shear Strength of Bagasse Fibre Reinforced Soil

Figure 2 displays variations of ultimate (peak) deviatoric strength versus BF content at different confining pressures. As illustrated in Fig. 2, the ultimate deviatoric strength of reinforced soils positively and significantly depended on the BF content. An increase in the BF content resulted in a corresponding increase in the ultimate deviatoric strength of reinforced soils as observed in Fig. 2 for any given confining pressures. This finding confirms the effectiveness of BF for expansive soil reinforcement in terms of the ultimate shear strength. The shear strength improvement of BF reinforced soils compared to non-reinforced soil might result from the interaction effect between fibre surface and clay particles due to the compaction energy. Such interaction effect improved with increasing BF content, which plays a key factor in increasing the ultimate shear strength of reinforced soils.

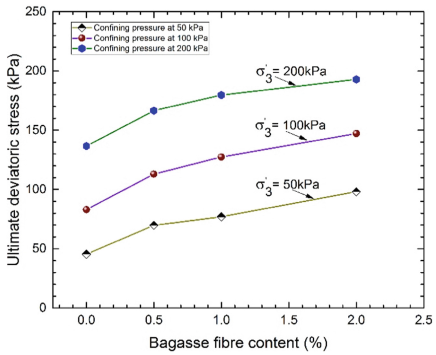

Fig. 2. Ultimate deviatoric strength of soil reinforced with different BF contents

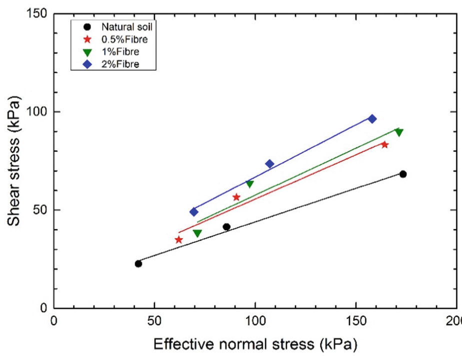

Fig. 3. Peak strength envelopes of soil reinforced with different BF contents

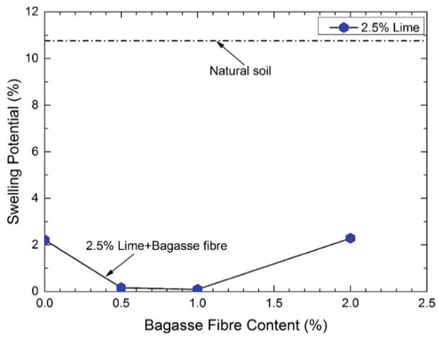

Fig. 4. Swelling potential of BF reinforced expansive soil with 2.5% lime

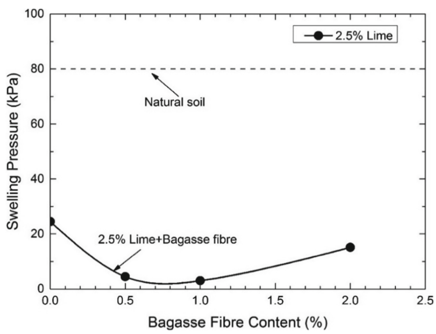

Fig. 5. Swelling pressure of BF reinforced soil with 2.5% lime

It should be noted that a nonlinear relationship between the ultimate deviatoric strength and the BF content was clearly depicted in Fig. 2 as the predominant mechanism for soils reinforced with BF. Moreover, the ultimate deviatoric strength was found to be significantly influenced by the applied confining pressures varying from a relatively low pressure level of 50 kPa to a high pressure level of 200 kPa. As expected, an additional increase in the confining pressure ranging from 50 kPa to 200 kPa improved the ultimate deviatoric strength regardless of adopted BF content. The improved ultimate shear strength was observed for both non-reinforced and reinforced soil specimens, which could be attributable to the effective stress increase corresponding to the confining pressure increase. From the test results, the peak shear strength envelops for both non-reinforced and BF reinforced soils are presented in Fig. 3. Overall, the slopes of the peak shear strength envelopes are steeper and their locations are higher for BF reinforced soils than those of non-reinforced soil. This pattern reveals the beneficial effect of BF reinforcement on the improvement in the peak shear strength of reinforced soils. From observation of Fig. 3, the peak shear strength parameters consisting of effective internal friction angle (φ') and intercept cohesion (c') were derived using linear regression analysis and noted that both φ' and c' values were found to increase with increasing BF inclusions. For instance, approximately 45% increase in the peak friction angle from 19.5° to 28° was observed when BF content increased from 0% for non-reinforced soil to 2% for soils reinforced with BF.

3.2 Effects of Bagasse Fibre and Lime on Swelling Potential

Figure 4 shows fluctuations in swelling potential of untreated soil and 2.5% lime treated soils combined with different contents of BF in a range of 0–2%. It can be observed in Fig. 4 that with the addition of 2.5% lime into soil mixture, the swelling pressure decreased significantly by 79% when compared to that of natural soil. Moreover, as illustrated in Fig. 4, it can be noted that the swelling potential of soils treated with a combination of 2.5% lime and BF reduced by almost 100% as BF inclusion increased from 0% to 1%. It is interesting to state that the 2.5% lime treated soil samples with BF reinforcement in the range of 0.5%–1% could be considered as non-expansive soil due to the negligible (almost zero) swelling potential obtained. However, when an additional increase of BF exceeded 1%, the soils stabilised with 2.5% lime and BF reinforcement exhibited a small reduction of the swelling potential improvement. Nevertheless, the measured swelling potential of 2.5% lime-soil mixture reinforced with 2% BF was very much smaller as compared to that of untreated expansive soil. This behaviour indicates that an appropriate combination of BF reinforcement and lime inclusion for treatment of expansive soil would be very effective in improving the swelling resistance of expansive soil.

3.3 Effects of Bagasse Fibre and Lime on Swelling Pressure

The fluctuations of swelling pressure of 2.5% lime treated soils reinforced with various contents of BF ranging from 0% to 2% are illustrated in Fig. 5. It is noted that the swelling pressure of about 80 kPa for expansive soil without chemical treatment and fibre reinforcement is also presented in Fig. 5 for better comparison purpose. As Fig. 5 shows, the addition of a relatively small content of 2.5% lime into soil was found to cause an approximately 70% reduction of the swelling pressure compared with untreated soil. Moreover, as observed in Fig. 5, the reduction of the swelling pressure was noted to be more significant as BF was inserted into 2.5% lime-soil mixtures. For example, the swelling pressure decreased to a nominal value of less than 5 kPa for 2.5% lime treated soil sample with BF reinforcement as the BF increased to 1%. It is possible to conclude that the soil sample treated with 2.5% lime in combination of BF reinforcement in the range of 0.5–1% could be considered as non-problematic soil because of its negligible swelling pressure as evident in Fig. 5. However, when BF insertion increased beyond 1%, an increase in the swelling pressure to a certain extent (e.g. 15 kPa) was observed for 2.5% lime treated soils reinforced with (e.g. 2%) BF as depicted in Fig. 5. Obviously, the swelling pressure change illustrates a similar trend of the swelling potential of 2.5% lime treated soils reinforced with increasing contents of BF.

3.4 Effects of Bagasse Fibre and Lime on the Compression Characteristics

Figure 6 shows changes in the compression curves of lime treated soils with BF inclusion after 3 days of curing and 4 days soaking (so-called 7 days of curing). As Fig. 6a displays, to examine the effect of BF reinforcement on the compressible property of lime-soil mixtures, a fixed lime content of 2.5% was added to BF-soil mixtures, while the BF content was varied from 0% to 2%. The compression curve of untreated soil is also plotted in Fig. 6a in order to compare with lime treated soils with BF reinforcement. Observation of the compression results reveals that adding BF into lime treated soil mixtures was found to reduce the compression characteristics of reinforced soils as BF content increased from 0% to 1%. Subsequently, the compressibility of lime treated soils reinforced with BF indicated a small increase when the addition of BF exceeded 1%. By comparing with 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 with BF reinforcement. Referring to Fig. 6a, the combination 2.5% lime and 1% BF was observed to cause the most notable improvement in the virgin curve of reinforced soils.

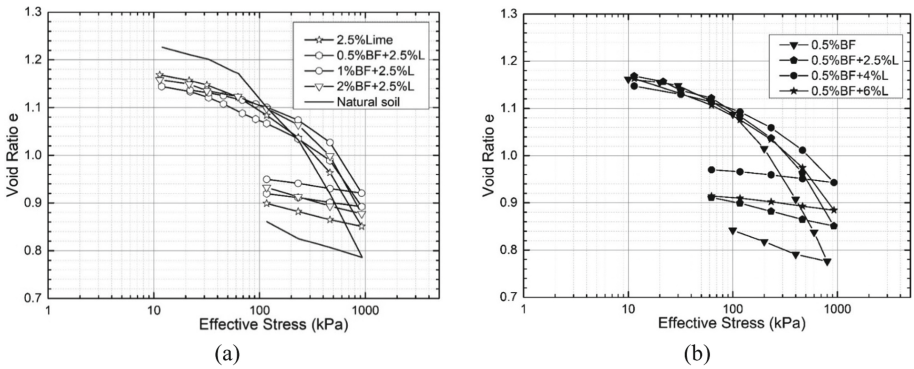

Fig. 6. Effective stress-void ratio curves of expansive soil reinforced with (a) various contents of BF and 2.5% lime (L); (b) various contents of lime and 0.5% BF

Furthermore, to comprehend the effect of lime stabilisation on the compressibility of expansive soils reinforced with BF, a fixed content of 0.5% BF was inserted to soils mixed with various contents of lime from 0% to 6% as plotted in Fig. 6b. The results indicate that a combination of 0.5% BF and various lime contents was found to decrease the compression characteristics of treated soils when increasing lime content from 0% to 4%. This trend was followed by a slight increase in the compressibility with a higher lime inclusion (e.g. 6%). As Fig. 6b illustrates, the most reduction of compression curve was observed for 4% lime treated soil sample reinforced with 0.5% BF.

4 Conclusion

This investigation has explored the potential reuse of a recycled and low-cost waste material (bagasse fibre) for sustainable development of civil infrastructure construction projects. Based on the test results, it was found that the ultimate deviatoric strength of reinforced soils was considerably depended on the BF content. The interfacial friction between fibre surface and clay particles due to compaction energy plays an important role in improving the ultimate shear strength of reinforced soils compared to the control sample. Adding lime and BF into soil mixtures resulted in a remarkable improvement in the swelling and compressible properties of reinforced soils. More interestingly, adding a relatively small content of 2.5% lime with 0.5% BF could result in non-swelling of treated soil. The compressibility of lime treated soils with fibre reinforcement were found to decrease with increasing lime content from 0% to 4% followed by a slight increase as lime content increased further to 6%. This finding reveals that adding a certain amount of BF into lime-soil mixtures is very effective in improving the compressibility characteristics of treated soil.

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