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Shear Strength and Bearing Capacity of Fibre-Reinforced Sand

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Abstract **-** In this paper, direct shear tests were conducted to evaluate the effect of randomly distributed fibres on the shear strength parameters of dry sand. Polyolefin fibre which is a polymeric produced from a simple olefin (CnH2n) was mixed with dry sand to investigate the improvement of shear strength and effect on volume changes. Specimens with 0.5%, 1%, 1.5% and 2% of fibre contents with different lengths (i.e. 15mm and 30mm) are prepared in repeatable steps and tested in direct shear tests. In addition, two sand types; coarse sand and fin sand were used in this investigation to study the grading size effects on the behaviour of the fiber-reinforced sand. Results indicated that, the inclusion of randomly distributed discrete fibres significantly improved the shear strength of sand. The existence of polymeric fibre inside the sand developed what is called apparent tensile cohesion in addition to the sand normal internal friction angle. The optimum fibre percentage for improving both friction angle and apparent tensile cohesion was about 1%. Adding fibre more than this ratio resulted in a significant reduction in both soil shear strength parameters. The effect of fibre on sand tensile cohesion is more pronounced compared to its effect on the friction angle. A bearing capacity of hypothetical footing resting on ground surface of fibre reinforced sand was estimated and discussed. Finally, quantitative effects of fibre contents on both shear strength and volume changes for sand are presented and discussed.

Keywords**:** Shear strength, Sand, Soil reinforcement, Bearing Capacity, Geo-Fibre.

1. Introduction

Soil reinforcement techniques have been developed and implemented successfully for four decades. Different forms of reinforcement such as, plane shape (geotextiles and geogrids), geocells, and discrete fibres are used in practice. Latha and Murthy (2007) concluded that, different forms of reinforcement are expected to give different strength improvements, despite that same quantity of material are used. They attributed the difference in strength improvement to the different mechanism of failure associated with different reinforcement forms and shapes. In addition, they concluded that randomly oriented discrete fibre showed insignificant improvement in stress–strain behaviour of sand. Furthermore, the failure plane of a randomly ordinated sand specimen tested on triaxial test was similar to that of pure sand specimen tested under same conditions. This minor contribution of the discrete fibre to the behaviour of sand could be attributed to the type of fibre used by Latha and Murthy (2007). A close look to the fibre indicated that it was very soft fibre with almost perfectly smooth surface. Therefore, it is expected that this type of fibre may reduce the internal friction between particles rather than increasing it. Despite of this, Latha and Murthy (2007) reported about 45% increase in the shear strength of pure sand when it is reinforced with discrete randomly distributed fibre.

Based on study of sand reinforced with discrete fibres on direct shear test, unconfined compression test, and triaxial test, significant improvement of shear strength of sand due to fibre inclusion was reported (Al-Refeai 1991; Ranjan et al. 1994; Consoli et al. 1998; Yetimoglu and Salbas 2003; Tang et al. 2007). Studies by Gray and Al-Refeai (1986) and Ranjan et al. (1994) indicated that the shear strength of fibre-reinforced sand increased with increasing both percentage and aspect ratio of the fibre. These studies also concluded that, the longer the fibre, the more improvement in the shear strength of the sandy soil. Regarding bearing capacity, El-Emam (2009) indicated that inclusion of one reinforcement layer improved the bearing capacity of soft clay significantly. In addition, the settlement of reinforced clay was considerably less compared to the unreinforced clay. Casagrande et al. (2009)

conducted plate load tests to investigate the bearing of polypropylene fibre-reinforced and non-reinforced sandy soil. Results of these tests concluded that the inclusion of fibre inside the sandy soil increased both strength and stiffness of the soil, which reflected on both loading and settlement of the plate. In addition, the inclusion of fibres changes the failure mechanisms observed for non-reinforced sand. Furthermore, the fibre-reinforced sand shows the ability to maintain strength (or even continue to increase strength) with ongoing deformation, suggesting a very ductile material. Therefore, Casagrande et al. (2009) suggested that the fibre-reinforced sand material could be potentially used in other earthworks that might suffer excessive differential settlement, such as part of cover liners of municipal solid waste landfills, and embankments over organic soft soils.

The current paper presents results from a series of direct shear tests conducted on large number of soil specimens reinforced with discrete polymeric fibre. Fibres with different percentages have been used with sand in order to quantify the optimum fibre content. Finally, the improvements on both shear strength parameters, and bearing capacity of shallow foundation are presented in a practical way.

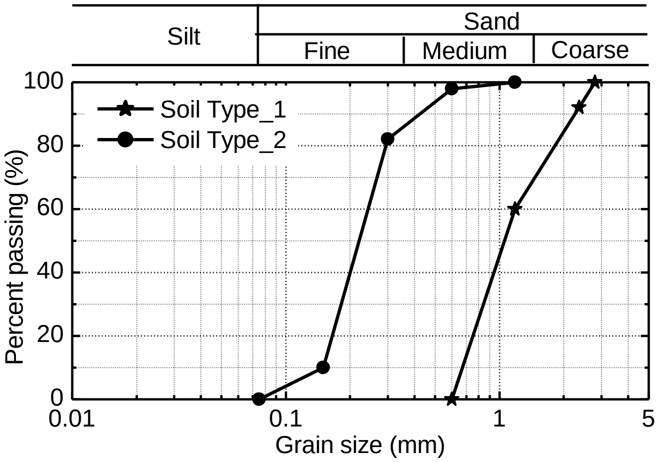

Figure 1: Grain size distributions for the used soils

2. Experimental Work

The granular soil types used in this investigation were clean uniformly graded sand. This sand was selected because it can be easily compacted with uniform mechanical properties and in the same time, ensure repeatable sand placement conditions for all direct shear tests. The particle size distribution curves for the two types of sand are shown in Figure 1. Both soil types 1&2 are classified as uniformly graded sand, while type_1 is considered medium to coarse and type_2 is considered fine to medium sand.

Dry sand Specimens with different percentage of geo-fibre were prepared inside the direct shear box. Percentages of geo-fibre by dry soil weight used in the current study are 0% (i.e. pure sand), 0.5%, 1%, 1.5% and 2%. At each fibre percentage, four specimens were prepared to be used in direct shear test. In all tests, the void ratio was kept constant trough the specimen by controlling weights of soil particles and fibre content. To maintain constant void ratio of all specimens, a pre-specified mass of dry sand was compacted in the direct shear box (60 mm x 60 mm) to achieve a specific height *h*. For reinforced sand specimens, a portion of sand equivalent to the volume of the additional geo-fibre was removed, and the sand-fibre admixture was then compacted inside the shear box to the same height, *h*. The fibre used in this investigation was Polyolefin produced from simple olefin (CnH2n). Yarns length is 30 mm with tensile strength of 533 MPa, Young's modulus of 7.1 GPa, and specific gravity of 0.91.

After specimen preparation inside the shear box, the box was fixed at the direct shear frame, and a constant normal stress was applied at the steel top cap. Once the soil specimen was fully consolidated, a horizontal stress was applied until the soil specimen failed or suffered excessive horizontal displacement. Vertical and horizontal displacements and shear force are recorded according to ASTM-D3080-90. At each fibre percentage, four soil samples were tested at different normal stress values, σ_N = 28, 56, 112, and 224 kPa.

2. Results and Discussions

Variation of shear strength (τ) versus shear strain percent at different fibre content percent, and different consolidation stresses (σ_N) are shown in **Fig. 2**. For all cases, the reinforced sand showed larger ultimate shear strength compared to pure sand tested at the same normal stress. However, in many cases, the ultimate shear strength for reinforced sand occurred at larger shear strain compared to pure sand. Moreover, the 1% strain secant shear modulus increased as the percentage of fibre content increased. Secant shear modulus is useful in calculating the elastic settlement of foundation (Bowles 1996).

Shear strength envelopes for sand reinforced with different fibre content percent are shown in **Fig. 3**. Envelop for pure sand is shown in all sub-figures for the sake of comparison. Fig. 4 shows that pure sand has relatively high friction angle ϕ = 49.6°, which means that the sand particles are approximately angular to sub-angular in shape. The figure indicates clearly that for all percentage of fibre contents used in this study, the friction angle was significantly increased beyond the value of pure sand. Despite that the pure sand showed zero cohesion, the fibre reinforced sand showed an apparent tensile cohesion, which is shown by non-zero intercept with shear strength axis in Fig. 3. This indicates that the geo-fibre inclusion in sand introduces an addition tensile strength to its frictional strength.

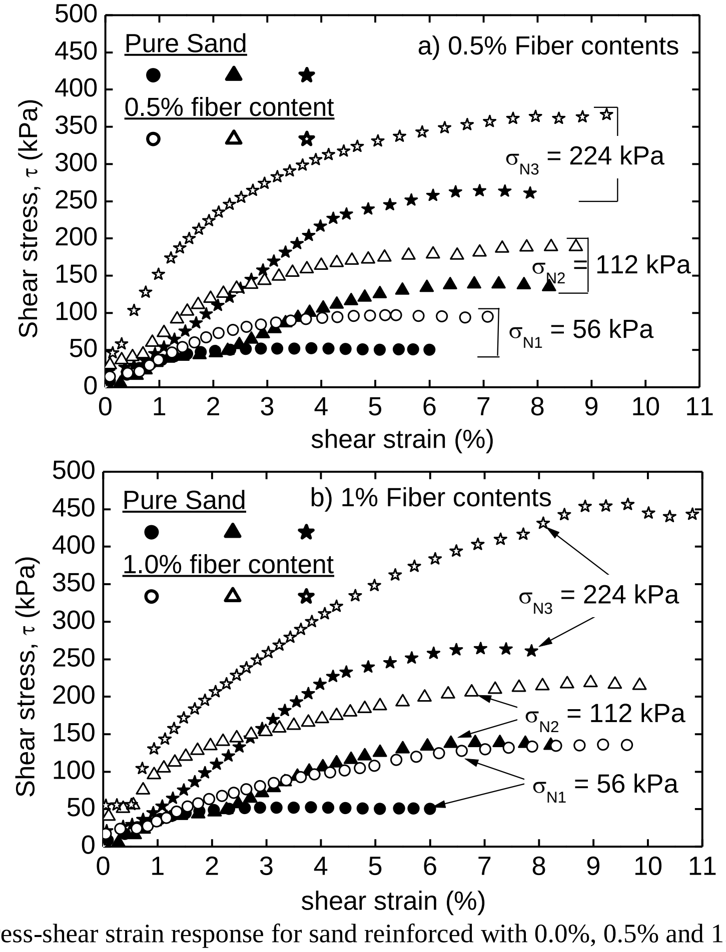

Figure 2: Shear stress-shear strain response for sand reinforced with 0.0%, 0.5% and 1.0% fibre contents.

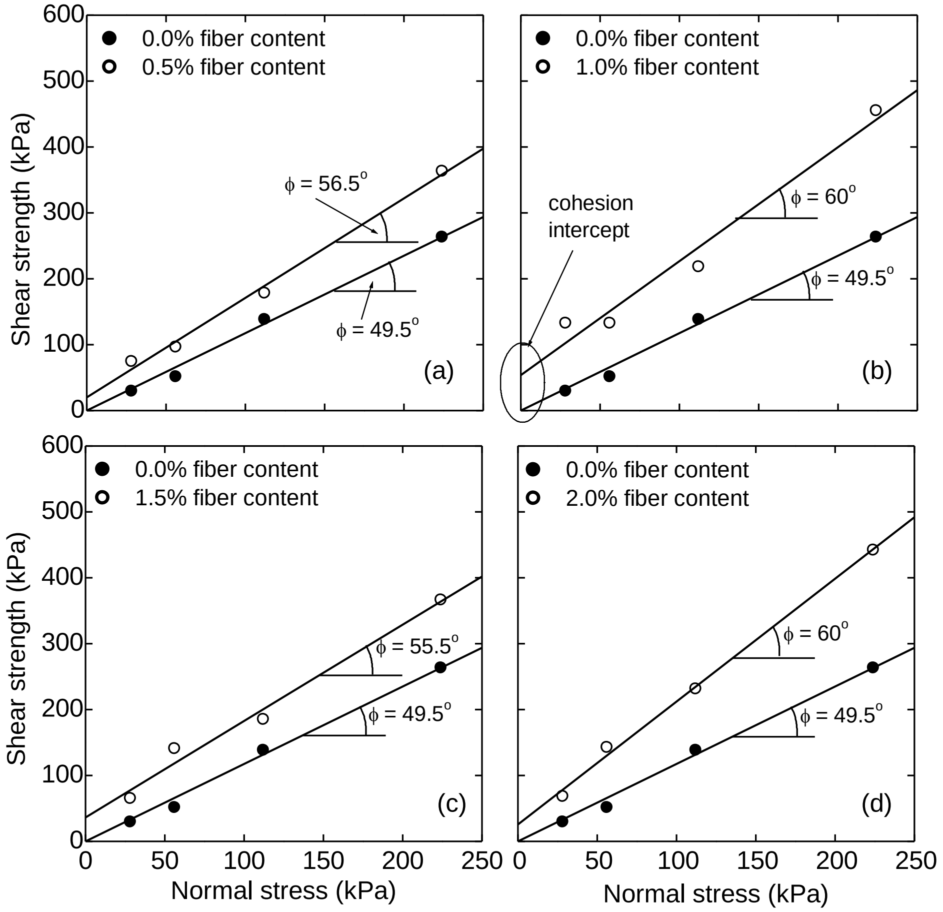

Figure 3: Shear strength envelopes at different fibre contents.

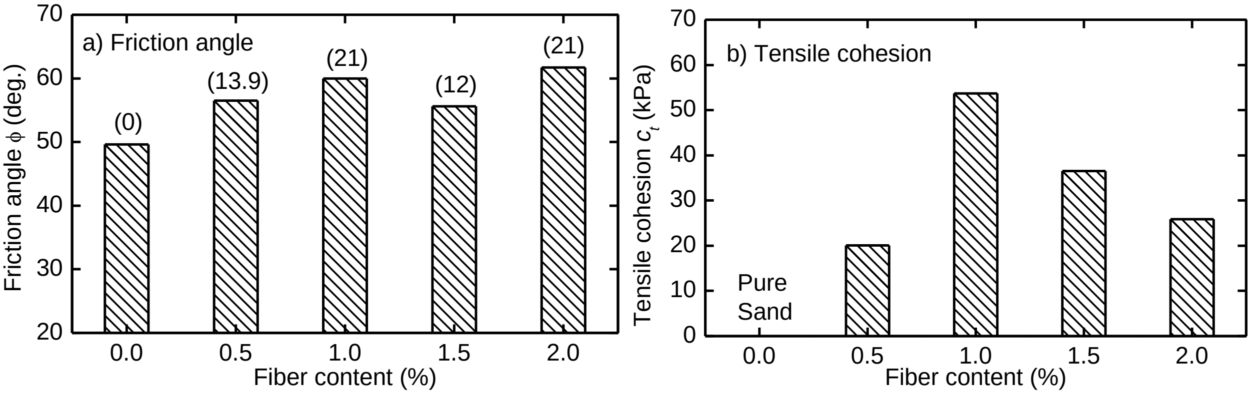

Figure 4: Variation of shear strength parameters with different fibre contents.

Internal friction angle, ϕ and tensile cohesion, c_t inferred from Fig. 3 are plotted in Fig. 4 a&b versus different fibre content percent. Shown also in Fig. 4a, in brackets above each bar, is the percentage increase in the friction angle relative to pure sand value. It is clear from the figure that the friction angle increased as the fibre content percent increased up to 1% fibre content, and decreased thereafter. The maximum percentage increase in ϕ was recorded at 1% fibre content was about 21%, which considered as significant improvement. Variation of the tensile cohesion, c_t with fibre content percent

(Fig. 4b) indicated a trend similar to the variation of the friction angle. The maximum tensile cohesion was measured at 1% fibre content. For other fibre content percent, the tensile cohesion was smaller than that associated with 1% fibre content.

3. Practical Application

In this section, a hypothetical model is used to simulate a strip footing over pure sand as well as sand reinforced with different fiber content percent. Shear strength properties measured in direct shear test for pure and improved sand were used to analyse the bearing capacity of the hypothetical footing. To eliminate the effect of foundation depth, all footings were assumed to be constructed at the ground surface with depth of foundation, $D_f = 0$ and foundation width B = 1m, as shown in Fig. 5.

The assumption of $D_f = 0$ reduced the number of terms used with Terzaghi's equation to calculate the ultimate bearing capacity of strip footing, q_u (Terzaghi 1943) to a shorter form as shown in Equation 1.

$$q_u = cN_c + \frac{1}{2}\gamma B N_\gamma \tag{1}$$

In Equation 1, c is the soil cohesion, γ is the soil unit weight, and B is the foundation width. Bearing capacity factors N_c and $N\gamma$ are calculated, using the soil friction angle ϕ, from Equations 2 and 3 respectively proposed by Vesic (1973).

$$N_c = cot\phi \left[\frac{e^{2\left(\frac{3\pi}{4}-\frac{\phi}{2}\right)tan\phi}}{2cos^2\left(45+\frac{\phi}{2}\right)} - 1 \right] \tag{2}$$

$$N_\gamma = 2\left[tan^2\left(45+\frac{\phi}{2}\right)e^{\pi\, tan\phi} + 1 \right] tan\phi \tag{3}$$

The friction angle (ϕ), measured in direct shear tests and represented in Fig. 4a, is used together with Equations 2 and 3 to calculate the bearing capacity factors N_c and N_γ. Then the measured tensile cohesion c_t, shown in Fig. 4b, and bearing capacity factors are used together with Equation 1 to calculate the ultimate bearing capacity, q_u for the hypothetical strip footing shown in Fig. 5. In an effort to isolate the effect of friction angle improvement from the tensile cohesion improvement, the bearing capacity is calculated based on each parameter individually in addition to using both parameters together. Results of bearing capacity analysis are shown in Fig. 6.

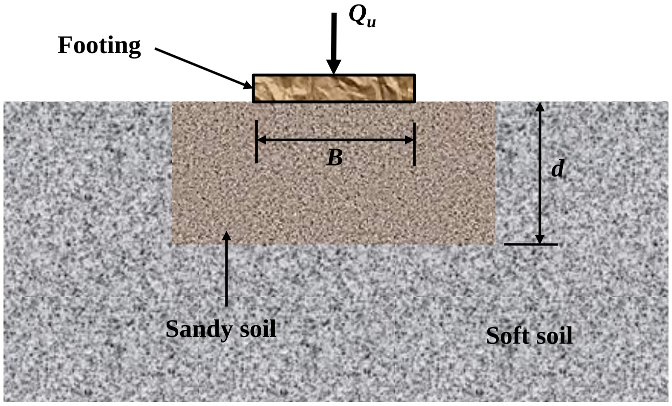

Figure 5: Parameters used with the hypothetical strip footing.

Figure 6a shows the effect of the improvement on friction angle ϕ on the bearing capacity of fibre reinforced sand. To isolate the effect of the friction angle, the tensile cohesion was assumed as $c_t = 0$, and the bearing capacity is presented as a ratio of pure sand bearing capacity ($q_{u\text{-Reinforced sand}}/q_{u\text{-Pure sand}}$). It can be seen that the bearing capacity ratio of fibre reinforced sand is larger compared to that of pure sand (i.e. sand with zero fibre content). In addition, the largest bearing capacity was calculated for sand with 1% fibre content, which showed a bearing capacity ratio of about 15. Similar bearing capacity ratio was calculated at 2% fibre content (Fig. 6a), however, at this fibre content percent, the measured cohesion was less compared to sand with 1% fibre content. In addition, at 2% fibre content, the quantity of fibre was too large to be self randomly distributed. Therefore, it was re-distributed manually, which might affect the uniformity of fibre distribution throughout the soil specimen.

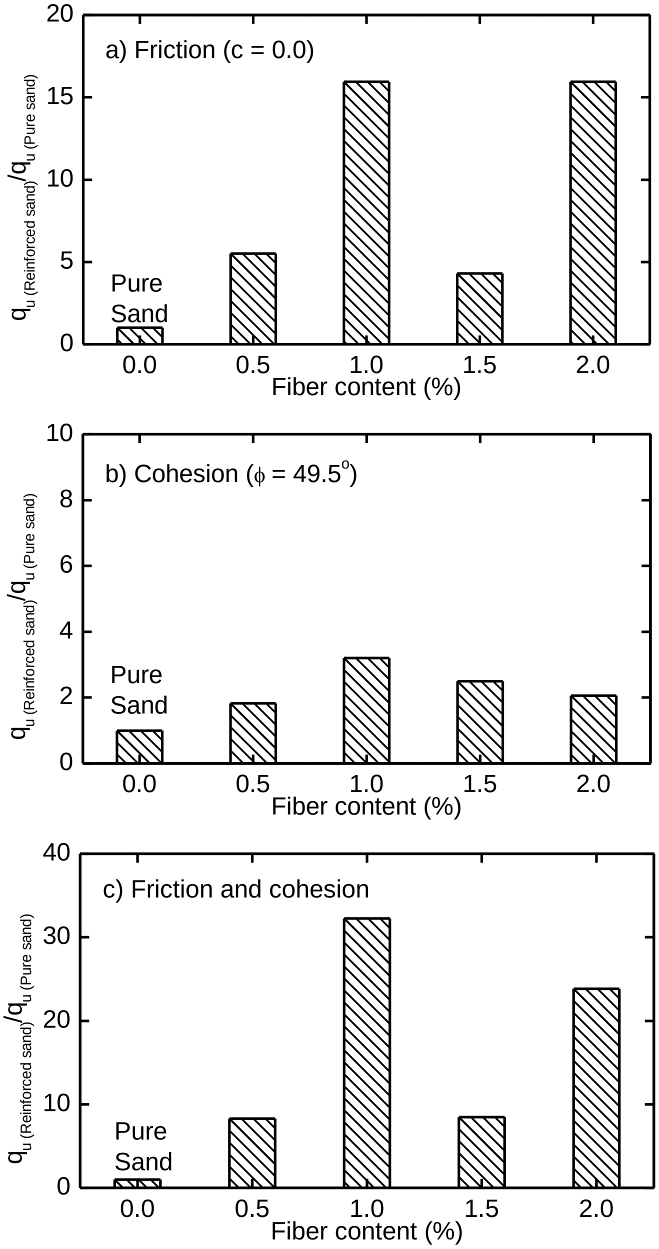

Figure 6: Bearing capacity improvement due to different fibre content percent.

Effect of tensile cohesion gained due to fibre content on the ultimate bearing capacity ratio is shown in Fig. 6b. The friction angle ϕ is assumed constant for sand with different fibre contents and equal to the pure sand friction angle (i.e. ϕ = 49.5°). It is clear from the figure that bearing capacity ratio is increased with the tensile cohesion which is in turn increased with the fibre content percent. The largest improvement on the bearing capacity was recorded at 1% fibre content, which was about 4 times the bearing capacity of pure sand. However, the effect of friction angle improvement on the bearing capacity ratio (Fig. 6a) is more pronounced compared to the effect of tensile cohesion improvement on the same ratio (Fig. 6b). This is attributed to the presence of the friction angle (ϕ) in calculation of bearing capacity factors N_c and N_γ. Equations 2 and 3, showed that N_c and N_γ are exponentially changed with the friction angle, ϕ. Therefore, a slight increase in the sand friction angle ϕ resulted in significant increase in both N_c and N_γ. The increase in N_c and N_γ could be dramatic when the sand friction angle increased beyond $\phi = 40°$, as the case of sand used in the current study.

Considering the justification explained above, the effect of improvement on both friction angle ϕ, and tensile cohesion c_t on the bearing capacity ratio is shown in Fig. 6c. It could be seen that concurrent improvement on both friction angle and cohesion significantly improved the bearing capacity ratio compared to the effect individual improvement of friction angle (Figure 5a) or cohesion (Fig. 6b). This attributed to the engagement of both N_c and N_γ in the bearing capacity calculation in case of friction angle and cohesion being exist. Therefore, introducing geo-fibre in sand resulted in a dramatic improvement of the bearing capacity due to the gaining of tensile cohesion. Fig. 6a concurred the 1% as optimum fibre content in this study. The findings are in agreement with Rong-Her et al. (2011) which reported 1-1.5% optimum fibre content with longer randomly oriented fibre.

4. Conclusions

Based on direct shear tests and bearing capacity calculations conducted in this study and the results presented in this paper, the following concluded remarks are summarised:

1. Fibre reinforced sand showed significantly larger ultimate shear strength compared to pure sand, which in turn occurred at larger shear strain compared to pure sand. Moreover, the 1% strain secant shear modulus improved with fibre content percent.
2. For all percentage of fibre contents used in this study, the friction angle was significantly increased beyond the value of pure sand. In addition, an apparent tensile cohesion was noticed when fiber was mixed with zero cohesion sand.
3. Effect of friction angle improvement on bearing capacity of reinforced sand is more pronounced compared to the effect of cohesion improvement. However, the combined effect of both friction angle and cohesion improvement on bearing capacity is dramatic.
4. With regard to friction angle, cohesion and bearing capacity, it can be concluded that the optimum fibre content percent for the sand used in the current study was found to be 1%. This percentage might be changed if the sand and/or fibre types are changed.

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References

[1] G. M. Latha and V. S. Murthy, "Effects of Reinforcement Form on the Behavior of Geosynthetic Reinforced Sand," *Geotextiles and Geomembranes*, vol. 25, pp. 23-32, 2007.

[2] T. Al-Refeai, “Behavior of granular soils reinforced with discrete randomly oriented inclusions,” *Geotextiles and Geomembranes*, Vol. 10, pp. 319–333, 1991.

[3] G. Ranjan, R. M. Vasan and H. D. Charan, “Behavior of plastic fibre-reinforced sand,” *Geotextiles and Geomembranes*, vol. 13, pp. 555–565, 1994.

[4] D. H. Gray and T. Al-Refeai, “Behavior of fabric vs. fiber reinforced sand,” *Journal of Geotechnical Engineering, ASCE*, vol. 112 (8), pp. 804–820, 1986.

[5] T. Yetimoglu and O. Salbas, “A study on shear strength of sands reinforced with randomly distributed discrete fibers,” *Geotextiles and Geomembranes*, vol. 21 (2), pp. 103–110, 2003.

[6] N. C. Consoli, P. D. M. Prietto and L. A. Ulbrich, “Influence of fiber and cement addition on behavior of sandy soil,” *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, vol. 124 (12), pp. 1211–1214, 1998.

[7] ASTM -D3080, “Method for Direct Shear Test of Soils under Consolidated Drained Conditions,” *American Society for Testing and Materials*, Philadelphia, Pennsylvania, USA, 1990.

[8] J. E. Bowles, “*Foundation Analysis and Design,*” 5th Ed., McGraw-Hill, New York, 1996.

[9] K. Terzaghi, “*Theoretical Soil Mechanics*,” John Wiley, New York, 1943.

[10] A. S. Vesic, “Analysis of ultimate loads of shallow foundations,” *J. Soil Mech. Found. Div., ASCE*, vol. 99(1), pp. 45, 1973.

[11] C. Rong-Her, C. Po-Chuan, W. Tai-Ching and H. Chia-Chun, “Shear Strength of continuous-Filment reinforced Sand,” *Journal of GeoEngineering*, Vol. 6, No. 2, pp. 99-107, August 2011.

[12] M. M. El-Emam, “Settlement and stress characteristics of reinforced soft clay strata under strip footing: A numerical study,” Int. Conf. on Computational Design in Engineering, CODE2009, Seoul, Korea, 2009.

[13] C. Tang, B. Shi, W. Gao, F. Chen and Y. Cai, “Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil,” *Geotextiles and Geomembranes*, vol. 25(3), pp. 194-202, 2007.

[14] M. Dal Toé Casagrande, N. C. Consoli, and A. Thomé “Behavior of plate tests bearing on fiber-reinforced sand Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, M. Hamza et al. (Eds.), pp. 905-908, 2009, doi:10.3233/978-1-60750-031-5-905.