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Sand reinforced with short length synthetic fibers randomly oriented

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ABSTRACT: An experimental program was carried out on the behavior of a granular soil mixed with discrete, randomly distributed synthetic fibers of short length. The influence of fiber surface texture (straight and crimped), fiber percentage and fiber length on the shear strength of reinforced sand was studied by means of direct shear laboratory tests. Both unreinforced (control) and fiber-reinforced sand samples was tested at the same density (16.5 kN/m^3) and the results analyzed. Results indicated that fiber reinforcement increases the shear strength and modifies significantly the stress-deformation behavior of sand. The shear strength of reinforced sand increases with an increase in both fiber percentage and fiber length. No appreciable advantage was gained in the shear strength of reinforced sand by using crimped fibers and the mixture was achieved with greater difficulty for this type of fibers.

1 INTRODUCTION

Reinforcing the soil is a very old technique used by our remote ancestors. Nowadays a great variety of oriented reinforcing elements are used all over the world to improve the behaviour of the soil. Over the recent years, attraction has been given to randomly oriented reinforcing elements, as it appears to be a very promising material for a variety of applications. The micro-reinforcement of the soil seems to have naturally emerged from the role played by vegetation on the restraint of the soil particles by the roots due to their tensile strength and frictional properties. It is excellent in erosion control, slope failure repair, reinforced embankment slopes and also to backfill bridge abutments. Reinforcing elements can have a variety of forms: mesh and fibrillated fibres, which allows interlocking of the soil particles, fibres of short length and continuous filaments. Recycling materials can also be used, provided they do not represent an environmental hazard.

The main objective of this investigation was to assess the relative reinforcing efficiency of the straight and crimped synthetic fibers on the shear strength of reinforced sand. The influence of fiber percentage and fiber length was also investigated.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 *Materials*

The soil used in the tests was readily available air dry sand, that was prepared by removing all material retained on the 2 mm sieve. It is classified as poorly graded sand (SP), according to USCS classification (ASTM D 2487). The main properties of the sand are summarised in Table 1.

The synthetic fibres are made of polypropylene and are used for producing nonwovens geotextiles. They were supplied by a local manufacturer in the form of long filaments with round cross section and fibre surface both straight and crimped. The crimp process is one of the current texturing processes for polypropylene fibres in order to improve the textile properties. The fibres were cut to nominal lengths of about 25, 50 and 100 mm. The percentage of fibres used to reinforce the sand samples was determined by the dry unit weight of the soil. Three different percentages of fibres were studied: 0.25%, 0.5% and 1.0%. The physical and mechanical properties of the fibres are summarised in Table 2. The manufacturer provided fibre properties.

Table 1. Sand properties

Property	Sand
Specific gravity, G_s (-)	2.65
Effective diameter, D_{10} (mm)	0.217
Mean diameter, D_{50} (mm)	0.567
Percent finer than #200 sieve (%)	0
Coefficient of uniformity, C_u (-)	3.45
Coefficient of curvature, C_c (-)	0.77

Table 2. Fiber properties

Property	Fibers
Specific gravity, G_f (-)	0.91
Denier (g/ 9000 m)	6
Tensile strength, σ (MN/m^2)	175
Young's modulus, E (MN/m^2)	1.5
Elongation at break, ε (%)	200
Moisture absorption	Nil
Color	White

2.2 *Preparation of test samples*

It is very difficult to prepare homogeneous and isotropic micro-reinforced soil samples for laboratory testing. (This is also recognized by several authors such as Gray & Al-Refeai 1986, Freitag 1986, Maher & Gray 1990, Ranjan et al. 1994, Morel & Gourc 1997, Gregory & Chill 1998, Santoni et al. 2001). Preparation of polypropylene fiber reinforced sand samples requires special procedures. Based upon both the experience gained from previous investigations and the results reported in the literature, the following procedure was adopted.

First, the quantity of sand and fibers required to fill a standard 60 mm square shear device at the desired density (16.5 kN/m^3) was determined. The sand was placed in a large metal bowl and mixed with some water in order to moisten the sand slightly. Water content of 5% was selected as it provided enough apparent cohesion to adequately mix the samples. If fibers are mixed in dry sand, a floating tendency of fibers during the mixing process and fiber segregation when the mix is transferred to shear box is observed. The unreinforced samples were tested at the same water content for comparison purposes.

Then the fibers were added to the moistured sand. It was found that spreading uniformly the fibers and the sand, layer by layer in a large metal bowl until all the moist sand and fibers have been added the mixture was achieved with more facility. Further mixing by hand was made until the fibres were uniformly distributed and randomly oriented throughout the sand. The degree of dispersion in the mixture was determined by visual inspection. Both fiber texture, fiber length and fiber percentage affect the mixing time. The greater the fiber percentage and the fibre length the greater time is required to ensure a uniform sand-fibre mixture. Fiber lengths of 100 mm and fiber percentage of 1% were regarded as upper limits in the present study because with higher values the mixing procedure becomes impracticable. The use of crimped fibers also results in relatively greater time necessary to obtain reasonably uniform distribution of the fibers.

Finally, the prepared samples were transferred and compacted directly in the shear box. The primary factor affecting the response of polypropylene fiber-reinforced sand was the compaction effort: the greater the fiber percentage, the greater the compactive effort required to maintain a given density (16.5 kN/m^3). It was observed that the standard method of compaction (in which the material is transferred in three approximately equal layers to the shear box, each layer being compacted by tamping to achieve a uniform density throughout the height of the sample) is not indicated for polypropylene fiber-reinforced sand, because in the final stage the fibers were not randomly oriented to the shear plane. The distribution was fairly uniform in all samples tested, but the layering was evident. Freitag (1986) and Take et al. (1997), who carried out compaction tests on polypropylene fiber-reinforced soil samples, have discussed this problem. Further experimental work is therefore desirable to determine a compaction technique for ideally homogeneous samples in order to minimize any perturbation (shear distortion and reorientation) during preparation of the test samples.

2.3 *Laboratory tests*

In this study, only direct shear tests are considered to determine the shear strength of reinforced sand samples. Although the direct shear test has numerous limitations and inherent errors, the simplicity of the test on granular soils and availability of equipment have resulted in continued widespread use. Both unreinforced (control) and synthetic fiber-reinforced sand samples were tested in 60 mm square shear box using a standard direct shear apparatus. Each test was carried out at a constant shear displacement rate of 1.0 mm/min. The shear tests were performed at normal stresses of 114.81 kN/m^2, 229.62 kN/m^2 and 344.43 kN/m^2 up to a total displacement of 10.5 mm (maximum shear strain allowed from the shear apparatus, which is of about 17%).

3 ANALYSIS OF TEST RESULTS

3.1 *Shear strength of fiber-reinforced sand*

The stress-deformation behavior of polypropylene fiber-reinforced sand is quite different from that of unreinforced sand (Fig. 1). While on unreinforced sand the well known curve shows a maximum strength followed by a smooth decrease to a residual value, on reinforced sand there is no peak stress and the strength is always increasing, up to the maximum deformation allowed from the shear apparatus. Ranjan et al. (1994) who carried out triaxial compression tests to determine stress-strain behavior of fine sand reinforced with discrete, randomly distributed plastic fibers and Morel & Gourc (1997) who studied the shear strength of sand reinforced with randomly oriented and vertically aligned polypropylene mesh elements in the large shear box, have also discussed this phenomenon. They explained that this increasing trend is caused by a progressive tensile mobilization of the fibers when the reinforced sand is subjected to deformation. Thus, for deformations beyond the peak strength of sand alone, although the strength of unreinforced sand may remain unchanged or may be slightly reduced, the reinforced sand tends to gain strength. It was observed that fibers do not rupture during shear and they just stretch. Polypropylene fibers increase the ductility and improve the shear strength of sand.

Under small deformations, the shear stress for reinforced sand samples in generally slightly lower than that for unreinforced sand samples, for the same displacement (Morel & Gourc 1997). Gray & Ohashi (1983) who performed direct shear tests on dry sand reinforced with both natural and synthetic fibers also observed this loss of stiffness on reinforced sand. The research results in the literature show stress-deformation curves of synthetic reinforced soil with moderate increase in shear strength accompanied by a rigidity loss under small deformations. In the present study, this behaviour is accentuated when using both crimped fibers and higher fiber percentage.

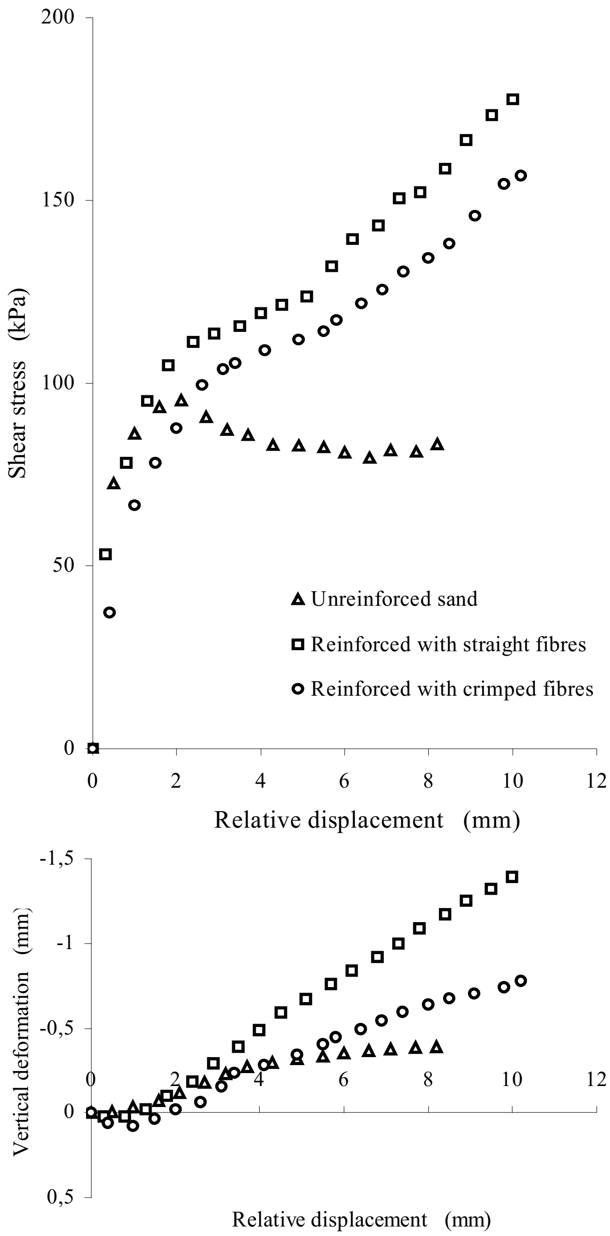

Figure 1. Shear stress-displacement-volumetric relationships (0.25% fiber percentage, 50 mm fiber length; 114.81 kN/m^2 normal stress).

The fibers also modify the amount of vertical deformation in sand. The response of reinforced sand becomes more compressive in the early stages of shear loading and more dilating afterwards, relating to the response of unreinforced sand. Greater dilation was observed as the fiber percentage was increased. It seems that the increase in dilation was likely caused by enlargement of the shear zone that occurred as the fibers were mobilized during shear (Benson & Khire 1992).

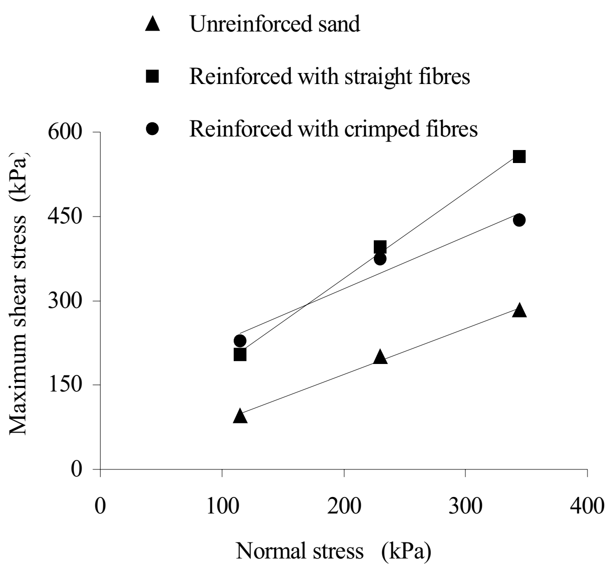

Figure 2. Mohr-Coulomb failure envelops (1.0% fiber percentage, 100 mm fiber length).

Figure 2 presents the Mohr-Coulomb failure envelopes of unreinforced and fiber reinforced sand for a fiber percentage of 1.0% and fiber length of 100 mm. The failure has been defined as corresponding to the peak stress condition or to 15% shear deformation whichever happens first. It is very clear that the fiber reinforcement significantly improves the shear strength of sand. The results show that there is an increase in both cohesion and peak friction angle values. Increasing shear displacement pull the fibers tightly around particles of soil increasing friction effect. In addition the entanglement of fibers brings further reinforcement into play as the soil is sheared, providing a cohesion intercept to the Mohr-Coulomb failure envelope for the composite material.

3.2 *Effect of fiber percentage*

The shear strength of reinforced sand increases with an increase in fiber percentage, as shown in Figure 3. Shear strength increases approximately linearly with increasing fiber percentage, then approaches an asymptotic upper limit governed mainly by level of normal stress and fiber length (Fig. 4). It was observed a linear relationship between fiber percentage and increased shear strength for lower values of normal stress or fiber length. For higher values, the rate of increase is higher for lower fiber percentages and not so higher for higher fiber percentages, which is in agreement with the literature.

3.3 *Effect of fiber length*

The effect of fiber length on shear strength of reinforced sand is illustrated in Figure 5. The results indicate that increasing the length of fiber reinforcement increases the shear strength of the reinforced sand. This trend appeared to be more evident as the fiber percentage increases. An upper value for shear strength is however observed, beyond which any further increase in fiber length had no significant effect. This can be explained as for higher fiber lengths the fiber may not remain straight and thus the effective length of the fiber available to mobilize shear strength reduces. On the other hand, for short fibers the length of fiber is insufficient to develop tensile stress along it. Figure 5 also indicates that the rate of increase in shear strength of reinforced sand is higher at higher normal stresses for the same fiber length.

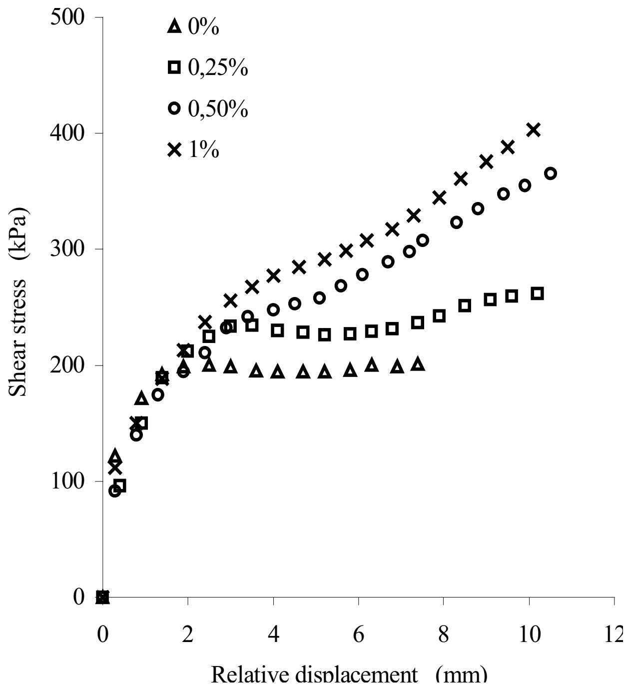

Figure 3. Shear stress-displacement relationships (crimped fibers, 100 mm fiber length, 229.62 kN/m^2 normal stress).

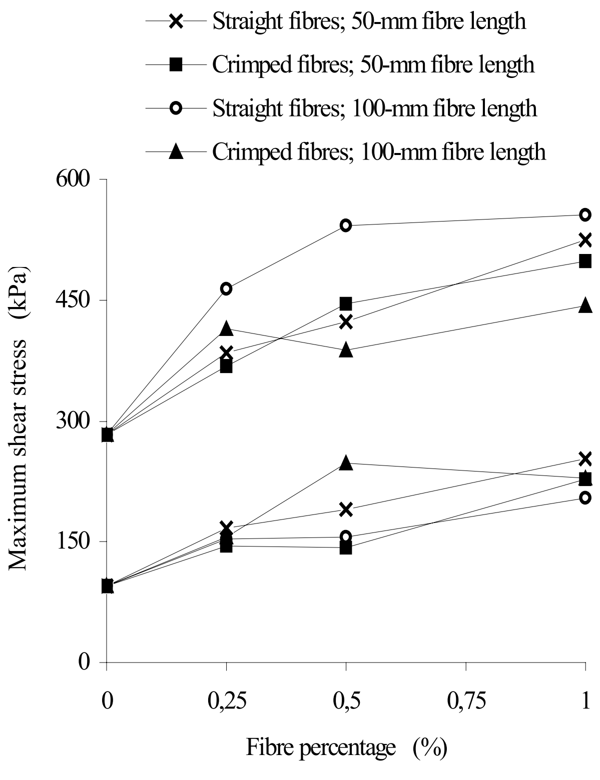

Figure 4. Shear strength-fiber percentage relationships (114.81 kN/m^2 and 344.43 kN/m^2 normal stresses).

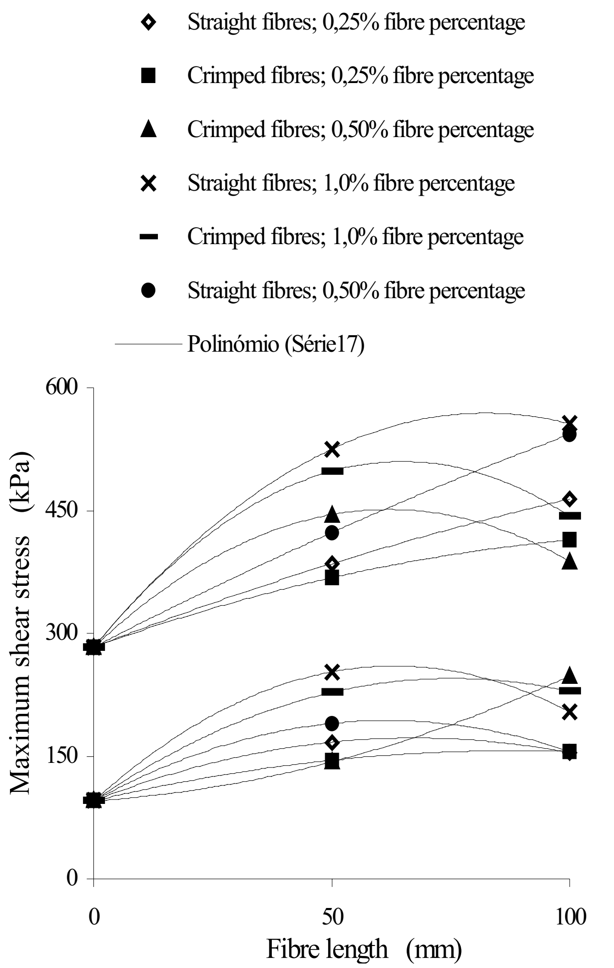

Figure 5. Shear strength-fiber length relationships (114.81 kN/m^2 and 344.43 kN/m^2 normal stresses).

3.4 *Effect of fiber texture*

For the same fiber percentage and fiber length the increase in shear strength of the reinforced sand is quite similar when using both straight and crimped fibers. No appreciable advantage was gained in the shear strength of reinforced sand by using crimped fibers (Figs 1, 2), contrarily to what could be expected. However, these results seem to be in conformity and can be explained. In fact, it is well known that the fibers need to be stretched enough to bring sufficient confinement to the sample. Therefore, samples reinforced with crimped fibers require larger shear displacement than that of samples reinforced with straight fibers. In addition, during preparation of samples it was observed that crimped fibers do not ideally enveloped the soil particles. They tend to form groups of fibers. Therefore, it is expected that the effect of crimped fibers on the shear strength properties of sand was as adding cohesion to the sand, as opposed the effect of straight fibers that add friction. The experimental results corroborate these findings (Fig. 2).

4 CONCLUSIONS

On the basis of the results of direct shear laboratory tests, it is concluded that the shear strength of short, randomly oriented polypropylene fibre-reinforced sand is a function of fibre percentage and fibre length. An optimum fibre percentage lies between 0.5% and 1.0%. The length of fibres was found to be important as friction is mobilised along the available length. No significant difference was found between straight and crimped fibres, although the mixing procedure was achieved with greater difficulty for the latter type of fibres. Test results also showed that fibre reinforcement improves shear strength and modify stress-deformation behaviour of sand in a significant manner.
Further experimental work is in progress to study the influence of fiber characteristics (percentage, length and denier) on the behavior of different types of soils.

5 ACKNOWLEDGEMENTS

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