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Shear tests on fibre reinforced sand

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ABSTRACT: The concept of reinforcing soils by introducing tension-resisting elements such as fibres is becoming widely accepted by geotechnical engineers. This follows research which shows that mixing sands with random discrete flexible fibres causes a significant increase in strength and a reduced post-peak strength loss. In this research Hostun RF sand reinforced with flexible discrete polypropylene fibres has been tested using direct shear tests and conventional triaxial tests. The moist tamping technique was used for specimen preparation. The results of the direct shear tests indicate that inclusion of fibres increases the peak shear strength and the strain required to reach the peak. A continuous increase of the deviatoric stress on the stress-strain response up to 30–40% of axial strain was recorded for conventional drained triaxial tests. A more dilative volumetric behaviour was systematically observed for the reinforced specimens.

1 INTRODUCTION

Reinforcement with randomly distributed discrete flexible fibres is an effective and reliable technique for increasing the strength and stability of granular soils in a variety of applications ranging from retaining structures and embankments to subgrade stabilization beneath footings, pavements and sport pitches.

The influence and the contribution of fibre reinforcement to shear strength of sand have been examined by various investigators (Gray & Ohashi 1983; Michałowski & Čermák 2003 and Heineck et al. 2005 among others). Several parameters such as confining stress, fibre type, volume fraction, density, length, aspect ratio, modulus of elasticity, orientation and soil characteristics including particle size, shape, gradation have been studied using monotonically loaded direct shear tests, consolidated drained triaxial tests or unconfined compression tests.

Presented in this paper are results of direct shear tests and drained triaxial compression tests for a fine sand, Hostun RF sand, reinforced with randomly distributed discrete flexible polypropylene fibres. The objective of this research is to examine the influence of fibre addition on stress-strain and volumetric behaviour of the fibre-reinforced composites.

2 EXPERIMENTAL CONDITIONS

2.1 *Materials*

The sand tested in this study was Hostun RF (S28) sand. The material characteristics of the sand were: mean grain size $D_{50} = 0.32$, coefficient of uniformity $C_u = 1.70$, coefficient of gradation $C_g = 1.1$, specific gravity $G_s = 2.65$ and minimum and maximum void ratio $e_{min} = 0.62$ and $e_{max} = 1.00$ respectively (Ibraim 1998).

Loksand™ discrete polypropylene crimped fibres (Fig. 1) of length $l_f = 35$ mm and of circular cross section with diameter $d_f = 0.1$ mm have been used. Other physical properties of Loksand™ fibres are reported in Table 1.

2.2 *Specimen preparation*

The specimen preparation involved two stages: mixing and compaction. In order to avoid the floating of fibres and segregation, the sand was mixed with some amount of water. The results of Modified Proctor compaction tests on fibre reinforced specimens indicated the existence of an optimum moisture content of 10%, independent of the amount of fibres (Ibraim & Fourmont 2006). Once the water is added to the sand, the fibres are progressively added and mixed through

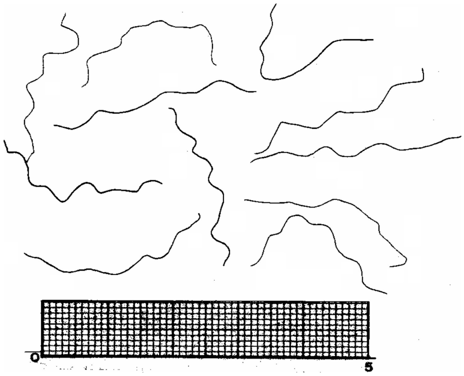

Figure 1. Specimen of individual crimped polypropylene fibres (scale in mm).

Table 1. Characteristics of Loksand™ fibres.

Weight (Denier)	Tensile strength (MPa)	Specific gravity	Elongation at break	Moisture regain
50	225	0.91	160%	<0.1%

using a small spoon. Mixing was stopped when, by visual examination, it was considered that the fibres were evenly distributed throughout.

Rectangular specimens of 100 × 100 mm and 45 mm height were used for the direct shear tests, whereas specimens with diameter 70 mm and height 70 mm were prepared for the triaxial tests. In both cases, three layers of soil were used. The amount of mixture required to form the first layer was delicately deposited into the specimen's mould to ensure a zero drop height and minimal disturbance to the fibre distribution. The mixture was then compacted by tamping with a light rectangular or circular hammer up to the desired layer height. It was observed that the already compacted layers did not under-compact during the formation of the subsequent layers.

Previous research (Diambra et al. 2007) has shown that fibres in reinforced specimens prepared with the moist tamping technique have a near horizontal orientation. 97% of fibres are orientated within 45° of the horizontal.

The average concentration of fibres added in the composite is defined as a fraction of dry mass of sand:

$$w_f = \frac{W_f}{W_s} \text{ x } 100\ (\%) \qquad (1)$$

where W_f is the weight of fibres and W_s is the weight of the dry sand.

The maximum amount of fibres that can be mixed with a given amount of sand, placed into a given

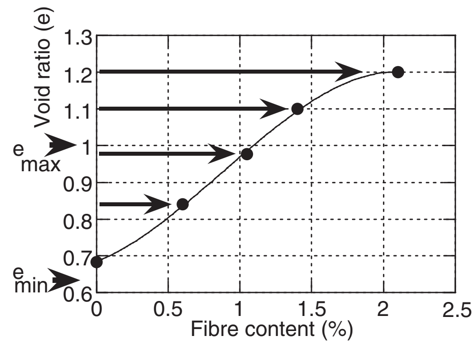

Figure 2. Maximum amount of fibres that can be mixed with a fixed amount of sand without leading to a change in specimen volume using moist tamping.

volume and compacted using moist tamping has been determined by Ibraim & Fourmont (2006). The results are presented in the Figure 2 where the minimum and maximum void ratios of the Hostun sand are also plotted. A value of 2% fibre content seems to be a limit beyond which sand reinforced specimens cannot be prepared.

3 DIRECT SHEAR TEST RESULTS

A recently improved Direct Shear Apparatus (Dietz 2000; Lings & Dietz 2004) was first used for fibre reinforced specimen testing. Three different nominal fabrication void ratios (e) of 0.8, 0.9 and 1.0 (which respectively corresponds to relative densities, D_r, 0%, 26% and 53%) have been chosen for the experimental testing programme. Details of the apparatus, measurement conditions and specimen reinforcement details are given elsewhere (Ibraim & Fourmont 2006). For consistency, similar densities and fibre contents have been used for the experiments conducted using the triaxial apparatus. In all cases, void ratio refers only to the sand matrix since fibres are considered as a part of voids.

Some typical direct shear responses for Hostun RF sand (e = 1.0) reinforced with randomly distributed polypropylene fibres are presented in Figure 3. The figure presents the variation of the shear stress and vertical displacement (v_y) with the horizontal displacement (v_x). The fibre contents are specified on the figure. As can be observed, the inclusion of fibres increases the shear strength of very loose specimens. Also, as observed by Palmeira & Milligan (1989), Kaniraj & Havanagi (2001), Jewell & Wroth (1987) and Shewbridge & Sitar (1989), the amount of vertical dilation increases with the amount of fibres.

Overall, as presented in Figure 4, the increase of the peak shear strength is very close to being a linear function of fibre content. For specimens of lower density at relatively low effective normal stresses the rate of the

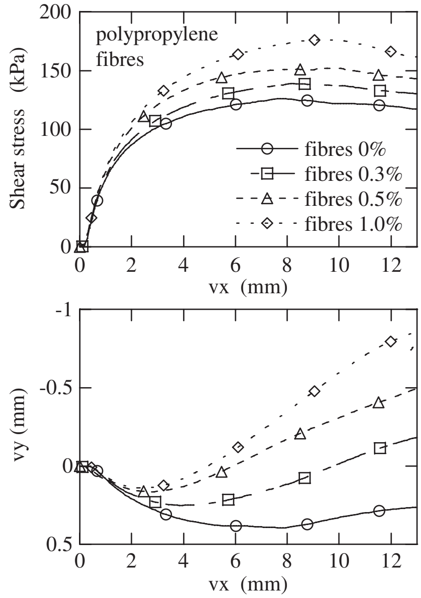

Figure 3. Typical direct shear box test results for Hostun RF sand (approximately 0% relative density) reinforced with polypropylene fibres.

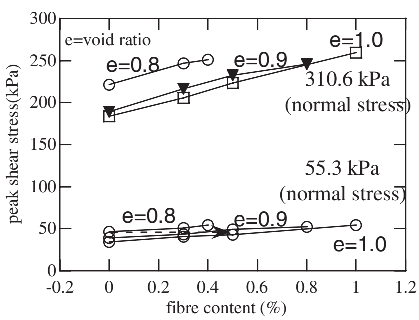

Figure 4. Evolution of the peak shear stress with fibre content, density and effective normal stress.

increase is less than for higher densities and confining stresses. Nevertheless, above some limiting fibre content, the peak stress increase approached an asymptotic upper limit, more pronounced for denser specimens and higher normal stresses. A similar trend was observed by Gray & Al-Refeai (1986), Ranjan et al. (1996) and Murray et al. (2000) but for lower confining stress levels. The loosest specimens at the highest fibre content (1.0%) revealed 40 to 60% gain in strength.

4 TRIAXIAL TEST RESULTS

Triaxial tests were conducted on fully saturated specimens using effective confining pressure ranging from 100 kPa to 300 kPa. Saturation has been achieved by firstly flushing CO_2 trough the specimen and then flushing water slowly trough the same. Satisfactory saturation was monitored in each test, ensuring a B value of at least 0.95 for drained tests and 0.97 for the undrained tests. A back pressure of 300 kPa was used in all the tests.

Table 2. List of the triaxial test performed ($p' = (\sigma'_1 + 2\sigma'_3)/3$, $q = \sigma'_1 - \sigma'_3$ and ψ_{max} is the maximum angle of dilation).

Test	Void ratio before starting the test	q/p' (at 20% strain)	ψ_{max} (degrees)
L100-00	0.991	1.374	0
L100-03	0.983	1.736	0.78
L100-06	0.979	1.984	2.51
L100-09	0.987	2.260	2.42
L200-00	0.980	1.326	0
L200-03	0.975	1.434	1.46
L200-06	0.969	1.808	1.90
L200-09	0.962	2.020	2.12
M100-00	0.914	1.352	2.78
M100-03	0.911	1.778	5.77
M100-03/2	0.936	1.704	4.30
M100-06	0.919	2.051	7.77
M100-06/2	0.931	1.994	7.24
M200-00	0.915	1.328	3.42
M200-03	0.918	1.615	4.62
M200-06	0.907	1.882	5.20
M300-00	0.928	1.314	2.31
M300-03	0.916	1.528	2.89
M300-06	0.928	1.773	4.59
D100-00	0.833	1.473	16.66
D100-03	0.832	1.947	18.52

$^*q/p'q/p'$ at 15% of strain

Axial strain was monitored with the use of an LVDT placed outside the cell and following the movement of the loading ram. Volumetric strains were measured by a double chamber volume change gauge which uses a LVDT to monitor the relative position of the two chambers. Pore pressure was measured by a pore pressure transducer with a capacity up to 800 kPa and a resolution of ± 0.05 kPa. The measurement system was completed by an internal 5 kN load cell.

Lubricated ends were used at the top and bottom of the specimen. The lubrication consisted on silicone grease and two or three latex rubber disks at the bottom and the top of the specimen, respectively. By visual inspection, the homogeneous shape of the specimen was well preserved at least up to 20% of axial strain (ε_a). Lubricated ends induced bedding error for the strain response, but no any correction has been applied to the results presented here. No membrane penetration correction has been considered either.

Table 2 reports a list of all the triaxial tests performed in this study. The test name gives an

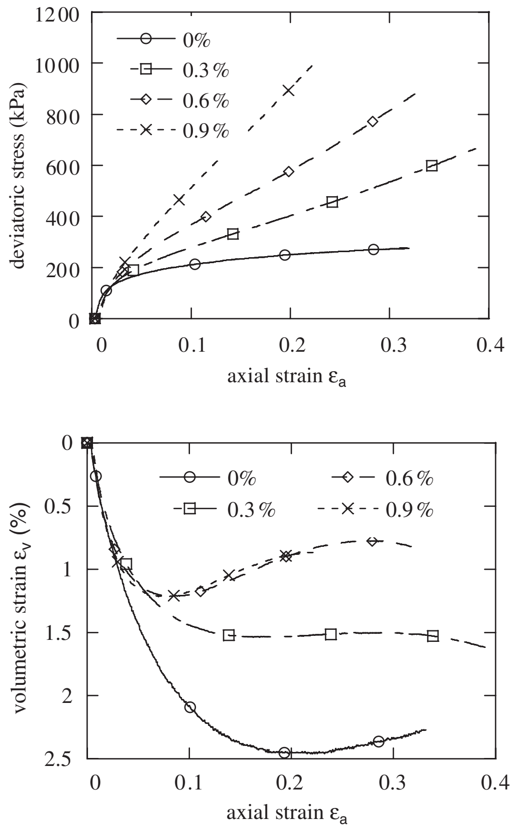

Figure 5. Stress-strain and volumetric behaviour for drained tests on L100 series specimens (legend gives the fibre content).

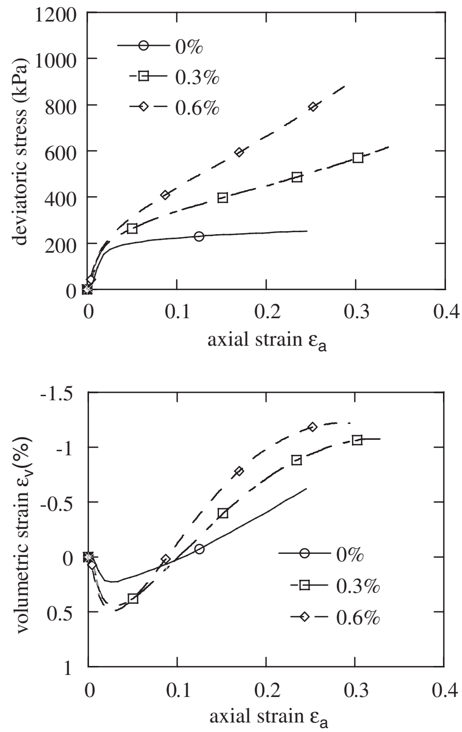

Figure 6. Stress-strain and volumetric behaviour for drained tests on M100 series specimens (legend gives the fibre content).

explanation for the test conditions: the first letter indicates the nominal density (L stands for loose, M for medium and D for dense), the following three figures indicate the testing cell pressure in kPa, and finally the used percentage of fibres (w_f) is mentioned. For example L200-06 means a test for a specimen with a void ratio close to 1, at a constant cell pressure of 200 kPa, reinforced with 0.6% of fibres. For two tests, the length of the fibres has been reduced by half (symbol '/2').

Typical results of drained triaxial tests are presented in Figures 5–7 where the variations of the deviatoric stress (q) and the volumetric strain (ε_v) are presented with the axial displacement (ε_a). The results for the unreinforced sand are in accord with the already published results on identical sand specimens (Ibraim 1998) and the maximum angles of friction mobilised at 20% of axial strain varies between 32°–34° for the test series L, M and 36° for the tests D.

The stress responses for unreinforced and reinforced sand seem to be similar at low displacements suggesting that the initial stiffness of the composite is not influenced by the presence of fibres (Heineck et al. 2005). With increasing axial strain, the contribution of fibres to the strength of the composite increases and the deviatoric stress for reinforced sand specimen is greater than for an unreinforced one. An increase of the mobilised angle of friction of up to 60% was recorded at 20% of axial strain for the loosest specimen at a cell pressure of 100 kPa. Despite the fact that some tests were carried out until the axial strain reached 30 to 40%, the reinforced specimens show a linear stress-strain relationship that does not seem to flatten. This pattern seems to suggest that the interaction mechanism between the fibres and the sand matrix is not weakened by the deformation process, the fibres are not pulled out and they do not break either. Although the use of a scanning electron microscope for the inspection of polypropylene fibres would be more recommended for a possible indication of the fibre deformation mode, at this stage of the research only visual inspection of the fibres was carried out. Exhumed specimens revealed no appreciable plastic deformation of the fibres and no breakages.

Figure 8 shows near linear trends of deviatoric stress increase with the fibre content added to the specimen.

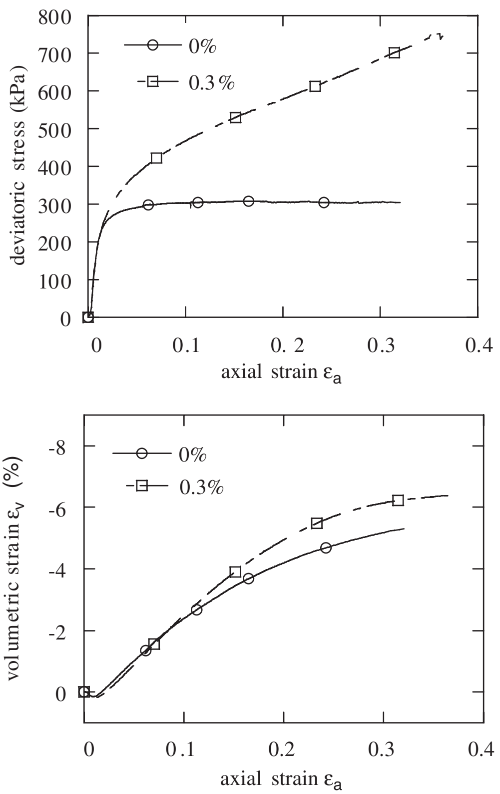

Figure 7. Stress-strain and volumetric behaviour for drained tests on D100 series specimens (legend gives the fibre content).

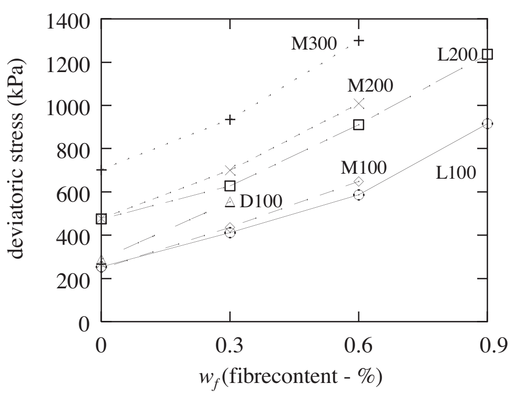

Figure 8. Trend of the deviatoric stress at 20% strain versus the fibre content for the tests performed.

As mentioned earlier, the specimens prepared with a moist tamping technique have a marked horizontal orientation of fibres. As in a triaxial test the direction of the tensile strain is horizontal, the contribution of

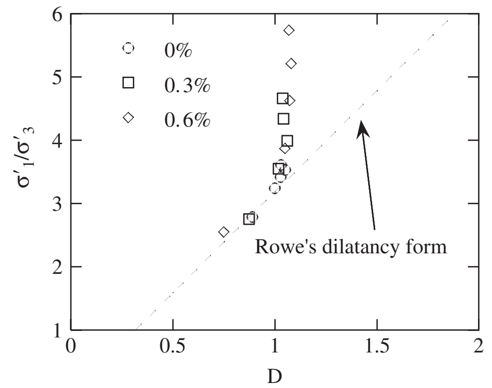

Figure 9. Stress dilatancy ratio for the test series M200 (legend express fibre content).

the fibres to the composite performance is enhanced by this particular orientation distribution.

For all the densities considered in this study, the shape of the volumetric curve response for reinforced sand, as for the unreinforced sand, showed an initial contraction followed by dilation. The addition of fibres to the composite resulted firstly in a decrease of the compression of the specimen followed then by a more dilative response, as also observed in the direct shear tests. The maximum recorded dilation angle, $\psi_{\max}$, is given in the Table 2 and ψ is defined as:

$$\tan\psi = -\frac{d\varepsilon_v^p}{d\varepsilon_a^p} \quad (2)$$

where the superscript p stands for plastic.

For some technical reasons, the volumetric change for the medium unreinforced sand at 100 kPa cell pressure (test: M100-00) did not follow the expected trend and this test will be performed again.

Figure 9 reports the trend of the dilatancy ratio evolution (defined as $D = 1 - dV/V/d\varepsilon_a$) with the principal stress ratio. Comparison with Rowe's relationship (Rowe 1962) for interparticle friction $\varphi_\mu = 31.5°$ is also shown. For a reinforced specimen, when the volumetric behaviour is constant, there is still an increase on the supported deviatoric stress leading to a vertical trend on the stress-dilatancy plane and the data diverge from the Rowe's relationship.

Few experiments were also conducted to investigate the influence of fibre length on the behaviour of the composite. Fibres having half the normal length were used in these tests, but for comparison the average concentration of fibres was kept constant. Although it was not possible to cut the fibres exactly in their mid point, the qualitative influence of fibre length on the stress-strain behaviour of the composite could still be assessed. Results demonstrated that the

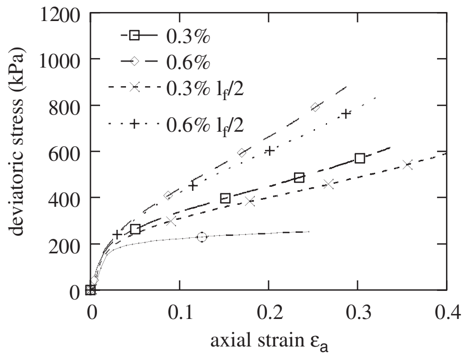

Figure 10. Influence of fibre length on the stress strain relationship on M100 specimens (legend express fibre content and fibre length).

performance of the composite was affected by decreasing the length of the fibres as shown in Figure 10. A drop of about 2° has been recorded for the mobilised friction angle at 20% of axial strain. Increasing the length of fibre reinforcements increases the shear strength of the fibre-sand composite (Al-Refeai 1991). However, this increase was effective only up to a point beyond which any further increase in fibre length had no effect on shear strength.

5 CONCLUSIONS

An experimental program was undertaken to investigate the individual effect of randomly distributed crimped polypropylene fibres on the mechanical behaviour of the Hostun RF sand. Direct shear tests and drained triaxial compression tests were performed on unreinforced and reinforced sand.

In both tests the addition of polypropylene fibres increases the shear strength response of the specimen and increased its dilative behaviour. For the highest fibre concentration used (1.0%), a gain on the peak strength of 60% was recorded in the direct shear test. In the triaxial tests an increase of the deviatoric stress apparently without limit was observed and an increase of the mobilised angle of friction (at 20% of axial strain) up to 60% was also observed.

Dilatancy ratio evolution with the principal stress ratio for reinforced specimens shows a different relationship from the one proposed by Rowe (1962).

The strength of the reinforced specimens was found to be dependent on the length of the fibres. A small reduction of the mobilised friction angle was recorded when shorter fibres were used.

These experimental results highlights the potential use of flexible discrete random fibres for the reinforcement of fine granular materials with applications including more resistant earthfills, foundations for buildings, heavy trafficked pavements and slope stabilization.

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