Stress-dilatancy behavior of microreinforced sand

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Keywords: soil reinforcement; triaxial tests; polypropylene fibers; aspect ratio

ABSTRACT: The purpose of the present investigation is the study of the mechanical behavior of a sand microreinforced with fibers of distinct aspect ratios. Through the results of a series of triaxial tests conducted on uniform sand reinforced with polypropylene fibers, the influence of fiber inclusion on the mechanical behavior as well as the specific significance of the fibers characteristics on the stress-dilatancy behavior of the fiber-reinforced sand were analyzed. Standard triaxial tests at effective confining pressures ranging from 20 to 200kPa were so carried out in this experimental program using fully saturated specimens. Non-plastic uniform fine sand was used in this experimental program. Monofilament polypropylene fibers (24 mm in length and 0.023 mm (dtex=3.3) and 0.1 mm (dtex=100) in diameter) were used throughout this investigation to reinforce the soil. The values of the studied fibers aspect ratios were 1043 and 240 respectively. The fiber content used in the experiments was 0.5% by weight of dry soil. The results show that fibers with higher aspect ratio produce higher strength envelopes and strain-hardening behavior in sand. The dilation behavior of sand was not significantly affected by fibers addition, except for the stress ratio (q/p') in which the critical state is approached. Besides, the mixtures final stress ratio was increased with the increase of fibers aspect ratio.

1 INTRODUCTION

Randomly distributed monofilament discrete fibers incorporated into sands improve their mechanical behavior by interacting with the soil particles through surface friction and also by interlocking. The role of friction and interlock is to transfer the stress from the soil to the tensile inclusions, and to mobilize their tensile strength and impart this resisting force to the sand, thus reducing the strains induced in reinforced sand which lead to the improvement in load carrying capacity of the material. The general characteristics of granular soils reinforced with discrete fibers have been reported in previous studies by several investigators (e.g., Gray and Ohashi 1983, Gray and Al Refeai 1986, Maher and Gray 1990, Ranjan et al. 1994, Morel and Gourc, 1997, Santoni et al. 2001, Zornberg 2002, Heineck et al. 2005 and Consoli et al. 1998, 2002, 2003, 2005, 2007a, 2007b, 2009a, 2009b).

The study of the mechanical behavior of a soil microreinforced with fibers of distinct aspect ratios (ratio between the fiber length and diameter) is the purpose of this investigation. Through the results of a series of triaxial tests conducted on uniform sand reinforced with polypropylene fibers, the influence of fiber inclusion on the mechanical behavior as well as the specific significance of the fibers characteristics on the stress-dilatancy behavior of the fiber-reinforced sand were analyzed.

2 EXPERIMENTAL PROGRAM

Triaxial tests were carried out in this experimental program on non-reinforced and fiber-reinforced sand specimens using fully saturated samples, at effective confining pressures ranging from 20 to 200kPa. Reinforced specimens consider one fiber length (24 mm), two diameters, 3.3 dtex (0.023 mm – very thin) and 100 dtex (0.1 mm – thin), and consequently two different values of aspect ratios, 1043 and 240 respectively.

2.1 *Experimental program*

Uniform quartzitic sand, Osorio Sand, from southern Brazil was tested in this experimental program. The Osorio Sand was sampled from the region of Osorio near Porto Alegre. The soil is classified as non-plastic uniform fine sand (SP) and the specific gravity of the solids is 2.62. The grain size distribution is entirely fine sand (0.075 mm < diameter < 0.42 mm), with an effective diameter of 0.09 mm and uniformity and curvature coefficients of 2.1 and 1.0, respectively. Mineralogical analysis showed that sand particles are predominantly quartz. The minimum and maximum void ratios are 0.6 and 0.9 respectively.

Monofilament polypropylene fibers were used throughout this investigation to reinforce the soil. Their average dimensions were 24mm in length and 0.023mm (dtex=3.3) and 0.1mm (dtex=100) in diameter, with a specific gravity of 0.91, tensile strength of 120MPa, elastic modulus of 3GPa and linear strain at failure of 80%. The values of the studied fibers aspect ratios were 1043 and 240 respectively. The fiber content used in the experiments was 0.5% by weight of soil.

2.2 *Testing methodology*

The compacted soil and fiber-reinforced specimens used in the triaxial tests were prepared by hand-mixing dry sand, water and polypropylene fibers, when used. During the mixing process, it was found to be important to add the water prior to adding the fibers, to prevent floating of the fibers. Visual and microscope examination of exhumed specimens showed the mixtures to be satisfactorily uniform. The undercompaction process (Ladd 1978) was used to produce homogeneous specimens that could be used for a parametric study in the laboratory-testing program. The specimens were statically compacted in three layers into a 100mm diameter by 200mm high split mould, to a moisture content of 10.0% and dry unit weight of 15.0kN/m^3, equivalent to a relative density of 50%. Each sample was compacted in a mould on the triaxial pedestal by applying a static load via the loading platen. The final height of the sample was controlled to ensure a relative density of 50%. Such relative density was selected because it was efficiently achieved for all inclusions used.

The triaxial tests were conducted using a computer controlled large triaxial cell. This apparatus allowed the tests to be conducted with constant radial effective stress. The samples were saturated under back pressure and saturation was monitored in each test, ensuring B values of at least 0.98 for all specimens. The axial strains were monitored inside the triaxial cell using a Hall effect sensor type of local strain transducer (Clayton and Khatrush 1986) and outside the cell using a standard type of displacement transducer. The volumetric strain was measured by an Imperial College volume gauge (Maswoswe 1985) connected to the drainage outlet. The triaxial tests were run at a sufficiently low axial strain rate to ensure full drainage within the sample, 0.015% per minute. Drainage was also monitored by measuring the excess pore pressure at the opposite end of the specimen to the drainage. The membrane and area corrections followed recommendations proposed by La Rochelle et al. (1988).

3 RESULTS AND ANALYSIS

3.1 *Stress-strain behavior*

The behavior of non-reinforced and fiber-reinforced sand with 0.5% monofilament polypropylene fibers by weight of sand (fiber length of 24mm - fiber diameters of 0.023 and 0.1 mm) was examined through drained standard triaxial tests results and their typical deviator stress [q, $(\sigma'_{axial} - \sigma'_{radial})$] : shear strain [$\varepsilon_s$, $\frac{2}{3}(\varepsilon_{axial} - \varepsilon_{radial})$]: volumetric strain [$\varepsilon_v$] curves. The results are grouped for effective confining stresses of 200, 100 and 20 kPa, and presented in Figures 1, 2 and 3, respectively.

The analysis of Figures 1, 2 and 3 shows, as expected, the increase of materials strength with the increase of effective confining stresses. It is also indicated the higher strength of fiber reinforced matrices. The largest gains in strength, according to the same figures, compared to the non-reinforced material, are found in mixtures reinforced with fibers aspect ratio of 1043.

The volumetric strain : shear strain curves suggest that fibers inclusion do not significantly alter the initially compressive and later expansive behavior of sand.

It can be seen in the same figures the strain hardening behavior of matrices reinforced with 1043 aspect ratio fibers, which is not clearly observed for non-reinforced and 240 aspect ratio fiber reinforced sand.

3.2 *Strength parameters*

The shear strength envelopes obtained from triaxial tests with polypropylene fiber-reinforced and non-reinforced samples of Osorio sand are shown in Figure 4, where the peak deviator stress [q] is plotted against the corresponding mean effective stress [p']. The shear strength envelope for the fiber-reinforced sand was taken at 17% shear strain. This was important because several test results on the fiber-reinforced sand were generally strain hardening until the maximum strain that the apparatus could reach, as can be seen in the stress: strain data in Figures 1, 2 and 3, so that a “strength” had to be defined at a specific strain.

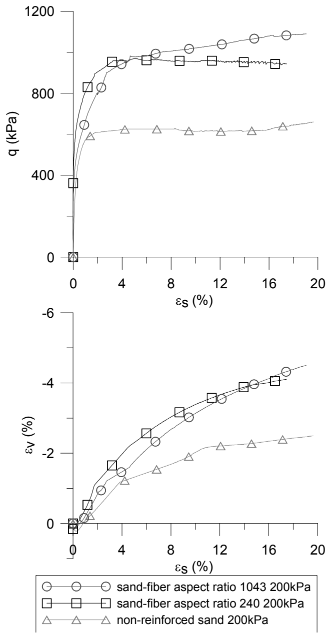

Figure 1. Stress-strain-volumetric response of the studied mixtures for a confining stress of 200kPa.

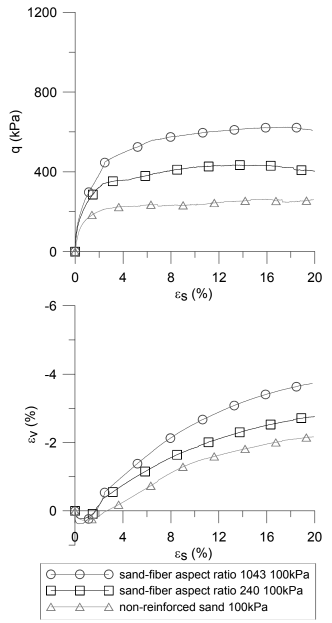

Figure 2. Stress-strain-volumetric response of the studied mixtures for a confining stress of 100kPa.

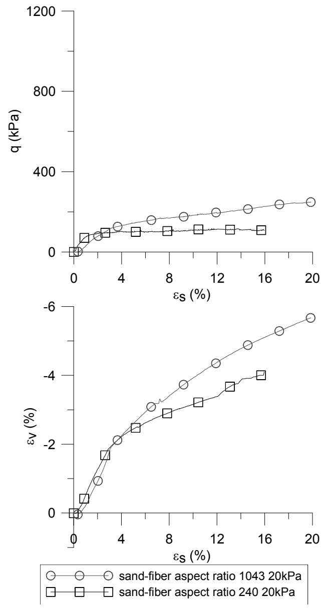

Figure 3. Stress-strain-volumetric response of the studied mixtures for a confining stress of 20kPa.

The strength increase from the fibers inclusion is also observed through shear strength envelopes and their corresponding strength parameters. According to Figure 4, the non-reinforced matrix friction angle [φ’] was 37.0° and its cohesive intercept [*c’*] was nil, whereas the strength parameters *c’*=4.8kPa and φ’=43.4° was observed for the 240 aspect ratio fiber reinforced matrix, and *c’*=30.9kPa and φ’=44.6° for the 1043 aspect ratio fiber reinforced matrix.

The parallelism of reinforced materials strength envelopes highlights the small influence of fibers aspect ratio over the values of mixtures internal friction angle. However, in the highest aspect ratio fiber reinforced mixture, the cohesive intercept is at least six times higher than in the lowest aspect ratio fiber reinforced mixture.

3.3 *Stress-dilatancy behavior*

Figure 5 shows the effects of fiber reinforcement (fibers aspect ratios of 240 and 1043) on the stress-dilatancy response of the sand at a confining pressure of 100 kPa. The arrows indicate the final portion of each test.

The mechanisms of behavior are investigated using a stress ratio (q/p’) – dilatancy ($d\varepsilon_v/d\varepsilon_s$) graph (dilation plotted as negative in the figure). Data for the unreinforced sand are also shown for comparison. The unreinforced sand displayed an initially compressive behavior typical of that of medium dense frictional materials, with the rate of compression reducing to reach zero and then presenting a light dilation reaching then critical state on the vertical axis. The fiber-reinforced samples showed a similar behavior [dilatancy ($d\varepsilon_v/d\varepsilon_s$) is kept unchanged], although increasing the stress ratio (q/p') in which the critical state is approached. In the present results, the greater the fiber aspect ratio, the greater the stress ratio (q/p') reached.

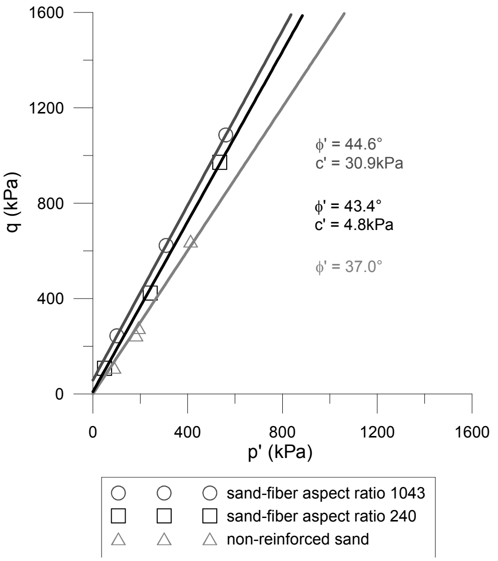

Figure 4. Shear strength envelopes of non-reinforced Osorio sand and fiber-reinforced Osorio sand.

3.4 *Fiber measurement*

After completing the standard drained triaxial tests on the fiber-reinforced specimens, the fibers were recovered from the specimens and their final lengths measured. Around 180 fibers were measured after each test. These data indicate that none of the fibers checked in the present study broke in tension. It could be suggested that the failure is a composite of slippage and yielding of fibers, as the fibers show only limited stretching, and so there is possibly slipping occurring between the fibers and the soil particles because of the low confining stress. The fibers have not broken because they are highly extensible with a fiber strain at failure of 80%, and the necessary strain to cause fiber breakage had not been reached under triaxial conditions at these strains.

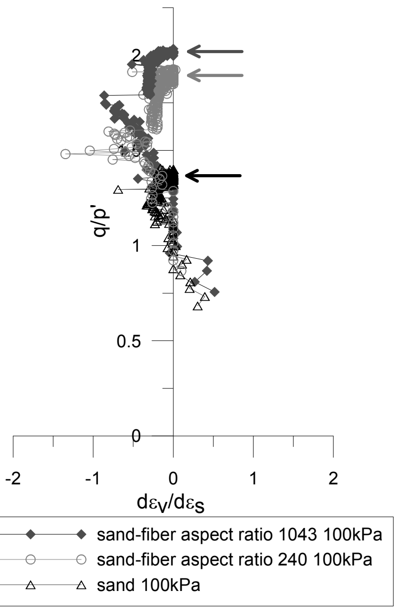

Figure 5. Stress ratio-dilatancy of sand and fiber-reinforced sand.

4 CONCLUSIONS

An extensive laboratory testing program was carried out in order to investigate the influence of monofilament extensible polypropylene fiber reinforcement on uniform sand. To accomplish this, drained triaxial tests were conducted for soil specimens, considering 24mm long fibers with two distinct fiber diameters and aspect ratios. The observations and conclusions can be summarized as follows:

- The reinforced matrices presented strength gains, compared to the non-reinforced sand, for both types of fibers added;
- The value of the fibers aspect ratio influences the mixtures behavior. The higher the aspect ratio value, the higher the strength gain of mixtures;
- High aspect ratio fibers, about 1000 in this study, provide the soil of a hardening behavior, which is not found in mixtures reinforced with fibers of low aspect ratio, about 240 in this study;
- The inclusion of fibers does not significantly alter the initially compressive and later expansive behavior of sand.
- There was an appreciable improvement of the strength parameters of the reinforced materials, compared to the non-reinforced sand, for both types of fibers added;

- The mixtures internal friction angle values were not influenced by the fibers aspect ratio. The shear strength envelopes are parallel. In contrast, the values of mixtures cohesive intercept were strongly influenced by fibers aspect ratio. The higher the aspect ratio, the greater the intercept cohesive.
- The dilatancy ($d\varepsilon_v/d\varepsilon_s$) is kept practically unchanged when introducing fibers in the sand; however the final stress ratio (q/p') is increased with the increase of added fibers aspect ratio.
- According to the fiber measuring data, it can be indicated that none of the fibers checked in the present study broke in tension. The failure was a composite of slippage and yielding of fibers, as the fibers shown only limited stretching.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Brazilian Research Council CNPq/MCT (Projects Produtividade em Pesquisa # 301869/2007-3, Edital Universal # 472851/2008-0 and PNPD # 558474/2008-0) and to Brazilian Electrical Energy Agency ANEEL (Project P&D 0089-036/2006 – CEEE-GT/9936455) for their financial support to the research group.

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