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MECHANICAL BEHAVIOR OF LOOSE SAND REINFORCED WITH SYNTHETIC FIBERS

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This work describes an experimental study about the effects the addition of randomly oriented polypropylene fibers have on the behavior of an alluvial fine to medium sand in a loose state. The study is focused on the characterization of the influence the fiber addition has on the shear strength and on the deformational modulus corresponding to low, medium, and large strain levels of the reinforced sand. The effect of the type (smooth and meshed), length, and fiber content, is analyzed by means of drained triaxial, direct shear, and shear wave velocity tests.

1. Introduction

Over the last decades, several researchers have developed soil reinforcement methods in order to improve engineering properties of soils. Most of them include the addition of external materials to the soil matrix, usually synthetic or nondegradable elements. This practice is ever more widely applied in geotechnical engineering. Soil reinforcement by means of fiber addition has been reported in the last few decades. In general, studies show that addition of fibers increase the shear strength at large strains of the reinforced soil. However, as far as we know, only a few studies dealing with the effect of fiber inclusion on the mechanical behavior of reinforced soil at low strain level have been published.

This work describes an experimental study on the effect that the addition of randomly oriented polypropylene fibers has on the behavior of an alluvial fine to medium sand in a loose state. The effect on shear strength and deformation modulus of the reinforced sand due to the inclusion of fibers is analyzed at low, medium, and large strain levels. The inclusion of smooth and meshed fibers is compared.

Several variables are involved in the behavior of the reinforced soil [1-5]:

– fiber properties: type of material, shape, length, aspect ratio, roughness, density, and strength.

– soil properties: granulometry, particle size and shape, fabric, void ratio, particle roughness, and water content.

– characteristics of the soil-fiber mixture: fiber content and orientation of fibers in the matrix of the soil.

Nowadays there is a greater awareness about contamination and an increasing need to use more environmentally friendly materials. Consequently, several investigations have used natural fibers for soil reinforcement. Some natural fibers employed are sisal fibers [6], coir fibers [7], palm fibers [8], and processed cellulose fibers [9]. However, biodegradation and poor chemical and corrosion-resistant properties appear to be the main disadvantages of this type of materials. Consequently, natural fibers must be protected or treated to ensure long-term performance [10].

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On the other hand, synthetic fibers are chemical and weather resistant and develop higher tensile strength than natural fibers. Polypropylene fiber is the most widely used inclusion in the laboratory testing of reinforced soils [4, 5, 11, 12]. Studies have also reported the use of polyamide monofilament fibers [3] and polyvinyl alcohol fibers [13]. Moreover, some researchers have employed recycled waste plastics to reinforce soils, such as polyethylene terephthalate [14], high-density polyethylene [15], and shredded waste tires [16, 17].

The usual fiber contents range between 0.25% and 3% of dry weight of soil. Fiber lengths usually vary from 10 to 60 mm and are related to particle size. Generally, specimens of reinforced soil are prepared by a mixing and a formation process [4]. The mixing procedure consists of creating an homogeneous composite of soil, fibers, and sometimes water. Then, the formation process involves compaction methods like moist tamping or vibration. Several authors noted that the presence of the reinforcement provides resistance to the compaction. Consequently, the higher the amount of fibers, the lower the compactness achieved.

Previous researches have shown that fiber reinforcement can significantly increase the peak shear strength and diminish the post-peak shear strength loss of a soil mass. However, beyond a certain fiber content, the strength increment of the reinforced soil seems to approach an asymptotic upper limit [4, 11, 12, 18].

Consoli et al. [19] noted that the failure envelope of a fiber reinforced sand is nonlinear, with a well-defined kink point. For this reason, these authors approximated the failure envelope by a bilinear curve in the τ (shear stress) – σ (normal stress) space.

Experimental results on fiber reinforced sands have shown that the strain level required to attain the peak shear strength increases with fiber content [3]. Loose sands reinforced with fibers achieved the maximum shear strength at strain levels as high as 20% and even higher [2]. In addition, other investigators concluded that fiber-reinforced soils present a ductile behavior [4].

Michalowski and Cermak [3] noted that fiber reinforcement becomes optimum when the length of fibers is at least one order of magnitude larger than the size of the grains and when the aspect ratio (length to diameter) of fibers is large.

Li and Zornberg [20] concluded that cohesive and granular soils are influenced by the addition of fibers, increasing peak and residual shear strength. Fiber reinforcement also tends to decrease the dilation tendency on dense sands.

There are a few studies related to the effect of fiber inclusion on the stiffness of reinforced soil. Li and Ding [21] carried out cyclic triaxial tests on fiber-reinforced sands. They found that shear modulus is affected by fiber content, confining pressure, strain level, and number of loading cycles. These authors reported that elastic modulus corresponding to medium to large strains increases with fiber content and confining pressure, and decreases with the number of loading cycles. Similar conclusions were obtained by Marandi et al. [8], who reported that inclusion of palm fibers increases the secant modulus of the reinforced soil.

However, experimental results of triaxial tests performed on fiber reinforced sand by Michalowski and Cermak [3] showed that initial stiffness is reduced when the amount of fibers is increased. These authors concluded that the loss of initial stiffness is probably due to changes in the sand fabric produced by the fiber inclusion, which causes a nonuniform porosity distribution. Other investigators [11, 22] reported that the addition of fibers causes a drop in the initial stiffness of soils reinforced with cement.

Finally, Heineck et al. [23] carried out bender element testing in order to study the influence of fiber addition in the initial stiffness of different soils. The authors concluded that at very small strains the introduction of fibers does not influence the initial stiffness of the reinforced soils.

Materials and methods

The soil used in the present study was an alluvial siliceous medium to fine sand. The main geotechnical characteristics of the sand are listed in Table 1.

TABLE 1

U.S.C.S.	C_U	C_g	D_{50}, mm	G_s, kN/m³	$\gamma_{d\max}$, kN/m³	$\gamma_{d\min}$, kN/m³
SP	2.4	1.4	0.5	2.68	16.56	14.2

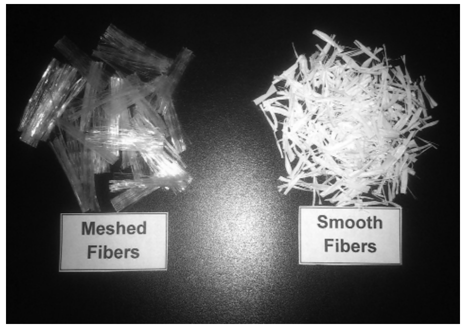

Fig. 1. Meshed and smooth fibers.

Polypropylene fibers were used throughout this work. Two kinds of polypropylene fibers were employed: smooth and meshed fibers (Fig. 1). Smooth fibers are flat with approximately 2 mm width and 0.1 mm thick, having lengths ranging from 5 to 20 mm. Meshed fibers were obtained from the concrete industry and are approximately 27 mm in length. The fiber contents range from 0 to 4% by dry weight of soil.

Triaxial tests and direct shear tests were carried out to characterize the shear strength parameters at large strain levels of the fiber-reinforced sand. The tests were conducted with the sand in a dry condition. The shear strain rates were selected slow enough in order to simulate a drained shear process.

A total of 14 triaxial tests and five direct shear tests were performed on the nonreinforced and fiber-reinforced sand. Triaxial compression tests were conducted on specimens 50 mm in diameter and 100 mm in length. Direct shear tests were performed on specimens 63.5 mm in diameter and 37.5 mm in length.

The samples of nonreinforced and fiber-reinforced sand were prepared at a loose state, with unit weights between 14.2 and 14.6 kN/m³. Smooth fiber-reinforced specimens were prepared with fiber contents of 1, 2, 3, and 4% by weight of soil, and with fiber lengths of 5, 10, and 20 mm. Meshed fibers were used in percentages of 1 and 2% by weight of soil.

To quantify the stiffness of the reinforced soil at low strain levels ($\varepsilon \approx 10^{-5}$), confined compression with shear wave velocity measurement tests were performed. These tests were conducted on a modified odometer with the incorporation of bender elements in its upper and bottom caps. A detailed description of this equipment is given in [24].

Shear Resistance Parameters

Fig. 2 shows the effect of fiber content and type of fiber on the internal friction angle at failure of the reinforced sand. The friction angle at failure is the friction angle corresponding to the maximum deviatoric stress. Both triaxial compression tests and direct shear tests results are presented in this figure. Meshed fibers and smooth fibers 10 mm in length were used.

The internal friction angle increases with fiber content up to a fiber content of 2% by weight of dry soil. Beyond this percentage of fibers, no appreciable improvement of internal friction angle is observed. The increase of internal friction angle is similar in smooth and meshed fibers. Meshed fibers seem to be slightly more effective than smooth fibers as reinforcement.

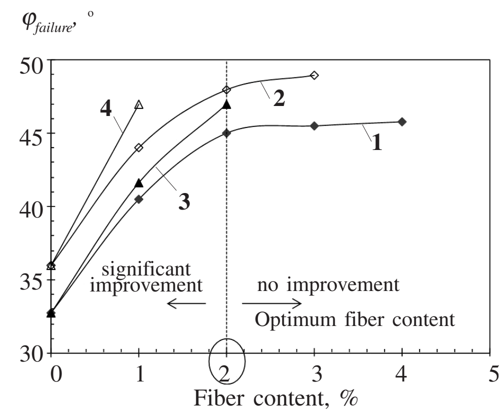

Fig. 2. Variation of internal friction angle at failure with fiber content in percentage by weight of dry soil: 1) smooth fibers (triaxial); 2) smooth fibers (direct shear); 3) meshed fibers (triaxial); 4) meshed fibers (direct shear).

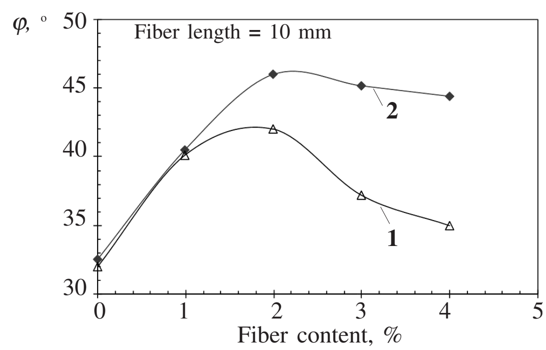

Fig. 3. Variation of internal friction angle, defined for vertical strains of 5% and 10%, with fiber content in percentage by weight of dry soil: 1) ε = 5%; 2) ε = 10%.

Although triaxial and direct shear tests show similar trends, the values of $\varphi_{failure}$ of direct shear tests were up to 7% higher than those obtained from triaxial compression tests. This effect may be a consequence of the nonuniform distribution of stresses under the load plate in the shear direct test because of the low unit weight of the sand.

If failure is defined as the deviator stress developed for a certain arbitrary strain, a new internal friction angle is obtained. This angle will depend on the vertical strain chosen as failure criterion. Fig. 3 shows the values of internal friction angle corresponding to vertical strains of 5% and 10%. These results were obtained from tiaxial compression tests on reinforced sand with 10 mm smooth fibers.

Contrary to the results presented in Fig. 2, the internal friction angle decreases when the fiber content is more than 2% by weight of dry soil, as shown in Fig. 3. Also, when the vertical strain at which failure is defined is reduced, the corresponding internal friction angle decreases. These observations seem to suggest that the reinforced soil gains ductility but loses stiffness when fibers are added to the soil matrix.

The influence of fiber length on the shear strength of the reinforced sand is presented in Fig. 4. Note that the internal friction angle for the reinforced sand increases with fiber length. However, if we define the internal friction angle for vertical strains of 5% and 10%, we observe that fibers longer than 10 mm do not produce a significant improvement on the shear strength defined in terms of the maximum allowable vertical strain (Fig. 4). These results demonstrate the need to evaluate both the failure envelope and the vertical strain, when the effect of fiber addition is analyzed.

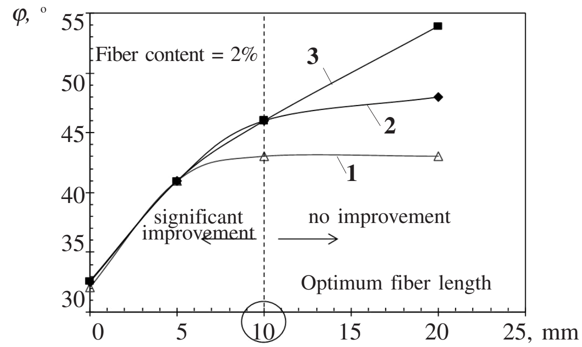

Fig. 4. Influence of fiber length on internal friction angle. Triaxial compression tests on reinforced specimens with 2% of smooth fibers. Internal friction angle at failure defined for vertical strains of 5% and 10%: 1) ε = 5%; 2) ε = 10%; 3) failure.

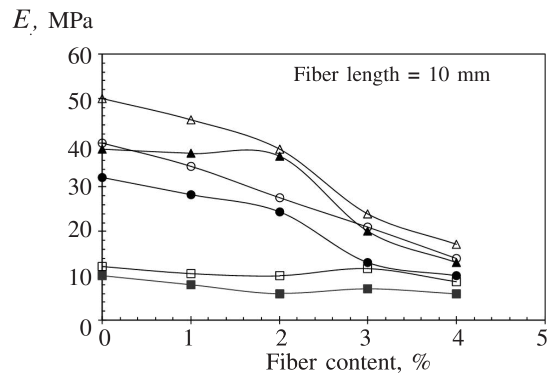

Fig. 5. Effect of fiber content on Young modulus of reinforced sand determined at two strains level: initial modulus (empty markers) for $\varepsilon = 10^{-3}$ and secant modulus (filled markers) for $\varepsilon = 10^{-2}$: –□–) confining pressure 50 kPa; –○–) confining pressure 100 kPa; –△–) confining pressure 150 kPa.

Stiffness modulus

The secant modulus was measured from the stress-strain curves of triaxial compression tests in the reinforced sand. For every confining pressure and fiber content, two moduli were obtained:

– initial modulus, corresponding to the minimum strain measurable with the LVDT (Linear Variable Differential Transducer) of the triaxial cell. The LVDT is capable of measuring strains (ε) as low as 10^{-3};

– secant modulus, measured at a vertical strain of 1% ($\varepsilon = 10^{-2}$).

Fig. 5 shows the variation of the initial and secant modulus for different fiber contents and confining pressures. The results correspond to smooth fibers 10 mm in length, with contents ranging from 0 to 4% by weight of dry soil. The applied confining pressures were 50, 100, and 150 kPa. Fig. 5 shows that both the initial and the secant modulus diminish with fiber content but increase with confining pressure.

Shear wave velocity measurement tests were performed to quantify the maximum Shear and Young moduli of the reinforced sand at low strain levels ($\varepsilon \approx 10^{-5}$). These tests were conducted on an odometer with bender elements.

The maximum shear modulus $G_{\max}$ was obtained from the shear wave velocity V_S and the soil density ρ as follow:

$$G_{\max} = V_S^2 \rho \ . \tag{1}$$

Assuming a constant value of the Poisson ratio for loose sand of 0.2 ([25]), the maximum Young modulus was calculated as:

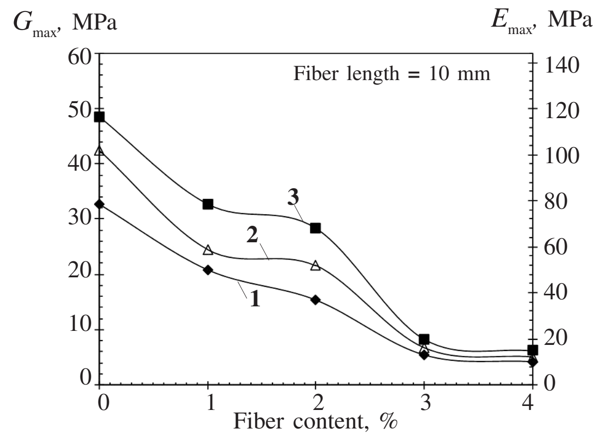

Fig. 6. Variation of maximum shear and Young moduli with fiber content and confining pressure, measured by shear wave velocity in confined compression tests ($\varepsilon \approx 10^{-5}$): 1-3) vertical pressure 50, 100, and 200 kPa, respectively.

$$E_{max} = 2(1 + \nu)G_{max} \; . \tag{2}$$

Fig. 6 illustrates the variation of the maximum shear and Young modulus obtained from Eqs. (1) and (2) with fiber content and confining pressure. Low strain stiffness decreases with fiber content but increases with confining pressure. These trends appear to be similar to those observed for the medium strain modulus (Fig. 5). This behavior may be the product of the loss of contact between particles due to the presence of fibers.

Conclusions

1. The addition of fibers increases the shear strength at large strain levels and the ductility of the reinforced sand.

2. The internal friction angle measured at failure increases with fiber content up to a 2% by weight of dry soil. Beyond this content, no significant improvement is observed.

3. Meshed fibers produce increments of shear strength slightly higher than those generated by smooth fibers.

4. Although the internal friction angles measured by direct shear tests are up to 7% higher than those obtained from triaxial tests, both triaxial and direct shear tests showed the same trends related to the effect of fiber on shear strength. The difference between direct shear and triaxial results may be a consequence of the nonuniform distribution of stresses under the load plate in the direct shear test because of the low compacity of the sand.

5. When the vertical strain selected as the failure criterion is reduced, the improvement of the resultant internal friction angle decreases, becoming even negative when the fiber content is equal to or larger than 2% by weight of dry soil.

6. The shear strength of the reinforced sand seems to increase indefinitely with fiber length. However, if failure is defined in terms of the maximum tolerable strain, fibers longer than 10 mm do not produce significant improvement in shear strength.

7. The Young modulus defined for large ($\varepsilon = 10^{-2}$), medium ($\varepsilon = 10^{-3}$) and small ($\varepsilon = 10^{-5}$) strain diminishes with fiber content. This behavior may be a consequence of the loss of contact between particles and a reduction in the particle-to-particle friction because of the presence of fibers.

8. Finally, we conclude that fiber content and fiber length have a significant influence on the stress-strain and strength behavior of the reinforced sand. The addition of fibers produces an increment in

the shear strength and ductility but a loss of stiffness. For this reason, the reinforcement of soils by means of fiber addition must be evaluated considering these two aspects (strength and stiffness) together.

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