Experimental investigation on the mechanical behavior of fiber reinforced sandy gravel and fiber-reinforced fine sand

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ABSTRACT: The use of short reinforcement fibers has become rather popular in structural engineering, but is a relatively new topic in geotechnical engineering. Recent experimental results obtained in laboratory on fiber-reinforced sands have clearly shown the beneficial effect of the fibers in the overall mechanical behavior of sands from small to large strains. Notwithstanding these encouraging results, there is still a lack of knowledge related to the effectiveness of fiber reinforcement on coarser materials, and this is a crucial issue to make this improvement technique commercially interesting, as most embankments are usually realized sandy gravels. As a consequence, a research joint activity was recently started by the authors to try and get some information on the fiber reinforcement of fine and coarse materials. Triaxial tests have been carried out in non-reinforced and polypropylene fiber-reinforced fine sand and fiber-reinforced sandy gravel. Fiber-reinforced specimens (fiber content used in the experiments was 0.2% by dry weight of soil) of both studied soils used monofilaments of 50 mm in length and 0.1 mm in diameter, resulting in a aspect ratio of 500. The paper reports the main results obtained, showing the effect of using fibers on the overall behavior from medium to large strains.

1 INTRODUCTION

The use of ground improvement techniques has been increasingly expanding in the last decades because of an increasing demand of the construction industry. As a consequence, techniques have been developed to solve most problems related to poor quality soils or construction materials. Little or no attention has been paid to sand and gravels because they usually show high permeability and good mechanical properties. However, there is a number of cases in which it would be very convenient to improve their mechanical performance, like for instance to reduce liquefaction risk or to allow steeper engineered slopes in any kind of embankments. Even though the latter topic can be tackled with traditional reinforcement techniques like geosynthetics, it has been recently shown that for granular soils there are alternative techniques which seem very promising, the main one being the use of diffused fiber reinforcement.

Experimental results gathered over the last years indicate that short fibers mixed into soils can have a noticeable reinforcing effect (e.g., Heineck et al. 2005, Diambra et al. 2007, Consoli et al. 2009a).

The study of the mechanical behavior of a coarse grained material (sandy gravel) and a fine sand microreinforced with fibers of large aspect ratio (about 500 in the present research) is the purpose of this investigation. Through the results of a series of triaxial tests conducted on both fiber-reinforced sandy gravel and fiber-reinforced uniform fine sand, as well as on the unreinforced soils, the effect of fiber reinforcement from fine to coarse materials is investigated.

2 EXPERIMENTAL PROGRAM

Triaxial tests were carried out in this experimental program on non-reinforced and fiber-reinforced sandy gravel and fiber-reinforced uniform fine sand specimens using fully saturated samples, at effective confining pressures of 50kPa. Reinforced specimens consider one fiber length (50 mm), one diameter (0.1 mm), and consequently an aspect ratio of 500.

2.1 *Experimental program*

The first soil studied herein is a calcareous coarse grained rockfill retrieved from an open pit in Southern Italy. The chosen grading (which fits typical road embankment construction rules) is reported in Figure 1. The soil is classified as non-plastic sandy gravel and the specific gravity of the solids is 2.72. Its effective diameter (D_{50}) is 3.0 mm and uniformity coefficient of 12.5. The minimum (e_{min}) and maximum (e_{max}) void ratios are 0.19 and 0.6 respectively.

Uniform quartzitic sand, Osorio Sand, from southern Brazil was also 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 and the specific gravity of the solids is 2.62. Grading is also presented in Figure 1. The grain size distribution is entirely fine sand (0.075 mm < diameter < 0.42 mm), with an effective diameter (D_{50}) of 0.16 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.

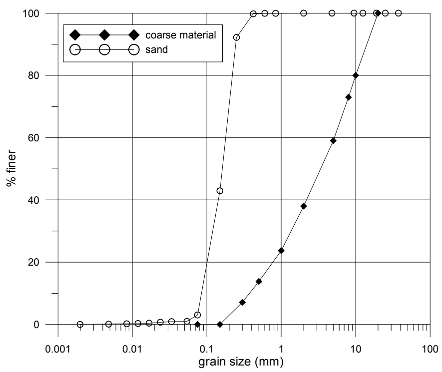

Figure 1. Grain size distribution of both coarse material (sandy gravel) and fine material (uniform fine sand).

Monofilament polypropylene fibers were used throughout this investigation to reinforce the soils. Their dimensions were 50 mm in length and 0.1 mm in diameter (aspect ratio 500), with a specific gravity of 0.91, tensile strength of 120 MPa, elastic modulus of 3 GPa and linear strain at failure of 80 %. The fiber content used in the experiments was 0.2 % by weight of soil. The addition of fibers to the sandy gravel affects the range of possible void ratios, largely increasing e_{max} to 0.85 and slightly changing e_{min} to 0.23. When added to the uniform fine sand, both changes were slight, e_{max} = 0.95 and e_{min} = 0.65.

2.2 *Testing methodology*

The compacted soils and fiber-reinforced specimens used in the triaxial tests were prepared by hand-mixing each specific dry soil, 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 non-reinforced sandy gravel specimens were compacted by wet tamping in five layers into a 200 mm diameter by 400 mm high split mould, to a moisture content of 10.0 % and voids ratio of 0.56, The same compaction technique was adopted for the fiber-reinforced sandy gravel specimens, with a moisture content of 10.0 % and a voids ratio of 0.79. The two voids ratio are different as the ranges of possible particle packing change because of the presence of fibers. The values were chosen close to the maximum possible voids ratio (e_{max}) to have very loose specimens (relative density D_r=7 % for the non-reinforced specimen, D_r=13 % for the reinforced one).

The non-reinforced uniform fine sand specimens were statically compacted in three layers into a 100 mm diameter by 200 mm high split mould, to a moisture content of 10.0 % and voids ratio of 0.75, equivalent to a relative density of 50 %. The fiber-reinforced fine sand specimens were also statically compacted in three layers into a 100 mm diameter by 200 mm high split mould, to a moisture content of 10.0 % and voids ratio of 0.80, equivalent to a relative density of 50 %. Then, the voids ratio of the reinforced sandy gravel and fine sand are similar, even though their relative densities significantly differ.

The triaxial tests were conducted using computer controlled large triaxial cells. 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. Drainage was also monitored by measuring the excess pore pressure at the opposite end of the specimen to the drainage.

3 RESULTS AND ANALYSIS

3.1 *Stress-strain behavior*

The behavior of non-reinforced and fiber-reinforced sandy gravel and uniform fine sand with 0.2% monofilament polypropylene fibers by weight of soil (fiber length of 50mm and fiber diameter of 0.1 mm) were examined through drained standard triaxial tests results and their typical deviator stress (q) : axial strain (ε_a) : volumetric strain [ε_v] curves. The results are grouped considering the two distinct soils studied; Figure 2 presents the stress-strain-volumetric response of the non-reinforced and fiber-reinforced sandy gravel considering a confining stress of 50 kPa. In Figure 2, at low strain levels, the fibre reinforced sandy gravel deforms considerably more than the unreinforced one.

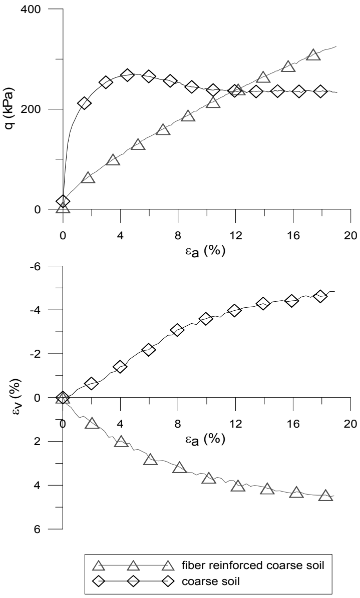

Figure 2. Stress-strain-volumetric response of the non-reinforced and fiber-reinforced sandy gravel for a confining stress of 50 kPa.

Figure 3 shows the stress-strain-volumetric response of the non-reinforced and fiber-reinforced uniform fine sand for a confining stress of 50 kPa. The fiber-reinforced specimen shows a marked hardening behavior up to the end of the tests at axial strains of about 18%, whereas for the non-reinforced specimens, an almost perfectly plastic behavior was observed at large strains. On the other hand, the volumetric response of the uniform fine sand was hardly affected by fiber inclusion, showing for both materials a slight expansion for low confining pressures.

Comparable triaxial tests on fiber-reinforced specimens prepared with the same uniform fine sand studied herein, the same fiber geometry (but higher fiber content – 0.5%) and several distinct confining stresses (from 20 to 200 kPa) were carried out by Consoli *et al.* (2009b) and also showed strain hardening behavior (see Fig. 4).

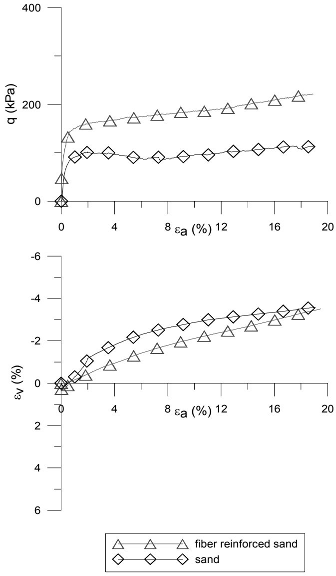

Figure 3. Stress-strain-volumetric response of the non-reinforced and fiber-reinforced uniform fine sand for a confining stress of 50 kPa.

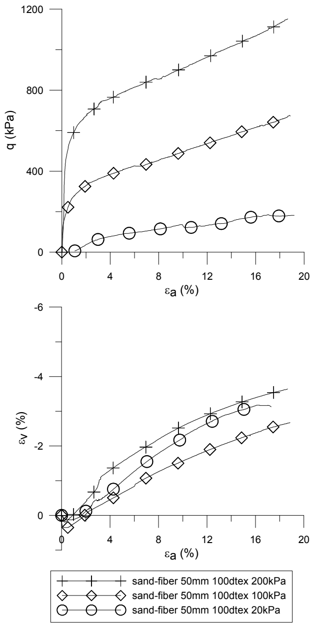

Figure 4. Triaxial test responses of fiber-reinforced fine sand containing 0.5% fiber content [adapted from Consoli et al. (2009b)].

Undoubtedly, one of the main advantages of the polypropylene fiber reinforcement of both soils was the strain hardening behavior induced even at large deformations. It is important to point out that the fiber-reinforced soil specimens did not present any localization of strains and the fibers were not found to be disrupted.

3.2 *Strength parameters*

The shear strength envelopes for the fiber-reinforced soils were taken at 17% axial strain. This was important because test results on all fiber-reinforced materials were strain hardening until the maximum strain that the apparatus could reach, as can be seen in the stress: strain data in Figs. 2, 3 and 4, so that a "strength" had to be defined at an arbitrary strain.

The cohesive intercept for all reinforced and non-reinforced materials studied was zero. The friction angle of the sandy gravel was φ'=45.2°, increasing to φ'=48.7° due to insertion of 0.2% monofilament polypropylene fiber content. The friction angle of the non-reinforced uniform fine sand is equal to 37.0°; increasing to 44.0° for 0.2% fiber content insertion and 48.3° for 0.5% fiber content insertion.

3.3 *Fiber measurement*

After completing the standard drained triaxial tests on both fiber-reinforced specimens, the fibers were recovered from the specimens and their final lengths measured. Around 100 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.

CONCLUSIONS

The following observations and conclusions are made regarding the engineering properties and triaxial behavior of polypropylene fiber-reinforced/non-reinforced specimens of a coarse sandy gravel soil from Italy, as well as of a uniform fine sand from southern Brazil.

- The polypropylene fiber-reinforced specimens showed a marked hardening behavior up to the end of the tests, at axial strains larger than 18% for both the coarse and the fine grained soils. The non-reinforced coarse grained (sandy gravel) specimen presented a peak followed by a strain softening behavior, whereas the non-reinforced fine sand demonstrated an almost perfectly plastic behavior at large strains. This improvement of soil behavior due to fiber addition suggests the potential application of fiber reinforcement in embankment dams and dykes, shallow foundations, embankments over soft soils, and other earthworks that need a ductile material behavior.
- Based on the shear strength envelopes obtained from triaxial tests, it can be defined an appreciable improvement of the strength parameters of the reinforced materials, compared to the non-reinforced soils.
- According to the fibers 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.

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