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SILTY CLAY REINFORCED WITH SHORT LENGTH SYNTHETIC FIBRES RANDOMLY ORIENTED

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ABSTRACT: This paper describes an experimental program that was carried out on the behaviour of a mixture of silty clay with short synthetic fibres, randomly oriented. The influence of some fibre characteristics such as the percentage, length and surface texture (straight and crimped) on the shear resistance of reinforced silty clay was studied by means of direct shear laboratory tests. The fibre reinforcement effect on the compressibility of the silty clay was also studied by means of oedometer tests. The best procedure to mix soil and fibres in order to obtain the most efficient composite material is described. Both unreinforced and fibre-reinforced silty clay samples were tested with the same water content (17%) and their behaviour were compared. The results are clear, as far as the shear resistance is concerned: fibre reinforcement not only increases the shear resistance but also modifies considerably the shear stress-deformation behaviour of the silty clay. The shear resistance of reinforced silty clay increases with an increase of both fibre percentage and fibre length. No substantial advantages were obtained in the shear resistance of reinforced silty clay when using crimped fibres instead of straight fibres. The failure envelopes of the fibre-reinforced silty clay appear to be linear, which are similar to that of unreinforced silty clay. This study suggests that the optimum fibre length is of about 25 mm and the optimum fibre percentage lies between 0.25 % and 0.5 %.

1 INTRODUCTION

Reinforcing the soil with tensile resistant materials is a very old technique used by our distant ancestors. Different reinforcing elements, convenient oriented and spaced have been used all over the world to improve the resistant characteristics of the soil. However, in more recent years, increasing attraction has been given to randomly oriented reinforcing elements of smaller size. The soil mixed with this type of reinforcement elements at random way results in which appears to be a very promising material suitable for a great variety of applications, presently not yet properly explored. This material is usually designated by Microreinforced soil (Pinto, (2000)).

The reinforcement elements intend somehow to be a manmade copy of the vegetation and therefore they are expected to perform similar tasks of the roots on the reinforcement of the soil. Reinforcing elements can have a variety of forms, such as mesh, fibres or continuous filaments and can be made of either of a synthetic or natural material. They can also be rescued materials from non hazards waste materials (Pinto, (2000)).

In the present study, short, monofilament and randomly oriented polypropylene fibres are used to reinforce a cohesive soil. The main objective of the investigation described in this paper (and described in more detail in Falorca (2002)) was the study of the benefits of the straight and crimped synthetic fibres on the shear resistance of a reinforced silty clay. The influence of fibre percentage and fibre length was also investigated.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 *Materials*

The soil used in the tests is a cohesive soil, that was initially air dried, and it was further prepared by removing all material retained on the 2.38 mm sieve. It is classified as a silty clay of low plasticity (CL-ML), according to USCS classification (ASTM D 2487). The main characteristics of the silty clay used in this study are summarised in Table 1.

The synthetic fibres are made of polypropylene and are used for producing nonwovens geotextiles. They were cutted from long monofilaments with circular cross section and fibre surface both with straight and crimped texture and were supplied by a local manufacturer. The fibres were cut to nominal lengths of about 25, 50 and 100 mm. Two different percentage of fibres were used to reinforce the clayey samples: 0.25% and 0.5% (by the dry unit weight of the soil). Both physical and mechanical properties of the fibres are summarised in Table 2. The mechanical properties of the fibres were determined in laboratoty during the study programme, while the physical properties were provided by the manufacturer.

Table 1 Silty clay properties

Property	CL-ML
Specific gravity, G_s (-)	2.78
Percent finer than #200 sieve (%)	53
Liquid limit, w_L (%)	23
Plasticity index, I_P (%)	7
Soil friction angle, ϕ' (º)	38
Cohesion, c' (kN/m^2)	30

Table 2 Fibre properties

Property	Fibres
Specific gravity, G_f (-)	0.91
Denier (g/ 9000 m)	6
Tensile strength, σ_t (MN/m^2)	200
Young's modulus, E (GN/m^2)	1.5
Elongation at break, ε_f (%)	300
Moisture absorption (%)	0
Colour	White

2.2 *Preparation of test samples*

It was found to be very difficult to prepare homogeneous and isotropic mixtures of soil with fibres for laboratory testing. Preparation of polypropylene fibre-reinforced soil samples requires special procedures. This in fact is also recognised by several authors such as Gray & Al-Refeai (1986), Freitag (1986), Maher & Gray (1990), Maher & Ho (1994), Ranjan et al. (1994), Nataraj & McManis (1997), Morel & Gourc (1997), Gregory & Chill (1998), Santoni et al. (2001). Three critical phases can be identified along the preparation of microreinforced soil samples: selection of water content, mixing procedure and compaction and moulding procedure. Based upon both the experience gained from preliminary unpublished investigations and the results reported in the literature, the following methodology was adopted for preparation of microreinforced samples.

First, the bulk of silty clay required to perform the experimental study was moistened into a plastic state of consistency in order to adequately mix and mould the microreinforced soil samples. If fibres are mixed in dry soil, a floating tendency of fibres during the mixing process and fibre segregation when the mix is transferred to a mould would be observed.

In the second step, the necessary quantity of fibres were added to the hydrated silty clay. The fibres which were previously separated by hand were afterwards uniformly spread over the soil layer, and that procedure was repeated layer by layer until all the soil and fibres have been added. Further mixing by hand needs to be carefully made until the fibres are finally uniformly distributed and randomly oriented throughout the soil. Both fibre length and fibre percentage affect the mixing time, independently of the fibre texture. Fibre lengths of 100 mm and fibre percentages of 0.5% were found to be the upper limits for the mixing procedure, as far as the practical aspects are concerned.

Finally, the fibre reinforced and unreinforced samples needed to be compacted, which was done in accordance with the procedure described for the standard Proctor test. It was found to be very difficulty to compact the unreinforced silty clay with a water content of 17% due to its plastic state of consistency. The presence of fibres altered dramatically the compaction behaviour as the fibre-reinforcement improved the workability of the soft hydrated silty clay. On the other hand, the fibre-reinforcement did not have a significant effect on the dry unit weight of the silty clay as it can be seen in Figure 1. Similar conclusions have been reported by Maher and Ho (1994), Nataraj and McManis (1997) and Dall'Acqua et al. (2000). Figure 1 presents some compaction test results and it shows that within the range of fibre percentages used, the dry unit weight of the microreinforced silty clay does not differ significantly from that of unreinforced silty clay.

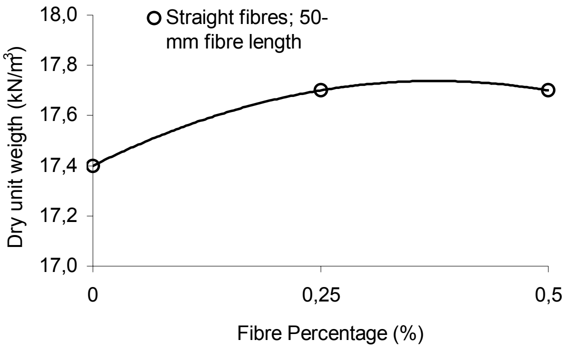

Figure 1 Effect of fibre percentage on the dry unit weight of silty clay moulded with a water content of 17%.

The standard method of compaction using a standard Proctor rammer (50 mm diameter face) seems not be indicated for polypropylene fibre-reinforced silty clay and further experimental work is therefore desirable to determine the best compaction technique for ideally homogeneous samples in order to minimise any disturbance (damage, shear distortion and reorientation of the fibres) during moulding the reinforced soil.

Test samples were cut from extruded fibre-reinforced and unreinforced compacted silty clay samples by using standard sample cutters and trimmed straight for direct shear and oedometer laboratory tests.

2.3 *Laboratory tests*

Some laboratory tests were carried out in order to perform a parametric study on the influence of the fibre length, fibre percentage and fibre surface texture (i.e., straight and crimped fibres) on the behaviour of the silty clay. In this study, only direct shear tests are considered to determine the shear resistance of reinforced and unreinforced silty clay samples. Although the direct shear test has numerous limitations and intrinsic errors, the simplicity of the test and availability of equipment have made it a widespread test. These shear tests were not intended to simulate field conditions but to provide a way of measurement for comparison purposes. Both unreinforced (control) and synthetic fibre-reinforced silty clay samples were saturated and tested in a 60 mm square standard direct shear apparatus. Consolidated drained tests were carried out up to a total displacement of 10 mm at normal stresses ranging from about 100 to 300 kN/m^2 and at a constant shear displacement rate of 0.5 mm/min. 10 mm is the maximum total shear displacement allowed from the shear apparatus, which corresponds to about 17% strain. The selected normal stresses are larger than the preconsolidation stress induced by the compaction process and therefore it can be assumed that the samples are normally consolidated during the test.

The one-dimensional consolidation behaviour of both fibre-reinforced and unreinforced silty clay samples was studied by means of oedometer tests, using a consolidation cell of the fixed ring type (cutting ring), with internal diameter of 63.5 mm and 20 mm height.

3 ANALYSIS OF TEST RESULTS

3.1 *Shear strength of fibre-reinforced silty clay*

The shear stress-deformation behaviour of polypropylene fibre-reinforced silty clay is considerably different from that of unreinforced silty clay as Figure 2 clearly shows. The normally consolidated unreinforced silty clay shows a well known behaviour with an increasing resistance to shear with shear displacement until a constant shearing resistance is developed, usually at a shear strain of about 10%. However, fibre-reinforced silty clay shows a shear resistance always increasing up to the maximum deformation allowed from the shear apparatus. This increasing trend for the shear resistance seems to be caused by a progressive tensile mobilisation of the fibres when the reinforced silty clay is subjected to shear deformations. Figure 2 also shows that the fibres increased the shear resistance developed at all shear displacements, even at very small displacements, which confirms the ability of the fibre-reinforcement to strengthen the soil. There is no evidence that the fibres suffer rupture during shear, actually, it seems that they just stretch.

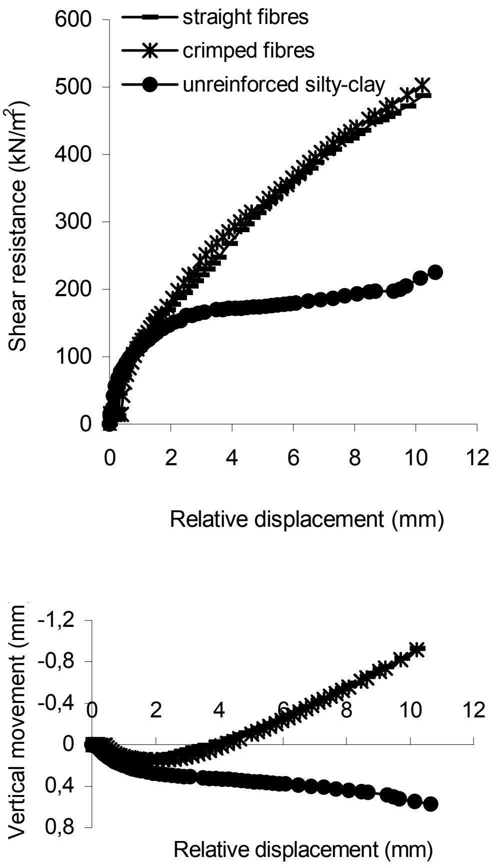

Figure 2 Shear resistance- displacement -volumetric relationships (0.5% fibre percentage; 50 mm fibre length; 229.62 kN/m^2 normal stress).

The fibres also modify the volumetric deformation of the silty clay during shear. A typical vertical movement during shear versus relative displacement for unreinforced and fibre-reinforced silty clay samples is plotted in Figure 2. While on normally consolidated unreinforced silty clay the well known curve shows a progressive decrease in the volume during shear, on fibre-reinforced silty clay, although it starts also by decreasing its volume, short afterwards it starts exhibiting dilation behaviour with shearing. Greater dilation was observed as the fibre length and fibre percentage increases. The increase of volume is likely to be caused by the enlargement of the active zone under shear, which occurs as the fibres are progressively mobilised during shear (Benson and Khire 1992).

Figure 3 represents the Mohr-Coulomb failure envelopes for unreinforced and fibre reinforced silty clay for a fibre percentage of 0.5% and 50 mm length. Failure has been defined as corresponding to 15% shear deformation. It is very clear that the fibre reinforcement significantly improves the shear resistance of saturated silty clay. The failure envelopes appear to be represented by straight lines within the selected range of normal stresses. The results show that there is an increase in both cohesion and peak friction angle values. The fibre-reinforcement effect on shear resistance of silty clay is more significant for low normal stresses.

3.2 *Effect of fibre percentage*

The effect of fibre percentage on shear resistance of reinforced silty clay is illustrated in Figure 4. It is clear that shear resistance increases with increasing fibre percentage. However, soil reinforced with different types of fibres show different behaviour: while for crimped fibres the resistance increases almost linearly, for straight fibres the relationship is not linear as the value of the resistance increases to a upper limit and then remains constant or even decreases. This upper limit is governed mainly by the normal stress level and fibre length. The results indicate that the optimum fibre percentage lies between 0.25 and 0.50% (of the dry unit weight of silty clay).

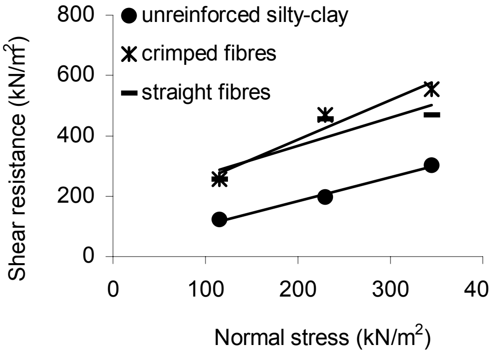

Figure 3 Mohr-Coulomb failure envelops (0.5% fibre percentage; 50 mm fibre length).

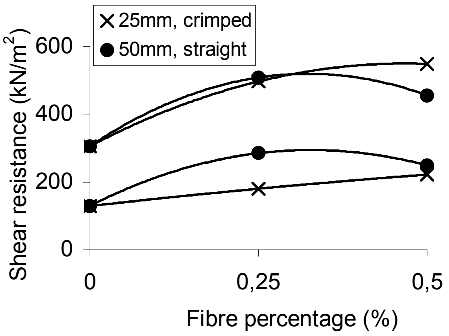

Figure 4 Shear resistance–fibre percentage relationships (114.81 and 344.43 kN/m^2 normal stresses).

3.3 *Effect of fibre length*

The shear resistance of reinforced silty clay increases with an increase in fibre length, as shown in Figure 5. However, for short lengths the increase of resistance is far more pronounced than for longer lengths (from 0 to 25 mm and from 25 to 50 mm, respectively). The results seem to indicate that fibre lengths beyond 25 mm didn’t significantly increases the shear resistance of the reinforced silty clay.

3.4 *Effect of fibre texture*

For the same fiber percentage and fiber length the increase in shear strength of the reinforced silty clay is quite similar when using both straight and crimped fibers. This can be observed by comparing the respective curves in Figure 2 and in Figure 3. These Figures show very close data for the two types of reinforcing elements. Therefore, it can be concluded that no appreciable advantage is gained in the shear resistance of reinforced silty clay by using crimped fibers.

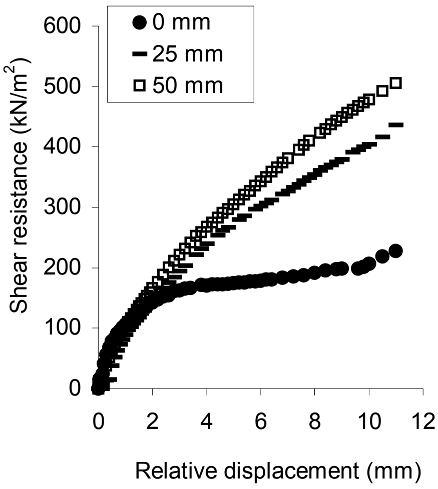

Figure 5 Shear resistance – displacement relationships (straight fibres; 0.25% fibre percentage; 229.62 kN/m^2 normal stress).

3.5 *Consolidation behaviour of fibre-reinforced silty clay*

The compressibility behaviour of fibre-reinforced and unreinforced silty clay is quite similar, as illustrated in Figure 6. For low vertical stress levels, the fibre-reinforced silty clay is deformed under one-dimensional compression and therefore there is no development of tensile strains, hence no tensile strength is mobilized in the fibres. For higher vertical stress levels, although the deformation is still under one-dimensional compression, it can be observed (Figure 6) a slight decrease in the compressibility of the silty clay when it is mixed with the fibres. It seems that this behaviour, consequence of the addition of fibres to silty clay, is due only to the occupancy of the part of the voids by the fibres hence to the direct affect on the voids ratio.

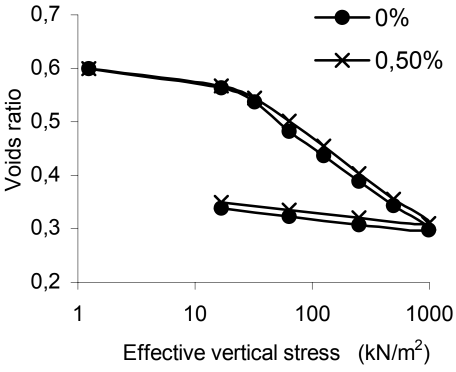

Figure 6 Voids ratio – log. effective vertical stress (25 mm fibre length; crimped fibres)

4 CONCLUSIONS

The direct shear laboratory tests on fibre-reinforced and unreinforced silty clay indicate that a substantial increase in shear resistance can be achieved with a small quantity of short, randomly oriented polypropylene fibres. Test results show that fibre reinforcement improves shear resistance and modifies shear stress-displacement behaviour of silty clay in a significant manner. An optimum fibre percentage seems to lies between 0.25 and 0.50%. Doubling-up the length of fibres from 25 to 50 mm had no important effect on the shear resistance of the reinforced cohesive soil. No significant increase of the resistance was found between straight and crimped fibres although the later fibres are far more difficult to mix homogenously than the former fibres. The compressibility behaviour of fibre-reinforced and unreinforced silty clay is quite similar. The results presented in this paper are not conclusive and therefore further studies are needed. This is especially important as far as the specimen size is concerned. A larger specimen size would be expected to be more suitable to investigate the influence of fibre properties on the behaviour of the silty clay.

5 ACKNOWLEDGEMENTS

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