

Residual shear strength of sandy clay reinforced with short polypropylene fibres randomly oriented

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ABSTRACT: This paper describes an experimental program that was performed on mixtures of sandy clay with short length synthetic fibres, randomly oriented, in order to understand the effect of fibres on the shear strength behaviour of such materials. The effect of fibres was studied by means of direct shear tests as well as ring shear tests. Both unreinforced (control) and fibre reinforced samples were tested with the same water content (17%) and their behaviour was compared. The results clearly indicate that fibre reinforcement increases the shear strength and modifies significantly the shear stress-displacement behaviour of the soil. Increases in shear strength higher than 20% were observed. The increase in shear strength of soils due to fibres depends on the shear displacement induced. The study also indicates that during shear deformation the fibre orientation varies, which influences significantly the increase of shear strength of fibre reinforced soils.

1 INTRODUCTION

Over the recent years, attraction has been given to mixtures of soil and small size reinforcing elements, as it appears to be a very promising material for a diversity of applications, presently not properly explored. The combination of soil and small size reinforcing elements is usually designated by Microreinforced soil.

Previous studies on Microreinforced soils have shown significant improvement of the shear strength (Pinto 2000, Falorca 2002). However, these studies have been restricted to small to large shear strains (from about 0.1 to 20%) due to the limitations of the equipment used. In order to better describe the shear strength behaviour of Microreinforced soils, it is essential to know the full shear stress-strain curve, including not only the eventual peak but also the residual value reached after large and very large shear strains respectively. Until now, no attempt was made for the development of a comprehensive experimental study to describe the full shear stress-strain behaviour of Microreinforced soils with extensible elements.

In the investigation described in this paper, short, monofilament and randomly oriented polypropylene fibres were used to reinforce a cohesive soil. The test materials, experimental procedure and analysis used in the investigation are presented. The main objective was to compare the strength and deformation behaviour

of unreinforced and fibre reinforced sandy clay from small to very large shear displacements. This is to determine the influence of fibre reinforcement on the strength behaviour, by clarifying how far the improvement of strength would be expected to occur.

2 TEST MATERIALS

The soil used in the tests was a cohesive soil, air dried, with all particles smaller than 2.38 mm. It is classified as sandy clay of medium plasticity (CL), according to the USCS classification (ASTM D 2487). The main characteristics are summarised in Table 1.

Table 1. Soil properties.

Property	Clay
Specific gravity, G_s (-)	2.78
Percent finer than #200 sieve (%)	53
Liquid limit, w_L (%)	35
Plasticity index, I_p (%)	19
Soil friction angle, ϕ' (°)	33
Cohesion, c' (kN/m ²)	8.5

The synthetic fibres are made of polypropylene and are used for producing nonwovens geotextiles. They were supplied by a local manufacturer in the form of long monofilaments with smooth surface and

circular cross section. The fibres were cut to nominal lengths of about 25, 50 and 100 mm. The percentage of fibres used to reinforce the clay samples was determined by the dry unit weight of the soil. Two different percentages of fibres were studied: 0.25% and 0.5%. Both physical and mechanical properties of the fibres are summarised in Table 2.

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

3 EXPERIMENTAL PROGRAM

The experimental program was performed on mixtures of sandy clay with short synthetic fibres, randomly oriented, in order to establish the effect of fibres on the shear strength behaviour of such materials. Fibre reinforced samples were prepared by hand mixing the fibres with hydrated sandy clay (with water content of 17%). The methodology for preparation of test samples is similar to that described in Falorca and Pinto (2004) and described in more detail in Falorca (2002). The effect of fibre percentage and fibre length was studied by means of direct shear laboratory tests. The effect of fibres when larger shear displacements take place was studied by means of ring shear tests.

3.1 Direct shear tests

Direct shear laboratory tests were carried out in order to perform a parametric study on the influence of fibres on the behaviour of reinforced sandy clay. Although the direct shear test has numerous limitations and inherent errors, the simplicity of the test and availability of equipment have made it a widespread test. These tests were not intended to simulate field conditions but to provide a way of measurement for comparison purposes. Both unreinforced (control) and fibre reinforced soil samples were saturated and tested in 60 mm diameter shear box using a standard direct shear apparatus. Consolidated drained tests were carried out up to a total displacement of 10 mm at normal stresses ranging from about 35 to 295 kN/m² and at a constant shear displacement rate of 0.04 mm/min. 10 mm is the maximum total shear displacement allowed from the shear apparatus, which corresponds to about 20% 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.

3.2 Ring shear tests

A ring shear apparatus developed by Bromhead was used in this study. An unlimited and continuous rotational shear displacement can be applied to the fibre reinforced soil with an area of shear remaining constant throughout the whole test. The ring-shaped sample has an outer and inner diameter of 100 and 70 mm respectively, and a thickness of 5 mm. This size is suitable for testing very fine soils according to Pinto, 1987. To test fibre reinforced soils, it was considered important to increase the roughness of the porous plates at top and bottom of the sample in order to avoid slippage between fibre reinforced soil and porous plates. Therefore the replacement of the porous plates was made and this allowed the increase of the sample thickness from 5 to 7 mm.

Both unreinforced and fibre reinforced samples were saturated, consolidated and sheared at a constant shear displacement rate of 0.036 mm/min. The testing method consists of shearing individual samples for each normal stress level. The normal stresses were selected taking into consideration the results of direct shear tests. These results show that the effect of fibres on shear strength of soil is more significant at low normal stresses (lower than 150 kN/m²).

4 ANALYSIS OF TEST RESULTS

4.1 Shear strength behaviour

The shear stress-displacement behaviour of polypropylene fibre reinforced sandy clay is quite different from that of unreinforced sandy clay as Figure 1 demonstrates. Normally consolidated unreinforced soil shows a well known curve with increasing shear resistance with shear displacement until a constant value is reached (usually at a shear strain of 10%). On fibre-reinforced soil the shear stress is always increasing up to the maximum deformation allowed by the shear apparatus. It seems that this increasing

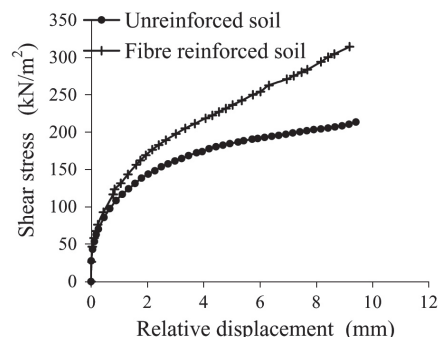


Figure 1. Shear stress - displacement relationships (0.5% fibre percentage, 50 mm fibre length, 294.84 kN/m² normal stress).

trend is due to a progressive tensile mobilisation of the fibres during shear. Figure 1 also indicates that the fibres increase the shear strength from the very beginning of shear, which confirms the ability of the fibre reinforcement to strengthen the soil.

The fibres also modify the volumetric deformation of the sandy clay during shear, and that is shown in Figure 2, for unreinforced and fibre reinforced sandy clay. While on normally consolidated unreinforced soil there is a well known progressive decrease in the volume during shear, on fibre reinforced soil the volume starts by decreasing and then it changes and it starts exhibiting dilation behaviour. The increase in dilation is likely to be due to the enlargement of the zone active in shear that occurs as the fibres are mobilised.

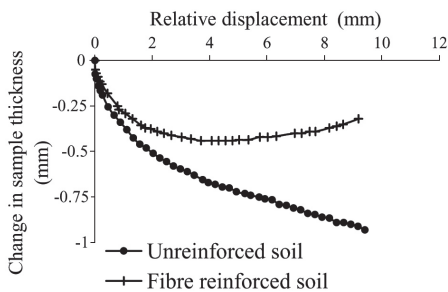


Figure 2. Change in sample thickness - displacement relationships (0.5% fibre percentage, 50 mm fibre length, 294.84 kN/m² normal stress).

The shear strength of unreinforced and fibre reinforced sandy clay was determined by a limiting deformation criterion. The values corresponding to 5%, 10% and 15% deformation are read off in Figure 1 and the ratio of increase in shear strength determined. The results are plotted and shown in Figure 3. The ratio of increase in shear strength is defined as:

$$\frac{\Delta\tau}{\tau_0} = \frac{\tau_f - \tau_0}{\tau_0}$$

Where, τ_0 = shear strength of unreinforced soil,
 τ_f = shear strength of reinforced soil.

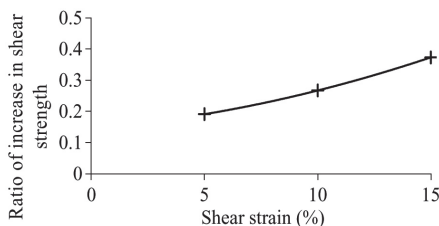


Figure 3. Relationship between ratio of increase in shear strength and shear strain (0.5% fibre percentage, 50 mm fibre length, 294.84 kN/m² normal stress).

It was found that fibre reinforcement improves the shear strength of soft sandy clay and the level of improvement was related to the deformation levels induced in the soil: the shear strength increases progressively with increasing shear strain. Increases of the shear strength higher than 20% were observed during the experimental program. Similar increase values, based upon the shear strength parameters, using fibre reinforcement, were reported by other researchers (Gregory and Chill 1998, Maher and Ho 1994, Nataraj and McManis 1997).

4.2 Very large shear displacement

It is important to clarify how far the improvement of the shear strength would go. Ring shear tests were performed in order to verify whether or not the improvement of strength would continue up to a certain threshold deformation value decreasing eventually afterwards. The results of ring shear tests on unreinforced and fibre reinforced sandy clay are shown in Figure 4. The shear stress-displacement behaviour of unreinforced and fibre reinforced soil is similar to that shown in Figure 1, up to the maximum deformation allowed by the direct shear apparatus.

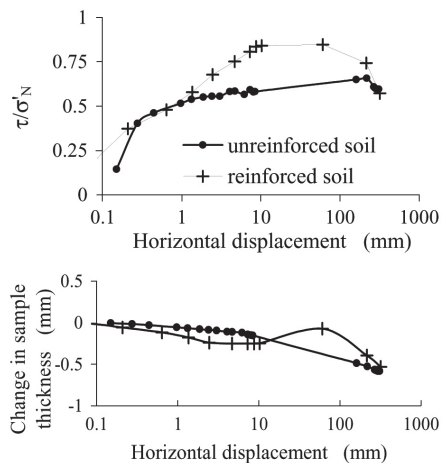


Figure 4. Shear strength coefficient - displacement - volumetric relationships (0.25% fibre percentage, 25 mm fibre length, 57.72 kN/m² normal stress).

It was expected that the effect of fibres in the increase in soil shear strength will diminish for very large horizontal displacements due to evolution of the fibre orientation during shearing. The influence of the initial orientation of fibres on the increase of shear strength is well recognized (Gray and Ohashi 1983, Gray and Al-Refeai 1986, Jewell and Wroth 1987, Michalowski and Cermák 2002). In fact, the results of ring shear tests shown in Figure 4 seems to indicate that the progressive strength increase shown in Figures 1 and 3 is an outcome of the evolution of

the fibre orientation. The shear strength of fibre reinforced soil at the initial stages is very close to that of unreinforced soil. However, after this small deformation (of about 1 mm) the shear strength starts to show an increase significantly higher than that observed for the unreinforced soil, up to a maximum shear strength. This maximum value seems to be reached when the horizontal displacement is of about the fiber length. After this maximum the shear strength decreases and finally approaches the same value as that measured for the unreinforced soil.

During the ring shear tests it was observed extrusion of some of the soil particles, on both unreinforced and reinforced soils. The soil particles come from the gap between the two parts of the cell as can be seen on Figure 5. Nevertheless, this extrusion was significantly more important on the unreinforced soil than on the reinforced soil, because the fibres managed to hold the soil particles inside.

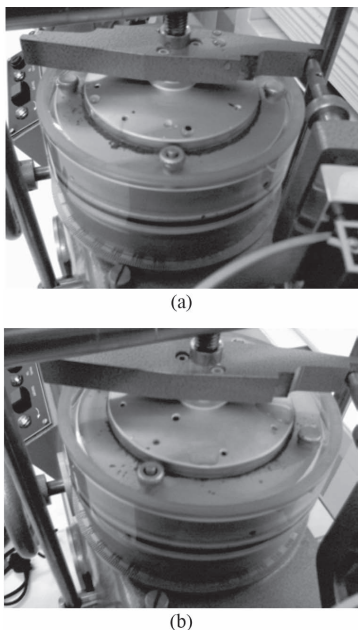


Figure 5. Soil extrusion of (a) unreinforced and (b) fibre reinforced samples, after 10 mm of horizontal displacement.

5 CONCLUSIONS

The results of laboratory tests on fibre reinforced and unreinforced sandy clay indicate that a substantial increase in shear strength can be achieved with a

small amount of short, randomly oriented polypropylene fibres. The increase in shear strength of soils due to fibres depends on the shear displacement. The fibre orientation varies during shearing, which influences significantly the increase of shear strength of fibre reinforced soils. The proposed work also contributes to a better understanding of fibre reinforced soil behaviour at the residual state. The results presented in this paper are not conclusive and further studies are needed.

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