The undrained mechanical behaviour of a fibre-reinforced heavily over-consolidated clay.

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ABSTRACT

The benefits of micro-reinforcement in soils have attracted a lot of research in the last couple of decades. However, not enough is known about the effects of the compaction procedure used to prepare samples in the laboratory.

This paper presents data from laboratory undrained triaxial tests on reinforced and unreinforced samples of heavily over-consolidated clay from the Lambeth Group. The samples were prepared by chopping the in-situ natural soil into small peds (typically 10 to 20mm) so that some of the in-situ characteristics of the natural soil would be retained. The soil peds were then dynamically compacted with and without the addition of fibres. Undrained triaxial tests were carried out using 100mm and 38mm diameter triaxial samples. The results presented have shown that the addition of reinforcement appear to cause a shift of the One Dimensional Normal Compression Line (1-D NCL) of the reinforced material.

The undrained shearing behaviour of the reinforced and non-reinforced soil is also analysed and conclusions drawn.

Fibre alignment studies were also conducted, indicating that the majority of the fibres are aligned within ±20º with the horizontal plane while more than 50% are oriented within ±10º. This preferred orientation is believed to be caused by the compaction method used to prepare the samples.

1. INTRODUCTION

The use of tensile elements within the soil mass was introduced more than 3,000 years ago by the Babylonians. They used intertwined palm branches to reinforce the "ziggurat" temple (Jha and Mandal 1988).

A similar procedure was followed by The Romans who built retaining walls by placing timber baulks perpendicular to the face of the walls. More recently, in 1822, Colonel Pasley introduced, in the British Army, a form of reinforced soil where the backfill was reinforced by horizontal layers of brushwood, wooden plants or canvas.

In the 1930s, the modern concept of soil reinforcing was proposed by Casagrande who idealised the problem in the form of a weak soil reinforced by high-strength membranes laid horizontally in layers. However, it was Vidal, in the 1960s, who investigated this field in detail. Vidal's concept was to lay flat reinforcing strips horizontally in a frictional soil, as this enabled the interaction between the soil and the reinforcement to create a friction force to hold the soil in place (Colin 1996). Reinforcing soils with tensile elements is still a common practice in many developing countries where soil and straw are mixed to be used as a construction material.

This paper presents data from laboratory undrained triaxial tests on laboratory-compacted Lambeth Group clay reinforced with polypropylene fibre. Extensive research has been performed on reinforced sandy soils with numerous types of fibres; however, there is a lack of knowledge in understanding the effects of discrete fibre reinforcement on heavily over-consolidated clays and the effects of in-situ mixing and compaction techniques in the response of the composite soil. This will provide effective guidance in the construction and remediation of slope failures and the widespread use of this type of reinforcement as an effective way to reduce maintenance works and costs on road embankments and cuttings. Improvements in soil characteristics using micro-reinforcement will also lead to a more sustainable way of using unsuitable soils.

The main objectives of this paper are as follows:

- To characterise and understand the undrained behaviour of compacted clay peds with and without reinforcement.
- To map the alignment of fibres generated by the compaction of clay peds in the laboratory and in-situ.

2. BACKGROUND

Consoli et al. (2005) studied the behaviour of polypropylene fibre-reinforced sand under isotropic compression and observed that the inclusion of fibres into sand can change isotropic compression behaviour. They also identified two distinct and parallel compression lines for the fibre-reinforced and non-reinforced sand. Similarly, Santos et al. (2010) assessed the behaviour of the host soil and that of the fibre-reinforced soil and concluded that, in volumetric space, the NCL of the sand-fibre material lies above that of the host sand, and parallel to it.
In a similar study Li (2005) assessed the mechanical response of fibre-reinforced clay by carrying out Consolidated Undrained (CD) tests and concluded that fibre-reinforcement restrains the volume dilation that leads to an increase of the excess pore water pressure in undrained conditions. The author also concluded that an increase in the deviator stress due to fibres is not as obvious as in the case of sand. In addition Ozkul and Baykal (2007) investigated the influence of rubber fibre inclusion on the strength and shear behaviour of clay under different loading conditions; the contribution of fibres to the strength of clay was found to decrease with increasing level of confinement. Maher and Gray (1990) also studied the effect of confining pressure on the response of fibre-reinforced sand samples under static loads. The findings showed that there is a critical confining pressure beyond which the stress-strain behaviour of the sample changes from a curved profile to a linear envelope (or bilinear curve). It was found that the maximum increase in strength for reinforced sand occurred at confining pressures less than this critical value of pressure.
Researchers have presented contradictive results on the compaction parameters of fibre-reinforced soils. Research conducted by Rifai and Miller (2004) and Al-Tabbaa and Aravinthan (1998) on polypropylene-fibre-reinforced soils have shown that the addition of 0% to 1.0% (in weight of dry soil) fibres in soil does not produce significant effects on the magnitude of the dry density or the optimum moisture content of the composite. On the other hand, Cetin et al. (2006) and Prabakar and Sridhar (2002) have reported that the inclusion of any percentage of polypropylene fibres is found to reduce the maximum dry density and increase the optimum moisture content.
Further studies (Ozkul and Baykal 2006) on the effect of compaction on composite materials revealed that the ASTM Standard dynamic compaction process causes a preferential alignment of fibres in a parallel direction to the compaction plane. Similarly, a study by Ozkul and Baykal (2007) confirmed that the compaction process induces preferential alignment of fibres in a horizontal direction. This preferential alignment (±45 of horizontal) was found to be favourable for the improvement of shear strength because it does not coincide with the plane of maximum shear strain expected in a triaxial test. Correspondingly, Diambra et al. (2007) investigated the alignment of polypropylene fibre in sand. The samples were prepared using the moist tamping technique, which produces a soil-fibre fabric that resembles that of compacted reinforced soil in field. The distribution was found to be far from isotropic: typically 97% of fibres have an orientation that lies within ±45º of the horizontal plane.

3. EXPERIMENTAL PROCEDURE

3.1. Site and Sampling

For laboratory testing, disturbed samples were collected from an excavation located near junction 23 of the M25, north of London. Mouchel and the Highways Agency, industrial partners on this project, used polypropylene fibres to reinforce a slope in the site. In order to be able to retain natural properties of the collected samples for preliminary testing and to create laboratory compacted samples for triaxial testing the required amount of disturbed samples from the excavated soil were stored in sealed containers to avoid loss of moisture and associated loss of natural properties.
The soil used in this study was Lambeth Group clay, natural over-consolidated fissured clay. The Lambeth Group, which was previously known as the Woolwich and Reading Beds, formed in the London and Hampshire Basins, where it directly overlies the Chalk or Thanet Sand Formation, and is succeeded by the Harwich and London Clay Formations (Skipper 2009). The group features notable lateral and vertical lithological variations, which have contributed to a long history of engineering problems in London (Hight et al. 2004).

3.2. Characterisation Tests

Atterberg limits, specific gravity and particle size distribution were performed on the soil samples. These tests provided standard data for the soil which will be used in subsequent analyses.

The grain size distribution is fairly uniform with 95% passing 0.05mm, 85% passing 0.015, 60% passing 0.004mm and 46% passing 0.001mm (Figure 1). The soil is classified as inorganic clay of high plasticity (CH), according to USCS classification (ASTM D 2487).

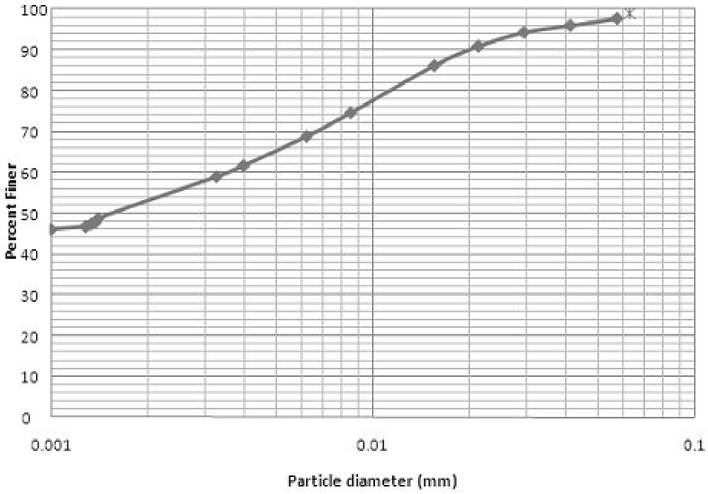

Figure 1: Grain size distribution of Lambeth Group clay tested

Table 1: Index properties of clay soil

Property	**Values**	**Unit**
Liquid Limit (wL)	59.5	%
Plastic Limit(wp)	24.1	%
Plasticity Index (Ip)	35.4	NA
Liquidity Index(IL)	0.01	NA
Particle Density (ρs)	2.65	g/ml

3.3. Fibre Properties

Most of the research on fibre-reinforced soils has made use of polypropylene fibres. It is the most commonly used synthetic material, mainly because of its low cost and environmental acceptability. The polypropylene fibres used in this investigation have a width of 4mm, length of 63mm and thickness of about 0.021mm. A summary of the properties of the fibres is presented in Table 2.

Table 2: Fibre Properties

Properties	**Values**
Specific gravity	0.91 g/cm3
Linear mass density	60 Denier*
Breaking tensile strength	350MPa
Elastic Modulus	3500MPa
Dispersibility	Excellent
Melting point	165 °C
Burning point	590 °C
Acid and alkali resistance	Very good
Moisture absorption	0 %
Breaking elongation	18%

*1Denier=1g/9000m

3.4. Sample Preparation

In order to simulate the in-situ compaction of heavily over-consolidated clays, the retrieved samples were chopped into small pieces of 10 to 15mm diameter (Photo 1). Compaction tests (Figure 2) were carried out to obtain the optimum moisture content (OMC) and the maximum density (MD). The results confirmed that there was no effect of fibres in the OMC and the MD of the soil, with the OMD being equal to 20.5% for the compacted samples and around 21.5% for the compacted soil with fibres. The maximum dry density of reinforced and non-reinforced compacted samples was found to be 1.70g/cm3 and 1.68 respectively (Figure 2).

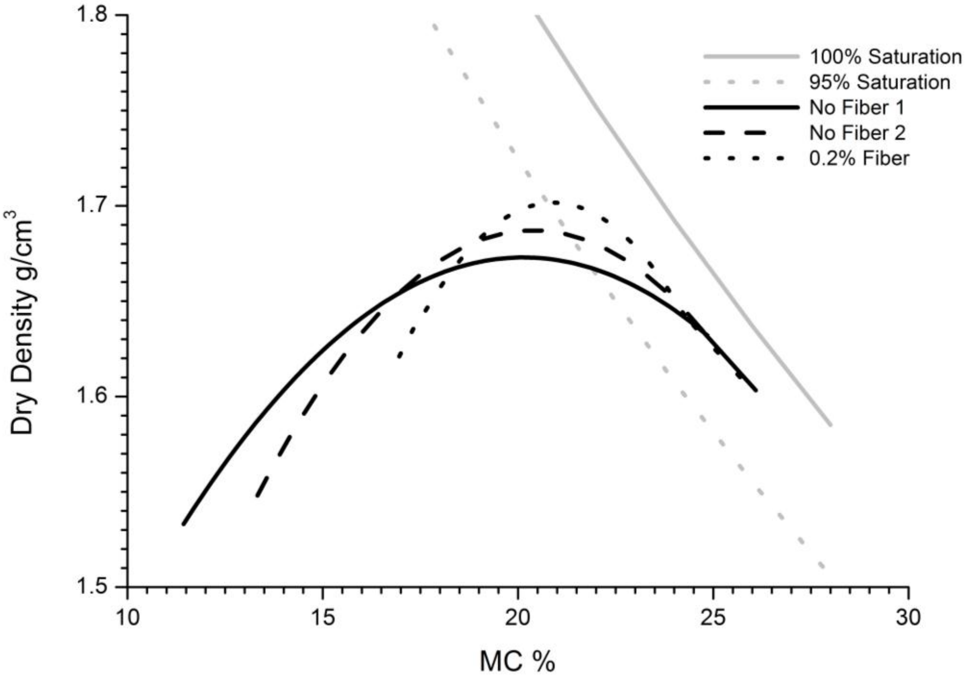

Figure 2: Compaction Curves of reinforced and non-reinforced samples

In order to achieve the desired moisture content, distilled water was sprayed onto the soil at regular intervals, over a period of several hours until reaching moisture contents 4% -5% higher than its respective optimum value. Following this, the clay peds were sealed in plastic containers in a controlled humidity room for several days, in order to achieve a homogeneous moisture content. There are two important reasons to follow such a procedure: a) to be able to retain some characteristics of the in-situ soil that will affect the mechanical response of the compacted soil; b) to create samples that will be representative of the in-situ behaviour of the compacted soil. The size of the peds was chosen to be 1/10 of the sample diameter, while in-situ size was similar to a golf ball.

Photo 1: Chopped clay peds in storage drum

A model proposed by Brackley (1975) considered that unsaturated clay soils exist as packets of soil particles, with each packet being completely saturated and the inter-pocket voids being filled with air (Figure 3). This meant that the soil mass was unsaturated whereas the individual soil packets were saturated. By assuming that the packets were saturated, Brackley developed the idea that the individual pockets retain the properties of the natural soil and the total volume change of the soil mass would be due to the summation of the effects of swelling or compression of the packets and their shear behaviour.

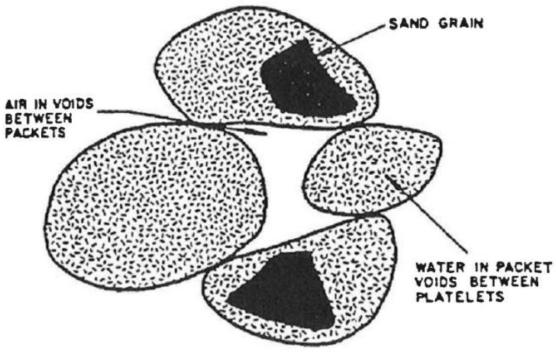

Figure 3: Model of unsaturated soil (Brackley, 1975)

This is one of the assumptions of this work; as you compact peds of heavily over-consolidated clay, the compaction energy is not enough to break shear them and therefore inter-pocket voids filled with air will be present in the compacted soil. The air pockets were assumed to be connected, therefore facilitating saturation; however initial saturation tests on compacted samples indicate that on the wet side of the optimum the saturation of the samples is faster, as would be expected.
All samples were compacted on a cylindrical mould with a diameter of 100mm and 200mm height, with a compaction effort equivalent to the light compaction described in the BS 1377-4:1990. The samples without reinforcement were trimmed down to 38mm diameter and 79mm height. These were tested on different Bishop Wesley triaxial equipment.
A similar methodology was followed in the preparation of reinforced samples. The main difference was the mixing procedure, where the entire mixing process was done manually by hand. The previously calculated weight of clay peds and fibre (0.2% of the dry weight of soil) were hand mixed in bag. As the fibres tended to lump together, considerable care and time was spent to get a homogeneous distribution of the fibres.

Photo 2: Reinforced sample compaction procedure

For the preparation of the oedometer sample a 77 mm diameter by 20 mm height ring was placed in a 100 x100 compaction mould and compacted by following the BS 1377-4:1990 light compaction procedure. In the preparation of the reinforced sample the author used fibre soil composite with 0.2% fibre content and moisture content at 5% wet of optimum.

3.5. Triaxial Testing

Undrained triaxial tests were carried out using two types of Bishop Wesley triaxial equipment, one capable of testing reinforced samples of 100x200mm and the other, more conventional, for samples of unreinforced soil of 38x79mm. Consolidation characteristics, stress-strain and pore pressure response of both reinforced and unreinforced samples were determined. Saturation was monitored in each test, ensuring B values of at least 0.98 for all samples. After saturation, the samples were isotropically consolidated under a back pressure of 320kPa to an effective confining stress between 50 to 500 kPa (table 3), in order to cover the range of stresses of most engineering applications. Local axial strains were measured using LVDT transducers as described by

Cuccovillo and Coop (1997). The shearing rates used during the shearing were calculated using the results of the consolidation stage (Table 3). In all tests, the effects of membrane and lateral drains were corrected.

Table 3: Specification of triaxial tests

Drainage Condition	Fibre Content	Size	Effective Stress	Weight	MC	Void Ratio	Shear Rate
	(%)	(mm)	(kPa)	(g)	(%)	NA	(%/hr)
CU	0	38	50	138.40	27.49	1.68	0.26
CU	0	38	100	183.08	24.26	1.59	0.08
CU	0	38	150	188.42	23.00	1.53	0.08
CU	0	38	300	185.36	25.30	1.55	0.04
CU	0	38	500	181.92	24.28	1.63	0.08*
CU	0.2	100	100	3456.50	26.47	1.68	0.2
CU	0.2	100	150	3474.50	21.67	1.61	0.15
CU	0.2	100	300	3400.00	25.85	1.70	0.05
CU	0.2	100	500	3500.00	24.40	1.63	0.02

*due to several failures of compressor during compression the stage shear rate has been estimated

3.6. Fibre Alignment

In order to verify the fibre alignment, samples with the same fibre and initial moisture content were dissected. The alignment of the fibres was observed by recording the X, Y and Z coordinates of one of the fibre ends. As the sample was dissected the horizontal and vertical angle of the fibre was determined. This procedure was followed for 100 randomly chosen fibres. A graphical representation of the procedure can be seen in Figure 4 while Photo 3 shows a series of snapshots of the sample being dissected.

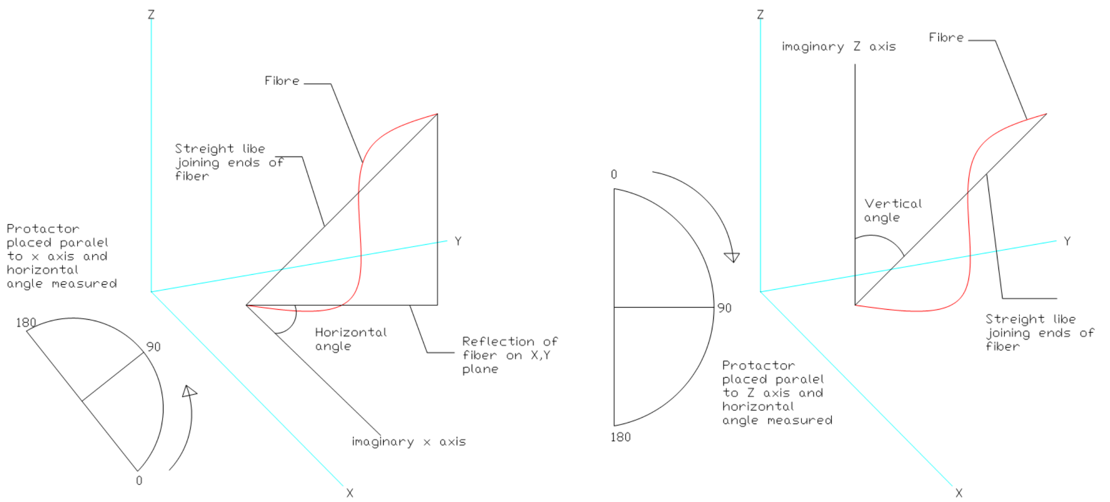

Figure 4: Method used in recording alignment of fibres in sample

Photo3: Extruding fibres from sample

The major challenge during this procedure was estimating the angles of the fibres which were circling peds, bent and overlapping others due to the mixing and compaction procedure.

4. RESULTS

4.1. Consolidation Characteristics

Figure 5 shows the results of the oedometer tests performed on reinforced and unreinforced compacted samples.

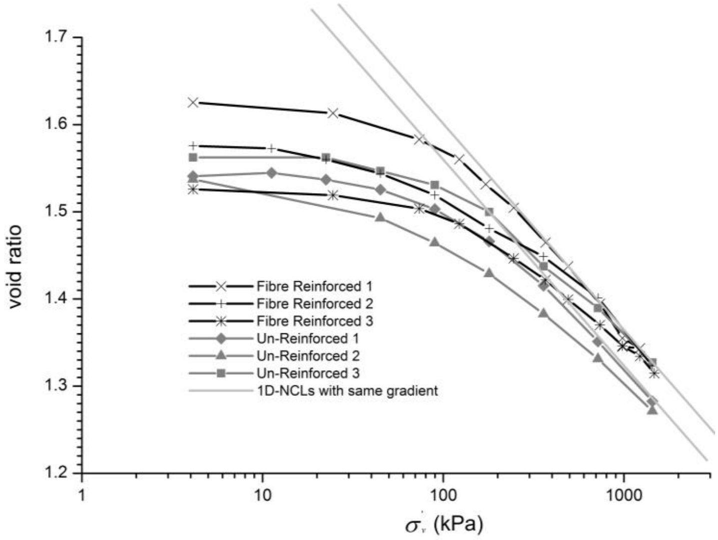

Figure 5: One-dimensional compression of fibre-reinforced and unreinforced clay samples

The oedometer test results appear to define two one-dimensional compression lines (1-D NCL); one for the reinforced soil and another for the un-reinforced soil. The two lines appear to be parallel, with a slope λ=0.114 and are represented by the two straight lines in Figure 5. Although the results appear to show different 1-D NCL for each type of material tested, the initial void ratio of the reinforced samples was not corrected to remove the effect of fibre inclusion. The authors believe that such correction would be minute but it should lower slightly the consolidation curves of the reinforced samples. It is also important to note that the methodology used to prepare the samples created similar initial void ratios, as described previously in the sample preparation. This fact reduces the confidence in the determination of a unique 1-D NCL for each material.

It is possible that a reinforced soil exists with a larger void ratio, due to the interlocking mechanism, created by the fibres. Dos Santos et al (2010) have seen this phenomenon in the isotropic compression of fibre reinforced sands.

4.2. Shearing behaviour

Figure 6 shows the stress-strain curves together with the changes in pore-pressure during the undrained shearing for all triaxial tests. Due to the long periods of time necessary for consolidation and shearing, the unreinforced samples were tested on 38mm triaxial equipment. Tang et al. (2008) have concluded that stress-strain curves of 38mm and 100mm samples are coincident for clay materials; however, Bishop and Little (1967) have shown that for a natural material, such as London Clay, planes of weakness are more evident in the preferred failure direction. The authors have shown that the strength of 38mm samples can reach values of the order of 1.5 times the strength of 100mm samples.

All tests have shown the same strain softening behaviour regardless of the reinforcement. However, with the unreinforced samples, a shear plane was observed in the samples tested with a confining stress of 150kPa and higher, while barrelling was observed for the lower stresses. All the fibre-reinforced samples have shown barrelling. According to Ozkul and Baykal (2007) this behaviour is linked to the fibres crossing the shear zone and restricting the development of a slip plane by transferring some of the shear stress and strains to zones further away.

Another important difference between the stress strain behaviour of reinforced and non-reinforced samples, is that the latter show no reduction of deviatoric stress for the range of confining stresses used, while the non-reinforced samples have shown a long peak for the higher confining stresses, followed by a continuous reduction of the deviatoric stresses. Even after 20% axial strain, there is no evidence that the samples will reach a constant deviatoric stress.

Although the non-reinforced samples reach higher effective stresses, this is not the case for the test performed with 100kPa of confining stress where the reinforced sample reached a higher strength.

The change in pore-pressure shows a similar behaviour although for smaller stresses it shows a peak, decreasing afterwards.

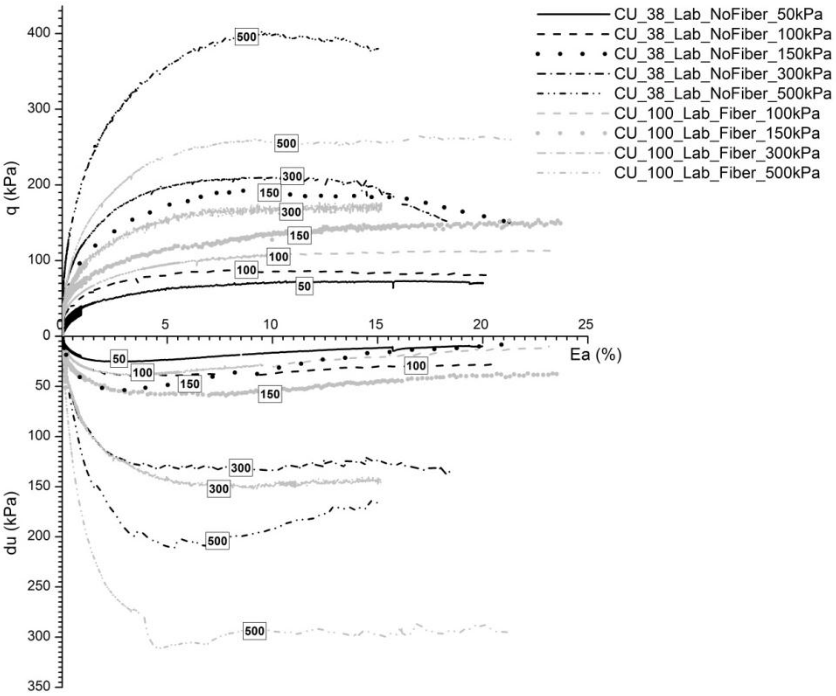

Figure 6: Stress-strain pore-pressure response of Lambeth Group clay and fibre-reinforced clay samples

The pore water pressure generated within the soil sample, which is related to the contractive or dilative tendencies of a soil during shearing, was consistently higher for the reinforced samples. Li (2005) attributed this increase in pore pressures to the fibres distributing stresses within the soil mass and, therefore, increasing the contractive deformations within the fibre-soil matrix. The pore-pressure distribution is also consistent with the study on the pore-pressure distribution at failure, conducted by Sandroni (1977). According to the author, the shear plane is associated with an increment of pore water pressure in the middle of the sample, evidenced only in the unreinforced samples, as the reinforcement provides restrain to the development of shearing surface.

4.3. Fibre alignment

The methodology described previously was used to desiccate 10 samples reinforced with 0.2% of fibres. All samples were prepared with the same initial moisture content. The results showed that nearly 80% of the fibres are located within ±20º with the horizontal plane and 51% are aligned within ±10º. This is a consequence of the sample preparation procedure since the fibre length is longer than the thickness of a compacted layer in the sample (Figure 7).

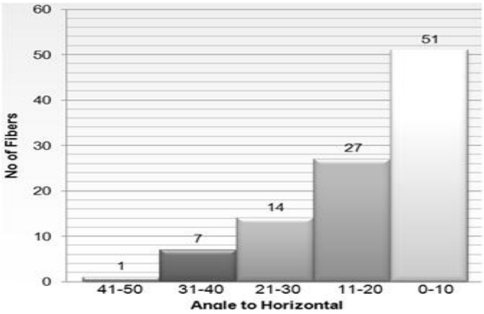

Figure 7: Alignment of fibres

The results are in agreement with Diambra et al. (2007), Ozkul and Baykal (2006) and Ozkul and Baykal (2007). These authors have also concluded that compacting soil-fibre mixtures during sample preparation leads to a preferential alignment of the fibres in a horizontal direction. Figure 8 shows a graphical representation of the fibre distribution on a dissected sample.

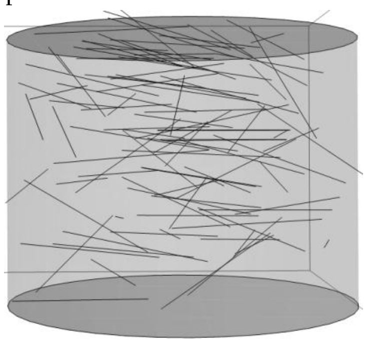

Figure 8: 3D orientation of the fibres on a dissected sample

5. CONCLUSIONS

As can be seen from the 1-D compression tests, the use of reinforcement appears to shifts the 1-D NCL of the reinforced soil to the right of the 1-D NCL of the non-reinforced soil. Although this behaviour have been seen before in isotropic tests on sands, more tests on these composite materials are necessary, as these are within the tolerance margins used to determine the void ratios.

During shearing the deviatoric stress of all reinforced samples reaches a constant value while for the non-reinforced samples, tested at 150, 300 and 500kPa, the deviatoric stress decreases with strain. A similar trend was found for the pore-pressure; the reinforced samples reach constant values of pore water pressure while in the non-reinforced samples, pore water pressure reduces after reaching a peak value.

The measurements performed on the fibre alignment have shown that nearly 80% of fibres are aligned within ±20º with the horizontal plane. This alignment is caused by the sample preparation procedure as the fibre length is higher than the compaction layer.

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