

Undrained Behaviour of Clay Reinforced with Surplus Carpet Fibres

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Abstract

A collaborative research programme between University of Bolton and Bradford University is investigating the effect of surplus carpet fibres on the strength as well as other important geotechnical properties of cohesive soils. Initial work concentrates on the manner in which the fibres affect the quick undrained properties of the reinforced soil. Four different surplus carpet fibre types are being used during the study (most popular in United Kingdom) mainly containing fibres from “top-finishing” and “shredded segments” of carpets.

Relatively low plasticity index clay has been prepared using commonly available clay within the North-West Region of the UK. A series of quick undrained (UU) triaxial compression tests is scheduled for 76mm in height by 38mm diameter soil specimens reinforced with target concentrations of 1%, 5%, and 10% of ‘surplus’ carpet fibres (by dry soil mass) compacted at optimum water content for the light (2.5kg) BS1377 method. The mixing efficiency of the surplus carpet fibres within the cohesive soil is of critical importance alongside the methodology for preparing samples to a uniform standard for research purposes.

Later stages of the work intend to extend the investigation into effective stress path testing, exploration of practical methods of mixing and compaction in the field for civil engineering applications.

1. Introduction

The roots of soil fibre reinforcing can be traced in history of human kind to thousands of years ago. The remainder of houses built with thatch, plant roots and other natural fibres as reinforcing elements to prevent cracking in masonry materials proves this historical fact. Such buildings can still be found in some rural places where people use low strength fibre-like materials like straw to reinforce low strength masonry walls.

From past decades, the beneficial effect of fibres in geotechnical engineering and construction engineering has become a known fact to all engineers. Several researchers have utilised different fibres including natural fibres and/or synthetics for reinforcing problematic soils specially for increasing shear strength of low strength granular soils.

Fibres can be utilised for reinforcing soils either in continuous insert form (sheets like woven/non woven geotextiles, strips and bars) or as randomly orientated

discrete inclusions. The first method involves introducing oriented layers of planar sheets into several layers of soil. Although planar inclusions increase the shear strength of soil between successive layers and introduce 'tensile strength' into reinforced soil, they at the same time decrease the shear strength of the composite soil at the interfaces due to less bonding strength between planar inclusions and soil rather than soil against soil.

When failure occurs in continuous sheet systems it most probably happens first through the interface between the soil and planar inclusion. Moreover, in this method the orientation of fibrous inclusion, number of layers and distance between layers are also important for reinforcement purposes.

With randomly orientated discrete fibres, where fibres are spread over the whole volume of the reinforced soil randomly by virtue of the mixing process, there should not be any discernible planes of weakness in the reinforced soil.

2. Objectives and scope

Statistics show that there are about 400 million tones of waste produced annually in the UK of which 2% of its weight is attributed to textiles generally in the form of carpet waste. One of the reasons for concentrating on carpet wastes is because they have a high volume to weight ratio, so once they have been 'dumped' into landfills they occupy a larger volume than other materials of similar weight. Moreover, based on value of the energy and materials required to produce carpet, carpet waste accounts for almost £70 million of lost revenue per year in the UK. Additionally, measures intent on minimising the dumping of wastes in the environment and incurred taxation on wastes are forcing manufacturers to find new applications for any of their produced wastes [1 and 2]. This is further amplified by an annual increase in landfill taxation and also an estimated 2.5% annual rise in carpet production and hence the associated waste arising.

The current research aims to find the most efficient way of using surplus carpet fibres retrieved from pre-and-post consumer waste streams to reinforce weak shear strength clayey soils or low grade problematic soils, since the environmental and financial advantages of doing so are clear.

3. Review of Literature

The concept of reinforcing soils with randomly discrete fibres has received increasing attention over the past few decades (e.g. OB Andersland et al. 1979 [3]; Gray and Ohashi 1983 [4]; Gray and Al-Refeai 1986 [5]; Maher and Gray 1990 [6]; Al-Refeai 1991 [7]; Ranjan et al. 1996 [8]; Wang et al. 1997 [9]; Consoli et al. 1998 [10], 2003 [12]; Ghavami et al. 1999 [11]; Ghiasian et al. 2004 [13]; Arvind Kumar et al. 2004 [14] and Al-Akhras et al. 2008 [15]).

Andersland et al. (1979) used pulp fibres with a length of 1.6mm and diameter of 0.02 mm to reinforce Kaolinite rich clay. It was concluded that addition of fibre to Kaolinite specimen leads to higher ultimate compressive strength, failure strain and stiffness.

Gray and Al-Refeai (1986) compared the effect of both continuous, oriented fabric layers and randomly distributed fibres on stress-strain behaviour of dry sand. The research outcomes demonstrated that, both fabric reinforced and fibre reinforced specimens show an increase in peak shear strength, axial strain at failure and in most cases limited reduction in post peak shear strength with increase in amount of reinforcement.

Maher and Gray (1990) investigated the effect of confining pressure, soil granulometry (particle size, shape and gradation) and fibre properties (content, aspect ratio and modulus of elasticity) on the response of fibre-reinforced specimens under static loads. The results showed that there is a critical confining pressure beyond which the stress-strain behaviour of the specimen changes from a curved profile to a linear envelope (or bilinear curve). It was found that the critical confining pressure is a function of fibre aspect ratio, grain shape and gradation rather than fibre content and the amount of medium grain size. It was found that the maximum increase in strength for reinforced sand occurred at confining pressures less than this critical value of pressure. The critical confining pressure decreases with increase in fibre aspect ratio (L/d).

Al-Refeai (1991) studied the effect of three different fibres on fine and medium sands. He concluded that, fibres increase the peak principal stress of sand and this increase is proportional to the length of fibres. Ranjan et al. (1996) investigated the effect of synthetic and natural randomly distributed fibres on sandy soils. Their test results indicated that there is a critical confining pressure below which fibres tend to slip. The critical confining pressure is a function of fibre aspect ratio. They also concluded that the shear strength of the reinforced soil increases with increase in fibre inclusion.

Wang (1997) used recycled carpet waste fibres for reinforcing soil as well as concrete. He concluded that waste carpet fibres increase the compression strength of soil and its ductility. He reported that fibre reinforced specimens exhibited significant increases in peak stress up to 303%.

Ghavami et al. (1999) introduced the application of sisal and coconut fibres as reinforcing material into soil. They found that the strength of reinforced specimen with 4% fibre content increases slightly but its ductility improves

much more significantly in which the strain at failure increased from 4% to 25%.

Consoli et al. (2003) utilised polypropylene fibres with different lengths and diameters at various fibre contents to reinforce sandy soil. They concluded that at large strains, the reinforced-soil specimen showed a marked hardening behaviour up to the end of the test. They also concluded that the deviatoric stress of reinforced soil specimen increased with increase in fibre length, fibre aspect ratio and fibre content, whilst it decreased with increase in fibre diameter alone.

Ghiassian et al (2004) conducted a series of triaxial compression tests on sandy specimens reinforced with recycled carpet wastes in the form of short strips of carpets. They concluded that inclusion of strips results in increase in peak and ultimate compressive strength and ductility of sandy soil specimens.

Kumar et al (2006) investigated the effect of adding polyester fibres in to soft clay soil by means of unconfined compression tests (UCS). They reported that there was a significant increase in unconfined compressive strength of highly compressive clay due to addition of polyester fibres and also the rate of increase in UCS value of soil increased with increase in length of fibres.

Al-Akhras (2008) et al. investigated the effect of natural and synthetic fibres on the swelling properties of clayey soils. They concluded that an increase in the fibre content of both types of fibres reduced the swelling pressure and swell potential of the clayey soils significantly.

There are also several other published articles about soil fibre reinforcement which have not been stated here but will be referred to as current project results become available.

A substantial amount of research has been performed on reinforced sandy soils with fibres but there is a lack of study on effect of fibres, particularly of surplus carpet fibres, on the behaviour of clayey soils. The authors believe that soil and fibre mixing criteria and also soil specimen preparation play a key role for the effectiveness of fibre reinforcement. Therefore the current research focuses on effect of surplus carpet fibres on shear strength and other important properties of cohesive soils. In this research authors try to develop new methods for mixing issues as well as specimen preparation.

4. Materials





4.1 Fibres

The details of four waste carpet fibres used in this research are shown in Table 1. The first three wastes are provided by Carpet Recycling UK¹ while the 4th one is provided by Milliken Industries².

4.2. Soil

For the current study, clay with low plasticity from the North West of United Kingdom has been utilised. Table 2 shows the physical properties of the soil and Figure 1 shows the soil classification curve of the soil used in this study. All soil classification tests have been done in accordance with BS 1377-2:1990.

Table 1. Specification of Fibres used in this study

No.	Name	Description	Composition	Other Specifications	Photograph
1	GBF	synthetic carpet shred	60% polypropylene 20% SBR latex 15% nylon 5% wool	Length : 2 to 20mm Diameter: 0.1 to 1mm Specific Gravity: 1.30	
2	RBF	bitumen backed tile shred	65 % limestone filled bitumen 10% SBR latex 8% nylon pile 8% polypropylene pile 8% PET fibre glass backings	large shredded pieces of backing Specific Gravity: 1.52	
3	TBF	wool/nylon tufted shred	40% wool 25% SBR latex 25% polypropylene 10% polyethylene	Length : 2 to 5mm Diameter: 0.2 to 0.4mm Specific Gravity: 1.34	
4	ABF	short fibres from shearing process	100% Nylon	Length : 2 to 5mm Diameter: 0.2 Specific Gravity: 1.31	

¹ www.carpetrecyclinguk.com

² <http://www.millikencarpeteurope.com>

5. Testing Program

The current report is based on preparation and preliminary tests carried out in advance of a major investigation into utilisation of surplus carpet fibres for reinforcement of low shear strength clayey soils. Hence, for the purpose of preliminary tests, the effect of inclusion of four different fibres (as identified in Table 1) on quick undrained strength of the samples (as shown in Figure 1) were investigated using the triaxial compression testing machine.

Given that the density of the fibres is less than that of the soil particles the density of the compacted composite soils would naturally be less than the density of compacted soil alone.

Table 2. Properties of utilised soil

Unified Soil Classification	CL	D_{50} (mm)	0.032
Specific Gravity	2.68	D_{30} (mm)	0.005
Percentage of Gravel	1.42	Liquid Limit (%)	29
Percentage of Sand	42.80	Plastic Limit (%)	12
Percentage of Silt	33.16	Plasticity Index (%)	17
Percentage of Clay	22.61	Maximum Dry Density (Mg/m^3)	2.01
D_{60} (mm)	0.090	Optimum Water Content (%)	11

This effect is demonstrated in the form of compaction curves with target fibre contents of 0%, 1%, 5% and 10% in Figure 2. All compaction tests have been carried out according to BS 1377-4 1990.

Using the triaxial machine, a series of quick undrained tests were also carried out on specimens reinforced with 1%, 5% and 10% TBF fibre contents. These results appear in Figures 5 and 6.

The triaxial compression tests have been carried out for partially saturated specimens, 76mm in height and 38mm in diameter at axial strain rate of 1mm per minute and confining pressure of 50 kPa.

To investigate the effect of the other fibres at the same density three more quick undrained tests were carried out on specimens reinforced with 1% RBF, 1% GBF and 1% ABF fibre contents.

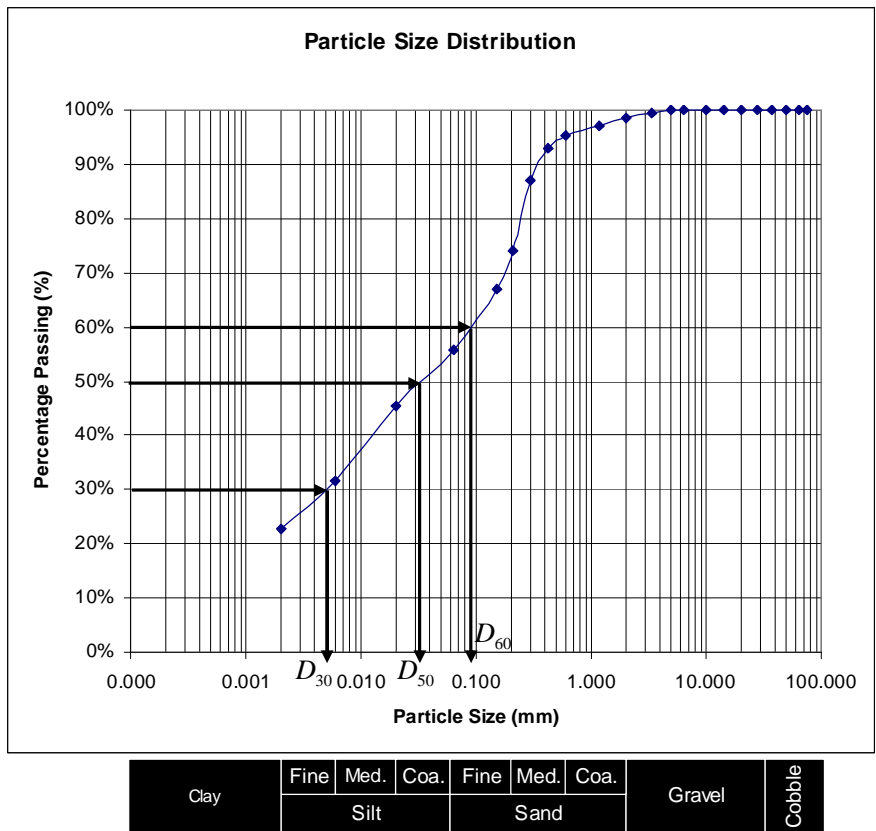


Figure 1. Soil Classification Curve¹ of the soil utilised in this study

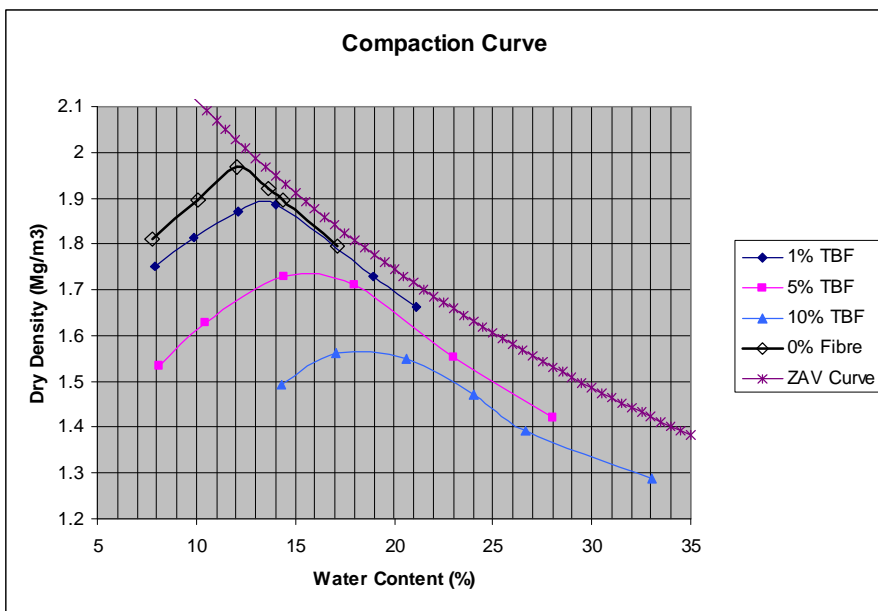


Figure 2. Compaction curve of reinforced soil with TBF

¹ Pipette test in accordance to BS 1377-2:1990 has been utilised for material smaller than 0063mm

Table 3. Effect of TBF fibres on density of the reinforced soil

Fibre Content (%)	MDD (Mg/m^3)	OMC (%)	Loss in MDD (%)	Gain in OMC (%)
0	1.97	12.0	-	-
1	1.89	13.3	4.06	10.83
5	1.74	16.0	11.67	33.33
10	1.57	18.0	20.30	50.00

MDD: Maximum Dry Density
 OMC: Optimum Moisture Content

5.1. Soil/Fibre Mixing Method

In order to a uniform mixture of clay and fibre to be prepared several trials have been undertaken. Eventually the following approach was adopted to make a uniform soil-fibre mixture for preparation of soil specimens for triaxial test.

First, the required amount of fibres based on dry mass of the soil is weighed and mixed with water thoroughly until all fibres look wet (Figure 3). About 20% of the soil required for making the specimen is spread over the wet fibres and mixed uniformly until a layer of fine soil grains coats all the fibres. The prepared mixture is placed in the oven to be dried at 105^{oc}. When the mixture is completely dried, it is crushed by hand once again to ensure all the soil is 'powder-like'. A required amount of water to reach a predetermined moisture content is added and the rest of the soil is added to the mixture and mixed thoroughly (Figure 4).



Figure 3. Mixing fibres with soil



Figure 4. Mixture of fibre, soil and water

Using this method a uniform and acceptable mixture is prepared. At the first stage with the mixture of wet fibres and oven dry soil, a thin layer of fine soil grains surrounds the fibres and it eases mixing of the rest of the soil with the current mixture because of stronger bonding between soil particles rather than soil particles and fibres.

5.2. Specimen Preparation Method

A common preparation method for forming soil triaxial test specimens from cohesive soils is by driving a steel tube into a previously compacted clayey soil in a compaction mould but this is not suitable for preparing fibre reinforced soil specimens. Some of the drawbacks of this method are as follows:

This method creates several (usually three) separate compacted layers which leads to creation of samples with zones of discontinuity. Therefore, these zones (weak planes in vertical profile of the specimen) are more prone to failure during loading. Furthermore, process of trimming off the ends of the prepared specimen disturbs the specimen because of the possible presence of long fibres close to the ends which leads to undesirable holes and uneven ends.

The developed method of specimen preparation avoids these shortcomings. A steel tube with thick wall is employed to compress the sample inside the specimen housing under compressive loading. Required amount of fibre, soil and water are mixed together as described earlier (section 5.1). The prepared mixture is compressed steadily using a variable speed loading frame in the mould at a constant low speed (e.g. $0.225 \frac{mm}{min}$) into an exact height of 76 mm. Using this technique ensures that the prepared specimen has trimmed ends and there are no weak layers along the height of the specimen (since all the soil has been compressed into one layer). Moreover compressing the soil at low speed allows enough pore water dissipation during preparing specimen to prevent swelling after exhausting the specimen from steel tube. The developed method creates satisfactory specimens for triaxial tests.

6. Results and Discussion

The results of compaction test with different TBF fibre contents have been shown in Figure 2 and Table 3. It can be seen that by including more fibres into the soil, the maximum dry density of the reinforced soil drops down and its optimum moisture content increases.

One of the reasons for this change appears to be the composition nature of TBF fibres which contains 40% wool. Wool increases the water absorption in composite media which results in increasing optimum moisture content of the reinforced soil. Moreover because of lower density of fibres in comparison with soil particles, the fibres which substitute for soil grains reduce the density of the composite.

The results of quick undrained triaxial tests on soil specimens reinforced with 1%, 5% and 10% TBF fibre content have been shown in table 4 and figure 5. All the

specimens have been prepared at a bulk density of $2.14 \frac{Mg}{m^3}$ and moisture content of 13.3% and also tested at a cell pressure of 50 kPa.

The results show that the peak deviatoric stress of reinforced specimen with 1% TBF is 22.5% more than that of unreinforced specimen. By increasing the amount of reinforcement to 10% the peak deviatoric stress is decreased continuously.

As it can be seen in the Table 4, reinforcing the soil with 5% and 10% TBF fibres result in loss of 17.6% and 25.4% respectively in peak deviatoric stress which shows that beyond the a certain value of fibre content, fibre reinforcement has an adverse effect on strength gaining of the reinforced soil.

It can be inferred from the results that either the strain equivalent to peak deviatoric stress or failure strain increase with increase in fibre content for specimens reinforced with TBF fibres.

For specimens reinforced with 1%, 5% and 10% TBF fibre content, the stress-strain behaviour is perfectly plastic, hardening and marked hardening respectively while unreinforced specimen shows a softening behaviour.

Figure 5 shows that the post peak deviatoric stress of reinforced specimen increases with increase in fibre content which is more significant in case of specimen reinforced with 10% TBF fibre content (as can be seen in Table 4).

Triaxial tests also have been carried out on specimens reinforced with 1% GBF, 1% RBF and 1% ABF fibre content to compare the effect of different fibres on stress-strain behaviour of the soil. The results are shown in Figure 6. More details have been shown in Table 5. One can conclude that the performance of 1% GBF fibre content for reinforcing the soil is even more significant than 1% of TBF fibre content as it has increased the peak deviatoric stress of soil specimen by 36.1 percent. GBF reinforced specimen showed a plastic behaviour and its post peak deviatoric stress did not change significantly which is a virtue of its plastic behaviour.

ABF fibres do not change the peak deviatoric stress of the soil specimen but they increase its post peak deviatoric stress and show a perfectly plastic behaviour.

RBF reinforced specimens showed a softening behaviour which failed at 15% of strain with loss of about 23.6% in peak deviatoric stress.

Fibres used in this study appear to contribute to strength gaining process. The results suggest that there is a limiting fibre content that beyond that value the fibre reinforcement of soil has an adverse effect rather than improving effect on its strength. The limiting fibre content which is called optimum fibre content is unique for each type of fibre.

Table 4. Triaxial test results on TBF reinforced specimens

	Bulk Density $(\frac{Mg}{m^3})$	Moisture Content (%)	Peak Principal Stress (Kpa)	Strain at Peak principal Stress (%)	Failure Strain (%)	Change in Peak Principal Stress (%)	Post Peak Principal Stress (Kpa)
0% TBF	2.14	13.3	555.2	4.0	10	-	457.8
1% TBF	2.14	13.3	680.6	13.5	22	+22.5	587.8
5% TBF	2.14	13.3	457.5	21.0	25	-17.6	389.0
10% TBF	2.14	13.3	414.0	27.6	>35	-25.4	402.0

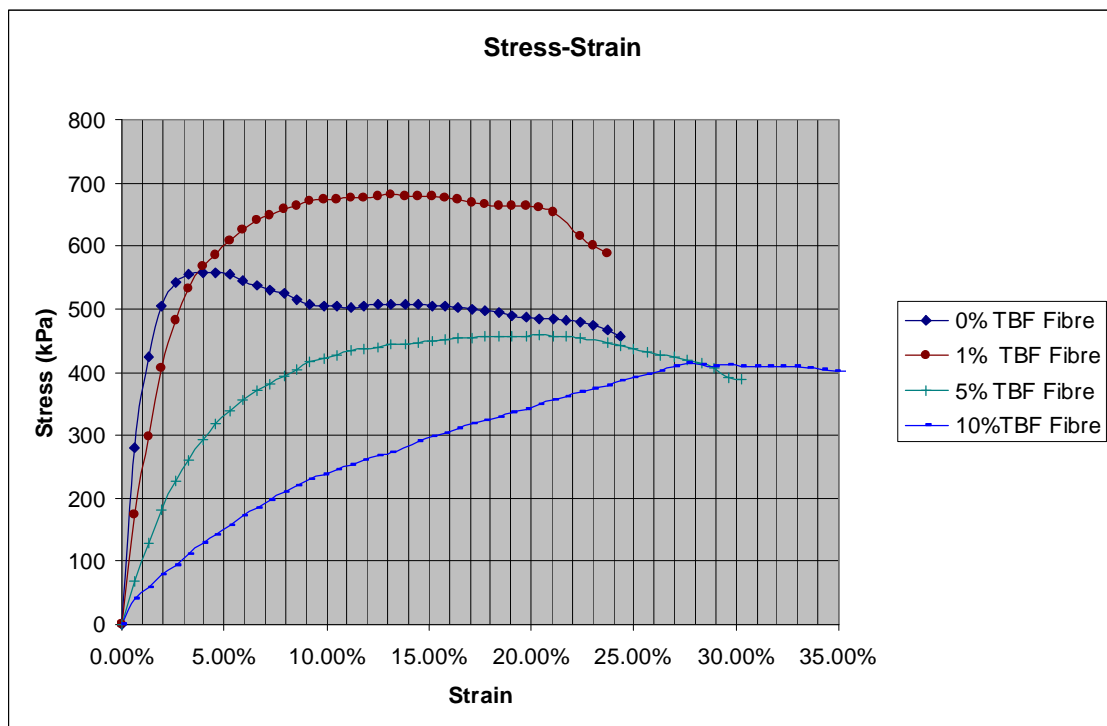


Figure 5. The results of triaxial tests on specimens reinforced with TBF fibres

Table 5. Triaxial test results on RBF, GBF, ABF and TBF reinforced specimens

	Bulk Density (Mg/m^3)	Moisture Content (%)	Peak Principal Stress (Kpa)	Strain at Peak principal Stress (%)	Failure Strain (%)	Change in Peak Principal Stress (%)	Post Peak Principal Stress (Kpa)
0% Fibre	2.14	13.3	555.2	4.0	10	-	457.8
1% TBF	2.14	13.3	680.6	13.5	22.0	+22.5	587.8
1% GBF	2.14	13.3	755.9	9.9	32.2	+36.1	664.0
1% RBF	2.14	13.3	424.3	10.5	14.5	-23.6	402.5
1% ABF	2.14	13.3	550.5	18.5	30.3	-0.80	470.8

The results of preliminary tests reported in this article will be used to influence the research programme and more detailed tests will be carried out in the next stage. According to the results to date, fibre reinforcing soil with 10% fibre content reduces its strength significantly. The reason for this finding could be because there is less density of soil-fibre composite specimen with 10% fibre in comparison with a non-reinforced soil specimen. Therefore, for the rest of the study a range of 0.3%, 0.5%, 1%, 3% and 5% fibre content will be chosen.

With all the fibres, they decrease the post peak deviatoric stress loss and change the stress-strain behaviour of the soil specimen from strain softening to plastic or even strain hardening behaviour.

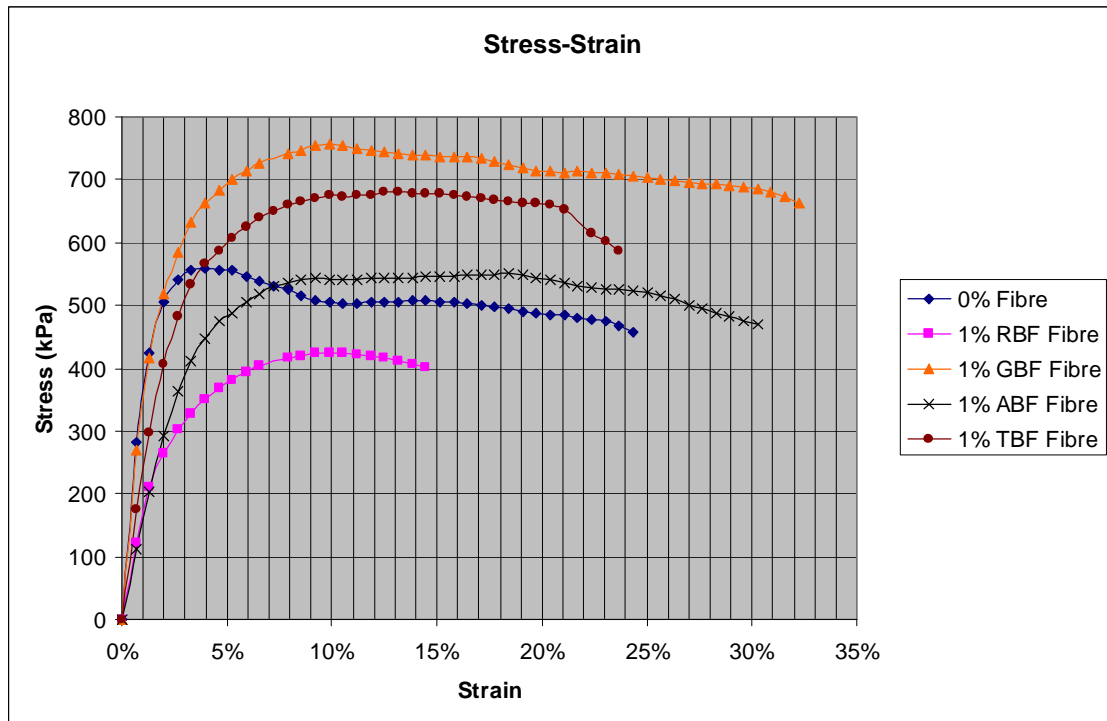


Figure 6. Triaxial test results on specimens reinforced with RBF, GBF, ABF and TBF

The latter effect could be because of tensile strength of the fibres which contributes to withstanding the tensile stress when fibres are in shear. Fibres do contribute in hardening process at higher strains when they are in tension.

More detailed tests are being carrying out for which the results will be published in a future article by the authors.

7. Acknowledgment

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