The strength properties of a fibre-reinforced engineered soil

Les propriétés de force d'une fibre ont renforcé le sol construit

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ABSTRACT: A highly organic engineered soil, produced by mixing green-waste with poor quality soil, has been created. The effect of reinforcing this product with polypropylene fibres on its engineering properties is being investigated, with a view to creating a commercially viable fill soil for use in load bearing surfaces and engineered slopes. The fibres used are commercially available, are currently being used in the sports soil LokSand and are crimped to aid stabilization. A series of consolidated drained triaxial compression tests were performed on this engineered soil as well as on a high quality sand with fibre reinforcement contents ranging from 0.0 to 1.2% by dry mass. Mohr-Coulomb plots show that the fibre-reinforcement of green-waste soil showed increases in ϕ' from 12° to 18° and c' from 10 kPa to 37 kPa at 0.6% fibre content by dry mass. Similar improvement was seen with fibre-reinforcement of the high quality sand.

RÉSUMÉ: Un sol construit extrêmement organique, un produit en mélangeant vert-gaspillage avec le sol de qualité pauvre, a été créé. L'effet de renforcer ce produit avec les fibres de polypropylene sur son construit des propriétés sont examinées, avec une vue à créer un commercialement viable remplit le sol pour l'usage dans les surfaces de direction de chargement et les pentes construites. Les fibres utilisées sont commercialement disponibles actuellement utilisé dans le LokSand de sol de sports et est ondulé à la stabilisation d'aide. Un feuilleton d'examens de compression de triaxial drainés consolidés a été exécuté sur ce sol construit de même que sur un sable de qualité supérieure avec les contenus de reinforcement de fibre étendants de 0.0 à 1.2%par la masse sèche. Le Mohr-Coulomb trace le show que le reinforcement de fibre de sol de vert-gaspillage a montré des augmentations dans ϕ' de 12° à 18° et de c' de 10 kPa à 37 kPa à 0.6% contenu de fibre par la masse sèche. L'amélioration similaire a été vue avec le reinforcement de fibre du sable de qualité supérieure.

1 INTRODUCTION

More and more waste plant material is being produced through the maintenance of municipal and private leisure facilities and green areas. This waste material contains grass cuttings, hedge cuttings, etc., and is known as green-waste. To date, most green-waste has been composted or land-filled, however upcoming UK and EU directives regarding land-filling has produced a need to find a use for the large volumes of this waste material.

It is believed that by mixing the green-waste material with a poor quality soil a commercially viable fill material capable of supporting vegetation can be produced. By using a poor quality soil, cost is kept to a minimum, essential if the material is to be widely used as a means of disposing of large quantities of green-waste. Early testing of this engineered soil has shown that a low ϕ' value limits its use as a load bearing surface or slope fill material. This paper details work done to reinforce this engineered soil with randomly orientated crimped polypropylene inclusions. It is hoped that this relatively new form of reinforcement will increase the ϕ' value enough to significantly improve the load bearing capacity of the green-waste soil.

Since the 1970's an increasing number of investigations into the use of root and fibre reinforcement of soils have been undertaken. Swanston (1970) began with investigations into the cause of slope failures in deforested areas of Canada and the USA. This early work suggested that the fibrous root material did enhance the mechanical properties of the soil. The work then developed to look at the addition of natural plant fibres to soil to improve their shear strength characteristics. Work by Gray (1983), Gray & Maher (1989), and Maher & Gray (1990) amongst others, showed that the reinforcement of soil through the addition of natural palmyra and reed fibres increase the strength properties of soil and reduced the loss of post peak strength. However, the lack of uniformity in inclusion size and strength as well as fibre degradation limited the use of fibre-reinforced soil in the commercial sector.

From natural fibres, the reinforcement of soils progressed through metallic, rubber and glass fibres to polypropylene mono-filament fibres and mesh elements. A large number of investigations have looked at the effect of using straight polypropylene fibres to reinforce clean sands, with the same effects observed as for natural fibres. For example, Bailey & Knox (1997) showed that reinforcing a uniformly graded sand with 0.45% polypropylene straight mono-filament fibres increased the ϕ' from 39° to 42°. These manufactured polypropylene fibres, with constant length, cross-section and density, now allow fibre-reinforced soil to be used in engineering designs, with less concern to fibre variability.

This paper describes the observations from drained triaxial compression tests carried out on two separate soil types, the green-waste soil and a high quality commercial sand. Both soils were tested unreinforced and reinforced with a new 'crimped' polypropylene fibre, at concentrations of between 0.15% and 1.20% by dry mass.

2 EXPERIMENTAL STUDY

2.1 *Materials used*

The polypropylene fibres used throughout are 35 mm crimped mono-filament fibres as used in Tarmac Quarry Products' LokSand. These fibres are supplied by Drake Extrusions Ltd., Bradford, UK. It is thought that the crimp improves the reinforcing action of the individual fibres. The fibres are produced in a melt spinning process in which the polymer and ingredients are extruded through fine holes to a diameter of 0.09 mm, drawn, stabilized, crimped every 10 mm and cut in line to 35 mm length.

The fibres, supplied in bundles, were then mixed by hand to a consistent homogenous mix at the desired fibre content.

Two separate soils were used within the testing procedure. The first was a high quality Leighton Buzzard sand supplied by Tarmac Quarry Products, Wolverhampton, UK. The sand is classified as a uniformly graded medium sand with sub-rounded particles. The D_{50} value of the sand is 0.430 mm with particle sizes ranging from 0.063 mm to 1.180 mm.

The second soil used is a mixture of poor quality soil and green-waste material supplied by Tarmac Quarry Products. The poor quality soil is classified as a very silty sand with 23.6% Silt and 16.6% Clay and 59.8% Sand. The D_{50} value is 0.140 mm. This soil was supplied pre-mixed with the green-waste plant material. This organic material contained wooded matter up to a length of 50 mm and other organic inclusions. A sample of this soil can be seen in Figure 1.

2.2 *Triaxial compression tests on the Leighton Buzzard sand*

A series of consolidated drained triaxial compression tests were carried out on samples of Leighton Buzzard sand both unreinforced and reinforced with LokSand Fibres. The tests were performed to BS1377:Part 4:1990 using disturbed samples of 140 mm height and 70 mm diameter. This larger sample size was used to accommodate the 35 mm long fibres. Effective consolidation stresses applied ranged from 10 to 200 kPa, with a back pressure of 100 kPa applied in all cases.

All samples were prepared to the same standards with initial moisture content of 6.0%, and compacted in five layers to a density of 1.67 Mg/m^3. With the addition of fibres more compactive effort was required to reach the same density, but it was felt that samples of the same density should be tested as opposed to samples compacted with the same effort.

An initial test was carried out using three samples of unreinforced sand at an effective confining pressure of 10 kPa. Two further unreinforced samples were tested at an effective confining pressure of 100 kPa and then another two at 200 kPa effective confining pressure. These tests were used to establish the baseline behavior of the unreinforced sand.

LokSand fibres were then mixed into separate samples of the Leighton Buzzard sand at concentrations of 0.15%, 0.30%, 0.60%, 0.90% and 1.20% by dry mass. All these samples were then tested at an effective confining pressure of 10 kPa. Finally, further samples were produced with 0.30% and 0.60% fibre content for testing at 100 kPa and 200 kPa effective confining pressure.

For all samples tested, measurements of deviator stress, strain, volume change and porewater pressure were taken throughout using an automated data logger.

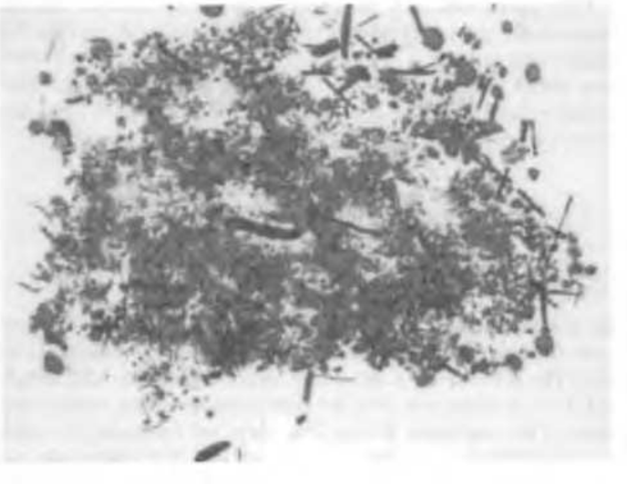

Figure 1. A sample of the green-waste soil.

2.3 *Triaxial compression tests on the green-waste soil*

A series of consolidated drained triaxial compression tests were also carried out on samples of the engineered green-waste soil. Samples of the soil both unreinforced and reinforced with fibres were tested. The tests were performed to BS1377:Part 4:1990 using disturbed samples of 140 mm height and 70 mm diameter. This larger sample size was again used to accommodate the 35 mm long fibres but was now also required due to the larger particle size of the green-waste soil. Before any triaxial tests were carried out any organic matter of length greater than 25 mm was removed and cut into a number of separate pieces, each less than 25 mm long. These pieces were then replaced into the sample to maintain the sample consistency whilst limiting the maximum inclusion size. The effective consolidation stresses applied ranged from 100 to 450 kPa, with a back pressure of 100 kPa applied in all cases.

All samples were prepared to the same standards with a moisture content of 4.6% and compacted in layers to a density of 1.55 Mg/m^3. As with the Leighton Buzzard sand samples, the addition of fibres meant more compactive effort was required to reach the same density. Again it was felt that samples of the same density should be tested as opposed to samples compacted with the same effort.

Three unreinforced samples of the green-waste soil were created and tested at effective confining pressures of 100 kPa, 300 kPa and 450 kPa. LokSand fibres were then mixed in by hand to produce soil samples with fibre concentrations of 0.30% and 0.60% by dry mass. Again these samples were tested at effective confining pressures of 100 kPa, 300 kPa and 450 kPa. At each confining pressure three samples were tested.

Measurements of deviator stress, strain, volume change and porewater pressures were taken as in the previous tests.

3 EXPERIMENTAL RESULTS

3.1 *Results of triaxial tests on Leighton Buzzard sand*

Figure 2 shows a plot of the deviator stress versus axial strain for the fibre reinforced compression tests with fibre contents of 0.15% to 1.20% as well as a test on a sample of unreinforced sand. Figure 3 shows the Mohr-Coulomb plot for the unreinforced sand and the sand reinforced with 0.60% crimped fibres at effective confining pressures of 10 kPa, 100 kPa and 200 kPa.

The three repeat tests on unreinforced sand all showed a peak deviator stress at approximately 2.5% axial strain, the peak values being 38, 43 and 45 kPa for the three tests, equating to a mean deviator stress of 42 kPa. The sample reinforced with 0.15% crimped polypropylene fibre shows a peak deviator stress of 72 kPa at approximately 6% axial strain. The other four samples did not reach a peak deviator stress within the 10% axial strain measured.

The effect of adding the crimped polypropylene fibres, taken as the ratio of peak deviator stress of the fibre-reinforced sand to the mean peak deviator stress of the unreinforced sand, was calculated for each fibre content tested. Where no peak was observed the deviator stress value at 10% axial strain was used. Table 1 shows the effect on deviator stress of reinforcing Leighton Buzzard sand with LokSand Polypropylene fibres at fibre contents ranging from 0.15% to 1.20% by dry mass.

From the Mohr-Coulomb plot it can be seen that ϕ' increases from 40° to 47°. At the same time the apparent cohesion, c' increases from 8 kPa to 50 kPa.

Table 1. Improvement to deviator stress from the addition of LokSand fibres to Leighton Buzzard sand for various fibre contents.

Fibre content	0.15%	0.30%	0.60%	0.90%	1.20%
Improvement Ratio	1.61	4.01	7.99	9.88	13.88

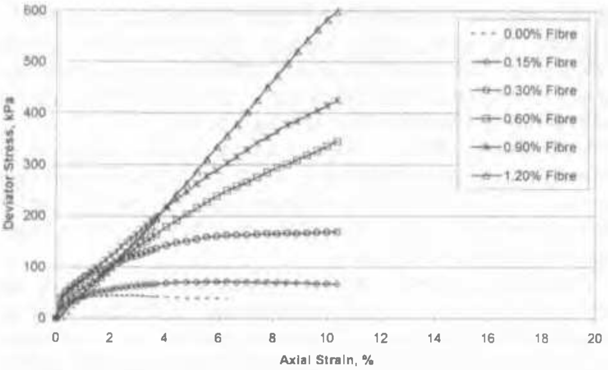

Figure 2. Stress-strain response for fibre reinforced and unreinforced Leighton Buzzard sand at an effective confining pressure of 10 kPa.

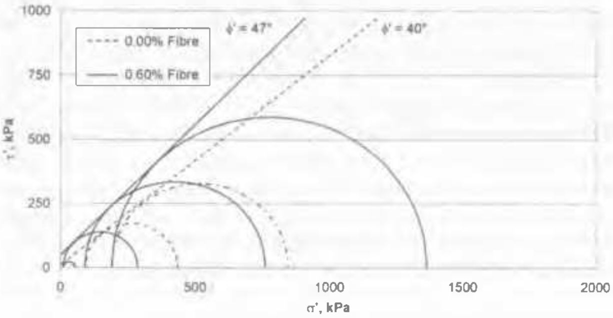

Figure 3. Mohr-Coulomb plots for Leighton Buzzard sand unreinforced and reinforced with 0.60% LokSand fibre.

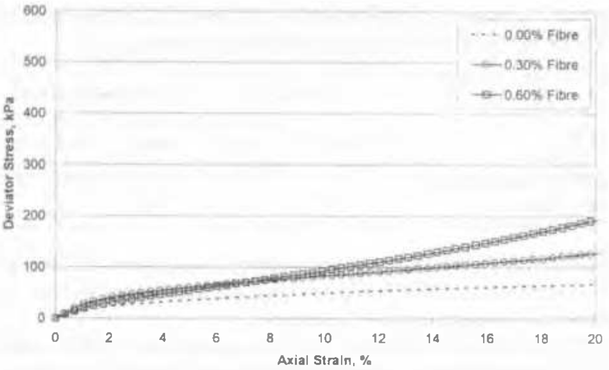

Figure 4. Stress-strain response for fibre reinforced and unreinforced green-waste soil at an effective confining pressure of 100 kPa.

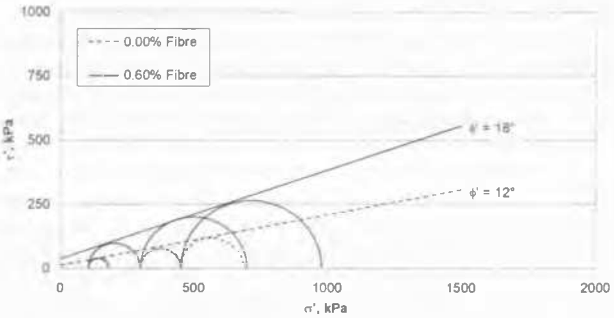

Figure 5. Mohr-Coulomb plots for green-waste soil unreinforced and reinforced with 0.60% LokSand fibre

3.2 *Results of triaxial tests on the green-waste soil*

Figure 4 shows a plot of the deviator stress versus axial strain for a sample of the green-waste soil reinforced with a fibre content of 0.30% and 0.60% as well as a test on a sample of unreinforced soil. Figure 3 shows the Mohr-Coulomb plot for the unreinforced soil and the soil reinforced with 0.60% crimped fibres at effective confining pressures of 100 kPa, 300 kPa and 450 kPa. To calculate σ_1' and σ_3' for the Mohr-Coulomb circles an average of the three repeat tests was taken for each fibre content and confining pressure. This was required due to the inconsistent nature of the material being tested showing a variability in results.

None of the three repeat tests on unreinforced soil showed a peak deviator stress within the 20% axial strain tested. Similarly, none of the samples reinforced with either 0.30% or 0.60% crimped polypropylene fibre showed a peak deviator stress within 20% axial strain. It is clear though that the reinforced samples show a more increasing deviator stress at this high axial strain. In accordance with BS1377:Part 4:1990 peak values were taken at 20% axial strain for all samples of the reinforced and unreinforced green-waste soil tested. Table 2 shows peak deviator stress values at 20% axial strain for each sample tested at 100 kPa effective confining pressure.

From the Mohr-Coulmb plot it can be seen that ϕ' increases from 12° to 18 °. At the same time the apparent cohesion, c' increases from 10 kPa to 37 kPa.

Table 2. Peak deviator stress values for green-waste soil at 100 kPa effective confining pressure at 20% axial strain.

Fibre Content	Sample 1 kPa	Sample 2 kPa	Sample 3 kPa	Mean Value kPa
0.00%	61	96	74	77
0.60%	218	199	164	194

4 DISCUSSION

The tests on unreinforced samples of Leighton Buzzard sand show the expected, brittle, strain softening response typical of drained triaxial compression tests on non-cohesive granular soils at low confining stresses. The strain softening response is characterized by a deviator stress which rises to a peak value at low axial strain and then reduces as the axial strain increases.

The Leighton Buzzard sand reinforced with 0.15% crimped polypropylene fibres showed a similar response to that observed with the unreinforced sand. The approach to a peak stress though was more gentle, occurring at approximately 6.0% axial strain, but at a considerably higher deviator stress.

At all other fibre contents, no peak strength was reached within the tests. These samples exhibited a ductile, strain-hardening response more typical of cohesive soils at low over-consolidation ratios, in which the deviator stress rises steadily over the range of strains typically encountered in the field. However, these tests did exhibit dilatant behavior, unlike the typical response of a soft cohesive soil. This result is similar to that shown by Bailey & Knox (1997) in which they compared the behavior of a sand reinforced with 0.45% straight polypropylene fibres to that of a heavily over-consolidated clay.

The behavior of the fibre-reinforced sand tests can be directly ascribed to the action of the fibres, which increases the effective stress within the sand as the sand dilates, stretching the fibre inclusions and therefore increase the strength of the soil. The data suggests that at a low confining pressure, a minimum fibre content of between 0.05% and 0.10% by dry mass would be required to observe this effect. It can also be seen that beyond that minimum fibre content the strength increase is proportional to fibre content up to 1.20% by dry mass. Although further work could determine a maximum fibre content at which point any increase in fibre content has little effect on soil strength, it is believed that fibre contents higher than this 1.20% value would be uneconomical.

It is also seen that the strain-hardening effect of the fibre-

Table 3. Summary of improvement to the strength parameters of 0.6% fibre-reinforced Leighton Buzzard sand and green-waste soil.

	Unreinforced		Fibre-reinforced	
	ϕ'	c'	ϕ'	c'
Soil Type	deg.	kPa	deg.	kPa
Leighton Buzzard sand	40	8	47	50
green-waste soil	12	10	18	37

reinforcement increases with increasing fibre content. With a fibre content of 1.20% it is seen that as strain increases the rate of increase in strength actually increases.

The stress-strain response of the unreinforced green-waste soil is very different to the unreinforced Leighton Buzzard sand. Even without any fibre-reinforcement, the green-waste soil shows no peak within the 20% axial strain range tested. The unreinforced soil also shows a slightly ductile response, similar to that of the 0.30% fibre-reinforced Leighton Buzzard sand.

The fibre-reinforced samples of green-waste soil show that the addition of crimped polypropylene fibres increase the strength of the soil, although unsurprisingly the deviator stresses reached are far lower than for the Leighton Buzzard sand. Both 0.30% and 0.60% fibre contents show an almost 100% increase in deviator stress at 20% axial strain on the previous lower fibre content. At the 0.60% fibre content a similar response to the Leighton Buzzard sand reinforced with 1.20% fibre content was observed with greater increasing strength with increasing axial strain. These observations suggest that an initial fibre reinforcement was seen within the unreinforced sample of green-waste soil. This is unsurprising due to the high organic and fibrous content of the green-waste soil, but does show that fibre-reinforcement does significantly improve the strength of an already fibrous soil.

The Mohr-Coulomb plots of both Leighton Buzzard sand and the green-waste soil clearly demonstrate an increase in the shear strength parameters of both soil types when reinforced with crimped polypropylene fibres. Table 3 shows the observed increase in ϕ' and c' for both soil types.

Clearly, an increase in both ϕ' and c' is observed for both Leighton Buzzard sand and green-waste soil. Due to the poor quality of the green-waste soil the ϕ' is considerably less than for the Leighton Buzzard sand. However, the increase is still significant, and it is expected that the observed increase in ϕ' would relate to a dramatic increase in the bearing capacity of the soil. The improvement in c' for the green-waste soil is smaller than for Leighton Buzzard sand, although this is in part due to the higher apparent cohesion of the unreinforced green-waste soil. However, an increase in c' from 10 kPa to 37 kPa is still very considerable, and together with the observed increase in ϕ' is expected to increase the load bearing capacity of the soil by a factor of between 3 and 4 through their effect on cNc, Nq and $N\gamma$ values.

The results obtained are similar to those observed in other investigations into fibre-reinforced soil. Without direct comparison tests being done with straight and crimped fibres, it is difficult to say conclusively whether any improvement in the fibre-reinforcement is achieved through the crimped fibres. However, comparing these results with those of Bailey & Knox (1997), using a similar high quality sand at a slightly lower fibre content of 0.45% by dry mass, it is seen that the observed increase in ϕ' from 40° to 47° compares favorably to their observed increase of 39° to 42°. The authors believe that this comparison suggests that the crimp in the fibre significantly aids the reinforcement of soil by improving the degree of intertwining of the fibres around the soil particles.

5 CONCLUSIONS

The results of the triaxial compression tests clearly show that large increases in peak deviator stress can be achieved through the reinforcement of soil by the addition of crimped polypropylene fibres. The results of the Leighton Buzzard sand triaxial tests show that the increase in reinforcing action is approximately linear with increasing fibre content up to the 1.20% fibre content tested at the 10 kPa effective confining pressure.

Mohr circle plots show that the strength improvement seen in the stress-strain responses can be carried over to show significant increases in the Mohr-Coulomb parameters, ϕ' and c'. Further work is needed to show whether these increases are also linear with increasing fibre content.

The authors believe that this increase in both strength parameters will provide a large improvement in the load bearing capacity of both the Leighton Buzzard sand and the green-waste soil. It is also expected that the increase in the shear strength of the green-waste soil in particular will enable this material to be used as an engineering fill material for embankments and other geotechnical structures.

The crimped polypropylene fibres, exclusive to the LokSand fibres used throughout the triaxial tests detailed, appear to be more effective, than the standard straight fibres. Although no direct comparison is made, the improvement seen within these tests is greater than improvements noted by other authors using straight polypropylene fibres. Further work repeating the tests, using straight polypropylene fibres would allow a direct comparison to be made between crimped and straight polypropylene fibre-reinforcement. The authors believe that such a comparison would show a dramatic improvement in the reinforcing action of the crimped polypropylene fibre over the straight fibre.

6 ACKNOWLEDGMENTS

This paper was prepared as part of a Ph.D. programme on fibre-reinforced soil structures, jointly sponsored by the Engineering and Physical Science Research Council, Tarmac Quarry Products Ltd. and Drake Extrusion Ltd., whose support is gratefully acknowledged. The authors would also like to thank Mr. Len Czekaj for helping with the preparation of the samples and testing apparatus.

REFERENCES

Bailey, R. & Knox, W.R.A. 1997. The strengh properties of fibre-reinforced sand. *Ground Improvement Geosystems, Densification and Reinforcement.* 349-357.

Gray, D.H. 1970. Role of woody vegetation in reinforcing soils and stabilising slopes. *Proc. of Symp. on Soil Reinforment and Stabilising Techniques in Engineering Practice.* 253-306.

Gray, D.H. & Maher, M.H. 1989. Admixture stabilization of sand with discrete randomly-distributed fibres. *Proc. XIIth Int. Conf. on SMFE, Rio de Janeiro, Brazil.* 1363-1366.

Maher, M.H. & Gray, D.H. 1990. Static response of sands reinforced with randomly distributed fibers. *Journal of Geotechnical Engineering, ASCE* 116(11): 1661-1677

Swanston, D.N. 1970. Mechanics of debris avalanching in shallow till soils of Southwest Alaska, USDA, Forest Services Res. Paper PNW-103, Pacific Northwest Forest and Ranger Experiment Station, Portland, Oregon.