Fibre Reinforcement of Prior Stream Sands

A. Sufian[1] and A.R. Russell[2]

[1]SMEC Australia Pty Ltd, Level 7, 76 Berry Street, North Sydney, NSW 2060, Australia; PH (612) 9900 7005; MOB (61) 412 080 962; FAX (612) 9925 5566; email: adnan.sufian@smec.com (formerly at The University of New South Wales)
[2]Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia; PH (612) 9385 5033; FAX (612) 9385 6139; email: a.russell@unsw.edu.au

ABSTRACT

This paper presents results of an experimental study on fibre reinforced soils to highlight how soil behaviour may be altered by mixing with discrete flexible fibres. Triaxial compression tests conducted on Prior Stream sands mixed with polypropylene fibres shows that a considerable strength increase is induced by the presence of fibres. This is attributed to the preferred near horizontal orientation of the fibres which resist tensile strain development. Simulations of triaxial test results are shown using a Mohr-Coulomb type constitutive model that incorporates the effects of fibre reinforcements and their preferred orientation.

Keywords: fibre reinforced soil, triaxial tests, orientation distribution, constitutive model simulation

1 INTRODUCTION

Fibre reinforced soils (FRS) are becoming increasingly known among geotechnical engineers due to their improved shear strength and deformation characteristics. Recent studies by Diambra et al. (2010, 2011) and Ibraim et al. (2010) on Hostun RF (S28) sand, Ahmad et al. (2010) on silty sand, Chen & Loehr (2009) on Ottowa sand and Sadek et al. (2010) on coarse and fine sands, among others, have demonstrated the improved shear strength characteristics of the fibre-soil composite. A variety of fibres of different material, aspect ratio, and ductility have been used in previous studies to various degrees of success. Through experimental testing and model simulations, this study explores the improvement in shear strength that results from the addition of polypropylene reinforcement fibres. The soil used for this study is the Prior Stream sands, which is used by the Roads & Traffic Authority (RTA) of New South Wales (NSW), Australia, in the south-west region of NSW as a pavement base course, even though it has poor strength and deformation characteristics, which can result in rut formation and surface cracking. This study aims to demonstrate the improved soil characteristics of the Prior Stream sands by randomly mixing discrete flexible fibres. Conventional drained triaxial compression tests were conducted with varying amounts of fibre reinforcement to demonstrate the improvement in shear strength of the composite material. The experimental results were simulated using the Mohr-Coulomb elastic perfectly plastic model and the framework presented by Diambra et al. (2007, 2010) for inclusion of fibre effects.

2 EXPERIMENTAL RESULTS

Conventional drained triaxial tests were conducted on 100mm diameter and 200mm long samples. This sample size was deemed necessary due to the relatively long fibres (50mm), which would induce boundary irregularities in smaller samples. Varying fibre concentrations (f_c) were used, including 0%, 0.3% and 0.6% concentration by dry mass of soil. Sadek et al. (2010) found that for larger concentrations no further increase in strength is achieved, partly because fibres clump together and hinder the effectiveness of the mixing and the compaction process. A limit of 20% axial strain was imposed for all tests.

2.1 Material and Sample Preparation

The soil used in this study is the Prior Stream sands and several key properties were established, including particle size distribution (Figure 1), optimum moisture content (OMC) of 10.5%, maximum dry density (MDD) of 2000kg/m^3. Polypropylene fibres have been used in this study. The fibres are commercially available and mostly used for concrete reinforcement, especially in pre-cast concrete and concrete slabs on ground. The fibres have a length of 50mm, diameter of 1.3mm and are crimped along their length, to offer better frictional characteristics. Unlike the 0.1mm diameter fibres used by Diambra et al. (2010), these polypropylene fibres possess higher stiffness and rigidity, with Xiao & Chin (2002) suggesting an elastic modulus of 3500MPa.

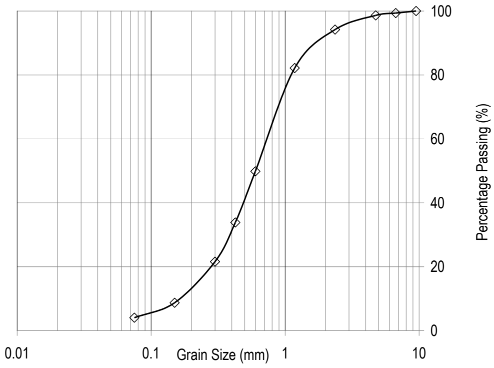

Figure 1: Particle size distribution for Prior Stream sand

Samples were prepared in a split mould at the OMC and at 95% of MDD. The provided soil contained a small fraction of gravel sized particles, which were removed to ensure uniformity in triaxial sample preparation. The provided soil was gently broken up and passed through a standard 4.75mm sieve and only the passing soil was used for the preparation of the triaxial samples. Each sample was prepared in five layers, with each layer manually compacted to meet the requirement of 95% MDD. The top and bottom layers (25mm thickness) contained no fibres, as in trials it was observed that when fibres were exposed on the top surface, the top cap of the triaxial apparatus was unable to sit squarely causing eccentric loading. The three reinforced layers (50mm thickness) contained the same amount of fibres and each was thoroughly mixed to ensure that fibres were allowed to randomly distribute and to prevent clumping. The compaction of the sample resulted in the majority of fibres being orientated horizontally causing an anisotropic characteristic of the composite, as discussed in detail below. Prior to loading into the triaxial cell, any protruding fibres were cut to ensure that the rubber membrane would not be pierced.

2.2 Results & Discussion

Conventional consolidated drained (CD) triaxial compression tests were conducted, and the results are summarised in Table 1. Samples were saturated using the CO_2 method where a minimum Skempton B factor of 0.95 was achieved and then consolidated under an effective stress of 100kPa. Under the consolidation stress, it was observed that the sample retained its shape. For shear loading a nominal strain rate of 0.15 mm/min was selected. The peak deviatoric stress is provided in Table 1 and Figure 2a and Figure 2b shows the plots of deviator stress *q vs.* axial strain ε_1 and volumetric strain ε_v *vs.* ε_1, respectively. Also listed in Table 1 are the initial void ratios of the prepared samples (e_0) and the void ratios at the end of isotropic consolidation (e_c). Fibres were treated as part of the solids in the void ratio calculations.

Table 1: Summary of triaxial results

f_c (%)	e_0	e_c	σ_{cell}' (kPa)	q_{peak} (kPa)
0.0	0.383	0.379	100	256
0.3	0.394	0.388	100	351
0.6	0.387	0.383	100	483

The initial part of the stress-strain relationship remained linear for all fibre concentrations, suggesting that tensile strains were not large enough for fibres to be noticeably effective. However, the yield point (point where the gradient of the stress-strain curve changes significantly from the initial linear response) of the composite increases with increasing fibre content, while Diambra et al. (2010) showed similar yield points for all fibre concentrations in a different fibre-sand composite. This difference is thought to be attributed to the use of stiffer fibres here, which are able to transmit much larger tensile stresses at smaller strains. The varying yield point suggests an increase in strength and friction angle of the composite with increasing fibre concentration. Further, the peak deviatoric stress (shown in Table 1) increased linearly with increasing f_c.

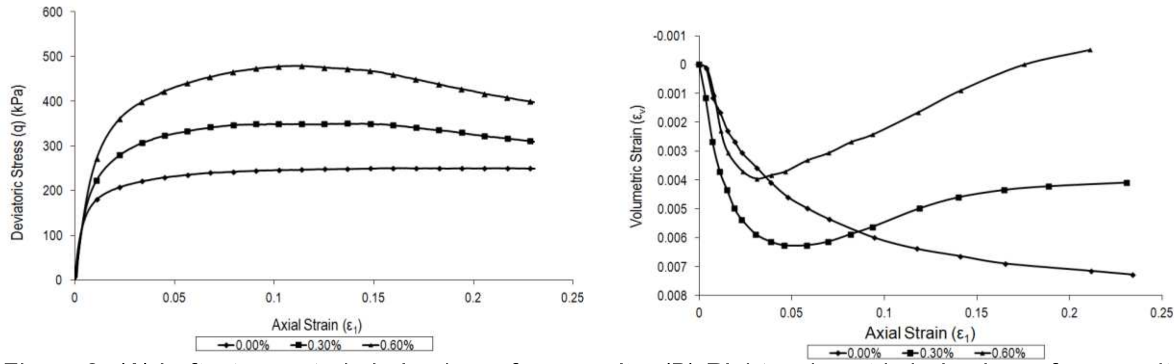

Figure 2: (A) Left: stress-strain behaviour of composite; (B) Right: volumetric behaviour of composite

The (approximately) bilinear stress-strain relationships observed have some similarities to those of Ahmad et al. (2010) and Michalowski & Cermak (2003). However, unlike Ranjan et al. (1994) and Diambra et al. (2010), the deviatoric stress does not continue to increase without bound as axial strain increases. Rather, after yielding, the composite deviatoric stress increased slightly with axial strain but then flattened after the maximum stress was reached. It is thought that this behaviour is a result of fibre slippage. At large axial strains, the induced tensile stresses are able to overcome the frictional resistance at the fibre-soil interface resulting in slipping and consequently reducing the strength gains that can be achieved. A potential reason for the occurrence of this behaviour is the fibre and soil types used and in particular the contact surface area between fibres and soil. For example, Hostun RF sand (used by Diambra et al., 2010) had D_{50} = 0.32mm and fibres had a diameter of 0.1mm, while the Prior Stream sand had D_{50} = 0.60mm and the fibres had a diameter of 1.3mm. The 0.1mm diameter fibres used with Hostun RF sand had a larger surface area per unit volume of composite than the 1.3mm diameter fibres used with the Prior Stream sand. Larger surface area leads to a larger contact area with the surrounding sand and therefore larger frictional resistance, and consequently less possibility of slipping (Maher & Gray, 1990; Michalowski & Cermak, 2003; Sadek et al., 2010). Observations of samples post-shearing showed several fibres partially pulled out of the sample, further justifying the above explanation for the plateau in the stress-strain curve.

The volumetric characteristic of the composite material is shown in Figure 2b and a reduction in compression is observed with increasing fibre content. The unreinforced sample experienced contraction up to 20% axial strain, while both reinforced samples showed an initial contraction followed by dilation. Increasing fibre concentration appears to make the soil behave in a more dilative manner with similar characteristics to dense sands, suggesting that fibres have a densifying effect on the soil. However, the dilation of soil can result in a reduction in contact area between soil and fibres (Michalowski & Cermak, 2003), which may have also attributed to the observed plateau in Figure 2a.

3 CONSTITUTIVE FRAMEWORK AND MODEL SIMULATION

3.1 Fibre orientation distribution function

An important of characteristic of FRS is the anisotropic strength of the composite due to the near horizontal arrangement of most fibres as a result of the compaction process (Diambra et al. 2010), both in laboratory specimens and expected field conditions. In order for a constitutive model to accurately simulate the behaviour of FRS, this anisotropy must be taken in account. This may be described using a fibre orientation distribution function, *ρ(θ)*, which represents the volumetric fibre concentration for fibres having an orientation of *θ* above the horizontal. The function presented by Michalowski & Cermak (2002) is used in this study:

$$\rho(\theta) = \bar{\rho}(A + B|cos^n \theta|) \quad (1)$$

where, $\bar{\rho}$ represents the volumetric fraction of fibres in the composite, and *A*, *B* and *n* are constants. The above function is applicable for continuous filaments, but if grain size is considerably smaller than the fibre diameter, then there exists sufficient contact between the sand grains and the fibres to consider the reinforcement as continuous and frictional (Michalowski, 1997). For the Prior Stream sand, D_{60} is 0.72mm which is significantly smaller than the 1.3mm diameter fibre; therefore the application of (1) is considered acceptable.

The constants A, B and n are determined through an experimental counting procedure (Diambra et al. 2007), which involved preparing a sample in a standard 1L compaction mould using a standard compaction hammer and compactive effort. The sample was prepared at OMC and at 95% MDD, using 0.3% fibre concentration and compacted in three layers, where fibres were evenly distributed through each layer. In order to count the number of fibres which intersect defined areas, three horizontal cuts were made between the compaction layers, and one vertical cut through the middle of the sample using a hand saw. However, due to the high strength of the polypropylene fibres, cutting through the sample proved to be a difficult task. Several fibres pulled out of the sample or fell from the cutting face. In order to maintain integrity of results, these fibres that were removed during the cutting process were included in the final analysis. The results of the counting procedure are presented in Table 2 as the number of fibres which intersect areas of 5675mm^2 and 2850mm^2 on horizontal and vertical planes, respectively.

Table 2: Experimental results of compaction test for fibre orientation distribution function

	Number of fibres in horizontal plane	Number of fibres in vertical plan
Averaged results	13.667	12.233
Excluding outliers[a]	17.250	12.760

[a] entry was regarded as an outlier if it was more than one standard deviation from mean

It was assumed that $A=0$, meaning no fibres have a vertical orientation. This is a reasonable assumption as the compaction procedure would prevent fibres from attaining a vertical orientation. Using the procedure outlined in Diambra et al. (2007), B can be determined for several trial n values and using the trial $\rho(\theta)$, the number of fibres in a vertical plane (N_V) and the number of fibres in a horizontal plane (N_H) can be calculated. A Gauss quadrature numerical scheme was applied to solve the triple integrals associated with N_V and N_H, and the results are presented in Table 3.

Table 3: Analytical results for fibre orientation distribution function

n	B	N_V	N_H	N_V/N_H
1	1.273	13.244	20.710	1.273
2	1.500	13.789	18.304	1.500
3	1.697	14.125	16.566	1.697
4	1.875	14.364	15.253	1.875

By comparing the experimental and analytical results in Table 2 and Table 3, respectively, the best-fit parameters are $n = 2$, $B = 1.500$ and $A = 0$. This fibre orientation distribution function indicates that 88% of fibres have an orientation with ±45° from the horizontal and a preferred plane of orientation is apparent, which will result in anisotropic strength for the composite.

3.2 Constitutive Modelling Framework

This study employed the constitutive modelling framework presented by Diambra et al. (2010), where the stress of the composite ($\boldsymbol{\sigma_c}$) is described using the rule of mixtures, (2), whereby each constituent is treated separately and superimposed according to their volumetric fraction. A simple Mohr-Coulomb elastic-perfectly plastic model is used to describe the soil stress ($\boldsymbol{\sigma_s}$), while fibres are assumed to behave elastically with stress $\boldsymbol{\sigma_f}$ given in Diambra et al. (2010). No plastic deformation or breakage of fibres were observed when a sample was dissected after shearing, suggesting that the assumption of elastically deforming fibres in the constitutive model is appropriate. It is assumed that the volumetric fraction of soil is equal to unity, as it is significantly larger than volumetric fraction of fibres. Additionally, a slippage constant (f) is included to account for the effects of fibre slipping, permitting the strains in the fibres to be equal to f times the strains in the composite.

$$\dot{\boldsymbol{\sigma}}_{\boldsymbol{c}} = \dot{\boldsymbol{\sigma}}_{\boldsymbol{s}} + v_f f \dot{\boldsymbol{\sigma}}_{\boldsymbol{f}} \tag{2}$$

3.3 Model Simulation

Simulation of the constitutive model requires several soil and fibre parameters. For soil, the Poisson ratio is assumed to be 0.3 and the dilation angle is set to 0°. Elastic modulus of soil (E_s) was back-calculated from experimental results for the unreinforced sample to be 25000kPa. The cohesion was set to zero (as the model only applies to cohesionless soil) and the friction angles determined through back-analysis were φ = 33.5° for f_c = 0.0%, φ = 36° for f_c = 0.3% and φ = 42° for f_c = 0.6%. The only fibre properties required is the elastic modulus of fibres (E_f). As mentioned previously, the polypropylene fibres have a typical elastic modulus of 3500MPa. The slippage function was back-calculated to be $f = 0.09$, which reiterates that a fair amount of fibre slipping is occurring. The simulations of the experimental results are presented in Figure 3.

The constitutive model appears to reasonably simulate the experimental data. A primary cause for divergence is the use of the Mohr-Coulomb model in the constitutive framework. As Figure 3 illustrates, the model is unable to accurately describe the non-linear behaviour of the composite particularly near the yielding points, but Diambra et al. (2010) states that the use of non-linear models is easily applicable. The initial linear segment of the stress-strain relationship is accurately represented by the simulations, and Figure 3 highlights that the effect of fibres are only really prevalent after yield. The use of a variable friction angle was able to improve the ability to simulate the increasing yield stress.

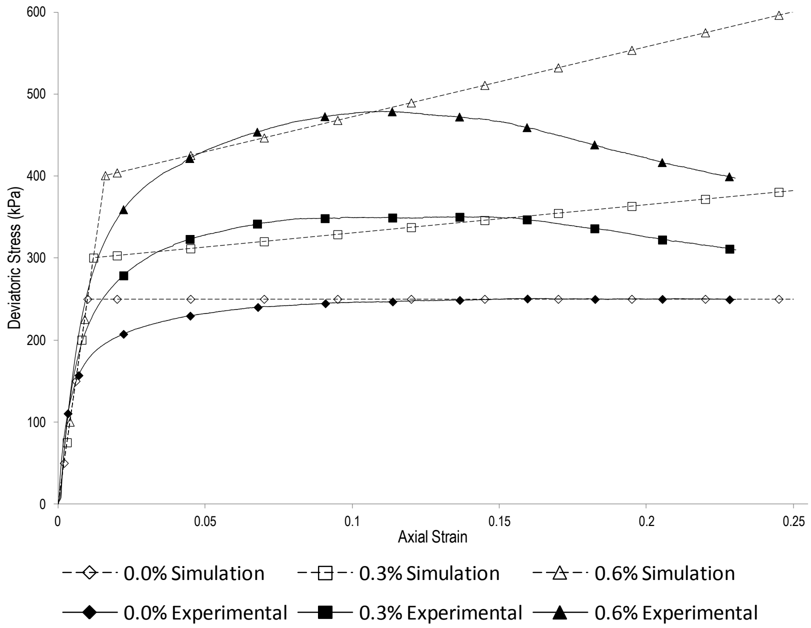

Figure 3: Simulation of experimental results

4 IMPLICATIONS FOR DESIGN

The experimental study presented above in conjunction with the results of several other studies has demonstrated the effectiveness of FRS. The principal factor in the design of geotechnical infrastructure with FRS is the selection of the most appropriate fibre which provides the best interaction with the native soil. In selection a suitable fibre, the fibre concentration, material and geometry must be considered. The relative influence of fibre concentration is strongly dependant on soil type used in the mixture. Small fibre concentrations are more effective in fine grained soils, while larger concentrations are more effective for coarse grained soils (Michalowski & Cermak, 2003; Sadek et al., 2010). As this study has shown, the relative size of fibres and soil particles defines the contact surface area which strongly affects the frictional interaction within the composite. Additionally, Michalowski & Cermak (2003) have demonstrated a slight reduction in initial stiffness of the composite. This is more apparent for polymeric fibres than steel fibres, and most prevalent at very high concentration. Further, several studies have stressed the importance of fibre geometry, where longer fibres and higher aspect ratios tend to contribute more to strength improvement (Maher & Gray, 1990; Michalowski & Cermal, 2003; Ahmad et al., 2010; Sadek et al., 2010). Hence, it can be seen that fibre reinforcement offers versatility to deal with the natural soils of the site and the expected stress environment.

There are many potential applications of FRS for geotechnical infrastructure. Chauhan et al. (2008) conducted experimental tests on silty sand subgrade reinforced with fibres and fly ash, and concluded that the inclusion of reinforcements are an effective means of increasing the strength characteristics of pavement subgrade. Santoni et al. (2001) conducted field test to show improvement in the load bearing capacity of FRS used for road construction. Similar improvements have been demonstrated for the Prior Stream sand, which is sometimes used as a pavement base course material. However, the use of FRS is not limited to pavement reinforcement, and can also be applied to slope stabilisation and repair of failed slopes, where irregular sections limit the use of conventional geotextiles (Ahmad et al., 2010). Further, Park & Tan (2005) employ a finite element method to demonstrate the improved performance of fibre reinforced earth walls, where a reduction in earth pressures and wall displacement was observed.

5 CONCLUSION

Conventional drained triaxial tests were conducted on 100mm diameter samples of Prior Stream sands mixed with polypropylene fibres with concentrations of 0.3% and 0.6% by dry mass of soil. The results of the experimental study revealed the effectiveness of discrete fibres in improving the strength and deformation characteristics of the fibre-soil composite. The composite showed a linear increase in peak deviatoric stress with increasing fibre concentration and the volumetric response showed a more dilative behaviour as fibre content increased. However, the stress-strain curve did not increase without bound, as suggested in other studies and this is thought to be a result of fibre slipping. Simulation of the experimental results was conducted through the constitutive framework presented by Dimabra et al. (2010). This was reasonable in replicating the experimental data, where the differences were primarily in the yielding region and the use of a simple Mohr-Coulomb model, which was not able to describe the non-linear behaviour of the composite. Within the modelling framework, the slipping of fibres was accounted for in a simplified and empirical nature and further investigation and research is required in regards to this phenomenon.

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