Some observations on the mechanics of fibre reinforced sand

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ABSTRACT: This paper discusses - through experimental and numerical results – different aspects of the behaviour of sand reinforced with discrete, flexible fibres particularly under isotropic compression and triaxial/biaxial loading conditions. The behaviour in small, medium and large strain domains with reference to the stress – strain and volumetric responses is considered for different test conditions. The effect of the local micro fabric and local structural re-arrangement on the interaction mechanism between the fibres and granular particles is particularly emphasised as well as the influence of the fibre orientation induced by the fabrication process on the general behaviour of the composite material.

1 INTRODUCTION

It is well known that the roots of surface vegetation contribute to the stability of slopes by adding strength to the near-surface soils in which the effective stress is low (Wu et al. 1988; Greenwood et al. 2004). Laboratory and some in-situ pilot test results (Jewell and Wroth 1987; Palmeira and Milligan 1989; Maher and Gray 1990; Al Refeai 1991; Michałowski & Čermák 2002; Consoli et al. 2005; Zornberg 2002, among others) have led to encouraging conclusions concerning the potential use of flexible fibres for the reinforcement of fine granular materials – providing an artificial replication of the effects of vegetation. Fig. 1a shows an example of some polypropylene fibres recently used as reinforcement for sand at the University of Bristol.

While the effectiveness of the reinforcement is influenced by fibre properties: type, volume fraction, aspect ratio, modulus of elasticity, orientation and also soil characteristics (particle size, shape, and gradation), as well as stress level and soil (matrix) density, the benefits of fibre reinforcement come from the mechanisms of fibre/particle interaction. The fibre inclusions act predominately in tension and observations of strength of fibre-reinforced sands consistently show an increase in strength (compressive strength) dependent on confining stress. This strength increase is linked with the ‘bonding’ of the sand grains by the flexible fibres but eventually the fibres slip past the particles, and may even break: the strength increase is limited.

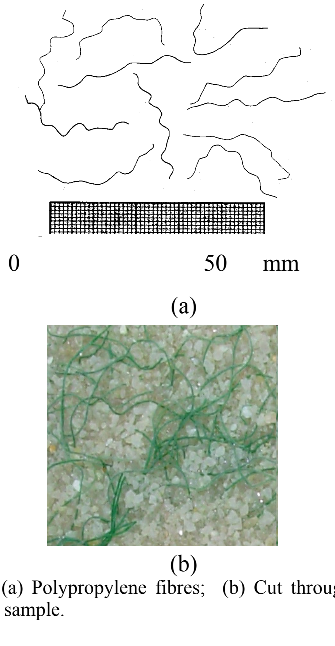

Figure 1. (a) Polypropylene fibres; (b) Cut through a fibre-reinforced sample.

Observations on reinforced soil samples also show that the fibres create a very dense network. A section through a fibre-reinforced sample is shown in Fig.1b. Although the fibre-fibre interaction is expected to be small, the influence of the fibre network on the kinematics of particle movement, including those particles not necessarily in contact with the fibres, may be important. Even though continuum models will eventually be developed for engineering application, simple particulate analogues need to be developed to understand how random flexible fibres generate a bond within the soil and affect the kinematics of the granular matrix.

This paper intends to summarise some behavioural features of fibre reinforced sands observed through recent experiments and numerical results published in the literature.

2 DISCUSSION OF RESULTS

2.1 *Isotropic behaviour*

High-pressure isotropic compression tests on fine sand unreinforced and reinforced with polypropylene fibres (0.5% fibre content by dry weight of sand) performed by Consoli et al. (2005) clearly show the existence of two distinct and parallel normal compression lines for the fibre-reinforced and unreinforced sand (Fig. 2). These results are confirmed by recent DEM simulations by Ibraim & Maeda (2007), Maeda & Ibraim (2008), Fig. 3. While for pressures up to approximately 300-400kPa the deformation responses for all specimens reinforced and unreinforced are almost identical, beyond these pressures, it is clear that the specimen reinforced with higher fibre content has a lower compressibility.

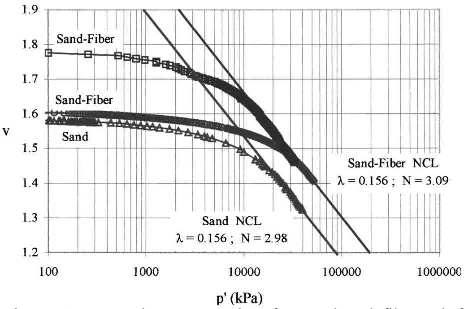

Figure 2. Isotropic compression for sand and fibre-reinforced sand (Consoli et al. 2005).

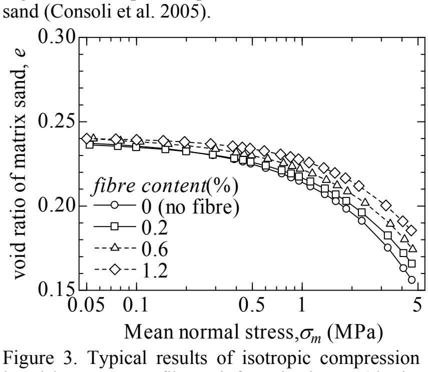

Figure 3. Typical results of isotropic compression tests analysed by DEM on fibre-reinforced mixture (Ibraim & Maeda 2007).

At the end of the isotropic compression test, Consoli et al. (2005) found that fibres had suffered extensive plastic deformations and broken. Even for specimens undergoing isotropic compression, important tensile stresses are developing for the fibres. Therefore, it is apparent that local micro-fabric and local structural re-arrangement can affect the interaction mechanism between the fibres and the grains. Ibraim & Maeda (2007) computed the averaged tensile stress for all the bond contacts on the fibres developed during an isotropic compression test (Fig. 4). As mean normal stress increases, the average tensile stress shows a steady increase too and it is highly possible to reach breaking point for those types of fibres with relatively low individual tensile strength.

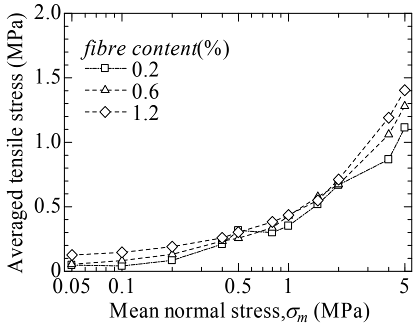

Figure 4. Average tensile stress in fibres developed during isotropic compression (Ibraim & Maeda 2007).

2.2 *Small strain behaviour*

It is widely recognised that soil stiffness evaluated in the laboratory with traditional external measurement devices is underestimated. The measurement of stiffness of soils in the small strain domain can be achieved using the following three methods: the resonant column test, the direct measurement of small strain and stress amplitude during monotonic or cyclic quasi-static loading, and the measurements of the body wave velocities within the soil element. So far as fibre-reinforced soils are concerned, the only attempt to properly assess their small strain behaviour was done by Heineck et al. (2005). The effect of the fibre-reinforcement at very small strains was obtained by measuring the elastic shear modulus (G_o) with bender elements. Fig. 5 shows the evolution of G_o with isotropic pressure (isotropic compression test) for unreinforced and fibre-reinforced Osario sand. As can be observed, the presence of fibres does not change the initial small strain stiffness of the sand material. This conclusion is also confirmed by the DEM analysis (Ibraim & Maeda 2007). The average tensile stresses in the fibres developed with macro shear deformation during a biaxial compression test (Fig. 6) remain practically unchanged in the small and even medium strain domains; the interaction mechanism between the fibres and matrix is not mobilised and the behaviour of the composite appears to be dominated by the sand matrix properties.

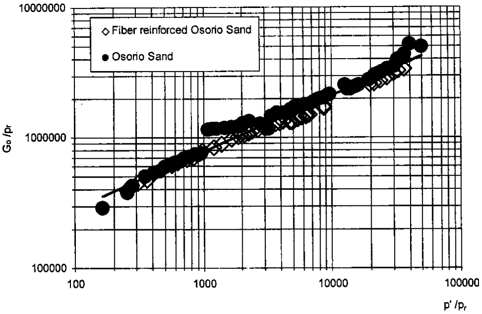

Figure 5. Initial shear modulus of unreinforced and reinforced sand with polypropylene fibres (Heineck et al. 2005).

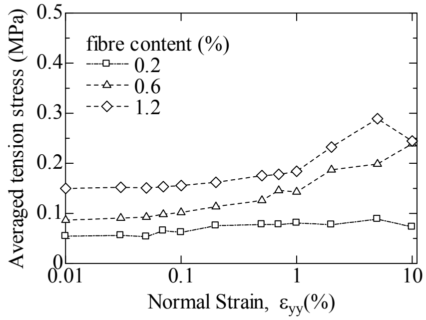

Figure 6. Average tensile stress in fibres developed with macro deformation during shearing (Ibraim & Maeda 2007).

2.3 *Stress-strain behaviour*

Typical results of drained triaxial compression and extension tests on isotropically consolidated unreinforced and reinforced specimens (low density specimens, reconstituted by moist tamping) at a consolidation pressure of 100 kPa are presented in Fig. 7 (Diambra et al. 2008b), where the variations of the deviatoric stress, q, and the volumetric strain, ε_v, are presented with the shear strain, ε_q, and w_f represents the fibre content by weight of dry sand. In compression, the contribution of fibres to the strength of the composite is evident: the deviatoric response is consistently higher when the concentration of fibres is higher (Fig 7a). At 20% shear strain and with w_f = 0.9%, the deviator stress is found to reach almost 300% increase compared with the unreinforced sand. This kind of behaviour is common for compression loading and similar results have been presented by Ranjan et al. (1996) for sand specimens reinforced with polypropylene fibres of high tensile strength. In contrast, in triaxial extension, the contribution of fibres to the deviatoric response appears to be very limited: the stress-strain relationships for reinforced specimens are almost identical to those for unreinforced specimens (Fig. 7a), though 8% to 10% net increase in strength is recorded for 0.6% fibre content. The strength response of the composite in extension therefore seems to be largely controlled by the sand matrix. The overall response of the fibre-reinforced soil appears strongly anisotropic most probably induced by the initial fibre orientation.

The influence of fibre orientation on the mechanical response of fibre reinforced soils has been experimentally investigated in tests with controlled orientations of fibres (Jewell and Wroth 1987; Palmeira and Milligan 1989; Michałowski and Čermák 2002). Many experimental studies implicitly assume that the fibres are initially randomly oriented throughout the soil mass and, as reported by others (Michałowski 2008, for example), there has been very little effort to check this hypothesis experimentally. However, in recent experimental and analytical work, Diambra et al. (2007) found that the moist tamping procedure (the most common procedure for preparing fibre-reinforced specimens) leads in fact to preferred sub-horizontal orientation of fibres, whereas the vertical direction is the direction of tensile strain in a triaxial extension test. These results clearly emphasise the key effect of fibre orientation on the performance of fibre-reinforced sands.

2.4 *Volumetric behaviour*

The volumetric behaviour of unreinforced and reinforced specimens is presented in Fig. 7b. While the volumetric responses for unreinforced sand, in both compression and extension, show initial contraction and only limited eventual dilation at large strains (greater contraction in compression than in extension), which is a typical pattern of a low density sand, the volumetric behaviour of the reinforced sand resembles the characteristic response of a dense granular soil. After an initial reduction in volume, less significant than for the unreinforced sand, there is volumetric dilation with the dilatancy increasing with the fibre content. Similar results have been observed by Ibraim and Fourmont (2006) in direct shear tests. For a given fibre content, the dilatancy is higher in extension than in compression. Although the stress-strain response in extension is not much influenced by the presence of the sub-horizontal fibres, the volumetric behaviour in both compression and extension loading is significantly affected. These results clearly suggest that the volumetric response of the composite could be a consequence of an apparent densification of the sand matrix resulting from the presence of the fibres in the voids: the fibres appear to steal some of the voids from the sand (Diambra et al. 2008a).

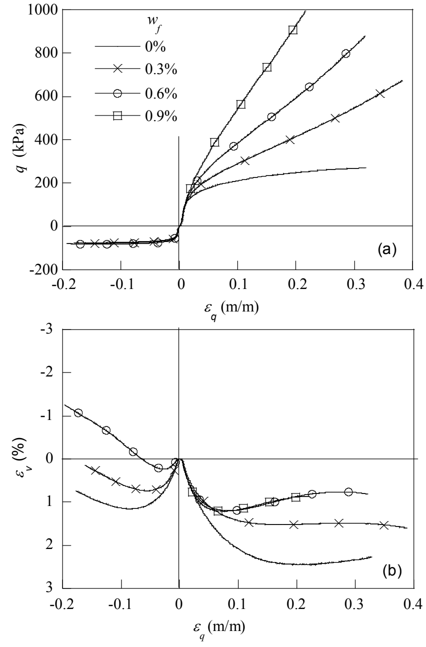

Figure 7. Deviator stress-shear strain and volumetric behaviour for drained compression and extension triaxial tests on isotropically consolidated specimens at 100kPa consolidation pressure (Diambra et al. 2008b).

3 CONCLUSIONS

The analysis of some recent experimental and numerical results on fibre reinforced and unreinforced sand has revealed a number of points of interest:

- The interaction mechanism between the fibres and the matrix is complex; local micro fabric and micro-structural rearrangement can play an important role.
- The fibre/matrix interaction mechanism is not mobilised in the small strain domain: the initial stiffness of the soil is not affected by the presence of fibres.
- The strength increase contributed by the presence of fibres is highly unbalanced between compression and extension triaxial loadings. Qualitative awareness of the actual orientation of fibres is needed to appreciate the difference in response especially if rotations of principal stress and strain axes are expected to occur within a soil mass. The consequence of an assumed isotropy of fibre orientation would be the overestimation of soil design strength for certain loadings and underestimation for others.
- The volumetric behaviour of fibre-reinforced sands has not always been consistently analysed. The change of the volumetric response from contractive for the unreinforced sand to dilative for the reinforced sand is an important characteristic which would be expected to affect the undrained behaviour.

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