STRESS-DILATANCY AND MICROMECHANICS OF FIBRE-REINFORCED SAND

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ABSTRACT

This paper investigates the stress-dilatancy relations of fibre-reinforced uncemented and cemented sand at a wide range of confining pressures. A detailed analysis of the effects of particle, bond and fibre damage on the stress-dilatancy behaviour of sand is presented. Results obtained from drained triaxial compression tests carried out on sand with various fibre and cement contents are compared and analysed. The effects of high confining pressure and fibre content on the stress-dilatancy behaviour of a cemented granular material reinforced with polypropylene fibres are discussed. The microstructure of pre- and post-loading triaxial test specimens is also analyzed using Scanning Electron Microscopy (SEM).

Keywords: Triaxial compression, dilatancy, fibre reinforcement, stress-strain behaviour, cemented sand

INTRODUCTION

A phenomenon of the volume expansion that occurs during shearing of dense granular materials is called dilatancy. This usually takes place after an initial compression and is dependent on the applied confining stresses.

The stress-dilatancy relationship plays an important role in understanding the mechanical behaviour and constitutive modelling of granular soils. The dilative behaviour has significant influence on the stiffness and strength of granular materials. Therefore, ignorance of such dilative behaviour can lead to significant errors in predicting stability or deformation geotechnical structures.

Numerous experiments on fibre-reinforced granular materials have been carried out over the last two decades (e.g. Maher and Gray 1990; Michalowski and Zhao 1996; Consoli et al. 2004; Diambra et al. 2010; Silva Dos Santos et al. 2010; Ud-din et al. 2011). However, the effects of varying fibre content, cement content and confining pressure on the stress-dilatancy behaviour have seldom been investigated. A detail review of the literature, regarding the dilation of fibre reinforced granular materials reveals that the previous studies provide very limited information on the stress-dilatancy behaviour and the dilation angle of fibre reinforced soils. Furthermore, most experimental data for fibre-reinforced cemented materials have been obtained at relatively low confining pressures and at macro-structure level.

In this paper the effect of polypropylene fibres on the stress-dilatancy characteristics of cemented and uncemented sand is investigated for a wide range of confining pressures. The microstructure of selected triaxial test specimens is also analyzed using Scanning Electron Microscopy.

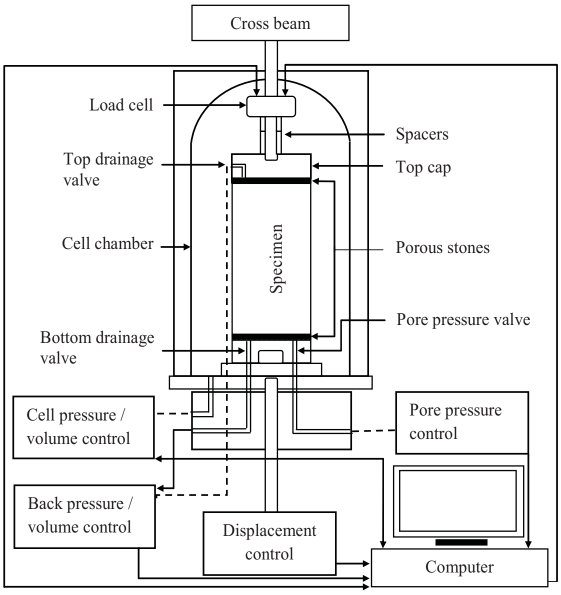
TESTING EQUIPMENT

High Pressure Triaxial Apparatus

A high pressure triaxial testing system, developed at the University of Nottingham, United Kingdom in conjunction with GDS Instruments Ltd. was used in this study. The testing system is shown schematically in Fig. 1(a) and the photograph of the high pressure cell is presented in Fig. 1(b).

It can be seen from Fig. 1 that displacement (or load) in the high-pressure system was applied from the bottom of a loading frame via a displacement controller. A 100 kN submersible load cell was used to measure the vertical load at the top of specimen. The cell pressure was applied through a digital pressure/volume controller (DPVC). Another DPVC was used to control the back pressure from the top of the specimen and measure the volumetric change in a drained test, or to control the volumetric change and measure the pore water pressure in an undrained test.

The DPVCs used in this study had a capacity of 64 MPa. A high capacity pressure transducer was also used to measure the pore water pressure at the bottom of the specimen.



(a)

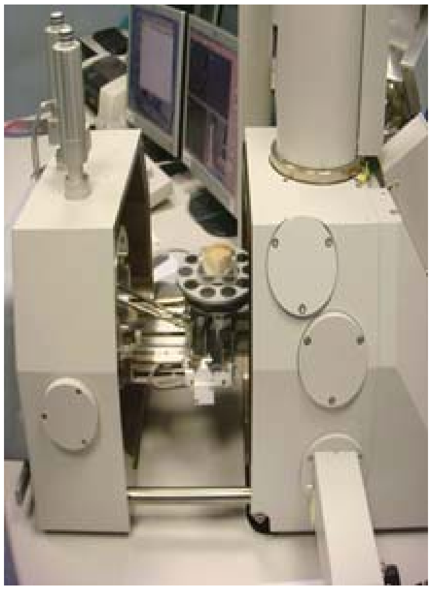
(b)

Fig. 1 High pressure triaxial testing system: (a)schematic diagram; (b) photograph of the cell in the loading frame.

Scanning Electron Microscope

Scanning Electron Microscopy (SEM) was carried out using an FEI Quanta 600 FEG microscope as shown in Fig. 2. It was used for qualitative, morphological analysis of the matrix/fibre interface using a standard Si(Li) back scattered electron (BSE) detector.

(a)



(b)

Fig. 2 Scanning Electron Microscope used in this study: (a) outside view; (b) inside view.

MATERIALS

A well-graded, medium quartz sand from Sheffield in England, called Portaway sand was used as the base material for the cemented specimens. The index properties of Portaway sand, determined by British Standard methods (BS 1377), are given in Table 1. The particle size distribution of Portaway sand is shown in Fig. 3. The sand grains are mainly sub-angular and sub-rounded in shape. Before the preparation of cemented specimens, the sand was passed through 2 mm sieve to remove gravel size particles and washed through 0.063 mm sieve under the running water to remove fines before subsequent specimen's preparation.

Table 1 Index properties of Portaway sand

Property	Values
Specific gravity, G_s	2.65
Mean grain size, D_{50} (mm)	0.39
Uniformity coefficient, D_{60}/D_{10}	2.21
Maximum void ratio, e_{max}	0.79
Minimum void ratio, e_{min}	0.46

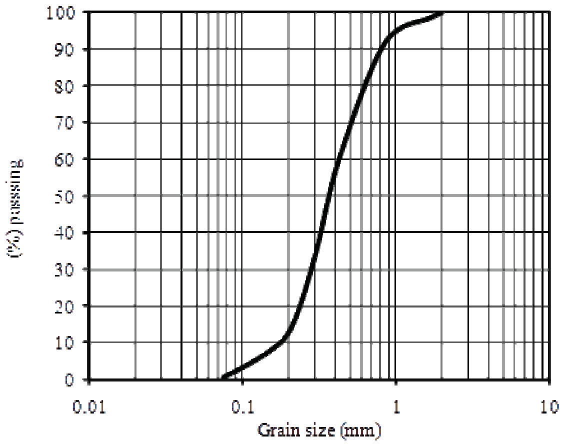


Fig. 3 Grain size distribution curve of Portaway sand

Portland cement and polypropylene fibres were used as binding and reinforcing materials. The physical properties of the fibres used are given in Table 2. A Portland cement (CEM I 42.5 N according to BS EN 197-1) with the initial setting time of 80 to 200 minutes and the specific gravity of 3.15 was used.

Table 2. Physical properties of polypropylene fibres

Property	Value
Length (mm)	22
Diameter (mm)	0.023
Tensile strength (MPa)	350
Young's modulus (GPa)	8
Elongation (%)	70-130
Density (g/cm^3)	0.91

METHODOLOGY

All the cemented specimens analysed in this study (50 mm diameter and 100 mm height) were prepared by mixing relevant amounts of dry Portaway sand and 5% ordinary Portland cement by weight of dry sand. Mixing of dry materials was continued until a uniform appearance of the sand-cement mixture was obtained. Water was then added to the mixture in accordance with the optimum moisture content of 10% and further mixing was performed until a homogeneous appearance of the moist sand-cement mixture was achieved. The mixture was then stored in an airtight container to avoid any moisture loss before subsequent compaction.

The fibre-reinforced uncemented and cemented specimens (50 mm diameter and 100 mm height), were prepared by mixing sand, 0.5% polypropylene fibres and 5% cement (if necessary). Fibres were mixed with sand prior to adding water to achieve uniform distribution of fibres. A thorough mixing of dry materials was continued until a uniform appearance of the sand-cement mixture was obtained. For the preparation of the cemented specimens, 5% Portland cement by weight of dry sand was then added and mixed thoroughly with the sand-fibre composite. After that water was added to the mixture in accordance with the optimum moisture content of Portaway sand and further mixing was performed until a homogeneous appearance of the sand-cement-fibre mixture was achieved.

All the specimens were compacted in three layers into a split mould to a target dry unit weight of 17.4 kN/m^3. The under-compaction method, proposed by Ladd (1978) was used to achieve a greater uniformity of specimens. After compaction, the specimens were allowed to cure inside the mould for 24 hours. The mould was then dismantled and the specimens were stored in a humid room to cure for 14 days before triaxial testing. After each triaxial test, the specimens were investigated for subsequent deformations and changes in the composite due to shearing.

STRESS-DILATANCY BEHAVIOUR

Effect of cement and fibres

The dilative behaviour of sand is significantly influenced by the addition of cement and fibre as shown in Fig. 4, in which the volumetric strain-axial strain and stress ratio-dilatancy curves obtained for a constant confining pressure of 1 MPa are plotted. The solid circles in Fig. 4 indicate the points of maximum dilatancy, which is determined using the parameter, D, equal to the negative value of the ratio of the increment in volumetric strain $d\varepsilon_v$ to the increment in shear strain $d\varepsilon_q$ i.e. $D= -d\varepsilon_v/d\varepsilon_q$. This parameter is often used for analysing dilatancy of various geomaterials (e.g. Bolton 1986; Yu et al., 2007; Consoli et al. 2009c; Silva Dos Santos et al. 2010. It should be noted that the points of maximum dilatancy were determined from the (q/p′)-D relationships plotted in Fig. 4(c) and then traced back into the stress-strain (Fig. 4a) and volumetric strain curves (Fig. 4b).

It can be seen from Fig. 4a that addition of 0.5% fibres has increased the effective stress ratio of both uncemented and cemented sand. In other words, the shear strength of Portaway sand increased due to 0.5% fibre content. It can also be observed from Figs. 4(a) and (c) that the maximum dilation occurs at $(q/p')_{peak}$ for both fibre-reinforced cemented and uncemented sand. This observation is different from that reported by Silva Dos Santos et al (2010) based on tests carried out at lower confining stresses. They reported that the inclusion of fibres increased the peak stress ratio, but unlike for pure sand, the peak stress ratio of fibre-reinforced sand did not correspond to the maximum dilatancy and seemed to occur at the end of dilation.

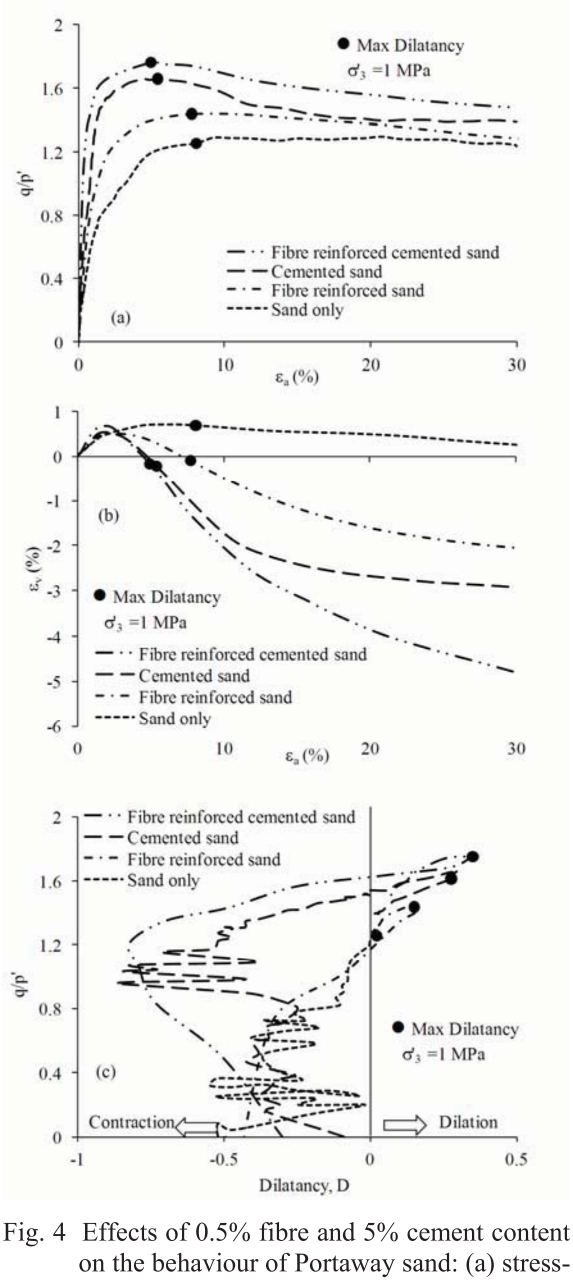


Fig. 4 Effects of 0.5% fibre and 5% cement content on the behaviour of Portaway sand: (a) stress-strain curves; (b) volumetric response; (c) stress-dilatancy.

Figure 4b shows volumetric strain curves of various types of Portaway sand. All the samples compress initially and then dilate until the end of tests. The tendency for dilation was found to be more significant in fibre-reinforced composites, as shown in Fig. 4b.

The (q/p′)-D plots are shown in Fig. 4(c). It can be seen that the addition of fibre has moved the plots to the left and upward, which suggests that the presence of fibres increases both dilation and effective stress ratio of uncemented and cemented sand. Similar results were obtained by Ibraim et al. (2010) who reported that the dilative response of the fibre-sand composite could be an outcome of an apparent densification mechanism of the sand matrix due to the presence of fibres in the soil voids. Fibres fill the voids in dense sand and provide an additional platform to the sand particles for rolling over during shearing, which increases dilation. Consoli et al. (2009c), on the other hand, presented different results for stress-dilatancy behaviour of fibre-reinforced cemented and uncemented sand. They reported that fibre-reinforced samples showed a similar maximum dilatancy to that of unreinforced sand, but it was reached at a higher effective stress ratio. In addition, Consoli et al (2009c) observed that after reaching the maximum dilatancy, the value of the maximum stress ratio was continuously increasing with decreasing dilatancy until reaching zero volume change at the critical state.

It should also be pointed out that the addition of cement has also the effect of increasing dilation in sand because of bonding (Marri 2010). However, the combined effect of fibre and cement is more significant, as shown in Fig. 4.

Effect of Confining Pressure

Fibre reinforced sand

The effect of confining pressure on dilative behaviour of Portaway sand is presented in Fig. 5. All the specimens were sheared under drained conditions in the wide range of effective confining pressures from 50 kPa to 20 MPa.

The ε_v - ε_a plots in Fig. 5(a) show that dilative behaviour of dense sand is suppressed by gradual increase in the confining pressure. It can be seen that at the effective confining pressures above 1 MPa there is a complete suppression of dilation, which is similar to the behaviour of loose sand at low confining pressures. This means that the effect of dilation on the shear strength of dense sand is diminished at high confining pressures. This is because the application of a high confining pressure suppresses both the opening of voids and the propagation of microcracks within the tested geomaterial. This suppression of dilative behaviour with the increasing confining pressure can also be observed in the stress-dilatancy relationships for the selected specimens of fibre-reinforced sand tested at σ_3' from 50 kPa to 1 MPa, as shown in Fig. 5(b). The maximum dilatancy (D) is obtained at the lowest confining pressure of 50 kPa and reduces gradually with increasing confining pressure (Fig. 5b).

The suppression of dilatancy with increasing confining pressures in a fibre-reinforced uncemented sand has also been reported by other researchers. However, the data is typically limited to the confining stresses below 1 MPa. As a result there is a lack of consensus on to what degree the confinement affects the dilatancy. For example, Consoli et al., (2009b) reported that there is no effect of confinement in the range of 100 kPa to 500 kPa on dilatancy behaviour of sand and fibre reinforced sand and only the stress ratio is reduced. As shown before, this observation agrees with the data published in this paper where a significant effect of high confining pressures on the dilative behaviour of fibre-reinforced sand occurs at approximately 1 MPa.

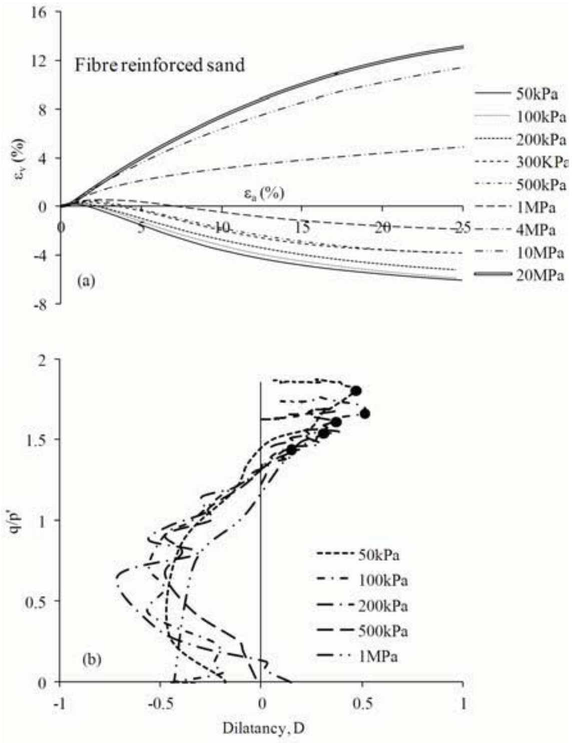


Fig. 5 Effect of confining pressure on dilative behaviour of fibre-reinforced sand (0.5% fibre): (a) ε_v-ε_a curves; (b) q/p'-D curves.

Fibre-reinforced cemented sand

The effect of confining pressure on the dilative behaviour of the fibre reinforced cemented sand is shown in Fig. 6, which shows a similar trend to that observed for the fibre-reinforced sand (see Fig. 5). It can be observed from Fig. 6a that the dilation of fibre-reinforced cemented sand decreases with the increasing confining pressure whereas the axial strain to the point of maximum dilation rate increases with increasing confining pressures. Thus, the ε_v-ε_a curves show that the dilation is gradually suppressed by increasing confining pressure until 4 MPa where the high confining pressure overcomes the dilative behaviour and total compressive behaviour is observed.

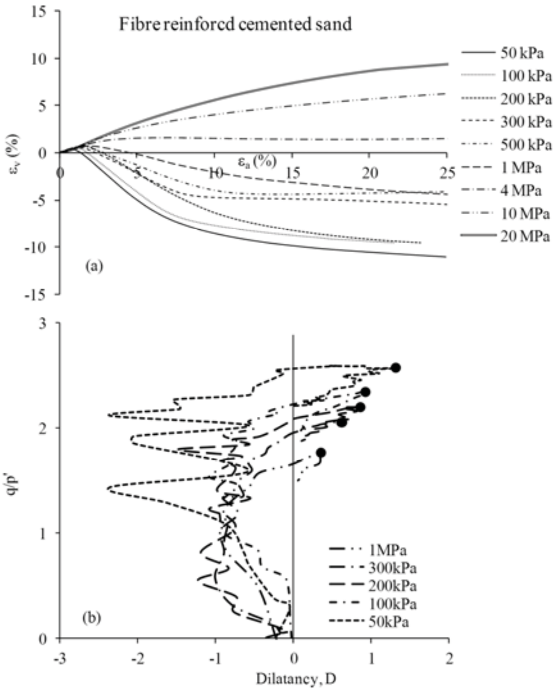


Fig. 6 Effect of confining pressure on dilative behaviour of fibre-reinforced cemented sand (0.5% fibre): (a) ε_v-ε_a curves; (b) q/p'-D curves

Dilation Angle

The angle of dilation is one of the most frequently used parameters to quantify dilative behaviour of granular materials. The peak strength is usually associated with the maximum angle of dilation defined as $\tan^{-1}(-d\varepsilon_v/d\varepsilon_1)_{max}$ where ε_v, is the volumetric strain and ε_1 is the major principal strain.

The maximum dilation angles of clean, fibre-reinforced uncemented and fibre-reinforced cemented sands, measured at different effective confining pressures, are plotted in Fig. 7. It can be seen that the dilation angles decrease with increasing confining pressure. Figure 7 shows that the positive dilation angles, indicating volumetric expansion, were measured up to 1 MPa. However, all the dilation angles measured above 1 MPa were negative, which indicates volumetric compression.

Figure 7 also shows that the effect of fibre-reinforcement on the maximum dilation angle is highest at lower confining pressures and reduces with increasing confining pressures. It can also be observed that overall compression increases with increasing confining pressures. Finally, comparison of the data obtained for fibre-reinforced uncemented and cemented sands reveals that the addition of both cement and fibres increases the dilation angle more significantly that the addition of fibres alone.

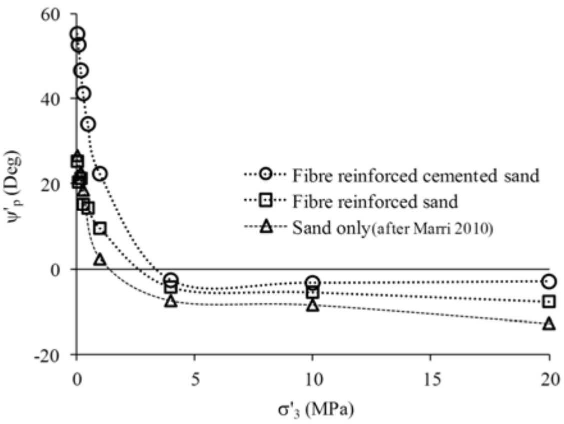


Fig. 7 Effects of fibre, cement and confining pressure on dilation angles of Portaway sand.

The effect of addition of fibre in sand and cemented sand can also be observed from Fig. 8, in which maximum dilation angles are plotted for all the composites tested at σ_3' = 1 MPa. It can be seen that the fibres have increased the maximum dilation angle of uncemented and cemented sands from 1.5° to 10.17° and from 15.95° to 18.9°, respectively. This means that the effect of fibre is more significant in uncemented sand than in cemented sand. Similar test results were obtained for other confining pressures (Ud-din et al. 2011).

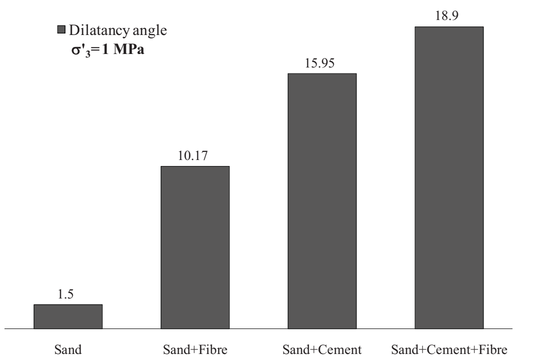


Fig. 8 Dilation angles measured at σ_3' = 1 MPa for different types of Portaway sand.

MICROMECHANICS

SEM analysis on selected specimens of Portaway sand was carried out before and after triaxial testing. The SEM micrographs helped investigate the mixing, distribution and homogeneity of fibres. Particle crushing, fibre damage and bond breakage was also visually assessed.

Figure 9 shows SEM micrographs of a representative fibre-reinforced cemented sample (Fig. 9a) and a fibre-reinforced uncemented sample (Fig. 9b) before testing. These SEM micrographs show typical fibre distributions observed for all the specimens analysed. However, it is important to note that the SEM micrographs shown in Fig. 9 represent the qualitative information with regard to the distribution of fibre limited to a very small area and to a specific horizontal or an inclined failure plane. As a result, reasonable uniform distribution of fibres observed at macroscale for most of the specimens (Ud-din 2012) may not have the same level of uniformity and consistency at micro level analysed for a relatively small area of the specimen, as shown in Fig. 9.

Nonetheless, it can be seen from Fig. 9 that fibres are distributed quite uniformly and create a network of fibres with sand grains. A similar fibre distribution has also been shown by Tang et al., (2007). In addition, fibres in the fibre-reinforced cemented sample shown in Fig. 9a appear well-coated by the cement. Whilst the bonding mechanism is likely to be frictional only, this suggests good compatibility of fibre/cement matrix during shearing.

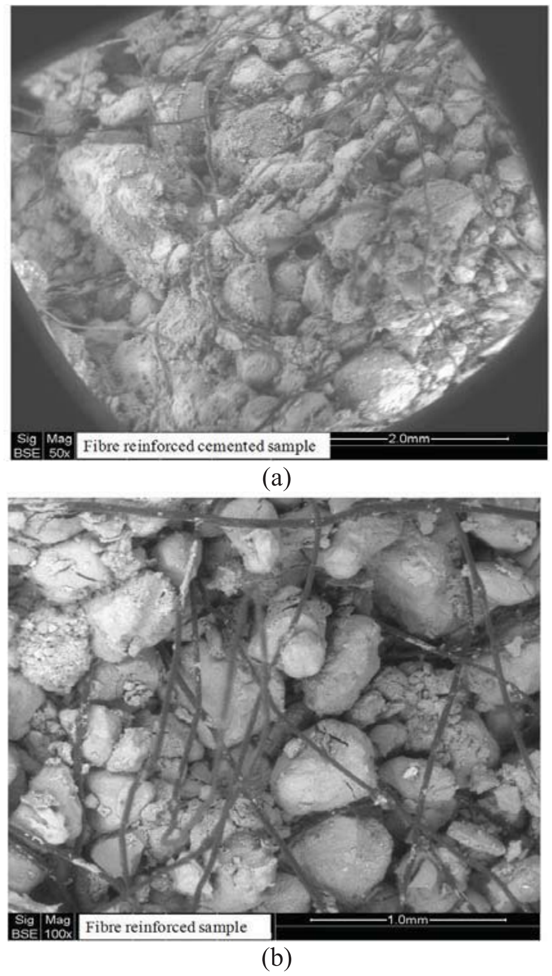
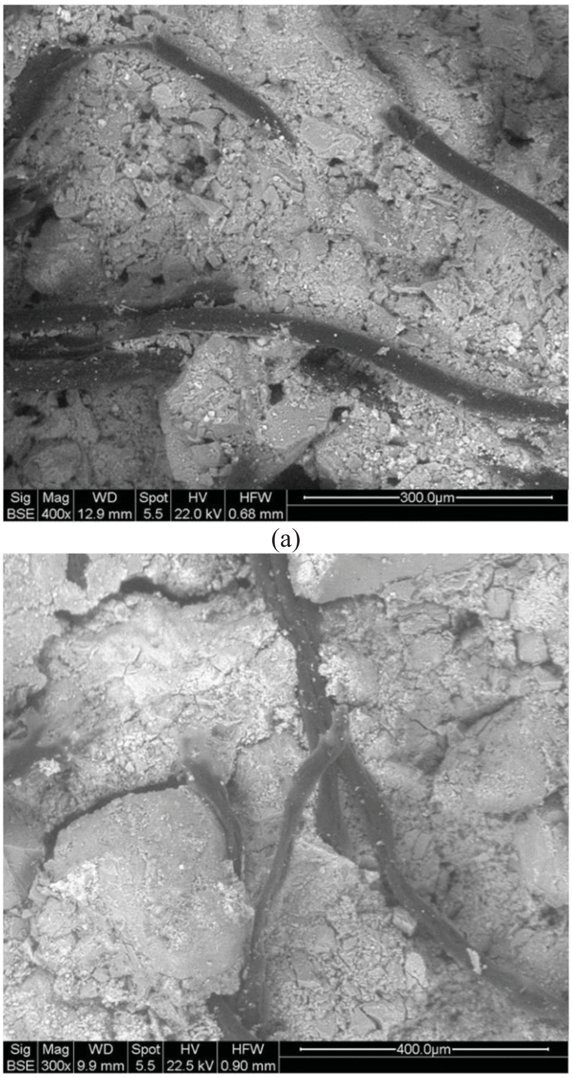


Fig. 9 SEM micrographs illustrating distribution of fibre in: (a) fibre-reinforced cemented sand (0.5% fibre and 5% cement); (b) fibre-reinforced uncemented sand (0.5% fibre and 0% cement).



(a)

(b)

Fig. 10 Examples of SEM micrographs of the fibre-reinforced specimens sheared at σ_3' = 1 MPa; (a) fibre-reinforced uncemented sand (0.5% fibre and 0% cement); (b) fibre-reinforced cemented sand (0.5% fibre and 5% cement).

Figure 10 shows two examples of SEM micrographs of the fibre-reinforced uncemented (Fig. 10a) and cemented (Fig. 10b) specimens, taken after drained shearing at the effective confining pressure of 1 MPa. A clear particle crushing in the uncemented specimen can be observed from Fig. 10a. A cement bond breakage accompanied by the particle crushing in the cemented specimen is also shown in Fig. 10b. However, only limited fibre damage in both uncemented and cemented specimens could be identified by the SEM analysis. This observation suggests that after the occurrence of particle and bond breakage, the fibres themselves could have resisted the shearing until their tensile strength was reached. In a brittle matrix composite such as the sand-cement with addition of fibre, the matrix will crack followed by gradual pull out of the ductile fibre.

It should also be pointed out that the tensile strength of the polypropylene fibres used in this study was quite high (see Table 2), so the fibres could provide a strong platform to the sand particle for rolling over when sheared to large strains. As a result, the dilation of fibre-reinforced specimens has increased significantly compared to that of unreinforced specimens.

Finally, Ud-din (2012) also observed the lack of interfacial debonding at the fibre/matrix interface of the fibre-reinforced cemented specimens. Since fibres and the matrix have different Young's moduli. This suggests the interface regions have experienced minimal strains, which reduced compressibility of the specimens.

SUMMARY

In this paper, the results of drained triaxial compression tests carried out on fibre-reinforced uncemented and cemented Portaway sand at a wide range of confining pressures, are presented and discussed. The mechanism of dilatancy, its significance and dependence on fibre, cement and confining pressures are investigated. The following conclusions can be drawn:

1) The dilative behaviour of Portaway sand is affected by the fibre content, cement content, and confining pressure. In particular, there is a significant effect of the addition of fibre on the response of both cemented and uncemented types of sand. The addition of fibres increases the dilative behaviour of the composite.

2) The addition of fibres increases the maximum dilation angle of uncemented and cemented sand. However, the effect of fibre is more pronounced in uncemented sand.

3) The confining pressure affects dilative behaviour of Portaway sand. The dilatancy of the sand reduces with increasing confining pressure. It was observed that at higher confining pressures the effect of confinement was dominated. As a result, at the effective confining pressures higher than 1 MPa the behaviour of fibre-reinforced uncemented and cemented Portaway sand was purely compressive (i.e. no dilation occurred).

4) SEM analysis revealed a significant particle crushing and bond breakage in the uncemented and cemented specimens sheared at high confining pressures. However, only limited fibre damage was identified. This suggests that the fibres could provide a strong rolling platform to the sand particle during shearing to large strains, which explains why the dilation of fibre-reinforced sand increased significantly compared

to that of unreinforced specimens. Furthermore, a strong, ductile fibre added to the cemented sand provided a strong fibre/cement matrix interfacial bond causing a high frictional resistance during shearing. Thus, post-crack fibre pull out resistance could explain the observed significant dilatancy behaviour of the fibre-reinforced cemented sand.

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