Effect Of High Confining Pressure On The Behaviour Of Fibre Reinforced Sand

S. Ud-din[1], A. Marri[2], and D. Wanatowski[1]
[1]*Nottingham Centre for Geomechanics, Faculty of Engineering, University of Nottingham, NG7 2RD, United Kingdom*
[2]*Department of Civil Engineering, NED University of Engineering and Technology, Karachi-75270, Pakistan*
E-mail: dariusz.wanatowski@nottingham.ac.uk

ABSTRACT: Several techniques of soil stabilisation and soil reinforcement are available for improving properties of geotechnical materials. However, the addition of fibre into soils has its unique potential. This is because friction between fibres and soil particles increases bonding between the particles. As a result, the stress-strain behaviour and failure characteristics of both cemented and uncemented soils reinforced with fibres can be improved. In this paper, the influence of fibre and cement on the behaviour of sand in a wide range of confining pressures is studied. Drained triaxial compression tests carried out on uncemented and artificially cemented Portaway sand with 0.5% randomly distributed discrete polypropylene fibres are presented. The experimental results show that stress-strain behaviour and strength characteristics of Portaway sand improve with addition of fibres. However, the effect of fibre reinforcement is more significant at lower confining pressures. At high confining pressures, the contribution of fibres is suppressed and the effect of high confinement becomes dominant.

1. INTRODUCTION

Fibre reinforcement of soil is an interesting and innovative solution for geotechnical engineering problems. The behaviour of fibre reinforced sand has been widely investigated and reported in the literature (Gray and Ohashi 1983; Gray and Alrefeai 1986; Maher and Gray 1990; Consoli et al. 2007b, 2009a, b; Michalowski 2008; Diambra et al. 2010). Numerous experiments carried out on fibre reinforced sand have shown that the peak shear strength of sand increases when discrete fibres are added to the soil.

Improving engineering properties of soils with both fibres and cement appears to be even more attractive. This is because the combined effect of adding cement and fibre improves further the engineering response of soils under structural loads and provides additional resistance to the subsequent deformations compared to the effects of cement or fibres alone (Maher and Ho 1993; Consoli et al. 1998, 2003, 2010; Ud-din et al. 2010). Combined usage of fibre and cement in the soils has its unique advantages. For instance, the use of cement increases the strength and induces brittleness into the soil. On the other hand, fibre induces ductility. Thus, the addition of fibre and cement not only improves the strength of the soil but also provides diversity into the resistance to deformations against imposed loads (Maher and Ho 1993; Consoli et al. 2004, 2007a; Tang et al. 2007).

Most research on fibre reinforced cemented granular materials has been carried out at relatively low confining pressures up to 1 MPa (Maher and Ho 1993; Consoli et al. 2009c; dos Santos et al. 2010a). More recently, dos Santos, et al. (2010b) reported experiments on fibre reinforced cemented sand under high pressure up to 40 MPa. It was reported that fibre reinforcement reduced the particle breakage and crack propagation in cemented sand. However, these results were obtained from isotropic compression tests. Experimental data on fibre reinforced cemented sand obtained from high pressure drained and undrained triaxial compression tests are still very limited (Ud-din et al. 2010). As a result, the effects of fibre reinforcement and cement stabilisation on the mechanical characteristics of granular materials sheared under high confining pressures are not fully understood.

The main objective of this paper is to investigate the behaviour of fibre reinforced cemented sand at high confining pressures. The results of isotropically consolidated drained (CID) triaxial tests carried out at confining pressures from 50 kPa to 20 MPa are presented. In particular, the effect of high confining pressures on the strength and deformation characteristics of fibre reinforced cemented sand are discussed. The stress-strain behaviour of a sand, fibre reinforced sand, cemented sand, and fibre reinforced cemented sand in drained triaxial compression is also discussed.

2. MATERIALS AND METHODOLOGY

2.1 Materials

Portaway sand, a well-graded concrete sand from Sheffield in England, was used as a base material for the preparation of specimens. The particles of Portaway sand are sub-angular and are mainly composed of quartz with some carbonate materials. The basic properties of the sand are given in Table 1.

A discrete monofilament polypropylene fibre was used in the study. The nominal length of fibre was 22 mm and the nominal diameter was 0.023 mm.

An ordinary Portland cement was used as a bonding agent.

Table 1 Index properties of Portaway sand

Property	Value
Mean grain size, d_{50} (mm)	0.47
Uniformity Coefficient, d_{60} / d_{10}	2.29
Specific Gravity, G_s	2.63
Maximum Void Ratio, e_{max}	0.686
Minimum Void Ratio, e_{min}	0.512

2.2 Sample preparation

The fibre reinforced cemented and uncemented specimens (50 mm diameter and 100 mm height), were prepared by mixing sand, polypropylene fibres and/or cement. Fibres were mixed with sand prior to adding the water to achieve uniform distribution of fibres. 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% of 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.

The specimens were compacted in layers into a split mould to a target dry unit weight of 17.4 kN/m^3. A thin plastic transparency sheet, cut according to the size of the mould, was used inside the mould before pouring the mix to prevent sticking the material to the walls and base of the mould. After compaction, the uncemented fibre reinforced specimens were ready for testing. However, the cemented specimens were cured for 14 days before carrying out drained shearing.

2.3 Testing system and procedures

A high pressure testing system, developed at the University of Nottingham (UK) in conjunction with GDS Instruments Ltd. was used for all the experiments presented in the paper. The testing system is shown schematically in Figure 1. The main components of the system include a loading frame, high pressure triaxial cell, digital displacement/load controller, two digital/pressure volume controllers, load cell, pore pressure transducer, data acquisition box and a computer.

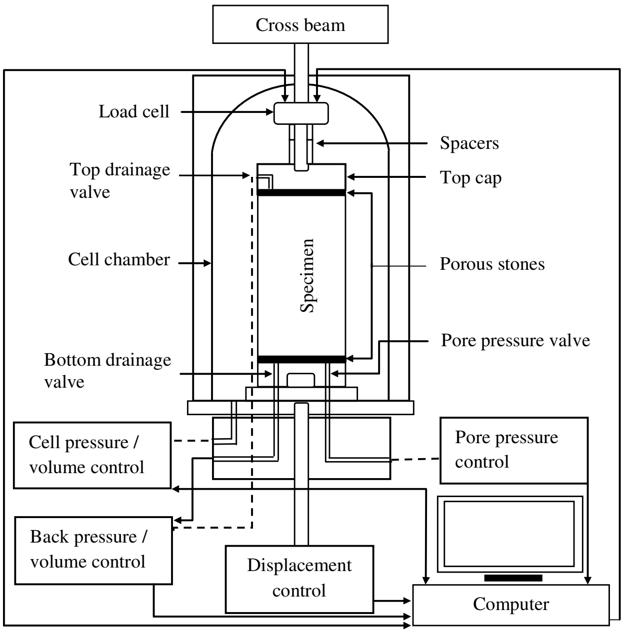


Figure 1 Schematic diagram of the high pressure triaxial testing system

The loading frame used in this study has a virtual infinite stiffness (VIS) system that improves accuracy of soil and rock stiffness measurement. This is because the VIS minimizes compliance errors of the loading system and the load measuring system. In the VIS axial loading system, both the measurement and control of platen displacement are automatically corrected so that the displacement corresponds to the deformation that occurs between the base platen and the load button of the load cell.

As shown in Figure 1, displacement (or load) in the high pressure system was applied from the bottom of a loading frame via a digital hydraulic force actuator. The actuator was controlled by a computer via a digital load/displacement control box. 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 GDS 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 photograph of the assembled high pressure triaxial cell is shown in Figure 2. The cell is made of stainless steel, has a pressure capacity of 64 MPa and a working axial load capacity of 250 kN. The high pressure cell has the balanced ram assembly, installed at the top of pressure chamber, which ensures zero uplift force and zero volume/pressure change inside the cell when the specimen is loaded at high cell pressure.

All the tests presented in this paper were carried out on specimens of 50 mm diameter and 100 mm height. The specimens were saturated by flushing with de-aired water from the bottom under a low water head. After flushing was completed, a saturation ramp was applied, in which both the cell pressure and the back pressure were increased simultaneously until Skempton's pore water pressure parameter (B-value) greater than 0.95 for uncemented and 0.90 for cemented specimens was obtained. The specimens were then isotropically consolidated to the required mean effective stress and sheared under drained conditions, i.e., with $\Delta\sigma'_3 = 0$. All the consolidated isotropically drained (CID) tests were carried out under a deformation-controlled loading mode at a constant deformation rate of 0.1 mm/min.

Figure 2 Photograph of the high pressure triaxial cell assembled in the loading frame

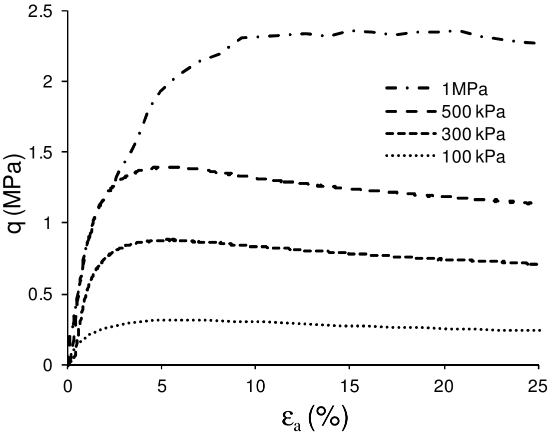
3. RESULTS

3.1 Unreinforced Portaway sand

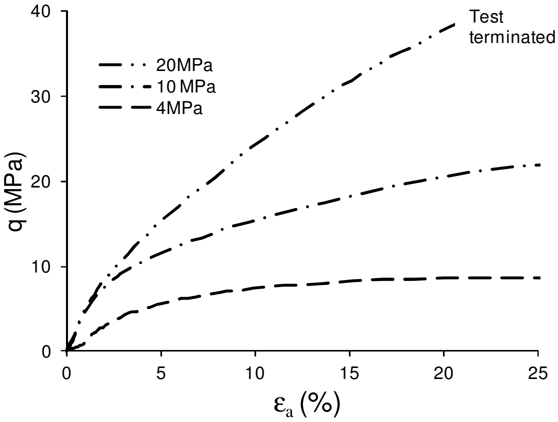
Typical results of CID tests on clean (i.e. unreinforced uncemented) Portaway sand are shown in Figure 3. The stress-strain curves of specimens sheared at confining pressures up to 1 MPa are shown in Figure 3(a). The stress-strain curves obtained from specimens sheared at confining pressures larger than 1 MPa are plotted in Figure 3(b).

It can be observed from the stress-strain curves that the increase in confining pressures increases the initial stiffness and the peak deviator stress of Portaway sand. It can be noticed from Figure 3(a) that at lower confining pressures there is tendency in the stress-strain curves to reach a peak deviator stress followed by subsequent strain softening. However, at higher confining pressures (Figure 3(b)) strain softening changes into strain hardening type of behaviour without any clear peak in the stress-strain curves.

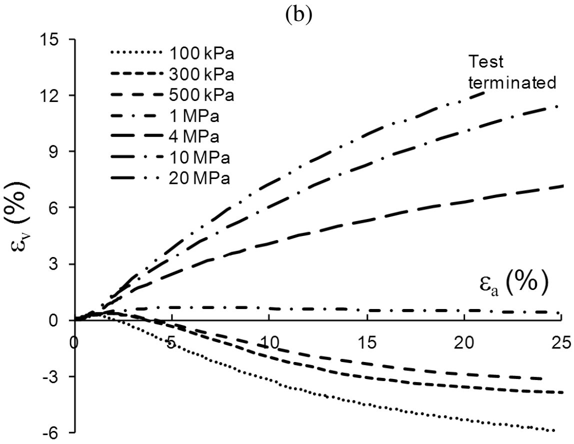
For the material tested in this study, the transition from strain softening to strain hardening behaviour occurs at the confining pressure of 1 MPa where material deforms at an approximately constant deviator stress after reaching the peak, as shown in Figure 3(a).



(a)



(b)



(c)

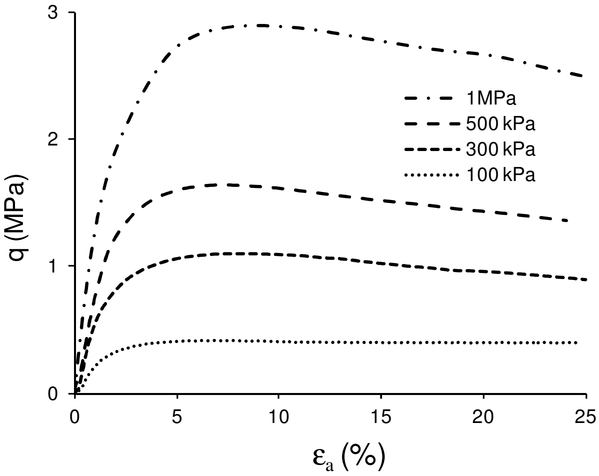
Figure 3 Drained behaviour of clean Portaway sand: (a) stress-strain curves for $\sigma'_3 \leq 1$ MPa; (b) stress-strain curves for $\sigma'_3 > 1$ MPa; (c) volumetric strain curves

The volumetric strain curves of clean Portaway sand are plotted in Figure 3(c). It can be seen that all the specimens exhibited an initial compression regardless of the magnitude of confining pressure. In the specimens sheared at $\sigma'_3 \leq 1$ MPa, the initial volumetric compression is followed by the subsequent volumetric dilation. However, in the specimens sheared at σ'_3 of 4 MPa to 20 MPa, the dilation is suppressed and only volumetric compression is measured.

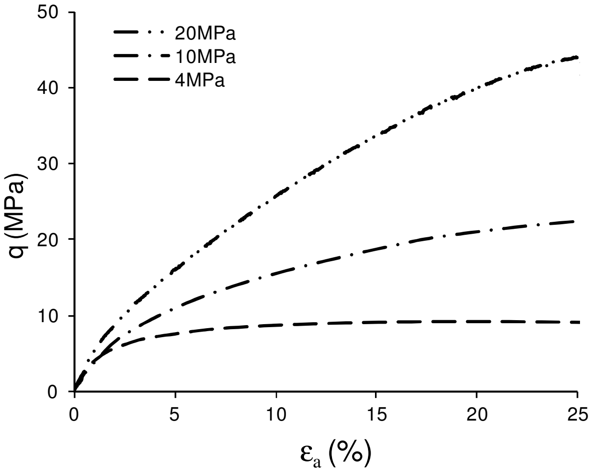
It can also be seen from Figure 3 that there is a tendency of the material to approach the critical state (i.e. deformation at constant deviator stress with no volume change). However, strictly speaking, the critical state was not fully reached in any of the tests as the volumetric deformation was still occurring at the end of shearing. This is consistent with observations made by other researchers who reported difficulties in achieving critical state conditions for granular materials tested in the laboratory (Chu and Lo 1993; Wanatowski and Chu 2007; Bobei et al. 2009).

3.2 Fibre reinforced sand

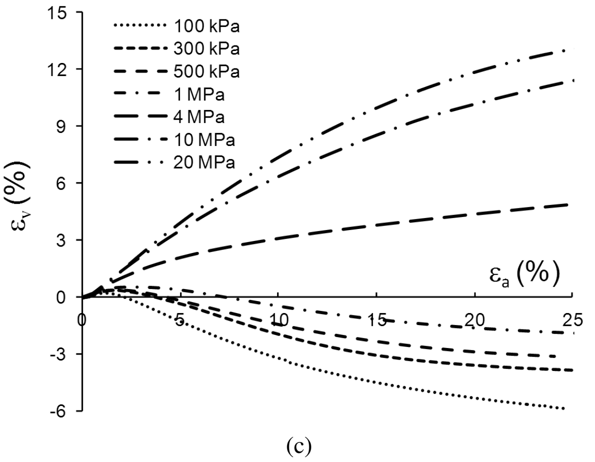
The effect of confining pressure on the fibre reinforced sand is illustrated in Figure 4.



(a)



(b)



(c)

Figure 4 Drained behaviour of fibre reinforced sand: (a) stress-strain curves for $\sigma'_3 \leq 1$ MPa; (b) stress-strain curves for $\sigma'_3 > 1$ MPa; (c) volumetric strain curves

The stress-strain curves obtained from the CID tests on specimens consolidated to confining pressures of 100 kPa to 20 MPa are shown in Figures 4(a) and 4(b). It can be seen from the stress-strain curves that the response of fibre reinforced sand is similar to that of uncemented sand discussed in preceding section. The stress-strain response changes from strain softening to strain hardening with the increasing confining pressure, as shown in Figures 4(a) and 4(b). However, an increase in the confining pressure resulted in higher peak and ultimate deviator stresses compared to those of the parent sand (see Figure 3). It can also be seen from Figure 4(b) that the transition from softening to hardening behaviour in fibre reinforced sand tested in this study occurred at σ_3' = 4 MPa.

The volumetric strain behaviour of the fibre reinforced sand is shown in Figure 4(c). It can be noted that the behaviour is similar to that of unreinforced parent sand shown in Figure 3(c). However, in general, more volumetric dilation (or less compression) is observed in the fibre reinforced sand compared to that in the unreinforced sand.

Similar to the response of clean Portaway sand the fibre reinforced sand tends to either dilate (at lower confining stresses) or compress (at higher confining pressures) at the end of each test, as shown in Figure 4(c). Therefore, the critical state has been approached but not fully reached by the fibre reinforced specimens.

3.3 Fibre reinforced cemented sand

The effect of confining pressure on the behaviour of fibre reinforced cemented sand is presented in Figure 5. The stress-strain curves obtained from the CID triaxial tests are shown in Figures 5(a) and 5(b). Similar to unreinforced and fibre reinforced uncemented specimens, increasing confining pressure increased the peak deviator and ultimate stresses of fibre reinforced cemented Portaway sand. Figure 5(a) also shows that specimens sheared at the effective confining pressures up to 1 MPa reached the peak deviator stresses followed by strain softening behaviour at large strains. On the other hand, the specimens sheared at higher confining pressures showed either very little strain softening (σ_3' = 4 MPa) or strain hardening (σ_3' = 10 MPa and 20 MPa) during shearing (Figure 5(b)). It should also be noted that the test carried out at σ_3' = 20 MPa was terminated at the axial strain of 20% because the load cell reached its capacity.

The volumetric response of the fibre reinforced cemented specimens is shown in Figure 5(c). It can be observed that with the increase in confining pressure dilative behaviour of specimens changes gradually into compression. Furthermore, the rate of dilation decreases and at a higher confinement, as shown in Figure 5(c).

Figure 5 also shows that the critical state was nearly reached in all the tests carried out on fibre reinforced cemented sand. However, similar to the behaviour of clean and fibre reinforced uncemented sand, the volumetric deformation did not cease at the end of each test.

4. DISCUSSION

4.1 Stress-strain behaviour

Figures 3 to 5, presented in the preceding section, clearly illustrated that the stress-strain behaviour of Portaway sand is influenced by the addition of both fibres and cement. As reported by Marri et al. (2010) and Ud-din et al. (2010), the behaviour of Portaway sand is also affected by the addition of cement alone. Therefore, in order to illustrate further the effects of fibre and cement on the stress-strain behaviour of sand, the results of four CID tests carried out on different types of specimens at the same effective confining stress σ_3' = 300 kPa are compared in Figure 6. It is worth nothing that in this study such a confining pressure is considered as low.

It can be observed from the stress-strain curves plotted in Figure 6(a) that the addition of 0.5% fibres, 5% cement or 0.5% fibres and 5% cement can be used to increase the peak deviatoric stress of the sand. However, the effect of fibre alone is not very significant. In order to improve the peak shear strength of the sand, either cement or fibre and cement must be added. It can be observed from Figure 6(a) that the cement stabilisation results in much stiffer response of the sand, in particular when it is combined with the use of polypropylene fibres. Figure 6(a) also illustrates that while the addition of cement or cement with fibres to the sand stiffens the stress-strain relationship, the addition of fibres alone results is a more ductile behaviour.

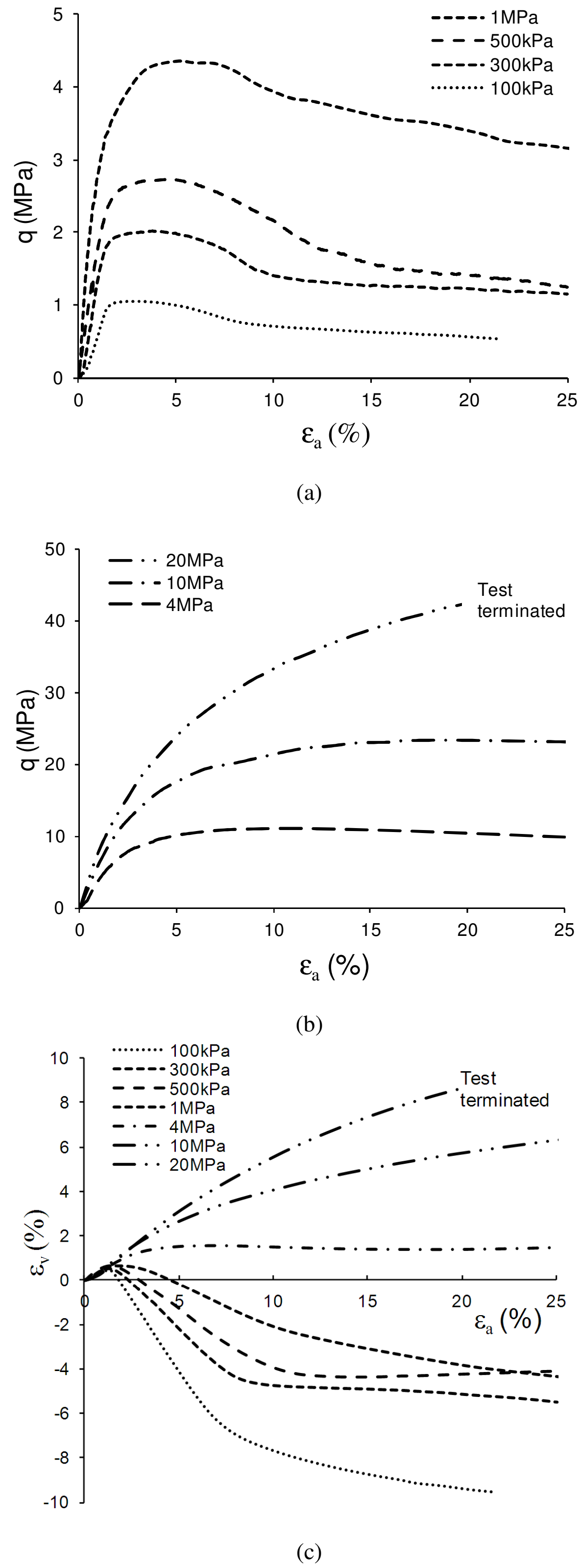
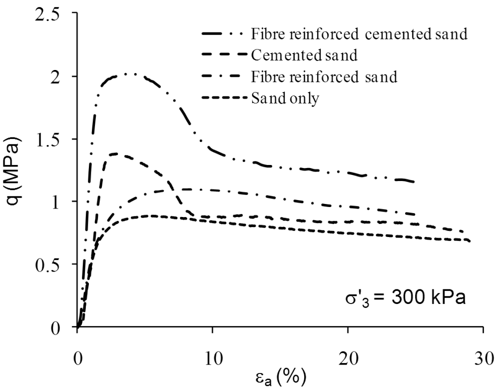


Figure 5 Drained behaviour of fibre reinforced cemented sand: (a) stress-strain curves for $\sigma'_3 \leq 1$ MPa; (b) stress-strain curves for $\sigma'_3 > 1$ MPa; (c) volumetric strain curves

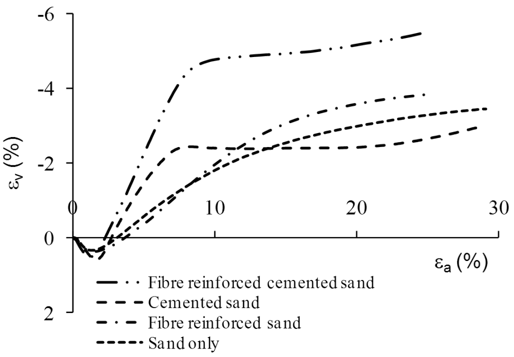
This is demonstrated by the larger axial strain at the peak state and less strain softening observed in the post-peak region of the fibre reinforced uncemented specimen.

The ε_v-ε_a curves obtained from all the tests carried out at the effective confining stress σ_3' = 300 kPa are compared in Figure 6(b). All the curves show an initial volumetric contraction followed by a subsequent volumetric dilation. However, the effect of the fibre reinforcement and the cement stabilisation is clearly observed. Firstly, the rates of dilation measured in all the tests are different. Secondly, the amounts of dilation obtained from each test are also different. In general, the amounts and rates of dilation changed from the lowest in the unreinforced sand to the highest in the fibre reinforced cemented sand with the dilation of the fibre reinforced and cement stabilized specimens in between (Figure 6b).

It can also be observed from Figure 6(b) that the rates of dilation in the two cemented specimens (i.e. with and without fibres) changed significantly at the axial strain of about 8%. These changes were coincident with the full development of shear bands in the specimens.



(a)

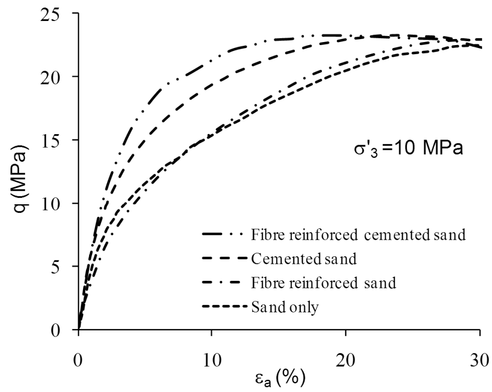


(b)

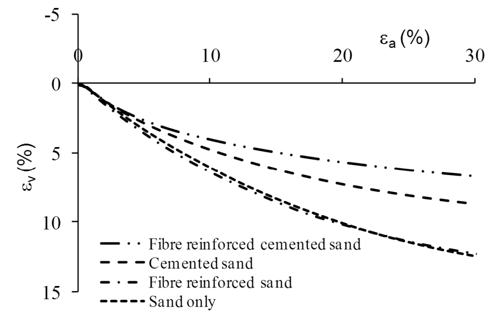
Figure 6 Effect of addition of 0.5% fibre and 5% cement at the confining pressure of 300 kPa: (a) stress-strain curves; (b) volumetric strain curves

The effects of cement and fibre on the stress-strain behaviour of Portaway sand in drained triaxial compression at the high effective confining pressure of 10 MPa are shown in Figure 7. It can be seen from the stress-strain curves plotted in Figure 7(a) that the behaviour of Portaway sand sheared at the high pressure is affected by addition of fibre and cement. However, the improvement is less significant compared to that at low confining pressure (Figure 6a).

As shown in Figure 7(a), the stress-strain curves of the clean sand and fibre reinforced uncemented sand are very similar. It can also be observed that the stress-strain behaviour of cemented specimens is stiffer than that of uncemented specimens. Nonetheless, the deviator stresses of all the specimens shown in Figure 7(a) increase continuously during shearing and reach maximum values at large strains. Maximum deviator stresses obtained in all the tests are very similar regardless of the material type. Figure 7(a) clearly demonstrates that the effectiveness of fibre reinforcement at the high confining pressure is significantly reduced and the effect of high confining pressure becomes dominant.



(a)



(b)

Figure 7 Effect of addition of 0.5% fibre and 5% cement at the confining pressure of 10 MPa: (a) stress-strain curves; (b) volumetric strain curves

The ε_v-ε_a curves of the four tests carried out at σ'_3 = 10 MPa are shown in Figure 7(b). All the specimens exhibited compressive volumetric change during the entire shearing. In other words, dilation was suppressed by the high confining pressure. It can be observed that the effect of 0.5% fibre content on the volumetric change of Portaway sand is negligible. This is consistent with the effect of fibre reinforcement on the stress-strain behaviour shown in Figure 7(a). Figure 7(b) also shows that the volumetric changes measured in cemented and fibre reinforced cemented specimens are significantly less compressive, which is consistent with the behaviour at lower confining pressure shown in Figure 6(b).

4.2 Failure characteristics

All the tests presented in this paper were carried out under drained conditions. Therefore, the peak state obtained from each test corresponds to the failure state. The failure states obtained from all the tests carried out in this study are plotted on the q-p' plane in Figure 8. Polynomial failure envelopes were fitted into the data points obtained for each type of specimens. The failure envelopes were also extrapolated to zero confinement. However, it should be pointed out that different opinions can be found in the literature with regard to the shape of failure envelope. For instance, Asghari et al. (2003), Lo et al. (2003) and Haeri et al. (2005) have reported curved envelopes for cemented soils. On the contrary, linear and bilinear failure envelopes have been reported by Consoli et al. (2007a, 2009c) and Consoli, et al. (2007b).

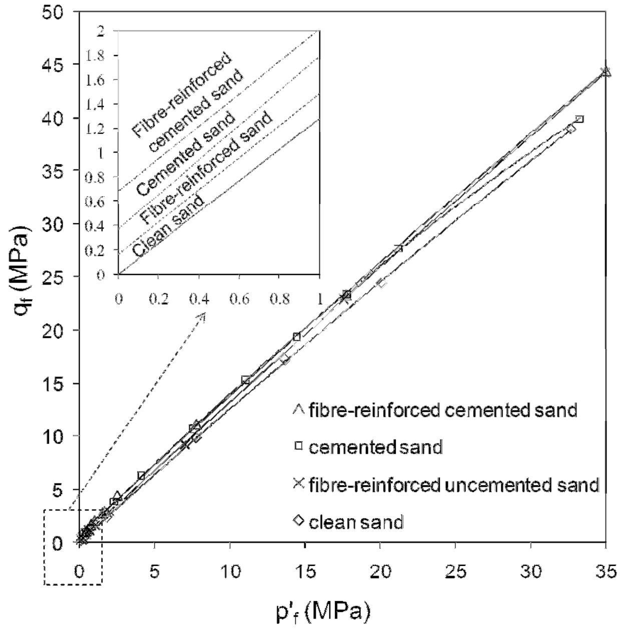


Figure 8 Failure envelopes of fibre reinforced cemented and uncemented sand

It can be observed from Figure 8 that the addition of fibre increases the strength of both uncemented and cemented specimens of Portaway sand. In a wide range of mean effective stresses, however, the differences between failure envelopes obtained from different types of sand are small. In a lower range of mean effective stresses, the differences are more significant, as shown by the zoomed-in part of the q-p' plot in Figure 8. In particular, it is evident from Figure 8 that the cohesion intercept (c) is affected by the addition of fibre and cement. Based on the best fit lines, the cohesion is zero for the unreinforced sand and increases to 163 kPa with the inclusion of fibres, to 368 kPa with cement stabilisation and to 682 kPa when both cement and fibres are added to the sand.

Although all the results reported in this paper have been obtained from CID tests, several isotropically consolidated undrained (CIU) tests were also carried out. In general, it was found that unique failure envelopes were obtained for each type of Portaway sand regardless of drainage conditions. For example, four typical effective stress paths obtained from CIU tests on the fibre reinforced cemented sand are shown in Figure 9. The failure line (FL) obtained from the CID tests on the same material is also shown in Figure 9.

It can be seen that all the specimens sheared under undrained conditions failed along or slightly above the failure envelope determined by the CID tests.

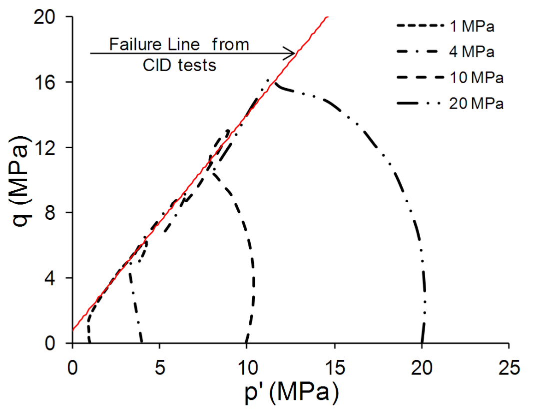


Figure 9 Effective stress paths obtained from CIU tests on fibre reinforced cemented sand

Similar observations were made for other types of Portaway sand tested in this study. It can also be seen from Figure 9 that with the increase in the mean effective stress the effective stress paths obtained from the CIU tests on fibre reinforced cemented sand resemble those normally obtained for loose uncemented sands under low confining pressures (Wanatowski and Chu 2007; Bobei et al. 2009; Tsai et al. 2010).

In order to illustrate the effect of fibre on the failure characteristics of Portaway sand, a relative increase of the deviator stress at failure (in %) obtained for fibre reinforced specimens is plotted versus effective confining stress (σ_3') in Figure 10. The relative increase in q_f is calculated with respect to the failure deviator stresses measured for uncemented and cemented sand, respectively. It can be seen from Figure 10 that the effectiveness of fibre reinforcement is significant at lower confining pressures. For example, at σ_3' = 100 kPa, the addition of fibres to uncemented and cemented sand increased the peak deviator stresses by 28% and 10%, respectively. However, Figure 10 shows that the effect of fibre is negligible at higher confining stresses. At the effective confining pressure of 10 MPa the addition of 0.5% fibres to uncemented sand increases the peak deviator stress by 2% whereas in cemented sand the increase due to fibres is less than 1%, as shown in Figure 10.

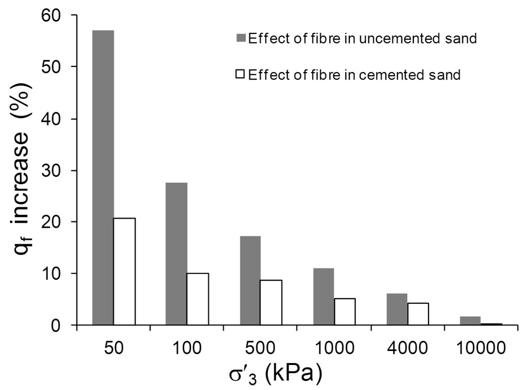


Figure 10 Effect of confining pressure on the effectiveness of fibre reinforcement in uncemented and cemented sand

The results presented in Figure 10 are consistent with those reported by Consoli, et al. (2007a, 2007b, 2009c) and dos Santos, et al. (2010a, b). It was observed that effect of fibres in clean sand was more significant compared to that in cemented sand. The difference in the effectiveness of fibre reinforcement in uncemented and cemented sand may be due the fact that fibres mobilize their full strength only after soil mass around them deforms significantly. As discussed earlier, the peak deviator stress in uncemented sand occurs at much larger strains compared to those in cemented sand. Therefore, polypropylene fibres in clean sand can fully develop their tensile strength. However, in the cemented sand, cement increases both strength and stiffness of the sand to such a level that significantly less stiff fibres are not able to mobilize fully their strength before the peak deviator stress is reached and shear bands are developed.

Figure 11 presents relationships between the failure friction angle (ϕ'_f) measured from all the tests and the effective confining pressure (σ_3'). Similar to the cohesion intercept discussed earlier, the lowest values of friction angle were obtained for unreinforced sand. An additional 0.5% of fibre or 5% of cement increased significantly the friction angle of Portaway sand. The largest increase in the friction angle was obtained when both cement and fibres were added to the sand.

It can also be seen from Figure 11 that the friction angle of sand depends not only on the reinforcement method but also on the effective confining pressure. Regardless of the material tested, the friction angle reduced with the increasing effective confining pressure. For instance, at σ_3' = 50 kPa, the friction angles of clean sand, fibre reinforced sand, cemented sand, and fibre reinforced cemented sand were 40.4°, 45.8°, 58.2°, and 65° respectively. However, the effect of fibres and/or cement becomes insignificant beyond σ_3' = 13 MPa. In other words, the effect of high confining pressure becomes dominant. It can be observed from Figure 11 that at σ_3' = 20 MPa the difference in friction angles for different types of Portaway sand is hardly noticeable and the curves show a tendency of approaching to a constant value of 32°.

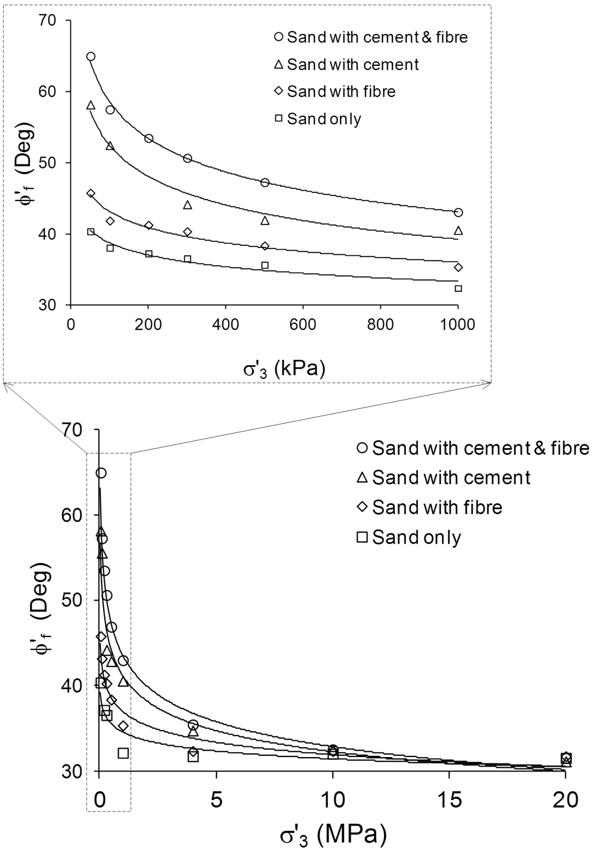


Figure 11 Effect of confining pressure on the peak friction angle

The results presented in Figure 11 are generally consistent with findings reported by other researchers for different types of soil. It was previously reported in the literature that the friction angle significantly increases with the increase in cement and fibre contents (e.g. Gray and Ohashi 1983, Consoli et al. 1998, 2003, 2004; Tang et al. 2007). However, most of the tests reported in the literature were carried out under conventional pressures (i.e. lower than 1 MPa) and the effect of high confining pressure on the friction angle has not been discussed in detail. For example, Consoli et al. (1998) reported the increase in the friction angle from 35 to 46° because of 3% fibre inclusion to the sand in the range of confining pressures from 20 kPa to 100 kPa. Consoli et al. (2004) also reported increase in the friction angle due to the increase in cement content for the same range of effective confining stresses from 20 kPa to 100 kPa. In the present study, the effects of fibres and cement on the friction angle of sand were further verified under high confining pressures.

5. CONCLUSIONS

A few series of isotropically consolidated drained tests on uncemented, fibre reinforced, cemented, and fibre reinforced cemented Portaway sand are presented and discussed in this paper. Based on the experimental results, the following conclusions can be drawn:

1) There is a significant effect of fibre reinforcement on the behaviour of cemented and uncemented sand. The addition of fibres increases the peak strength and the stiffness of sand. However, the effectiveness of fibre reinforcement is affected by confining pressure. The increase in strength continuously reduces with the increase in confining pressure. For example, the addition of 0.5% fibre increases the peak strength of cemented sand by 21% at the effective confining pressure of 50 kPa. However, the same fibre content increases the peak strength of cemented sand by less than 1% at the effective confining pressure of 10 MPa. In general, the effectiveness of fibre reinforcement in uncemented and cemented sand was not evident at pressures above 10 MPa.
2) The addition of fibre affects volumetric behaviour of uncemented and cemented sand in drained triaxial compression. The behaviour of fibre reinforced sand is more dilative compared to that of sand without any fibres. Similarly, fibre reinforced cemented sand exhibits more dilative behaviour compared to fibre reinforced uncemented sand.
3) The Mohr-Coulomb shear strength parameters, i.e. cohesion intercept (c) and friction angle (ϕ'_f) of sand are affected by fibre and cement content. In general, the shear strength parameters increase significantly with addition of either fibres, cement, or both. However, the friction angle of unreinforced or reinforced sand reduces with increasing effective confining pressure. The effect of fibre reinforcement and/or cement stabilisation has a negligible effect on the shear strength of sand when the effective confining pressure is higher than 13 MPa.

6. REFERENCES

Asghari, E., Toll, D.G. and Haeri, S.M. (2003) "Triaxial behaviour of a cemented gravely sand, Tehran Alluvium", *Geotechnical and Geological Engineering,* 21(1), pp. 1-28.

Bobei, D.C., Lo, S.-C.R., Wanatowski, D., Gnanendran, C.T., and Rahman, M.M., (2009) "Modified state parameter for characterizing static liquefaction of sand with fines", *Canadian Geotechnical Journal,* 46(3), pp. 281-295.

Chu, J., and Lo, S.-C.R., (1993) "On the measurement of critical state parameters of dense sand", *Geotechnical Testing Journal,* 16(1), pp. 27-35.

Consoli, N.C., Prietto, P.D.M. and Ulbrich, L.A. (1998) "Influence of fiber and cement addition on behavior of sandy soil", *Journal of Geotechnical and Geoenvironmental Engineering,* 124(12), pp 1211-1214.

Consoli, N.C., Vendrusco, M.R.A., and Prietto, P.D.M. (2003) "Behavior of plate load tests on soil layers improved with cement and fiber", *Journal of Geotechnical and Geoenvironmental Engineering,* 129(1), pp. 96-101.

Consoli, N.C., Montardo, J., Donato, M. and Prietto, P.D.M. (2004) "Effect of material properties on the behaviour of sand-cement-fibre composites", *Ground Improvement, Proceedings of ICE,* 8(2), pp. 77-90.

Consoli, N.C., Casagrande, M.D.T., and Coop, M.R. (2007a) "Performance of a fibre-reinforced sand at large shear strains", *Geotechnique,* 57(9), pp. 751-756.

Consoli, N.C., Heineck, K., Casagrande, M.D.T. and Coop, M.R. (2007b) "Shear strength behavior of fiber-reinforced sand considering triaxial tests under distinct stress paths", *Journal of Geotechnical and Geoenvironmental Engineering,* 133(11), pp. 1466-1469.

Consoli, N.C., Casagrande, M.D.T., Thome, A., Dalla Rosa, F., and Fahey, M. (2009a) "Effect of relative density on plate loading tests on fibre-reinforced sand", *Geotechnique,* 59(5), pp. 471-476.

Consoli, N.C., Festugato, L., and Heineck, K., (2009b) "Strain-hardening behaviour of fibre-reinforced sand in view of filament geometry", *Geosynthetic International,* 16(2), pp. 109-115.

Consoli, N.C., Vendruscolo, M., Fonini, A. and Dalla Rosa, F. (2009c) "Fiber reinforcement effects on sand considering a wide cementation range", *Geotextiles and Geomembranes,* 27(3), pp 196-203.

Consoli, N.C., Bassani, M.A.A., and Festugato, L., (2010) "Effect of fiber-reinforcement on the strength of cemented soils", *Geotextiles and Geomembranes,* 28(4), pp. 344-351.

Diambra, A., Ibraim, E, Muir Wood D., and Russell, A.R., (2010) "Fibre reinforced sands: Experiments and modelling", *Geotextiles and Geomembranes,* 28(3), pp. 238-250.

dos Santos, A.P.S., Consoli, N.C. and Baudet, B.A. (2010a) "The mechanics of fibre-reinforced sand", *Geotechnique,* 60(10), pp. 791-799.

dos Santos, A.P.S., Consoli, N.C., Heineck, K.S. and Coop, M.R. (2010b) "High-pressure isotropic compression tests on fiber-reinforced cemented sand", *Journal of Geotechnical and Geoenvironmental Engineering,* 136(6), pp. 885-890.

Gray, D. and Ohashi, H. (1983) "Mechanics of fiber reinforcement in sand", *Journal of Geotechnical Engineering,* 109(3), pp. 335-353.

Gray, D. and Alrefeai, T. (1986) "Behaviour of fabric-reinforced versus fiber-reinforced sand", *Journal of Geotechnical Engineering,* 112(8), pp. 804-820.

Haeri, S., Hamidi, A. and Tabatabaee, N. (2005) "The effect of gypsum cementation on the mechanical behavior of gravely sands", *Geotechnical Testing Journal,* 28(4), pp. 380-390.

Ladd, R. (1978) "Preparing test specimens using undercompaction", *Geotechnical Testing Journal,* 1(1), pp. 563-579.

Lo, S.-C.R, Lade, P.V. and Wardani, S.P.R. (2003) "An experimental study of the mechanics of two weakly cemented soils", *Geotechnical Testing Journal,* 26(3), pp. 328-341.

Maher, M. and Gray, D. (1990) "Static response of sand reinforced with randomly distributed fibers", *Journal of Geotechnical Engineering,* 116(11), pp, 1661-1677.

Maher, M. and Ho, Y. (1993) "Behaviour of fibre reinforced cemented sand under static and cyclic loads", *Geotechnical Testing Journal,* 16(3), pp. 330-338.

Marri, A., Wanatowski, D. and Yu, H.-S. (2010) Drained Behaviour of cemented sand at high pressures", *Proceedings of the 17th Southeast Asian Geotechnical Conference,* Taipei, Taiwan, 10-13 May, Vol. 1, pp. 17-20.

Michalowski, R.L. (2008) "Limit analysis with anisotropic fibre-reinforced soil", *Géotechnique,* 58(6), pp. 489-501.

Tang, C., Shi, B., Gao, W., Chen, F. and Cai, Y. (2007) "Strength and mechanical behavior of short polypropylene fibre reinforced and cement stabilized clayey soil", *Geotextiles and Geomembranes,* 25(3), pp 194-202.

Tsai, M.-T., Wanatowski, D., Marri, A. and Ud-din, S. (2010) "Undrained behaviour of cemented sand at high pressures", *Proceedings of the 17th Southeast Asian Geotechnical Conference,* Taipei, Taiwan, 10-13 May, Vol.1, pp. 29-32.

Ud-din, S., Marri, A., Wanatowski, D. and Reddish, D.J. (2010) "Effect of fibre reinforcement on drained behaviour of cemented sand", *Proceedings of the 17th Southeast Asian Geotechnical Conference,* Taipei, Taiwan, 10-13 May, Vol. 1, pp. 134-138.

Wanatowski, D., and Chu, J., (2007) "Static liquefaction of sand in plane-strain", *Canadian Geotechnical Journal*, 44(3), pp. 299-313