Impact of Fiber Reinforcement on Deformation Characteristics of Cemented Sand-Gravel Mixtures

Dehghan A., *Hamidi A.;

School of Engineering, Kharazmi University, Tehran, Iran

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Abstract

This paper describes triaxial compression tests conducted to determine the effect of fiber inclusion on stiffness and deformation characteristics of sand-gravel mixtures. Tested soil was a mixture of Babolsar sand from the shores of the Caspian Sea and Karaj River gravel. Portland cement was used as the cementing agent and fibers 12mm in length and 0.023mm in diameter at 0%, 0.5% and 1.0% were added to the mixtures. Triaxial tests were performed on saturated samples in consolidated drained and undrained conditions at confining pressures of 100, 200 and 300 kPa. Deviatoric stress-axial strain, volumetric strain-axial strain, pore pressure-axial strain curves with deformation and stiffness characteristics were investigated. Tests results show that fiber addition increased peak and residual shear strength of the soil. Fiber addition resulted in an increase of the maximum positive and negative volumetric strains. In undrained condition, fiber inclusion caused increase in initial positive pore pressure and final suction. It has also been observed that fibers decreased initial tangent stiffness of the cemented sand-gravel mixture.

Keywords: Triaxial tests, reinforced soil, cement-fiber inclusion, stiffness, yield.

*Corresponding author hamidi@khu.ac.ir

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Introduction

Different techniques like cementation, grouting and fiber reinforcement have been used to improve soil capability against deformation. Fiber reinforcement of the soil has been an interesting method of soil improvement for geotechnical engineers. New concept of soil reinforcement was introduced by the French engineer Vidal (1966). He demonstrated that the introduction of reinforcing metal elements in a soil mass increases the shear strength of the medium. Geosynthetics have been used from 1980 instead of metal as reinforcing elements extensively. According to the literature, the applied stress to the soil transfers to the reinforcing material by frictional mechanism. The resistance of reinforcing material against lateral deformation results in the increase in bearing capacity of the reinforced soil.

The behavior of cemented soil has been studied by a number of researchers (Clough et al. 1981; Coop and Atkinson 1993, Consoli 2000, Hamidi and Haeri 2008). Based on the results, cementation increased peak strength and initial stiffness of the soil and changes its behavior to a more brittle one. In order to reach to a more ductile behavior, some studies performed on the behavior of cement-fiber reinforced soils (Maher and Ho, 1993; Consoli et al, 2009, 2010, 2013; Park, 2009 and 2011; Dos santos, 2010; Heeralal and Prareen, 2011; Salah-ud-din, 2012; Festugato et al. 2013 and Hamidi and Hooresfand, 2013). These studies showed that fiber inclusion to the cemented soil results in an increased peak and residual strength and makes the brittle behavior of the soil softer compared to the unreinforced material. Park (2011) implied the increase in shear strength of fiber reinforced soil due to the increase in dilation by fibers reinforcement. Hamidi and Hooresfand (2013) investigated the effect of fiber reinforcement on triaxial shear behavior of cemented sand. The results showed an increase in friction angle and cohesion intercept and increased principal stress ratio by fiber addition. Influence of fiber inclusion decreased by increase in confining pressure.

Limited studies have been carried out on the influence of fiber inclusion on the mechanical behavior of cemented sand-gravel mixtures. Conventional triaxial compression tests are used in present study to investigate peak and residual shear strengths, volume change, deformation characteristics and stiffness of the soil and the influence of different variables on the results is evaluated. Special consideration is paid to the effect of fiber content, confining pressure and drainage condition on deviatoric stress, stress ratio, dilation angle, tangent stiffness and shear modulus of the material.

Physical properties of tested soil

Clean sub-round to sub-angular sand from the shore of the Caspian Sea (Babolsar city) was used as the base material in the tests and it was sieved using a #30 sieve. Clean gravel from the river of Karaj, Iran was used. Uni-sized gravel particles between 0.5 inch and 0.375 inch sieves were added to the sandy soil. Gravel contents used in

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present study were 30% and 50%. Figure 1 shows gradation curves of the base soils and Table 1 lists its physical properties. All physical properties were determined according to the ASTM (1998) standard methods.

Table1. Physical characteristics of the mixtures

Parameter	Sand with 30% gravel	Sand with 50% gravel
Soil name	SP	GP
C_u	3.37	57.13
C_c	0.78	0.037
e_{max}	0.51	0.42
e_{min}	0.37	0.30
G_s	2.709	2.69
$\gamma_{d,min}$ (kN/m^3)	17.60	18.58
$\gamma_{d,max}$ (kN/m^3)	19.40	20.29

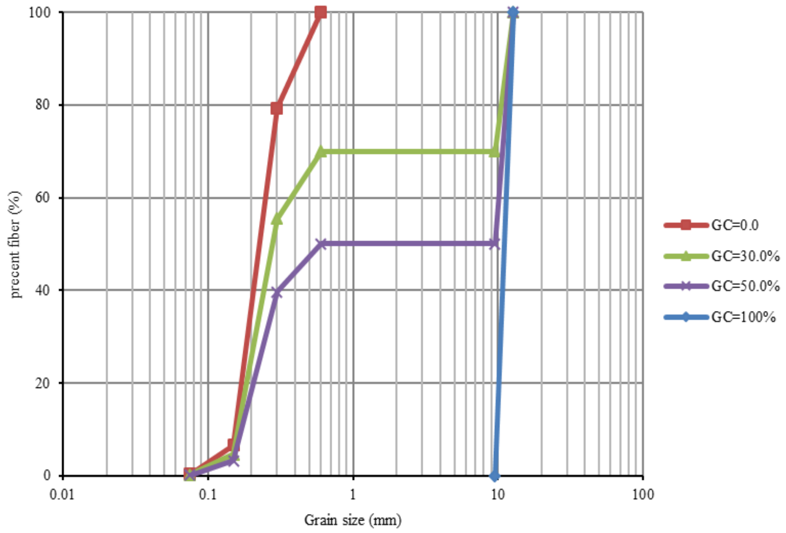

Figure 1. Gradation curves of sand, gravel and sand-gravel mixtures

Polypropylene fiber with circular cross sections, 12mm in length and 0.023 mm in diameter with the aspect ratio of about 500, average tensile strength of 400 MPa were used as fibers. It was the same that used by Hamidi and Hooresfand (2013) which exhibited very good consistency with the cementing agent. Fiber contents of 0.0%, 0.5% and 1% by dry weight of the base soil were used in the experiments. Cementation agent was Portland cement (Type II) which was sieve using a #100 sieve and added in 3% content to the samples.

Sample preparation

Samples used for triaxial testing were prepared by mixing sand, gravel, cement, water and polypropylene fibers using an electric mixer. During the mixing process, 8% distilled water was added to the fibers. Samples prepared using a split mold 100 mm in diameter and 200 mm in height. Samples were compacted in eight layers. Each layer was poured into the mold and compacted using a metal hammer. The tests were performed on samples in a relative density of 70%. Each sample was cured in a humid room at 25± 2°C for one day with mold and six days without mold. Table 2 shows the variables considered in sample preparation.

Testing program

After seven days for curing, the samples were set up in a triaxial cell. Saturation of samples was carried out in three stages. First, the sample was flushed with carbon dioxide (CO_2) with 15 kPa pressure. After that the water was flushed from the bottom of the sample under a very low pressure of 20 kPa about 45 minutes. Finally, the sample was saturated using back pressure of 300 kPa. The saturation process was considered to be complete when a *B* value of 0.90 or more was reached. After consolidation, shear loading was applied at rates of 0.15 mm/min and 0.3 mm/min for drained and undrained tests, respectively.

Table2. Description of variables in present study

Variable	No. of levels	Description of samples
Type of soil	2	Poorly graded gravel sandy that sand from the shores of Caspian Sea and gravel from Karaj river
Cementing agent	1	Portland cement (type II)
Type of fiber	1	White monofilament polypropylene fibers
Gravel content	2	30.0% and 50.0% dry weight of base soil
Cement content	1	3.0% dry weight of base soil
Fiber content	3	0.0, 0.5% and 1% dry weight of sand-cement
Relative density	1	70%
Water content	1	8% weight of base soil
Sample size	1	100 mm diameter and 200 mm height, compacted in eight layers
Curing condition	1	Cured for seven days in humid room

Analysis of the results

The present study used the results of triaxial tests on cemented gravel sandy (with gravel content 30% and 50%) and fiber content of 0.0%, 0.5% and 1.0% under confining pressures 100, 200 and 300 kPa in drained and undrained condition. The effect of fiber addition has been investigated on the behavior, deformation characteristics and stiffness of the reinforced material.

1. Effect of fiber reinforcement on shear strength behavior

Figure 2 plots the variation of deviatoric stress-axial strain, volumetric strain-axial strain and dilation rate-axial strain in drained condition with different fiber contents. Stress-strain curves showed that maximum deviatoric stress and residual stress increased with increase in fiber content. It illustrated that fiber inclusions increased softening after failure point. Volumetric strain-axial strain curves show that contraction volumetric strain increased when fiber content increased. Volume of samples increased while axial strain increased. It has been shown that the rate of dilation increased when fiber content increased. This is agreement with the results of Chen 2006, Consoli 2004, 2009 and Salehuddin 2012 that reported an increase in maximum initial contraction and final dilation when fiber content increased. Rate of dilation $(\frac{d\varepsilon_v}{d\varepsilon_a})$ versus axial strain changes showed that the maximum rate of dilation decreased as fiber content increased. The maximum amounts have been indicated on stress-strain curves as points that take place after the failure. Leroueil and Vaughan 1990 showed that in uncemented soil, when dilation is due to the dense packing, failure and maximum rate of dilation are coincided but when the peak strength is controlled by cementation rather than density, the maximum rates of dilation take place after bond yield point. In fact in cemented samples, failure point happened after some bond breakage while some others stand against increase in volume. Fibers play the same role in fiber reinforced cemented soil. But for sandy soils, the maximum dilation rate and failure point are coincided. Data for other confining pressures (100 and 300 kPa) have shown similar trends, but are not shown here for the sake of conciseness

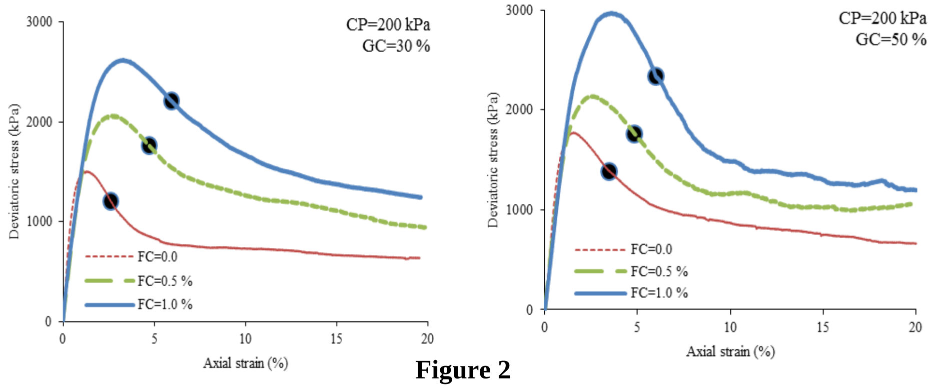

Figure 2

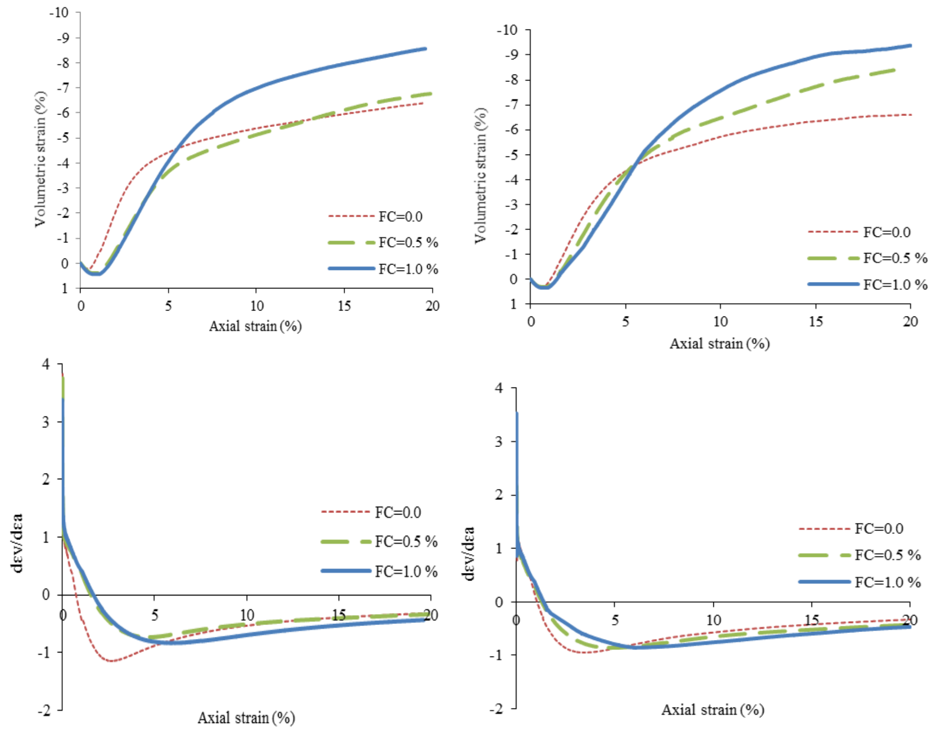

Figure2. Variation of deviatoric stress-axial strain, volumetric strain-axial strain and dilation rate-axial strain for different fiber contents in drained conditions for 30% and 50% gravel contents

The changes in deviatoric stress-axial strain, pore pressure-axial strain and rate of pore pressure versus axial strain in undrained condition are shown in Fig 3. Failure strength in undrained condition are more than drained condition and the rate of softening after failure is lower for undrained condition than drained one. Moreover, undrained residual stress is higher than drained state. Pore pressure-axial strain curves exhibit initial positive pore pressure and final suction that increased with increase in fiber content. This situation is obviously observed for the samples with 50% gravel content. This type of behavior is the same as changes of the volumetric strain versus axial strain in drained condition. Rate of pore pressure ($\frac{du}{d\varepsilon_a}$) with axial strain showed that the rate of maximum pore pressure generation decreased when fiber content increased (as are plotted in stress-strain curve). As of maximum dilation rates in drained condition, maximum pore pressure generation rates take place before failure point and in lower axial strains with fiber addition.

Figure 4 plots the change in stress ratio versus dilation rate. After that the stress ratio increased sharply toward point *(a)* which shows the beginning point of bond degradation, it reaches to its maximum value at point *(b)*. The rate of change in stress ratio is small up to point *(c)* which corresponds to the maximum rate of the volume change. According to the figure, the maximum stress ratio increased when fiber content increased in the soil. Also the maximum dilation rate decreased with increase in degree of fiber reinforcement.

2. Dilation angle

One of the parameters used to quantify the dilation is the angle of dilation. It is defined by the ratio of volumetric stain and shear strain increments (Bolton, 1986).

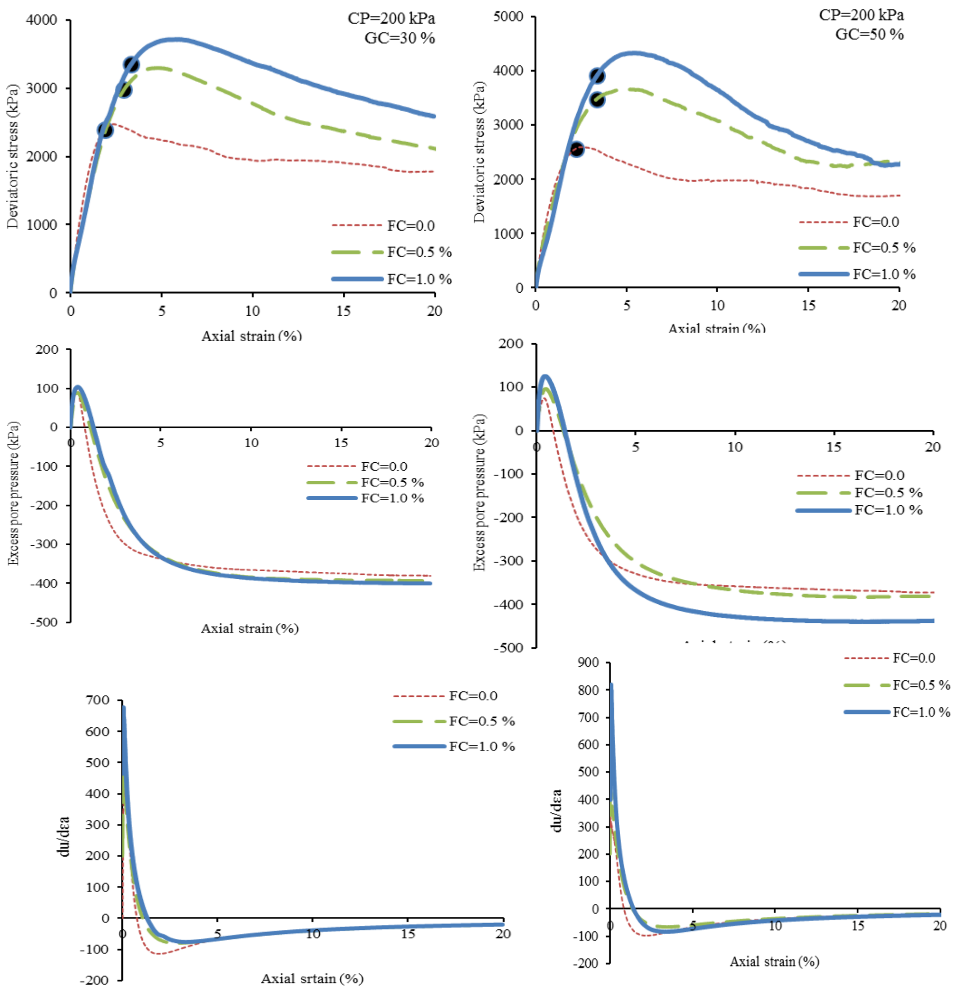

Figure3. Variation of deviatoric stress-axial strain, volumetric strain-axial strain and dilation rate-axial strain for different fiber contents in undrained condition for 30% and 50% gravel contents

$$\psi = \tan^{-1}\left(\frac{-d\varepsilon_v}{d\varepsilon_s}\right) \tag{1}$$

Where ε_v is the volumetric strain and ε_s is the shear strain. The negative sign is required so that a negative change in volume corresponds to a positive rate of dilation.

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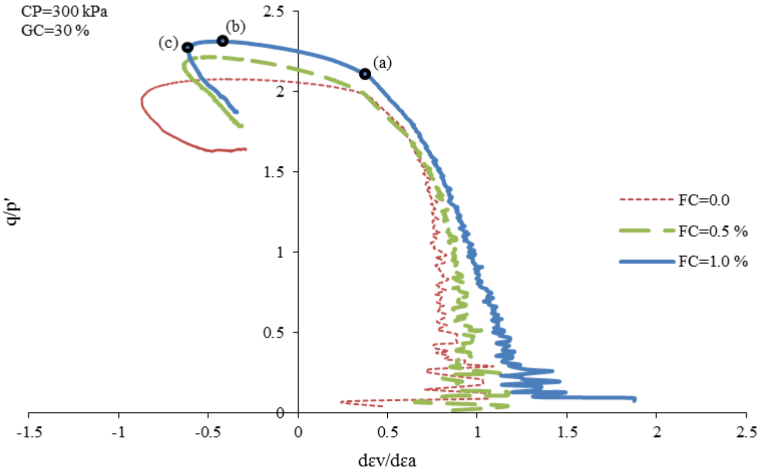

Figure4. Variation of stress ratio-dilation rate for different fiber contents

The change in dilation angle versus axial strain is plotted in Figure 5-a. dilation angle decreased in negative area that showed contractive behavior. After maximum compaction, dilation angle increased extremely towards the maximum dilation angle. Increasing axial strain, dilation angle reduced and tended to reach constant dilation toward the end of all the tests. Dilation angle in higher axial strains decreased when fiber amount increased.

Figure 5-b shows maximum dilation versus confining pressure in reinforced cemented sand-gravel mixture with different fiber contents. The figure displays that dilation angle increased with increase in confining pressure. Also dilation angle decreased by increase in fiber content, but the effect of 0.5% fiber content on the maximum dilation angle is nearly the same as 1.0% fiber inclusion. Indeed, increase in fiber content increases the surrounding between soil grains and acts as an extra confinement which results in lower dilation angles compared

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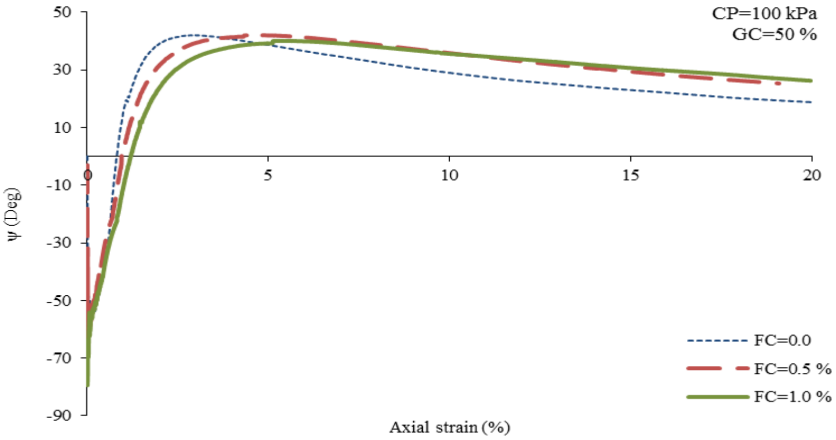
to the unreinforced material. This is accordance with the results of Michalowsky and Zhao (1996) and Michalowski and Čermák (2003).

3. Effect of fiber reinforcement on stiffness

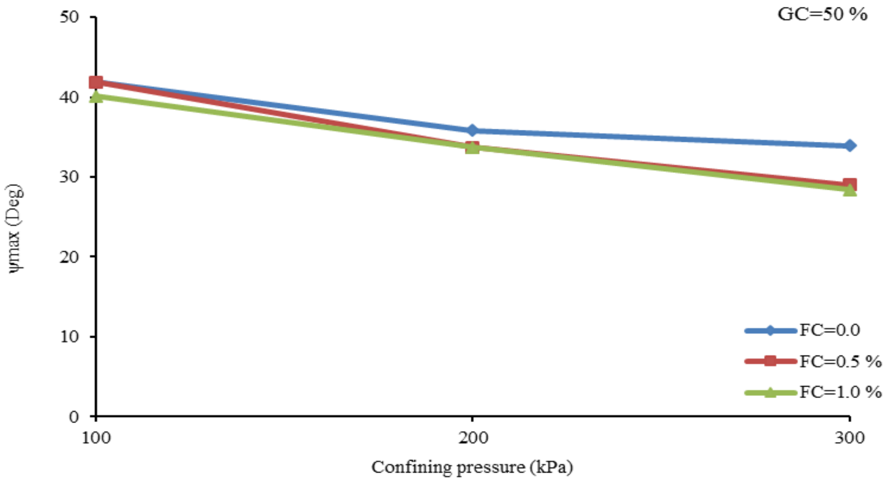
There are usually four major parameters to define the elastic properties of the soil. These are Young’s stiffness, shear modulus, bulk modulus and Poisson’s ratio. Although the definitions of these parameters are different, they are interrelated. In this study two of these parameters are focused. The first one is Young’s modulus in the form of tangent stiffness to determine deformation parameters under triaxial loading. The second is the shear modulus to define by the ratio between the shear stress and shear strain in the cemented sand-gravel mixture. Toll and Malandraki 1993 defined the first yield of a cemented soil as the beginning of dropping point in tangent stiffness-strain curve in a double logarithmic space. Maccarini 1987 defined the first yield as the end of linear part of stress-strain curve. Airey 1993 defined the first yield as the end point of linear part of deviatoric stress-strain curve to be as the end of elastic behavior of the soil. Coop and Atkinson 1993 defined an equivalent final yield point as a point that all the cemented bonds fail.

Figure 6 shows the bond yield and failure points for triaxial tests in drained and undrained conditions. The bond yield is defined as the point in which the slope of the tangent elastic modulus-axial strain curve is sharply decreased. The first yield cannot be estimated exactly due to the external strain measurement. At this point the bonds are not able to withstand more shear stress. As a result the stiffness decreases dramatically. Also the final yield or failure is marked on this figure which is associated with zero tangent stiffness. The tangent stiffness is determined using the following equation:

$$E_{tan} = \frac{\Delta q}{\Delta \varepsilon_1} \quad (2)$$



a



b

Figure5. a) Variation of dilation angle with axial strain, b) Maximum dilation angle with confining pressure for different fiber contents

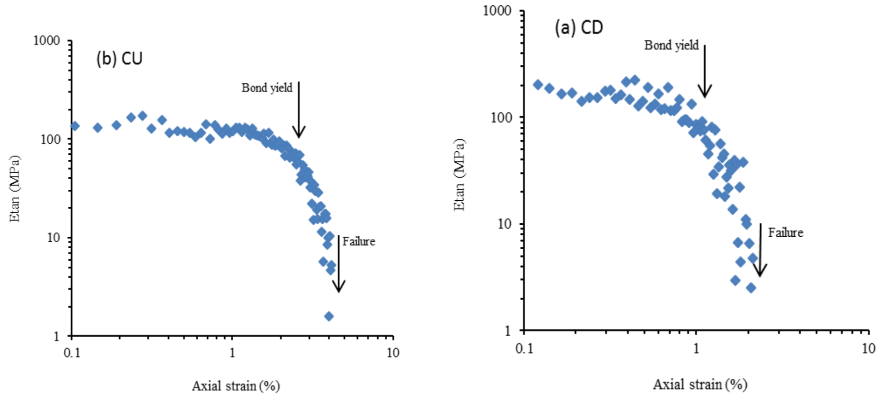


Figure6. Bond yield and failure points for 0.5% fiber and 50% gravel content under 100 kPa confinement
a) Consolidated-Drained b) Consolidated Undrained

Figure 7 plots the variation of bond yield and failure envelopes versus different fiber contents in drained and undrained condition. Based on this figure the position of the yield envelopes moved up with increase in fiber content. The results of both drained and undrained tests are used to determine the envelopes. Curves of bond yield envelope are close to each other in different fiber contents, but curves of failure envelope have clear distance. Slope of the curves at bond yield and failure are higher for samples having 50% gravel than samples with 30% gravel content.

Variations of the drained tangent stiffness with axial strain for unreinforced and fiber reinforced samples are shown in Figure 8 in logarithmic space for different confining pressures. The figure shows that tangent stiffness of the unreinforced cemented soil is more than fiber reinforced soil. Contribution of tensile strength and pull out of fiber reinforcement starts in higher axial strains, so the tangent stiffness of fiber reinforced mixture was more than the unreinforced

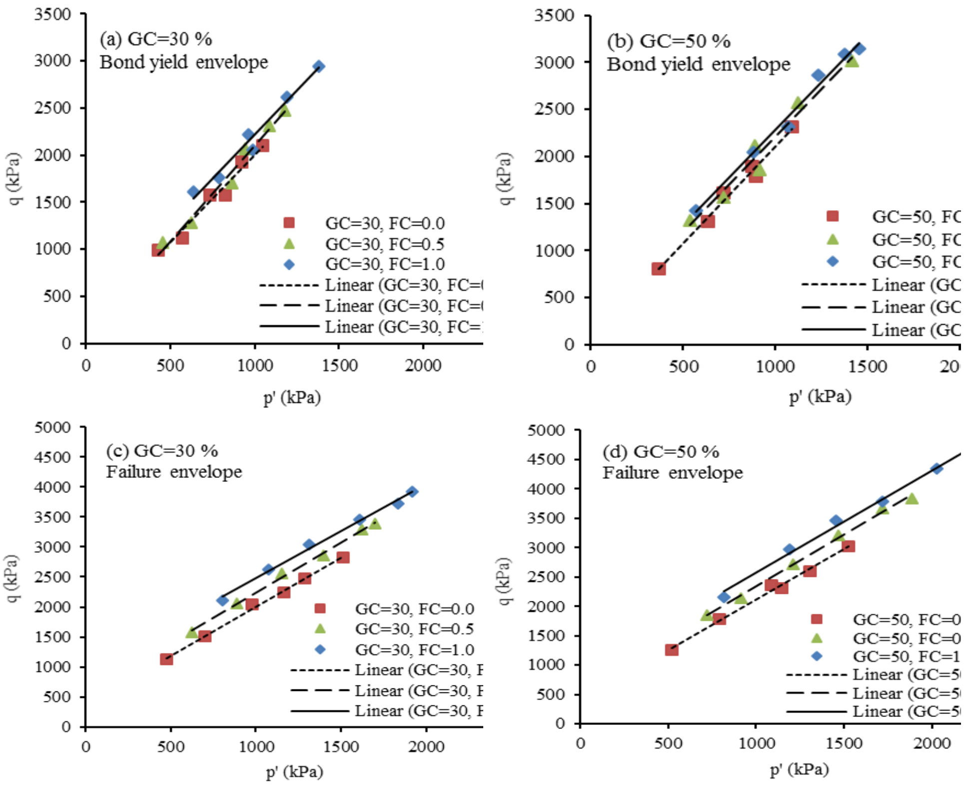


Figure7. variation of bond yield and failure envelopes for different fiber contents

samples in higher strain levels. There was small difference between two curves associated to 0.5% and 1.0% fiber contents and they are nearly coincided.

In order to investigate the effect of drainage condition on the deformation parameters, drained and undrained tangent stiffness are depicted in Figure 9 for different confining pressures. The figure shows that bond yield in drained condition occur in more strains than undrained one. Also the difference between drained and undrained tangent stiffness reduced with increase in confining pressure. The

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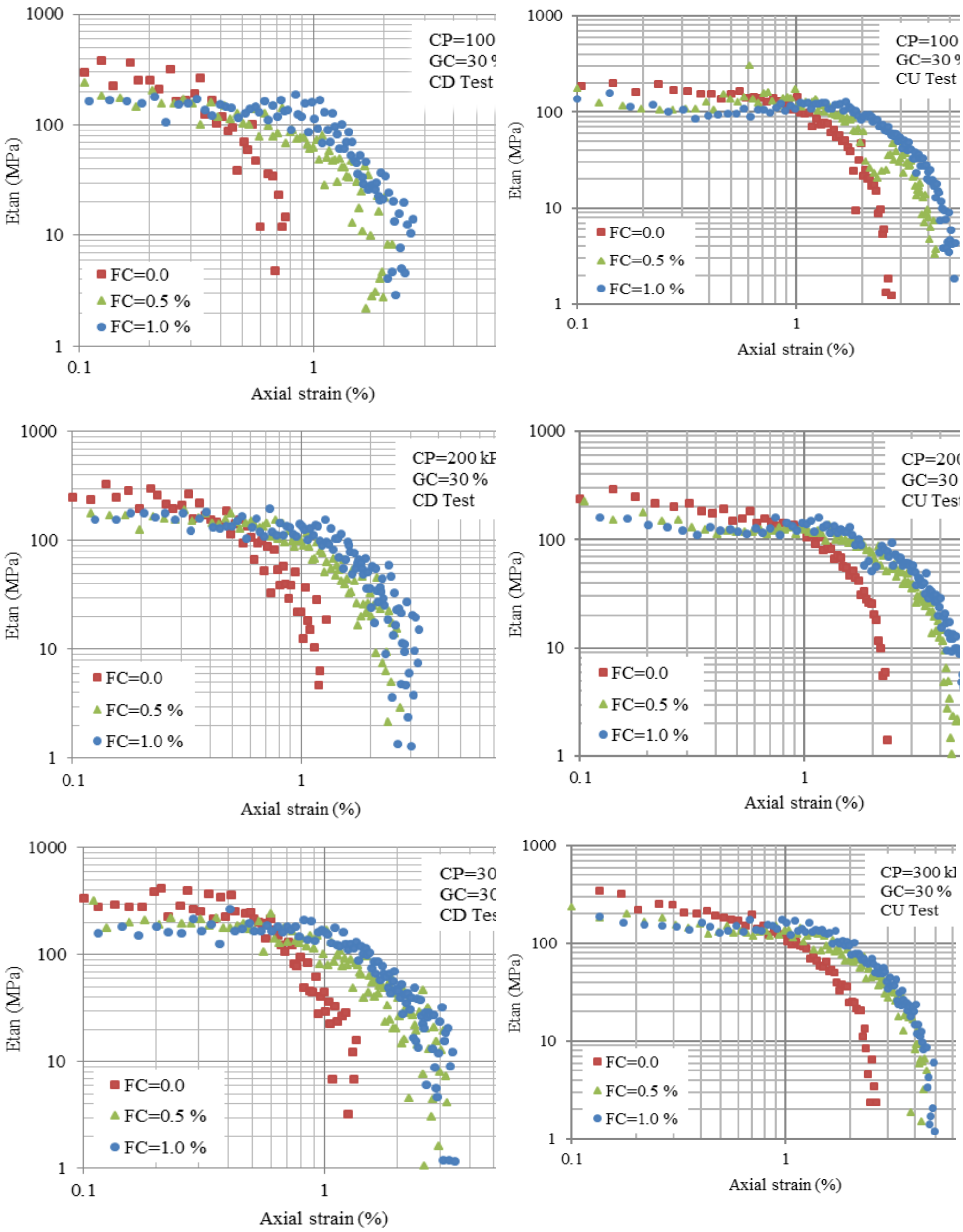

Figure8. Variation of tangent stiffness with versus axial strain for different fiber contents

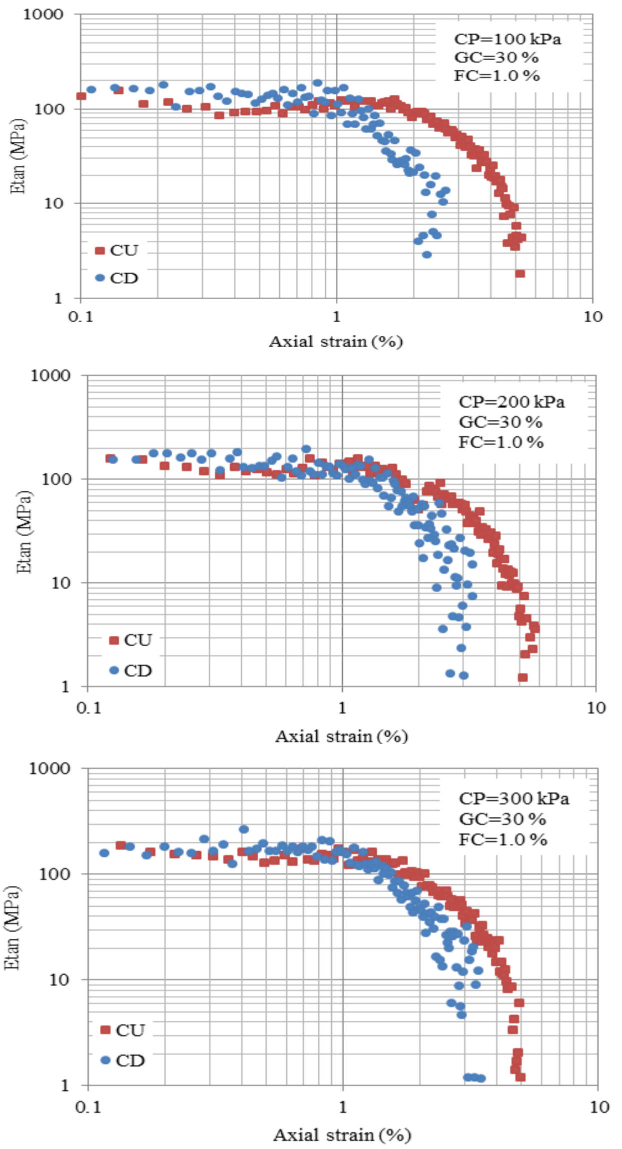

Figure9. Variation of tangent stiffness versus axial strain for drained and undrained conditions

bond yield stress and failure point of two different conditions get closer to each other in higher confinements. In higher confining pressures, bond breakage is due to the combination of confinement

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and shear stress. As the specimen is more confined, movement and slip of the grains are less dilative which results in less brittle failure and less contribution of the cemented bonds and fibers. As a result the stiffness of the reinforced soil was more different for drained and undrained conditions in high confining pressures.

Shear modulus is defined by the rate of shear stress and shear strain. The variation of shear modulus versus shear strain is plotted in Figure10. This curve exhibits that the shear modulus of the unreinforced cemented soil is slightly less than the shear modulus of fiber reinforced mixture. However, they got closer to each other when confining pressure increased.

Conclusions

- Maximum deviatoric stress and residual stress increased with fiber content with softer behavior after failure point. Maximum shear strength in undrained condition was more than drained condition
- Initial volumetric strain and final dilation increased with fiber content. Also positive pore pressure and final suction increased with more fiber inclusion.
- Maximum stress ratio increased when fiber content increased and rate of dilation rate increased by more fiber addition
- aximum dilation rates take place after failure point in drained condition, but maximum rates of pore pressure generation take place before failure point.
- Dilation angle decreased with increase in confining pressure and fiber content.

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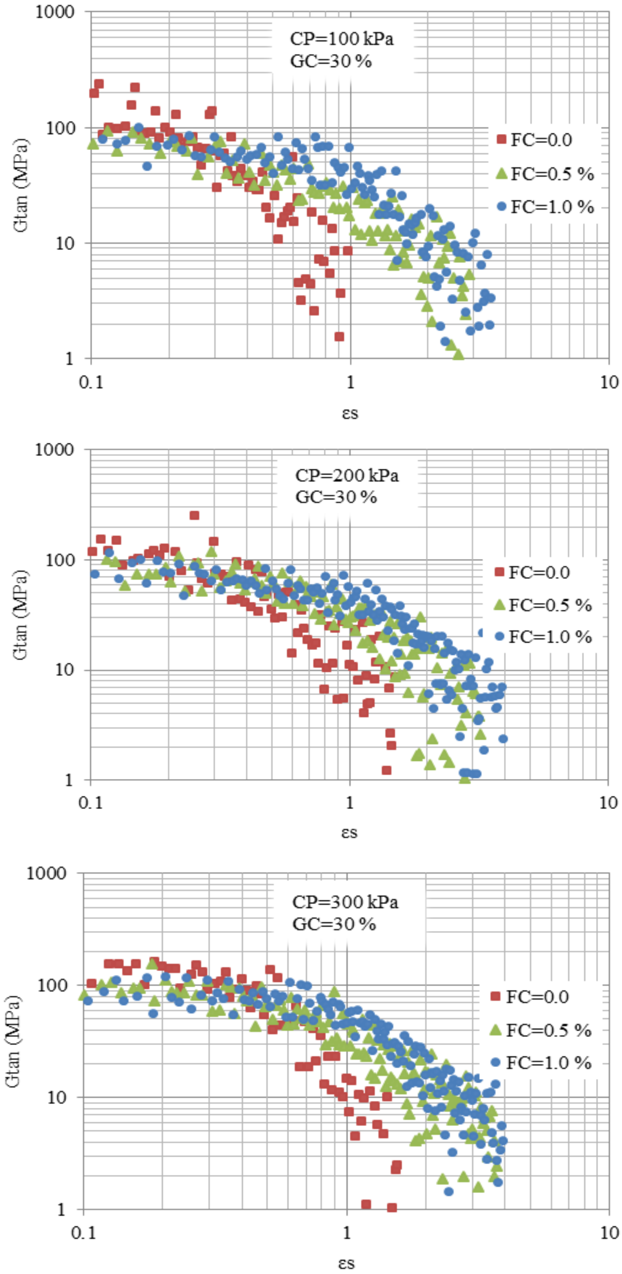

Figure10. Variation of shear modulus versus shear strain for different fiber content

- Tangent stiffness and shear modulus of the unreinforced cemented soil was slightly more than the fiber reinforced one. The tangent stiffness and shear modulus of fiber reinforced mixture were more than the unreinforced one in higher strain levels.
- There is small difference between two curves of tangent stiffness and shear modulus variations with axial strain for 0.5% and 1.0% fiber contents.
- Bond yield in drained condition occurred in higher strain levels than the undrained one. Also the difference between drained and undrained tangent stiffness reduced with increase in confining pressure with closer bond yield and failure points.

References

1. Airey D.W., "Triaxial Testing of Naturally Cemented Carbonate Soil", Journal of Geotechnical Engineering Division, ASCE 119 (11) (1993)1379-1398.
2. Bolton M.D., "The strength and dilatancy of sands",Géotechnique, 36 (1986) 65-78.
3. Chen C.W., "Drained and undrained behavior of fiber-reinforced sand", Transportation Scholars Conference, Iowa State University, November 15 (2006).
4. Clough G.W., Sitar N., Bachus R.C., Rad N.S., "Cemented sands under static loading", Journal of Geotechnical Engineering Division, ASCE 107 (6) (1981) 799-817.

5. Consoli N.C., Montardo J.P., Donato M., Prietto D.M., "Effect of material properties on the behavior of sand-cement-fiber composites", Ground Improvement 8 (2) (2004) 77-90.
6. Consoli N.C., Vendruscolo M.A., Fonini A., Dalla Rosa F., "Fiber reinforcement effects on sand considering a wide cementation range", Geotextiles and Geomembranes 27 (3) (2009) 196-203.
7. Consoli N.C., Bassani M.A.A., Festugato L., "Effect of fiber-reinforcement on the shear strength of cemented soils", Geotextiles and Geomembranes 28 (4) (2010) 344-351.
8. Consoli N.C., Consoli B.S, Festugato L., "A practical methodology for the determination of failure envelopes of fibre-reinforced cemented sand. Geotextiles and Geomembranes", http://dx.doi.org/10.1016/j.geotexmem (2013) 07,010.
9. Coop M. R., Atkinson J. H., "The mechanics of cemented carbonate sands", Journal of Geotechnique 43 (3) (1993) 53-67.
10. Dos santos A.P.S., Consoli N.C., Heineck K.S., Coop M.R., "High-pressure isotropic compression tests on fiber-reinforced cemented sand", Journal of Geotechnical and Geoenvironmental Engineering 136 (6) (2010) 885-890.
11. Festugato L., Fourie A., Consoli N. C., "Cyclic shear response of fibre-reinforced cemented paste backfill", Geotechnique Letters 3(1) (2013) 5-12.
12. Hamidi A., Haeri M., "Stiffness and deformation characteristics of a cemented gravely sand", International Journal of Civil Engineering 6 (3) (2008) 159-173.
13. Hamidi A., Hooresfand M., "Effet of reinforcement on triaxial shear behavior of cement treated sand", Geotextiles and Geomembranes 36 (1) (2013)1-9.

14. Heeralal M., Praveen G.V., "A study on effect of fiber on cement kiln dust (CKD) stabilized soil", Journal of Engineering Research and Studies 2 (4) (2011) 173-177.
15. Leroueil S. and Vaughan P. R. "The general and congruent effects of structure in natural soils and weak rocks", Geotechnique, London 40(3) (1990) 467-488.
16. Maccarini M., "Laboratory studies of a weakly bonded artificial soil. Ph.D. Thesis, University of London (1987).
17. Maher M.H., Ho Y.C., "Behavior of fiber-reinforced cemented sand under static and cyclic loads", Geotechnical Testing Journal, ASTM 16 (3) (1993) 330-338.
18. Michalowsky R., Zhao A. "Failure of fiber-reinforced granular soils", Journal of Geotechnical Engineering, ASCE 122(3) (1996) 226-234.
19. Michalowski R., Čermák J., "Triaxial compression of sand reinforced with fibers", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 129(2) (2003) 125-136.
20. Park S.S., "Effect of fiber reinforcement and distribution on unconfined compressive strength of fiber-reinforced cemented sand", Geotechnical and Geoenvironmental 27 (2009)162-166.
21. Park S.S., "Unconfined compressive strength and ductility of fiber-reinforced cemented sand", Construction and building materials 25 (2011)1134-1138.
22. Salah-ud-din M., "Behavior of fiber reinforced cemented sand at high pressures", Ph.D. Tesis, University of Nottingham (2012).
23. Toll D.G. and Malandraki V., "Triaxial Testing of a Weakly Bonded Soil", In Proceedings of Geotechnical Engineering of Hard Soils-Soft Rocks, Anagnostopoulos et al. eds., Balkema, Rotterdam (1993) 817-823.

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