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Effect of Coir Fiber on the Stress–Strain Behavior of a Reconstituted Fine-Grained Soil

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The heterogeneous nature of the soil poses great challenge as well as opportunity to geotechnical engineers all over the world. As the availability of good sites is becoming difficult, active research is going on throughout the world to improve the engineering properties of the soft soils. Among all the ground improvement techniques, the soil reinforcement is emerging as an attractive alternative. Addition of natural fiber to the soil is a very good soil-reinforcement technique in the context of sustainable development. Coir fiber can be effectively used to tackle many short-term stability issues in geotechnical engineering related to shear strength, permeability, etc. In the present study, comprehensive experimental work has been conducted to investigate the effect of coir fiber on the stress–strain characteristics of a reconstituted cohesive soil. Laboratory model studies are conducted to study the effect of length and amount of fiber on the shear strength of soil. Tests were carried out using fiber contents varying in the range of 0%–2% by dry weight of the soil. The unconfined compressive strength of soil is significantly increased when coir fiber is added to it. The increase is directly proportional to the quantity of the fiber used. The peak compressive strength of the fiber-reinforced soil with 1.5% fiber content is more than twice that of the un-reinforced soil. Mixing of fiber of length 15 mm is found beneficial from laboratory experiments on 38-mm (diameter) × 76-mm (height) samples. Triaxial compression tests results showed that the fiber content in the range of 1.5%–2% is highly beneficial to enhance and strength of the fine-grained soil. Also, it is observed that peak

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deviator stress increases with increase in fiber content for all confining pressures. A remarkable increase in cohesion and friction angle values has been observed with the addition of fiber, and they increases nonlinearly with the fiber content. Moreover, the stiffness and ductility of the soil are quite improved with the use of natural fiber.

KEYWORDS coir fiber, kaolin, stress-strain behavior, fiber dosage, fiber length

INTRODUCTION

Modern world is developing at a rapid pace and good soils for construction are rarely available now. Use of planar and discrete geosynthetic materials, in the form of geogrids, geotextiles, and geofibers, etc. is increasingly practised all over the world to improve the geotechnical characteristics of natural ground for various applications. Though these synthetic materials proved successful, the use of natural fibers for ground improvement may be highly desirable from the economic and environmental point of view. Fibers are the raw materials from which all other geotextiles and membranes are made. Any development activity should go hand in hand with much needed ecological balance. Sustainable development is gaining more and more acceptance in the current era. Inclusion of natural coir fiber for ground improvement is one big step toward this direction. Coir fiber is a natural material obtained from coconut husk. Majority of coir in the world is produced in South Asia. Coir fiber is abundantly available in India, and most of the coir produced in India comes from the rural regions of south India. Studies on coir fiber-reinforced soil gained popularity only in the recent past. The use of coir fiber for field applications has not gained enough momentum, mainly because of limited experimental findings associated with its use. Limited literature is available regarding the use of coir fiber as reinforcement, and hence, more qualitative research needs to be carried out before it can be formally put into use.

LITERATURE REVIEW

Many small-scale laboratory investigations have been carried out to understand the effect addition of discrete randomly distributed synthetic fiber (polypropylene or polyester) on the compressive stress–strain behavior, peak compressive strength, ductility, splitting tensile strength, and flexural toughness of fine-grained soils, and it is observed that fiber-reinforced soil performs better in all the above aspects compared to that without reinforcement (Freitag 1986, Maher and Ho 1994, Ranjan et al. 1996, Kudo et al.

2001, Kumar et al. 2005, Sung-Sik 2009). Influence of aspect ratio and dosage of fibers on the flexural and permeability characteristics of a cohesive soil has been studied by Viswanadham et al. (2008), and concluded that an increase in friction angle and decrease in adhesion were observed with the increase in fiber content. On similar lines, many researchers studied the influence of discrete synthetic fiber on the shear strength and stiffness properties of natural or artificially cemented cohesionless sand (Maher and Gray 1990; Consoli et al. 2010) and the triaxial results clearly demonstrate that the peak strength and ultimate strength have increased with fiber reinforcement whereas the initial stiffness is apparently unchanged. It was also observed that the contribution of the fibers to the composite strength is the largest when they are placed in the direction of the largest extension of the composite (Michalowski and Cermark 2003), and fibers performed under their elastic limit when deviator stress is applied, and no breakage or plastic behavior of the fiber is observed even at the end of the tests (Diambra et al. 2010).

Studies have also been conducted to understand the influence of natural fiber in the form of coconut and sisal fibers, on the shear strength, ductility, and volumetric shrinkage, piping characteristics of various fine-grained soils (Ranjan et al. 1996, Ghavami et al. 1999, Puppala and Musanda 2000, Sivakumar Babu and Vasudevan 2008, Viswanadham et al. 2009a, 2009b), and the results show that shear strength and ductility were increased considerably with the addition of fibers to soil; also, a substantial decrease in volumetric shrinkage was observed when fibers are mixed with expansive soils (Puppala and Musanda 2000, Viswanadham et al. 2009b).

Zornberg (2002) derived equations for finding the shear strength parameters of fiber-reinforced soils when the failure is governed by pullout of the fiber. The equations are given below:

$$C'_{eq,p} = C'\left(1 + \alpha\eta\chi C_{i,c'}\right),$$

$$\left(\tan\phi'\right)_{eq,p} = \left(1 + \alpha\eta\chi C_{i,\phi'}\right)\ \tan\phi',$$

where, $C'_{eq,p}$ is the equivalent cohesive component of fiber-reinforced soil when the failure is occurring by fiber pullout, C' is the cohesion intercept of un-reinforced soil, α is the empirical coefficient accounting for the effect of fiber orientation and mobilization of fiber-induced tension $\alpha = 1$ for randomly distributed fibers), η is the aspect ratio of the fiber, χ is the gravimetric fiber content, $C_{i,c'}$ is the interaction coefficient of the cohesive component of interface shear strength, and $C_{i,\phi'}$ is the interaction coefficient of the frictional component of interface shear strength.

Sivakumar Babu and Vasudevan (2008) proposed analytical models for finding out the major principal stress at failure and shear strength parameters of fine-grained red soil. However, the analytical model proposed by them is soil-specific. The regression equations obtained by them are as given below:

$$\sigma_{1f} = (159.1 + 3.96\sigma_3 - 0.0083\sigma_3^2 - 2959f_d + 4866.5f_d^2 - 37.01f_c + 17.35f_c^2 + 58.8f_l - 1.69f_l^2 + 2.69\sigma_3 f_d + 548.61f_d f_c + 6.21f_c f_l - 0.016f_l\sigma_3),$$

$$c = 76.5 + 156.4f_d - 102.1f_d^2 + 126.1f_c + 39.3f_c^2 + 20.2f_d f_c,$$

$$\phi = 23.1 - 78.55f_d + 191.1f_d^2 + 7.03f_c + 2.38f_c^2 - 15.02f_d f_c,$$

where, σ_{1f} is the major principal stress at failure of the fiber-reinforced soil in kPa, C is the cohesive component of the fiber-reinforced soil in kPa, ϕ is the frictional component of the fiber-reinforced soil in degrees, σ_3 is the confining pressure in kPa, f_d is the diameter of the coir fiber in mm, f_c is the fiber content in percentage by dry weight of the soil, and f_l is the length of the coir fiber in mm.

On the basis of the available literature, it can be concluded that there are not many studies available that observes the influence of natural fiber on the shear strength characteristics of cohesive soils. As the natural fiber is abundantly available in many parts of the world, their bulk use in geotechnical applications can only be justified with the availability of more research studies on the performance of natural fiber-reinforced soils. Hence, the following main objectives have been identified for the present work:

1. To obtain the unconfined compressive strength of fine-grained soil specimens of size 38 mm × 76 mm, randomly reinforced with various quantities of coir fiber.
2. To obtain the stress–strain behavior of coir fiber-reinforced fine-grained soil by conducting unconsolidated undrained triaxial compression tests on 38-mm × 76-mm soil specimens.
3. To find the effect of fiber inclusion on the peak deviator stress, major principal stress at failure, shear strength parameters, and stiffness characteristics of the soil, under the influence of confining pressure.

MATERIALS USED AND THEIR PROPERTIES

A reconstituted cohesive soil, Kaolin, obtained from Kutch region of Gujarat, India, was used in this study. The physical properties of the soil are given in Table 1.

TABLE 1 Physical Properties of Soil Obtained from Laboratory Tests

Physical property	Value
Classification (USCS)	CL
Specific gravity, G_s	2.6
Liquid limit	32%
Plastic limit	18%
Plasticity index	14%
Maximum dry density	16.8 kN/m^3
Optimum moisture content	20%

TABLE 2 Physical Properties of Coir Fiber Used in the Study

Property	Value
Length	50–200 mm
Breaking load	5.0 N
Diameter	0.1–0.45 mm

High quality white coir fiber obtained from Kollam district of Kerala, India is used for mixing with soil. The coir fiber is bleached and cut into 15-mm long stripes. The coir fiber used in the present study has an average diameter of 0.25 mm. The physical properties of fiber used in this study are listed in Table 2.

SAMPLE PREPARATION AND TESTING OF SOIL SPECIMENS

All soil specimens were prepared at maximum dry density (MDD) and optimum moisture content (OMC), as shown in Table 1. Dry soil of specified weight was mixed with required quantity of water and kept in desiccator for moisture equilibrium. Subsequently, the wet soil was taken out from the desiccator and spread over a plane glass plate for mixing. The specified amount of fibers in percentage by dry weight of the soil was distributed uniformly over the soil and mixed with the help of a spatula. The fiber soil mix was kept for almost 1 hr in desiccator. After this period it was taken out again and mixed thoroughly. The above procedure is followed, as wet soil is more suitable for mixing with fibers than the dry soil. In the case of dry soil, there is a tendency for segregation of fibers. The entire soil is filled in three layers, in a cylindrical mould, and compacted to obtain reinforced soil sample of standard dimension (38-mm diameter × 76-mm height) for unconfined and triaxial tests. Tests were carried out using fiber dosage of 0, 0.1, 0.5, 1, 1.5, and 2% by dry weight of the soil. The preparation of the specimen becomes difficult if the fiber content is more than 2%, and the fiber exhibits higher tendency to agglomerate and form weak planes inside the sample when the fiber content is increased beyond 2%. Hence, the mixing was limited to 2% coir fiber only. The specimen is then mounted on the pedestal of a loading platform. An axial strain rate of 1.2 mm/min is used throughout the testing program. The tests are continued until either the specimen fails in shear or the axial strain reaches 20%, whichever is earlier.

UNCONFINED COMPRESSION TESTS ON SOIL

In order to understand the effect of addition of coir fiber on the unconfined compressive stress, a number of unconfined compression tests are conducted on un-reinforced and randomly reinforced soil. Fibers of 30-mm length are added to the soil at a dosage of 0.1% of dry weight of the soil, and the results are shown in Figure 1. From the figure it can be noted that the addition fiber decreased the compressive strength. The same trend is continued for repeated trials. Based on the analysis of test results with various dosages of fiber, it is believed that the failure in the soil specimen would be taking place along the length of fiber, and reinforced soil specimen may be failing along these weak planes, instead of failing along a path connecting least shear strength points. This may be due to using 30-mm-long fibers with smaller soil specimens. Thus, noticeably decreased compressive strength is observed with the addition of fibers.

Keeping the above in mind, a reduced length of fiber is selected, and it is noticed from Figure 2 that when soil is reinforced with fiber length of 15 mm, the unconfined compressive strength increases with increase of fiber dosage, and the soil shows a ductile behavior with addition of fiber, which are in line with previous research findings. Hence, fiber length of 15 mm is used for further studies. The peak compressive strength increases with

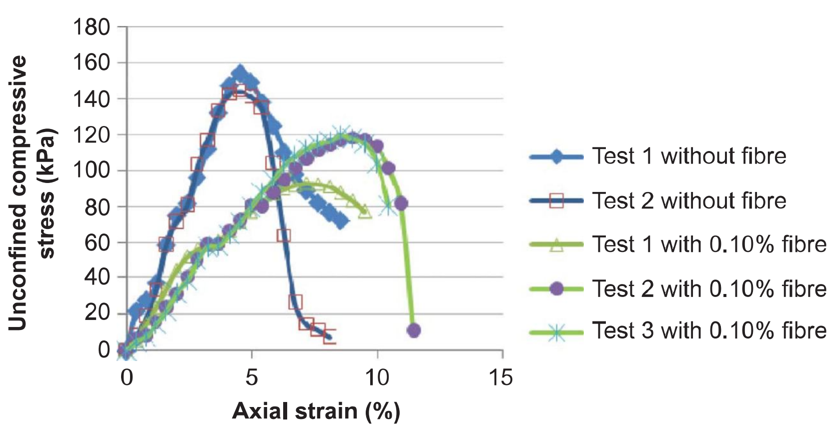

FIGURE 1 Stress–strain response of soil mixed with coir fiber in various dosages (length of fiber = 30 mm) (color figure available online).

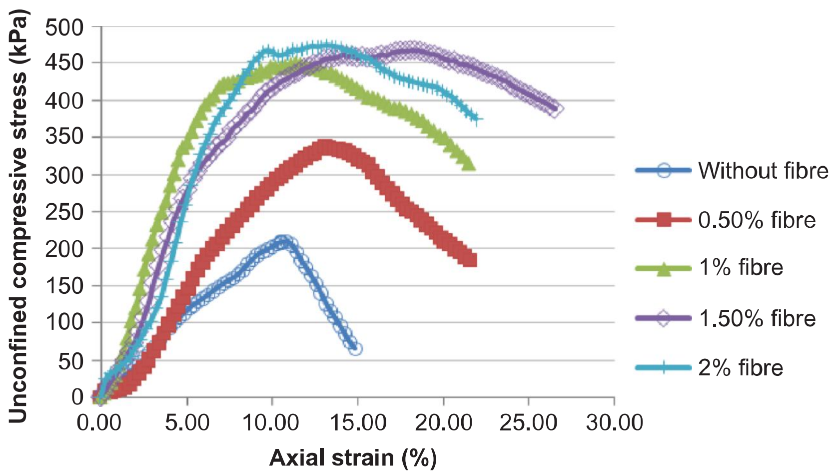

FIGURE 2 Stress strain response of soil mixed with coir fiber in various dosages (length of the fiber = 15 mm) (color figure available online).

increase in fiber dosage up to 1.5%, and thereafter the compressive strength does not increase considerably with further increase in fiber dosage. As the fiber content increases, the failure would take place slowly and the sample behaves like a ductile material. Well-defined failure surfaces could not be seen due to the increased ductile behavior. It can be seen from the figure that the peak compressive strength at 1.5% fiber dosage is about twice that for soil without fiber reinforcement.

TRIAXIAL COMPRESSION TESTS ON COIR FIBER-REINFORCED SOIL

Tests are also conducted on soil specimens of standard size 38 mm × 76 mm in triaxial cell under unconsolidated undrained (UU) conditions, using three sets of confining pressures, viz., 50, 100, and 150 kPa. Strain-controlled tests are conducted throughout with an axial strain rate of 1.2 mm/min. The test results are analyzed further to understand the following:

i. Stress–strain response with various fiber dosages.
ii. Modified Mohr–Coulomb failure envelope and shear strength parameters.
iii. Effect of fiber on stiffness modulus of soil

STRESS–STRAIN RESPONSE WITH VARIOUS FIBER DOSAGES

Figures 3, 4, and 5 show the deviator stress versus axial strain response of coir fiber-reinforced soil for various fiber dosages, for confining pressures

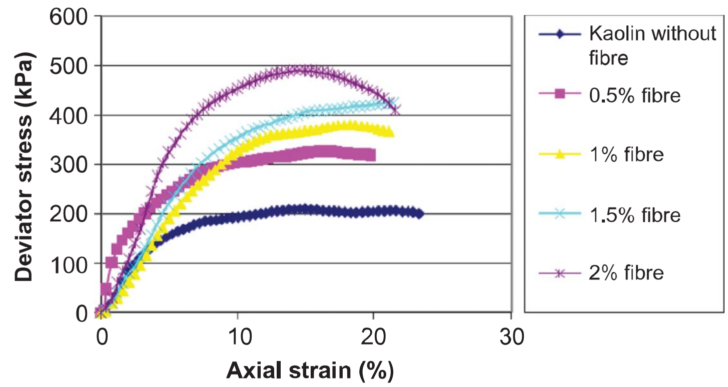

FIGURE 3 Stress–strain response of soil with various fiber contents and 50-kPa confining pressure (color figure available online).

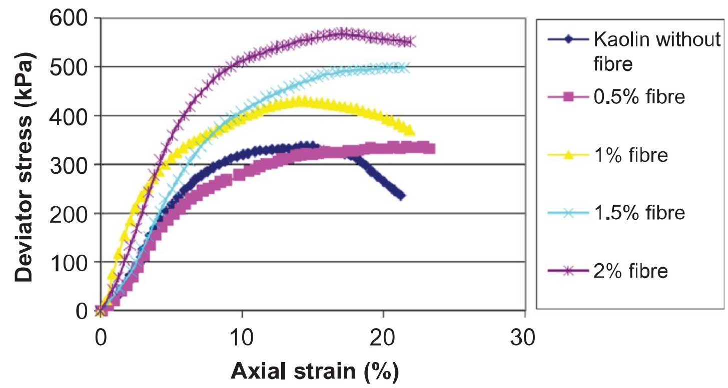

FIGURE 4 Stress–strain response of soil with various fiber contents and 100-kPa confining pressure (color figure available online).

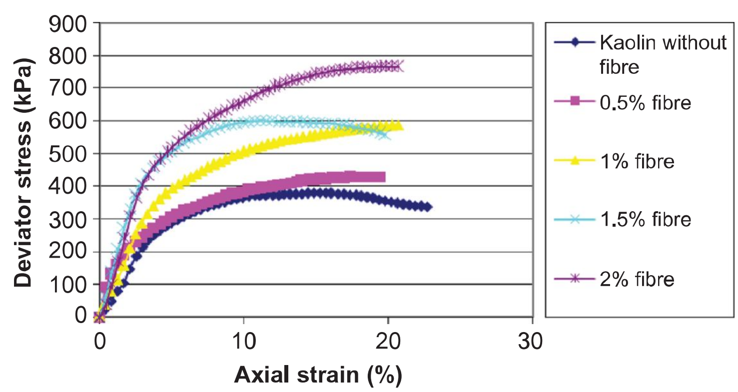

FIGURE 5 Stress–strain response of soil with various fiber contents and 100-kPa confining pressure (color figure available online).

of 50, 100, 150 kPa, respectively. It can be observed that the peak deviator stress is shown to increase with increase in the fiber content. The peak deviator stress increased to twice that of un-reinforced soil, when it is reinforced with 1.5% fiber at a confining pressure of 50 kPa. The peak deviator stress

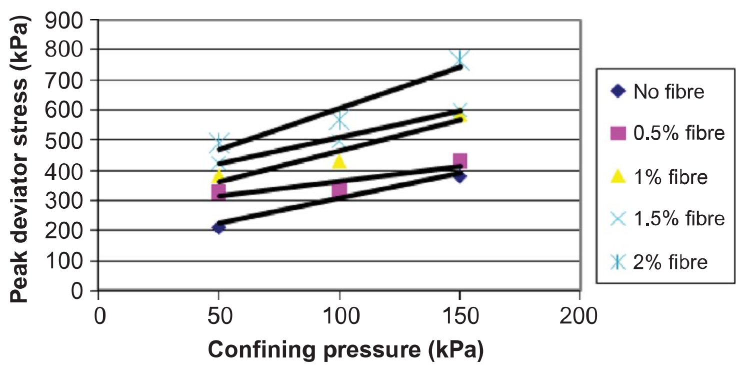

FIGURE 6 Peak deviator stress versus confining pressure for various fiber contents (color figure available online).

increased by about 1.5 to 2.3 times over un-reinforced soil by the addition of various amounts of fiber at a confining pressure of 50 kPa. In the case of 100-kPa confining pressure, the peak deviator stress increased by about 1.6 times over unreinforced kaolin, when the soil is reinforced with 2% fiber, and for 150-kPa confining pressure the increase in peak compressive strength is of the order of 1.1 to 2.

In the case of un-reinforced soil, the peak deviator stress is reached at lower strain level of around 12%, whereas in the case of reinforced kaolin the peak deviator stress attains at much higher strain levels. This clearly indicates that the fiber–soil composite is more ductile compared to un-reinforced soil, and the ductility increases with increase in fiber dosage. It can also be seen from Figures 3, 4, and 5 that the peak deviator stress increases with increase in confining pressure for the same fiber content. The effect of confining pressure on the increase of peak deviator stress is clearly seen from Figure 6 for both un-reinforced and reinforced soils.

EFFECT OF FIBER ON MAJOR PRINCIPAL STRESS AT FAILURE

The triaxial test results are analyzed to study the influence of coir fiber on major principal stresses at failure. The major principle stress at failure was increased with increase in the fiber content, for all the three confining pressures, as shown in Figure 7. The ratio of major principal stress at failure of fiber-reinforced specimen to that of un-reinforced specimen is almost identical for all the three confining pressures. Similarly, the major principal stress at failure increases with increase in fiber content for all the three confining pressures.

Sivakumar Babu and Vasudevan (2008) developed an empirical equation to predict the major principal stress at failure of coir fiber-reinforced red soil as a function of fiber content and confining pressure. Figure 8 shows results obtained from the present study, and that obtained using the above

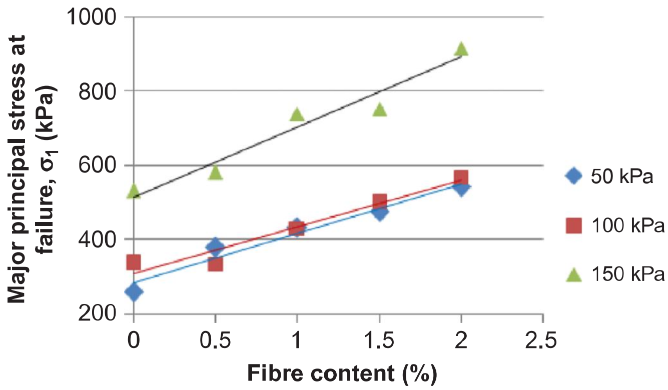

FIGURE 7 Variation of major principal stresses at failure as a function of fiber content and confining pressure (color figure available online).

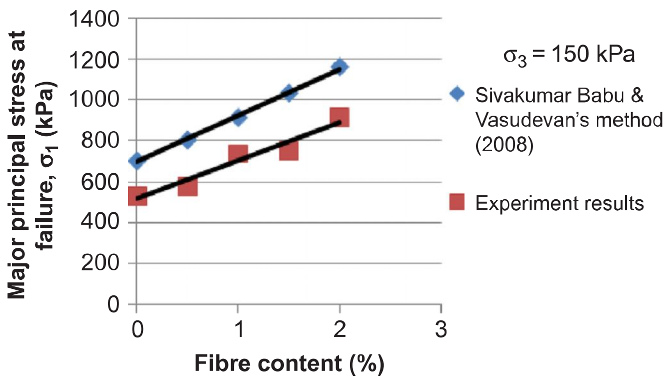

FIGURE 8 Major principal stresses at failure as a function of fiber content from experimental results and regression model studies for a confining pressure of 150 kPa (color figure available online).

regression model, for a confining pressure of 150 kPa. Both the studies predict a linear increase in major principal stress at failure with increase in fiber content, though the regression model overpredicts the principal stress at failure, as it was developed for a relatively stiffer soil.

MODIFIED MOHR–COULOMB ENVELOPES AND SHEAR STRENGTH PARAMETERS

Modified failure envelopes, shown in Figure 9, are developed from triaxial UU results for both un-reinforced and reinforced soils, and the shear strength parameters of un-reinforced and coir fiber reinforced soil are determined. It is observed from the figure that the shear strength parameters, viz., cohesion and friction angle, have improved with addition of coir fiber; their variations

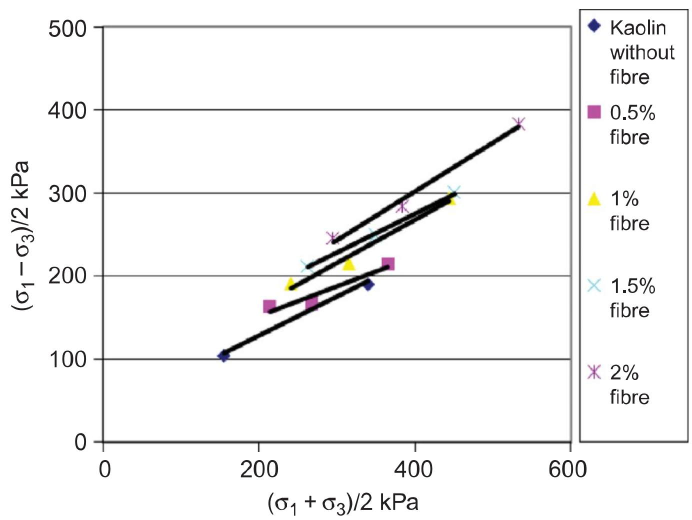

FIGURE 9 Modified Mohr–Coulomb diagrams for various fiber dosages (color figure available online).

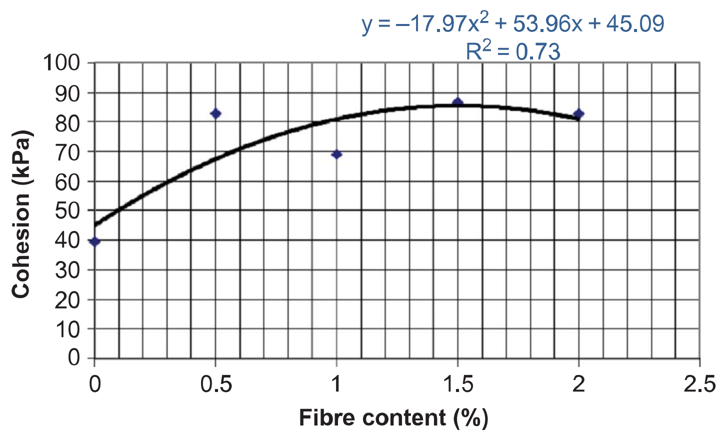

FIGURE 10 Variation in cohesion of soil with various fiber dosages (color figure available online).

are shown in Figures 10 and 11. For the soil under consideration, the cohesion is increased from 40 kPa for un-reinforced soil to around 85 kPa, at 1.5% fiber dosage.

Shear strength parameters showed an overall improvement by the addition of coir fiber to reconstituted cohesive soil. From Figure 10 it is clear that the cohesion value increases gradually and reaches a maximum value at a fiber content of 1.5%, and thereafter cohesion is almost constant with further increase in fiber content. The friction angle shows a decreasing trend in the beginning up to a fiber content of 0.5%. Thereafter, the friction angle exhibits an increasing trend with increase in the fiber content. No considerable increase in friction angle is however observed at 1.5% fiber content. The variation of friction angle up to 1.5% fiber content assumes particular interest, at which the cohesion attains its peak value. After 1.5%

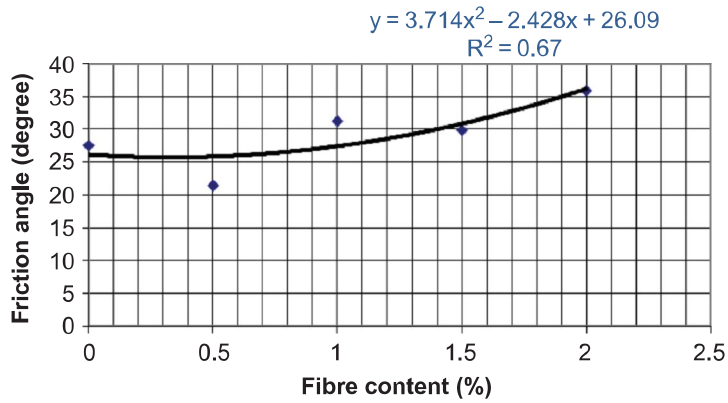

FIGURE 11 Variation in friction angle of soil with various fiber dosages (color figure available online).

fiber dosage, the cohesion starts decreasing and frictional angle shows considerable increase, with fiber dosage. Combining the above results, it can be inferred that fiber content in the range of 1.5%–2% can practically be considered, as it is clearly observed in the present study that mixing more than 2% fiber to soil is very difficult.

The regression models developed by Zornberg (2002) and Sivakumar Babu and Vasudevan (2008) for predicting cohesion and friction angle of reinforced soil specimen are used to compare the results obtained from the present study. The input parameters in these models were fiber content and fiber diameter. The average diameter of fiber used in the present study is 0.25 mm. Figures 12 and 13 show the variation of cohesion and friction angles with fiber content from present study, and using the above regression models.

From Figure 12, it is revealed that cohesion intercept increases with fiber content, and after attaining a peak value it reduces with further increase in fiber content. According to the Zornberg (2002) model, cohesion

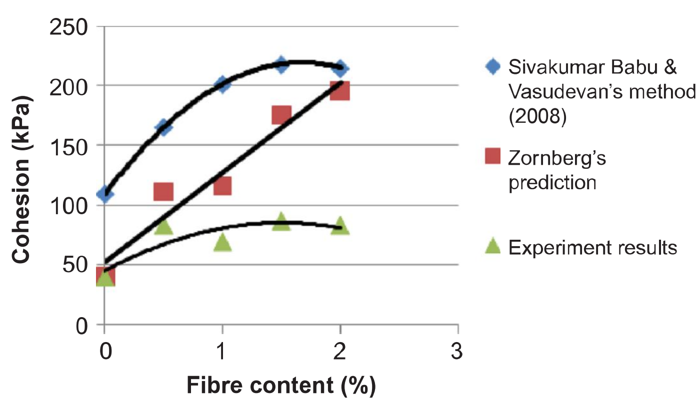

FIGURE 12 Variation of cohesion with fiber content (color figure available online).

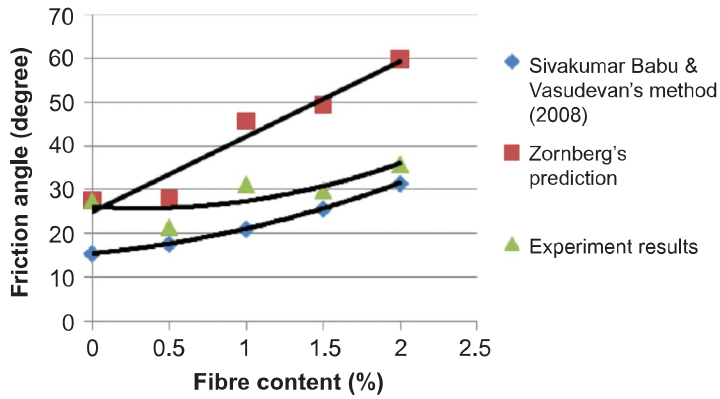

FIGURE 13 Variation of friction angle with fiber content (color figure available online).

increases almost linearly with increase in fiber content, and it overpredicts the cohesive strength of coir fiber-reinforced soil. This inconsistency may be attributed to the use of synthetic fibers, for which the Zornberg (2002) regression model was obtained. The model developed by Sivakumar Babu and Vasudevan (2008) also overpredicts the cohesion intercept. However, the trend between cohesion intercepts and fiber content obtained in the present study is very well matching with that using the regression equation of Sivakumar Babu and Vasudevan (2008), which was developed for red soil reinforced with natural coir fiber. Use of similar fibers in the present study and studies by Sivakumar Babu and Vasudevan (2008) may be attributed to the similarity in trend. In both cases the cohesion value is increasing with fiber content until it reaches a peak and decreases with further addition of fiber to the soil. The peak cohesive strength is attained at 1.5% fiber content in both the curves. Even though these two curves are almost parallel to each other, a big difference is observed in the cohesion values obtained in both cases. This variation can be attributed to difference in the properties of the soil used in the two studies and the variability in the quality of coir fiber.

Figure 13 shows variation of friction angle with fiber content. The results obtained from the present study show a marginal decrease with increase in the fiber content at lower fiber dosages. With further increase in fiber dosage, the friction angle shows an increasing trend. The regression model of Sivakumar Babu and Vasudevan (2008) also follows a similar trend. However, since the above model is soil-specific, i.e., meant for fiber-reinforced red soil, the two curves are not coherent. Zornberg (2002) model predicts a linear trend for friction angles with increase in fiber content, similar to that observed in the case of cohesion intercept. The predicted friction angles by the Zornberg (2002) model are also higher compared to the results obtained from the present study for all fiber contents. This model clearly overestimates the shear strength of coir fiber-reinforced soil.

EFFECT OF COIR FIBER ON THE STIFFNESS OF THE SOIL

The stiffness modulus at a particular strain level is defined as the ratio of deviator stress to the corresponding strain. The stiffness modulus of un-reinforced and coir fiber-reinforced soil are studied in a triaxial setup under UU conditions. Figure 14 shows the variation of stiffness with axial strain for a confining pressure of 150 kPa. It can be seen from the figure that reinforced specimens exhibit very high stiffness at small axial strains of the order of 2%, compared to un-reinforced specimen. With further increase in strain, there is a considerable reduction in the stiffness. After a small amount of strain is mobilized, the stiffness response is seen to be following a common trend with increase in fiber content. As the axial strain reaches around 5%, the trend is more pronounced, i.e., the stiffness is more for the soil specimen having higher fiber content. The same trend continues with further increase in axial strain. It is observed from the results that there is dramatic increase in stiffness of the fiber-reinforced specimen with increase in fiber content at low to medium strain levels. The stiffness modulus for reinforced soil with 1.5%–2% fiber content is almost double compared to un-reinforced kaolin. Also, it can be understood that a large amount of stiffness is mobilized in the initial stages of strain and with further increase in strain, the stiffness values reduced noticeably. Similar trends are observed for confining pressures of 50 and 100 kPa.

CONCLUSIONS

The present study focuses on the use of coir fiber to enhance the strength and stiffness response of reconstituted cohesive soil through small-scale laboratory experiments. The following are some of the salient conclusions drawn from the study:

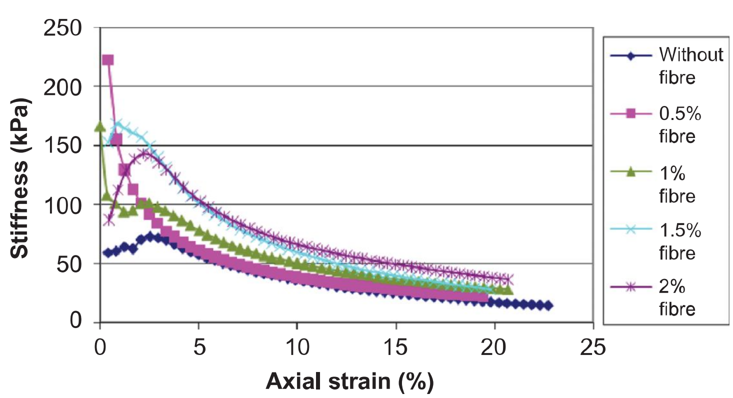

FIGURE 14 Stiffness versus axial strain with various fiber contents at 150-kPa confining pressure (color figure available online).

(1) When soil is reinforced with coir fiber of 15-mm length, the unconfined compressive strength increases with increase in fiber dosage, and the soil shows a ductile behavior with addition of fiber. The UCS of reinforced kaolin at 1.5% fiber dosage is more than twice that of the un-reinforced soil. However, it is noticed that the unconfined compressive strength of coir fiber-reinforced soil with 30-mm length fiber is less than that for un-reinforced soil. When 30-mm length coir fiber is used for preparing a standard specimen of 38-mm diameter, it is suspected that the fiber may be helping to induce a predefined failure plane in the specimen. It can be justified that for such a specimen, use of lower fiber lengths of the order of 15 mm may be recommended.

(2) Addition of coir fiber in the dosage range of 1.5%–2% is found beneficial from both UCS and UU triaxial tests. With fiber dosages less than 1.5%, the improvement in strength and stiffness is not very significant. With higher fiber dosages of above 2%, the preparation of a specimen becomes difficult, and fiber shows higher tendency to agglomerate and form weak planes inside the sample.

(3) The peak deviator stress and major principal stress at failure increase with increase in fiber content for all confining pressures, and fiber-reinforced soil exhibits improved ductility with increase in fiber content.

(3) The cohesion and friction angle are increased significantly by the addition of coir fiber. Cohesion attains a peak value at 1.5% fiber content, and it reduces with further increase in fiber content. However, there is a steady increase in friction angle with increase in fiber content. Both cohesion and friction angles vary nonlinearly with addition of fiber.

(4) The stiffness response of coir fiber-reinforced soil is better than that of un-reinforced soil. The stiffness modulus increases with increase of fiber content, and for reinforced soil with 1.5%–2% fiber content stiffness is twice compared to that of un-reinforced soil.

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