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Experimental Investigation on Strength Aspects of Glass Fiber-Reinforced Fine Grained Soil

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Abstract: A series of consolidated undrained (CU) triaxial tests was carried out on glass fiber-reinforced fine grained soil to investigate the influence of fiber reinforcement on the strength, stiffness and energy absorption capacity of soil compacted at different dry unit weights. Soil with varying compacted dry unit weight (γ_d = 14.3 to 16.8 kN/m^3) was reinforced with 20 mm long fiber of varying fiber content (f_c = 0.25 to 1%). Test results have shown that the addition of fibers has significantly improved the stress-strain, stiffness and EAC response of soil. The strength improvement is more pronounced with increasing compacted dry unit weight and fiber content up to an optimum value of 0.75% fiber content. Both cohesion and friction components of shear strength parameters have increased with fiber content and they further improve with compacted dry unit weight. Contribution of fiber in strength improvement is higher at low confining pressure and decreases with increase in confining pressure. Fiber inclusions have restrained the soil dilatancy which decreases with increasing dry unit weight of soil. Fiber reinforcement improves the stiffness modulus and energy absorption capacity of soil which increases with fiber content, confining pressure and compacted dry unit weight. Glass fiber can be used as reinforcement material to strengthen the soil for different geotechnical applications.

Keywords: *Triaxial test, Dry unit weight, Shear strength, Stiffness modulus, Energy absorption capacity, Cohesion*

1. Introduction

Fiber-reinforced soil is one of the soil improvement methods which have been in focus of research from the last 25-30 years. Although this technique has originated in ancient years in the form of reinforcing earth with natural fiber materials [1], this has gained more popularity in recent 2-3 decades. Fiber-reinforced method has been successfully used in more than 50 embankment slopes between 1990 to 2006 in the United States [2]. This technique can be used in several geotechnical structures like pavements, slope stabilization, earth retaining structures, compacted clay liner and cover system [3-6]. Unlike the traditional planer earth reinforcement methods, fiber reinforcement maintains strength isotropy within soil mass by evading any potential weak plane which occurs along the reinforcement direction [7]. Its mixing and placement in the field is easy and can be easily used in limited space of restricted area [8, 9]. Other chemical stabilization methods of soil by lime, cement or fly ash changes the natural properties of soil which is irrecoverable [10] while fiber inclusion only changes the physical properties of soil mix and has no impact on environment [11]. Fiber reinforcement leads to significant modification and improvement of engineering behavior of soils. These advantages have made fiber-reinforced soil an attractive material for several applications in geotechnical engineering.

Several studies on fiber-reinforced soil have been carried out through unconfined compression tests[12-20], triaxial compression tests [7, 14, 15, 18, 21-25], isotropic compression tests [26, 27], repeated triaxial test [15], direct shear tests [13, 28, 29], pullout tests [24], CBR tests [13, 30], plate load tests [31, 32], tensile tests [10-12, 14, 18, 19] and flexural tests [33].Fiber reinforcement reduces residual strength and decreases stiffness and induces ductility in brittle soil [10, 14, 34]. Most of the studies on fiber-reinforced cohesive soil have been carried out on OMC and MDD of soil and soil-fiber mix. In very few unconfined compressive strength tests [13, 19] and tensile strength tests [10, 11] the effect of moisture content and soil unit weight variation on strength aspects has been investigated. The effect of compacted soil unit weight on fiber-reinforced cohesive soil shear strength by triaxial compression test has not been reported in literature. Keeping this in consideration, this paper presents an experimental investigation on glass fiber-reinforced soil with varying compacted dry unit weight of soil by means of consolidated undrained (CU) triaxial compression tests. The effect of compacted dry unit weight, fiber content, fiber length and confining pressure on shear strength, stiffness modulus and energy absorption capacity has been investigated.

2. Materials and Methodology

2.1. Materials

The soil used is a cohesive soil of red colour which is used in routine earth construction in the area. The soil was initially air dried and then sieved through 2 mm size sieve. The soil contains 25% sand size, 54% silt size and 21% clay size and is classified as low plastic clay (CL) as per ASTM D2487 [35]. The maximum dry density (MDD) and optimum moisture content (OMC) of soil are 16.8 kN/m^3 and 19.4% respectively. Commercially available glass fibers were used as reinforcement material. The glass fiber was of white colour with 0.15 mm as average diameter. The specific gravity, tensile strength, modulus of elasticity, percentage elongation at breakage and moisture absorption capacity of fiber are 2.57, 1.5 GN/m^2 and 110 GN/m^2, 1.7% and zero respectively. Glass fiber of 20 mm length and four different fiber content (f_c = 0.25, 0.5, 0.75 and 1% by dry weight of soil) was used as reinforcement and compacted with four different dry unit weights of soil (γ_d = 14.3, 15.1, 16 and 16.8 kN/m^3) at water content equal to 19.4% by soil dry weight.

2.2. Methodology

Glass fiber and soil were weighted as per their proportion initially. Required amount of water was mixed in soil homogeneously and then fibers were added slowly and uniformly after separating them properly in different stages. All the mixing (water and fiber) was done manually and when it was noted from eye observation that the fibers were uniformly mixed, the soil fiber mix was kept in a closed polybag for moisture equilibrium within soil-fiber mix for 24 hrs. in an air tight desiccators. Thereafter the soil-fiber mix was transferred in a compaction mold of 38 mm diameter and 76 mm height which has additional detachable collars at both ends. The mold was initially coated with oil prior to transferring the soil-fiber mix inside it. To ensure uniform compaction of specimen, the entire required quantity of the moist soil-fiber mixture was poured inside the mold-collars assembly and compressed in three steps from the two ends simultaneously till the specimen reached the fixed dimensions of the mold. The compacted specimen was extruded from the mold immediately using a hydraulic jack and was kept in desiccator to ensure no loss of moisture prior to assembling it for triaxial testing.

Once the specimen was assembled in triaxial cell, the specimen was saturated by using back pressure while maintaining 20 kPa positive difference between cell pressure and back pressure keeping the cell pressure higher. At every increment of cell pressure, the Skempton's pore water pressure parameter B was checked for knowing the saturation level of specimen. Once the B value reached 0.95, the saturation was stopped and the specimen was set for consolidation stage under required effective confining pressure (σ_3) which ranged between 100 to 400 kPa. After the pore pressure under consolidation state became constant, the strain controlled shearing of specimen was done at a rate of 0.12 mm/min. Specimen shearing was continued up to 20% axial strain deformation. The CU triaxial testing was done as per ASTM D 4767 [36].All the shearing data (i.e. load on specimen, axial displacement and pore pressure) was electronically stored in computer and was further used for analysis.

3. Results and Discussion

3.1. Stress-Strain Response

Typical stress-strain and pore pressure response of fiber-reinforced are presented in Fig. 1 for specimens compacted at 16.8 kN/m^3 dry density and sheared at 100 kPa confining pressure. The stress-strain response is significantly enhanced with fiber content up to 0.75% fiber content. For 1% fiber-reinforced specimen, the response has not improved and is found to be similar to that of 0.75% fiber content with improvement nearly equal to 2 times that of unreinforced soil.

Similar response has been found for specimens compacted under other dry unit weights where effect of reinforcement was most effective up to 0.75% fiber content with different strength improvement levels. At initial stress-strain response the effect of fiber is marginal and fiber effect starts to dominate after some specimen deformation as the tensile strength of fiber is mobilized after deformation of soil around fiber. As the specimen deforms, it stretches the fibers by surface friction and mobilizes tension in the fiber which add to the soil strength.

The pore pressure of fiber-reinforced specimen is found to be positive which increases with fiber content (Fig. 1b). Increasing positive pore pressure response with fiber content indicates the tendency of volume shrinkage which restrains the dilatancy of reinforced soil specimen, resulting in strength improvement with increased fiber content. The presence of fiber within soil helps in restraining the soil dilation and supports large volume condensation which increases with fiber content. Similar response has been absorbed by earlier research under consolidated undrained test [21-25].

Typical effect of dry unit weight of soil on stress-strain and pore pressure response of fiber-reinforced soil (f_c = 0.75%) is shown in Fig. 2. The stress-strain response of reinforced specimen improves significantly with increasing dry unit weight. The effect of dry unit weight on stress-strain response is visible from smaller strain level and the initial response of specimen is steeper for specimen compacted with higher soil density. Similar response has been observed with specimens reinforced with other fiber contents. With increased dry unit weight of soil in fixed specimen volume, the inter-particle contact between soil particles and soil-fiber particles improved significantly resulting better mobilization of tensile capacity of fiber and interfacial shear strength at the time of shearing. This leads to the improved stress–strain response with increased dry unit weight of soil.

The pore pressure response of reinforced specimen is found to be positive which decreases with increase in dry unit weight. This indicates that the restraining of dilatancy by fiber decreases with increased dry unit weight. Variation of stress-strain response between specimens compacted at 16.8 kN/m^3 and at 16 kN/m^3 dry unit weights is small compared with that of other compacted specimens (γ_d = 15.1 and 14.3 kN/m^3). Overall the specimen strength improves with increase in dry unit weight for both unreinforced and fiber-reinforced soil.

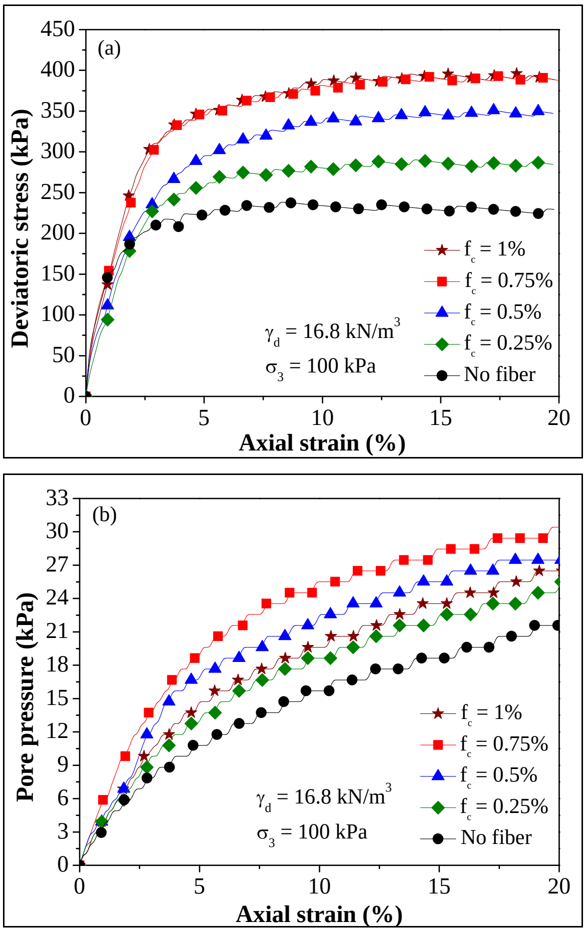
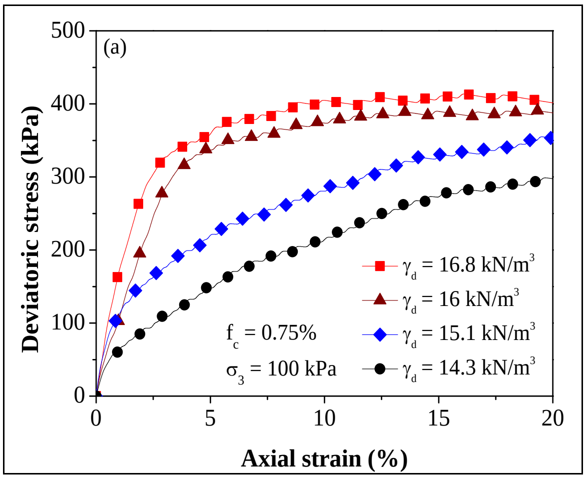


***Figure 1** Effect of fiber content on (a) stress-strain and (b) pore pressure response*



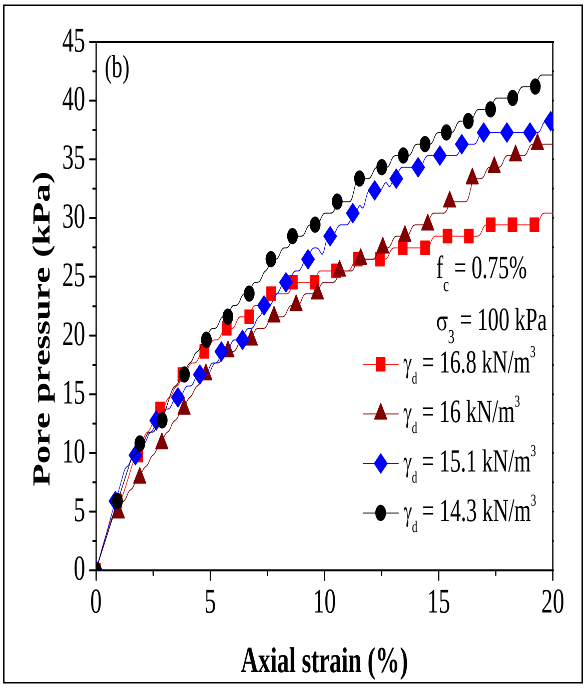


***Figure 2** Effect of dry unit weight on (a) stress-strain and (b) pore pressure response*

3.2. Peak Strength Variation

No peak has been observed from stress-strain response plotted for unreinforced and fiber-reinforced soil up to 20% axial strain loading. For defining the failure behavior and analysis of results, stress corresponding to 10% axial strain has been chosen as the failure stress as this strain level typically represents the failure criteria for several geotechnical applications.

Improvement in strength with fiber reinforcement is defined in terms of strength ratio (*SR*). *SR* is the ratio of failure stress of fiber-reinforced soil to that of unreinforced soil under similar shearing condition.

Fig. 3 shows the effect of fiber content on strength ratio of fiber-reinforced soil at different confining pressures for specimens compacted at 16.8 kN/m^3 dry unit weight. *SR* improves with fiber content under all confining pressures up to 0.75% fiber content.

Improvement in *SR* decreases with increasing confining pressure indicating that the benefit of fiber reinforcement is higher under low confinement and it can be significantly used for shallow foundation, pavements, slope repairing etc. Maximum strength improvement is found to be nearly 1.75 times that of unreinforced soil under 100 kPa confining pressure for 0.75% fiber inclusion.

The effect of compacted dry unit weight on *SR* of reinforced soil is presented in Fig. 4 for the specimens reinforced with 0.75% fiber dose. *SR* value is found to be higher at low confining pressure for any compacted dry unit weight of soil and decreases with increase in confining pressure up to 400 kPa confinement.

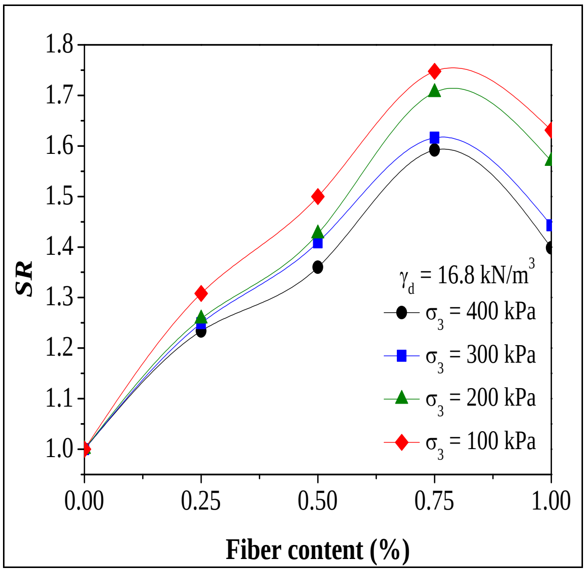


Figure 3 *Effect of fiber content on SR at different confining pressures*

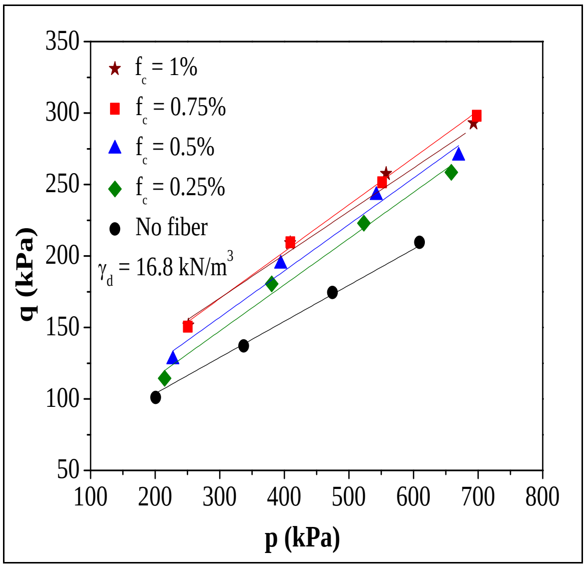


Figure 5 *Effect of fiber content on modified failure envelope of fiber-reinforced soil*

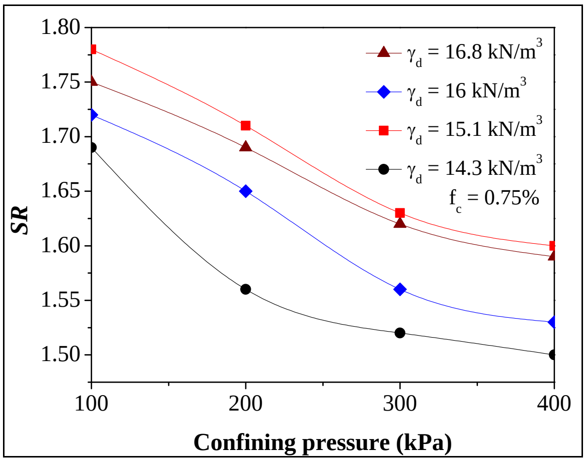


Figure 4 *Effect of dry unit weight on SR at different confining pressure*

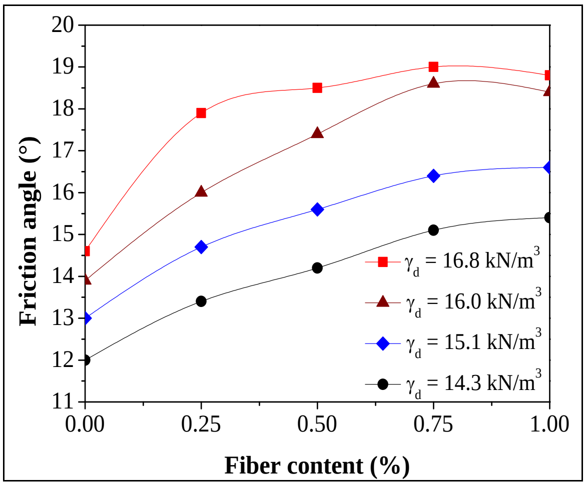


Figure 6 *Combined effect of dry unit weight and fiber content on friction angle*

3.3. Shear Strength Parameters

Shear strength parameters (c and φ) have been calculated by plotting modified failure envelope in terms of p-q plot where, p= $(\sigma_1 + \sigma_3)/2$ and q = $(\sigma_1 - \sigma_3)/2$ to find the effect of fiber content and dry unit weight of soil. The cohesion (c) and friction angle (φ) are found out through the relationships, $c = a/\cos\varphi$, $\sin\varphi = \tan\alpha$; where, a and α are the intercept and slope of the p-q plot respectively [37]. Stress corresponding to 10% axial strain level has been taken to calculate the shear strength parameters.

Typical p-q plots showing the effect of fiber content for specimens compacted at 16.8 kN/m^3 dry unit weight are shown in Fig. 5. Both the intercept and slope of the plots increases with increase in fiber content indicating the improvement of cohesion and friction component with fiber inclusion. Shear strength parameters (c and φ) in terms of total have been calculated for different dry unit weights and are presented in Figs. 6 & 7.

Both friction angle and induced cohesion increases with increasing fiber content up to optimum fiber content value of 0.75% for specimen compacted at 16.0 and 16.8kN/m^3 dry unit weight and 1% for specimen compacted at 14.3 and 15.1kN/m^3 dry unit weight. Shear strength parameters improve significantly with increased dry unit weight at all fiber contents (Figs. 6 & 7). For unreinforced soil, the friction component has improved from 12° to 14.6° and cohesion value from 25 kPa to 46 kPa as dry unit weight increased from 14.3 kN/m^3 to 16.8 kN/m^3. For reinforced soil, the friction component and cohesion value have improved maximum to 15.1° and 56 kPa for specimen compacted at 14.3 kN/m^3 dry unit weight, and to 19° and 102 kPa for specimen compacted at 16.8 kN/m^3 with 0.75% fiber reinforcement. The improvement in friction component is contributed to the tensile restraint produced by fiber which tends to act to increase the friction component of the strength [32].

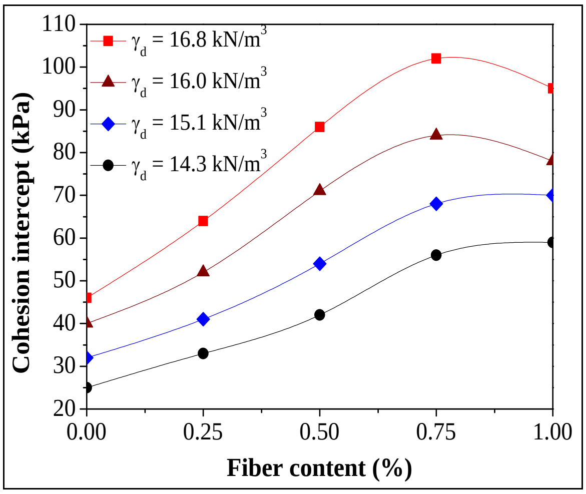


Figure 7 *Combined effect of dry unit weight and fiber content on induced cohesion*

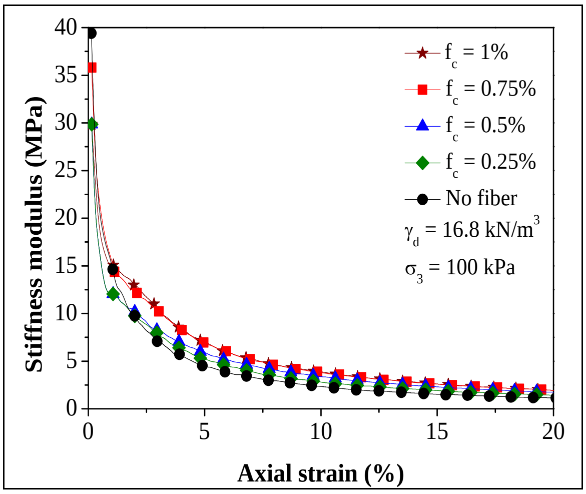


Figure 8 *Effect of fiber content on stiffness modulus response*

3.4. Stiffness Modulus Variation

Stiffness is a measure of resistance of a material by virtue of which it resists the deformation in response of external applied force. Stiffness modulus is the ratio of stress to the corresponding strain. Soil stiffness at different strain levels has been obtained at different strain level from the stress-strain response of triaxial testing results. Figs. 8-10 indicate the variation of the soil stiffness due to fiber inclusions at different strain levels for different fiber contents, confining pressures and soil dry unit weights. Soil stiffness is found to increase with fiber content, confining pressure and dry unit weight. Stiffness modulus is higher at small axial strain level which decreases with increasing axial strain and remains almost constant at larger strain value greater than 15%.

Stiffness of the specimen increases up to 0.75% fiber content and becomes almost constant at 1% fiber content. The effect of fiber content on stiffness variation is very high up to initial 1% strain. Thereafter the variation in stiffness is almost parallel with axial strain for different fiber contents (Fig. 8). Similar response of fiber content on stiffness modulus has been obtained for specimens compacted at all dry unit weights at any confining pressure.

Stiffness modulus increases with increasing confining pressure and variation becomes almost parallel at larger axial strain (Fig. 9). The effect of confinement increment appears from very small strain level and this effect is higher at low strain level which progressively decreases with increasing strain. Similar response was found for all fiber contents and compacted dry unit weights. Specimen compacted at higher dry unit weight shows greater stiffness from the initial loading stage (Fig. 10). It decreases with increasing axial strain and becomes very close at strain level higher than 15% irrespective of compacted dry unit weight.

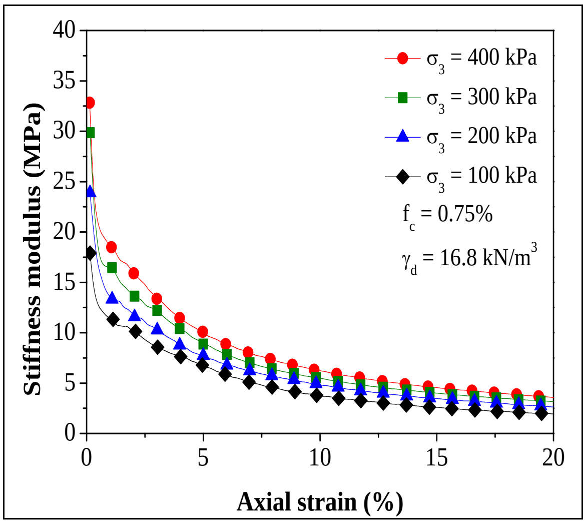


Figure 9 *Effect of confining pressure on stiffness modulus*

Comparing the effect of dry unit weight and confining pressure on stiffness modulus improvement at 10% axial strain level, it has been found that, for specimen reinforced with 0.75% fiber content, the stiffness modulus improved maximum from 2.16 MPa to 4.11 MPa (i.e. 1.95 MPa improvement) when dry unit weight increases from 14.3 kN/m^3 to 16.8 kN/m^3 under 100 kPa confining pressure. In case of varying confining pressure the stiffness value increases from 3.73 MPa to 6.18 MPa (2.45 MPa improvement) as confining pressure increased from 100 kPa to 400 kPa for specimen compacted at 16.8 kN/m^3 dry unit weight and reinforced with 0.75% fiber. Stiffness modulus of unreinforced specimen which is 2.31 MPa increased with fiber content to a maximum value of 3.82 MPa (i.e. 1.51 MPa improvement) at 0.75% fiber content under 100 kPa confining pressure compacted at 16.8 kN/m^{3}dry unit weight. Comparing the stiffness improvement, it can be noted that the effect of confining pressure is higher than that of dry unit weight or fiber content.

Overall it has been noted that inclusion of randomly mixed fiber results in overall improvement of soil stiffness which increases with increase of fiber content, confining pressure and compacted dry unit weight.

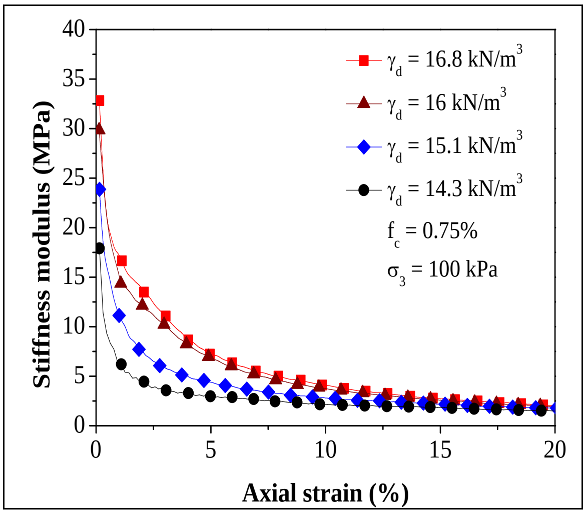


Figure 10 *Effect of dry unit weight on stiffness modulus*

3.5. Energy Absorption Capacity Variation

Energy absorption capacity (EAC) is the energy required to deform the specimen. It measures the toughness of any specimen. EAC can be found by calculating the area under stress-strain curve. In this study, the EAC has been calculated by measuring the area under stress strain curve up to 10% axial strain level. The effect of confining pressure and fiber content for fiber-reinforced soil is presented in Fig. 11. EAC of soil is found to improve with increasing fiber content. As the confining pressure increases the EAC further improves. The EAC of unreinforced soil which is 2131 kJ/m^3 at 100 kPa increases to 3449 kJ/m^3 at 400 kPa confinement for specimen compacted at 16.8 kN/m^3 dry unit weight. However, the EAC value has increased maximum from 3319 kJ/m^3 at 100 kPa to 6458 kJ/m^3 at 400 kPa with 0.75% fiber reinforcement. With increased confinement, the lateral spreading of specimen is restricted which results in more interaction between soil particles and soil-fiber particles which in turn needs more energy for its deformation.

As the compacted dry unit weight of soil increases, EAC further improves significantly at all confining pressure (Fig. 12). Similar results have been found for unreinforced specimen and specimen compacted at all fiber contents. The EAC of reinforced specimen with 0.75% fiber inclusion at 100 kPa confining pressure and compacted at 14.3 kN/m^3 dry unit weight is 1461 kJ/m^3 and has improved to 3319 kJ/m^3 at 16.8 kN/m^3 dry unit weights. At 400 kPa confining pressure, it has further improved to 3375 kJ/m^3 and 6458 kJ/m^3 for 14.3kN/m^3 and 16.8 kN/m^3 compacted dry unit weight respectively.

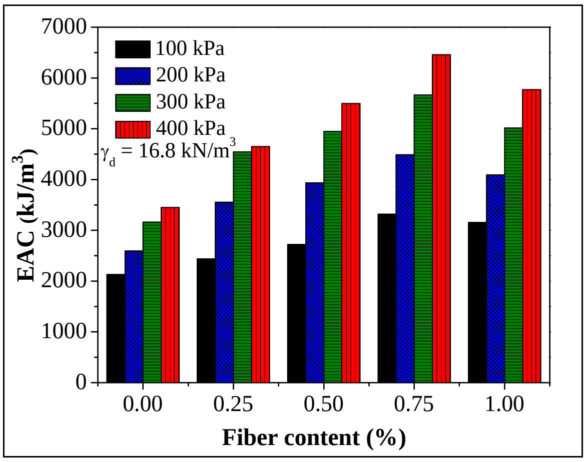


Figure 11 *Effect of fiber content on EAC*

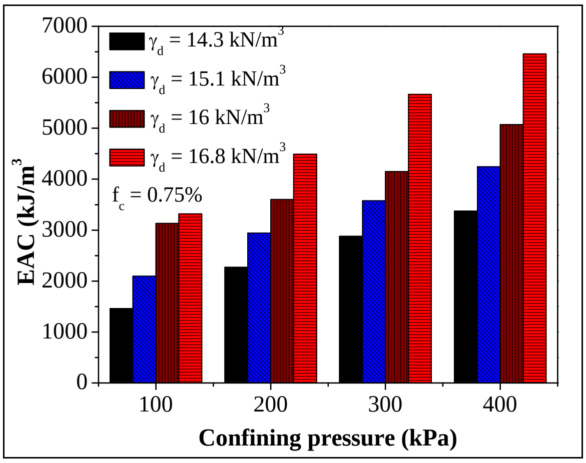


Figure 12 *Effect of dry unit weight on EAC*

Comparing the relative effect of fiber content, dry unit weight and confining pressure on EAC improvement, it has been found that the EAC of unreinforced soil which is 3449 kJ/m^3, maximum improved to 6458 kJ/m^3 (i.e. 3009 kJ/m^3 improvement) when specimen reinforced with 0.75% fiber content under 400 kPa confining pressure and compacted at 16.8 kN/m^3 dry unit weight. When confining pressure increased from 100 to 400 kPa, EAC improved from 3319kJ/m^3 to 6458kJ/m^3 (i.e. 3139kJ/m^3 improvement) for specimen compacted at 16.8 kN/m^3 dry unit weight and reinforced with 0.75% fiber content. As dry unit weight increases fron 14.3 kN/m^3 to 16.8 kN/m^3, the EAC of specimen reinforced with 0.75% fiber content maximum increases from 3375 kJ/m^{3}to 6458 kJ/m^3 (i.e. 3083kJ/m^3 improvement) at 400 kPa confining pressure. Comparing the EAC improvement, the effect of confining pressure and dry unit weight is found to be relatively higher than that of fiber content.

4. Conclusions

A series of CU triaxial compression tests were conducted to study the strength aspects of randomly distributed glass fiber-reinforced soil. Based on obtained results, the following conclusions can be made:

1) The stress-strain and pore pressure response are highly influenced by compacted dry unit weight, fiber content and confining pressure. The improvement of stress-strain response with fiber reinforcement occurs up to 0.75% fiber content. However, for all reinforcement doses the stress-strain response improves continuously with both increasing dry unit weight and confining pressure. Fiber addition increases the generated positive pore pressure by restraining the dilatancy of specimen, which increases with increasing fiber content and decreases with increasing dry unit weight.
2) Strength ratio of fiber-reinforced soil is higher at low confining pressure for all reinforcement doses and compacted dry unit weights, and progressively decreases with increased confinement indicating that fiber reinforcement is more beneficial at low confinement.
3) Shear strength parameters (c and φ) of reinforced soil increase with increasing compacted dry unit weight. At lower dry unit weights (γ_d = 14.3 and 15.1kN/m^3), the shear strength parameters increase with fiber content even up to 1%, but at higher dry unit weights (γ_d = 16 and 16.8kN/m^3), the shear strength parameters increase only up to 0.75% and then decrease.
4) Stiffness modulus of soil improves with fiber content at all strain levels up to 0.75% fiber content. At failure axial strain, the effect of confining pressure on stiffness is found to be greater than the effect of dry unit weight or fiber content.
5) Energy absorption capacity of soil increases with fiber reinforcement up to 0.75% fiber content. EAC further improves continuously with dry unit weight and confining pressure for all reinforced specimens. The effect of confining pressure or dry unit weight in EAC improvement is greater than the effect of fiber content.

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