Comparison of shear strength characteristics of sandy and clayey soils reinforced with glass fibres

Comparaison des caractéristiques de résistance au cisaillement des sols sableux et argileux renforcés de fibres de verre

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ABSTRACT: Shear strength and deformation aspects of glass fibre-reinforced sand and clay have been investigated and compared in this study. A poorly graded sand and a low plasticity clay were reinforced with glass fibres of 0.15 mm diameter and 20 mm length up to the maximum feasible mixing contents of 4% and 1%, respectively. The reinforced sand specimens were moulded at different relative densities, while the reinforced clay specimens were compacted at varying dry unit weights. Consolidated drained triaxial tests were performed on the sandy soil, whereas consolidated undrained triaxial tests were conducted on the clayey soil. Due to glass fibres inclusion, the shearing stress of both soils has been noted to improve significantly with shear strain. At the same strain, the increase in deviator stress is more for the sandy soil than the clayey soil. A clear peak is noted for the reinforced sandy soil, whereas there is no clear peak for the reinforced clayey soil. Glass fibre reduces the post peak stress drop in sand, and the residual stress of reinforced sand at higher shear strain is greater than the peak stress of unreinforced native sand. The increase of shear strength is primarily due to induced cohesion in the sandy soil, whereas it is due to both increased friction angle and induced cohesion in the clayey soil. The inclusion of fibres reduces shear failure zone of the sandy soil and bulging zone in case of the clayey soil.

KEYWORDS: Shear strength; glass fibre; deviator stress; triaxial test; induced cohesion.

1 INTRODUCTION

Fibre-reinforced soil method where short fibres as tensile resisting element are randomly mixed in the soil mass has been widely accepted in the geotechnical engineering field due to its added advantages over traditional planar soil reinforcement. Fibre-reinforced soil maintains strength isotropy within soil mass and can be used in the place where there is limited space to use planar reinforcement (Zornberg 2002). This method can be used in any type of soil like other admixtures (lime, cement etc.) prior to compaction (Tang et al. 2007), and the addition of fibres only modifies the soil physical characteristics and has no impact on environment (Li et al. 2014).

Fibre-reinforced soil can be used to repair local slope failures (Gregory and Chill 1998), construction of embankment and reduction of expansion-contraction cracks of clay (Zeigler et al. 1998), maintenance of flexible pavements (Choubane et al. 2001), as base layer of airstrip surface (Webster and Santoni 1997; Tingle et al. 1999) and as a liner material (Miller and Rifai 2004).

Randomly distributed short discrete fibers have been found to improve the strength and deformation aspects of soils significantly under different loading states which includes triaxial shearing (Anagnostopoulos et al. 2013; Li and Zornberg 2013; Patel and Singh 2017c, 2019), unconfined compression (Kumar et al. 2006; Nguyen and Fatahi 2016; Patel and Singh 2017a), CBR testing (Patel and Singh 2017b), plate load test (Consoli et al. 2009) and tensile loading (Divya et al. 2014; Tang et al. 2016). From the earlier investigations, it is found that the strength and deformation response of fibre reinforced soil depends on fibre characteristics (length, content, diameter, surface roughness), soil grain properties (gradation, sphericity), specimen compacted states (dry unit weight and moisture content), loading condition and confining pressure.

There is extensive literature reported by many researchers related to specimen relative density of fibre-reinforced sand on its shear strength aspects, but studies related to specimen compacted density of fibre-reinforced clay on shear strength behaviour are limited. Further, there is relatively lesser study reported on the comparative shear strength characteristics of fibre-reinforced sand and clay prepared at different specimen densities. To this aim, an attempt has been made to conduct a comparative investigation of shear strength and deformation characteristics of glass fibre-reinforced sandy and clayey soils under varying specimen densities by performing triaxial compression tests.

2 MATERIALS AND METHODS

2.1 *Materials*

The sandy soil was collected from the nearby bank location of Brahmaputra River in Guwahati city. The specific gravity of the sand particles is 2.69. The coefficient of uniformity and coefficient of curvature of the soil are 1.58 and 0.97, respectively. The soil is classified as poorly graded silty sand (SP-SM) as per ASTM D2487 (2011). The minimum ($\gamma_{d,min}$) and maximum ($\gamma_{d,max}$) dry unit weights of the sand are 13.66 and 16.52 kN/m^3, respectively as per ASTM D4254 (2006). For the experimental study, sand at three relative densities (D_r = 35, 65 and 85%) were used without and with fibres.

The clayey soil was obtained from 0.4 m depth below the surface of a nearby hill inside IIT Guwahati campus to evade humus and vegetation roots. The soil comprises 25% sand, 54% silt and 21% clay size particles. The specific gravity of soil solids is 2.63. The values of liquid and plastic limits are 46% and 25%, respectively. The soil is classified as low plastic clay (CL) as per ASTM D2487 (2011). The maximum dry unit weight (MDU) and optimum moisture content (OMC) of the clay are 16.8 kN/m^3 and 19.4%, respectively, as per ASTM D698 (2012). In this study, soil at four different compacted densities (γ_d = 14.1, 15.3, 16.0 and 16.8 kN/m^3) were used for unreinforced and fibre-reinforced clay.

Glass fibre has been used as reinforcement in this study as among different fibres, the strength and stiffness values of glass fibre are comparatively high (Lutz and Grossman 2001). It is more appropriate for long-term soil reinforcement due to its ready availability and non-biodegradable nature (Mujah et al. 2013). Even under 450°C temperature, glass fibre retains 70-75% of its original tensile strength and elastic modulus (Ahmad et al. 2012). Glass fibre used in this study was of 20 mm length and 0.15 mm average diameter with specific gravity and tensile strength values of 2.57 and 1.53 GN/m^2, respectively. Its elastic modulus, elongation at break and water absorption capacity values are 112.3 GN/m^2, 1.8% and zero, respectively as given by the supplier. Five different fibre contents (f_c = 0.5, 1, 2, 3 and 4%) were mixed with the sandy soil at varying relative density, whereas four fibre contents (f_c = 0.25, 0.5, 0.75 and 1%) were mixed with the clayey soil at varying compacted density.

2.2 *Specimen Preparation*

For sandy soil specimen, dry sand of definite weight was initially mixed with a minimal water content of 2% to control fibre segregation during mixing. Thereafter, weighted fibres were mixed manually in small increments to make a homogeneous sand-fibre mix. The homogeneous mixture was then poured in three equal layers in a rubber membrane kept within a split mould sampler of 38 mm internal diameter, fixed at the pedestal of the triaxial cell. Proper compaction was given to each layer as per undercompaction method of Ladd (1978). Once the specimen was moulded to desired height of 76 mm, the split sampler was removed.

For clayey soil specimen, initially the required weight of dry soil and fibres were taken in a steel tray. The measured quantity of water was first added to the dry soil and mixed uniformly. Thereafter, the weighted fibres were added progressively in small increment to the soil manually. The homogeneous soil-fibre mix was then shifted in an airtight plastic bag and kept for 24 hrs in a desiccator to confirm moisture equilibrium in the soil-fibre mix. The soil-fibre mix was then moulded in a 38 mm inner diameter cylindrical mould by compacting statically up to a length of 76 mm. The moulded specimen was then mounted on the triaxial base plate.

Inside the triaxial cell, each soil specimen was first saturated using back pressure method. Subsequently, different soil specimens were consolidated under effective confining pressures (σ_3) of 100, 200, 300 and 400 kPa. The sandy soil specimens were then sheared under drained condition whereas the clayey soil specimens were sheared under undrained condition, at axial strain rates of 0.03 mm/min and 0.12 mm/min, respectively. The drained and undrained triaxial tests were performed as per ASTM D4767 (2011).

3 RESULTS AND DISCUSSION

3.1 *Comparison of Stress-Strain Response*

3.1.1 *Effect of fibre content*

Typical effect of fibre content on the stress-strain response of glass fibre-reinforced sandy soil specimens of 85% relat ive density and clayey soil specimens of 16.8 kN/m^3 dry unit weight are shown in Figs. 1a and 1b, respectively. With increasing fibre content, the deviator stress increases expressively only up to 3% fibres for sandy soil, and up t o 0.75% fibres for clayey soil. The initial stress-strain resp onse seems to be unaffected by glass fibre reinforcement. Fibre contribution on shear strength starts at higher axial s train, and the contribution of fibres is noted to increase wi th increasing axial strain up to peak stress. A clear peak along with post-peak stress drop occurs in the sandy soil specimens (Fig. 1a). This post-peak strength is noted to become almost constant around 15-20% strain. The post-peak strength of reinforced sand is noted to be nearly close or higher than the peak strength of the unreinforced sand, demonstrating that the glass fibre-reinforced sand can resist larger deformation efficiently. This also indicates that the fibre-reinforced soil will provide ample time to engineers for the proper maintenance of geotechnical structures.

For any clayey soil specimen, no clear peak appears up to 20% axial strain and they seem to show strain-hardenin g response (Fig. 1b), and the strength of clayey soil speci men with any fibre content is noted to reach some consta nt value after 12% axial strength. In case of sandy soil, cl ear peak is noted for all tested specimens and the failure axial strain is observed to increase with increasing fibre co ntent along with reduction in post-peak stress drop (Fig. 1 a) indicating more ductile behaviour of glass fibre-reinforce d sand. It can further be noted that the peak deviator stres s of reinforced sand is much higher than that of reinforce d clay, even at the same fibre content of 1%.

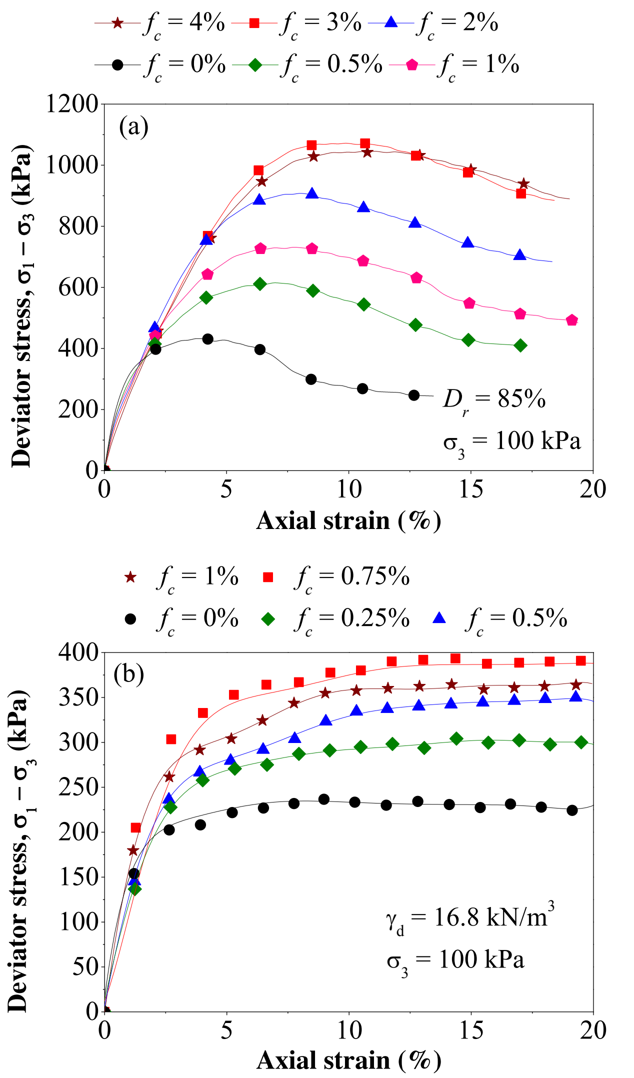

Figure 1. Effect of fibre content on stress-strain response: (a) sandy soil; (b) clayey soil.

The clayey soil response is similar to that reported by Estabragh et al. (2011) where no clear peak was noticed up to 20% axial strain. There is noted to be only a marginal effect of fibre addition on the initial stress-strain response up to around 2% axial strain, and the deformation pattern of reinforced specimen is similar to that of unreinforced soil specimen. With increasing axial deformation, the soil particles stretch the fibres resulting in the mobilization of fibre's tensile strength as fibres work in tension (Zornberg 2002). This counteracts and redistributes the coming axial load, causing the improvement in deviator stress of soil. Thus, the behaviour of composite soil is governed by the incremental contribution of active fibres within the soil. With increasing fibre content, the number of fibres in the fixed volume of specimen increases supporting the strength increment of soil in terms of surficial friction and bond strength between soil and fibres. At higher fibre contents of 3% and 1%, respectively in sand and clay, the availability of the soil particles in the vicinity of distributed fibres is not enough to support proper surficial interaction and soil-fibre bonding, which reduces the fibre contribution causing decrease in strength improvement.

3.1.2 *Effect of specimen density*

Typical effect of compacted density on the stress-strain res ponse of reinforced sandy and clayey soils sheared under 100 kPa confining pressure are presented in Figs. 2a and 2b, respectively. The stress-strain response is noted to increase with increasing specimen density from the initial deformation due to increasing surficial interaction of soil-fibre with increasing specimen density as also reported by Tang et al. (2010). This improved interfacial interaction limits the fibre sliding and enriches fibre stretching. This fiber stretching allows the tensile stress development which helps the soil strength enhancement. Frost and Han (1999) also noted an increase of the interface friction angle between sand particles and polymers with increasing specimen density.

Further, at lower compacted density, fibres may not be anchored properly in soil matrix leading to easier pullout of fibres causing relatively lower contribution to soil strength. Also with increasing specimen density, the surficial contact area between soil particles increases, causing higher resistance against specimen deformation which increases overall strength. Initial stiffness of specimen is also noted to be greater with higher compacted density. The improvement in response of sand specimen with increasing relative density is due to more initial interlocking of soil particles. A clear peak well before 20% axial strain can be noted in case of reinforced sand of all relative densities. However, no peak has been noted for any compacted density of clay specimen up to 20% axial strain. The failure axial strain of sand specimen is noted to be less for higher compacted relative density. At any compacted density, deviator stress is found to be much greater for sandy soil than clayey soil.

3.2 *Comparison of Volume Change and Pore Pressure Response*

3.2.1 *Effect of fibre content*

Effect of fibre content on volumetric response in sandy soil and pore pressure development in clayey soil are depicted in Figs. 3a and 3b, respectively. From volumetric strain curve of 85% relative density sand specimen (Fig. 3b), it can be seen that specimen undergoes initial contraction at smaller strain. Thereafter, it undergoes dilation at higher strain. As the fibre content increases, the initial compression increases and then the subsequent dilation decreases. In this way, added fibres restrain the dilation of the sand, resulting in enhanced soil-fibre surface contact, leading to overall strength improvement.

There is noted to be continuous development of positiv e pore pressure for all specimens. The gradient of pore pr essure curve indicates the contractive or dilative nature of specimen during shearing (Estabragh et al. 2011). A positi ve slope states contraction and a negative slope specifies d ilation. As in this present study, developed pore water pres sure is positive throughout for all specimens, and the slop e of the pore pressure curve is positive. The positive gradi ent of pore pressure curve slope is increasing with growin g fibre content, indicating more contractive response of fib re-reinforced increases with fibre content for clayey soil.

3.2.2 *Effect of specimen density*

Figures 4a and Fig. 4b present the effect of specimen density on the volumetric strain response of reinforced sandy soil and pore pressure response of reinforced clayey soil, respectively. From volumetric strain curve of sand, it is observed that 35% relative density sand specimen undergoes pure compression for the entire range of shearing strain (Fig. 4a). As the specimen relative density increases to 65% and 85%, the specimens undergo small contraction up to initial small axial strain and then exhibit dilation at higher axial strain. The axial strain up to which the specimen undergoes initial contraction decreases with increasing specimen density. The specimen dilation is noted to increase with increasing axial strain. The extent of specimen dilation is noted to be greater for higher relative density of sand. Similar volumetric behaviour of sand specimen of varying relative density and reinforced with tyre chips was noted by Mashiri et al. (2015).

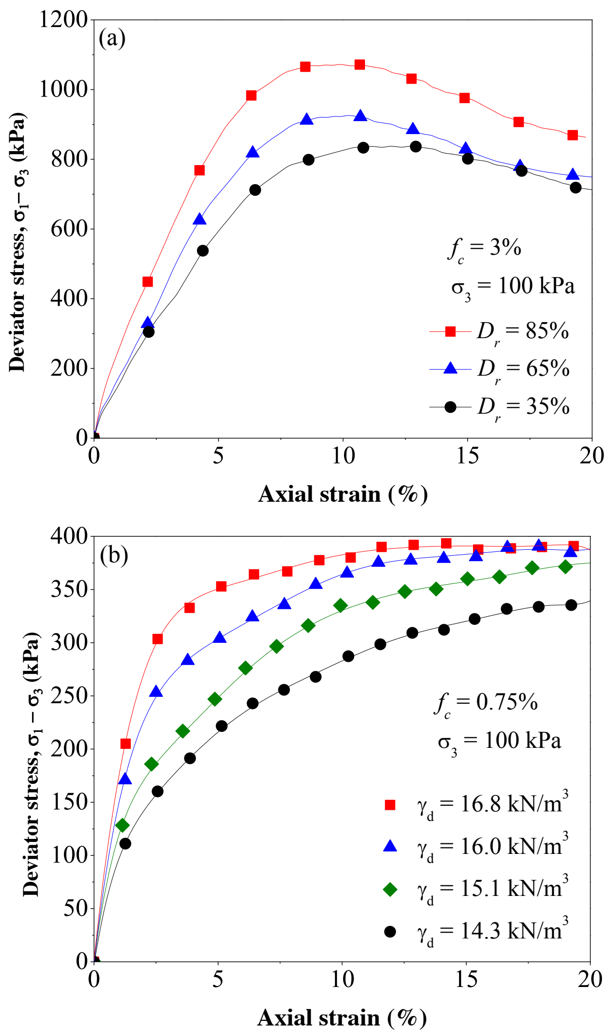

Figure 2. Effect of specimen density on stress-strain response: (a) sandy soil; (b) clayey soil.

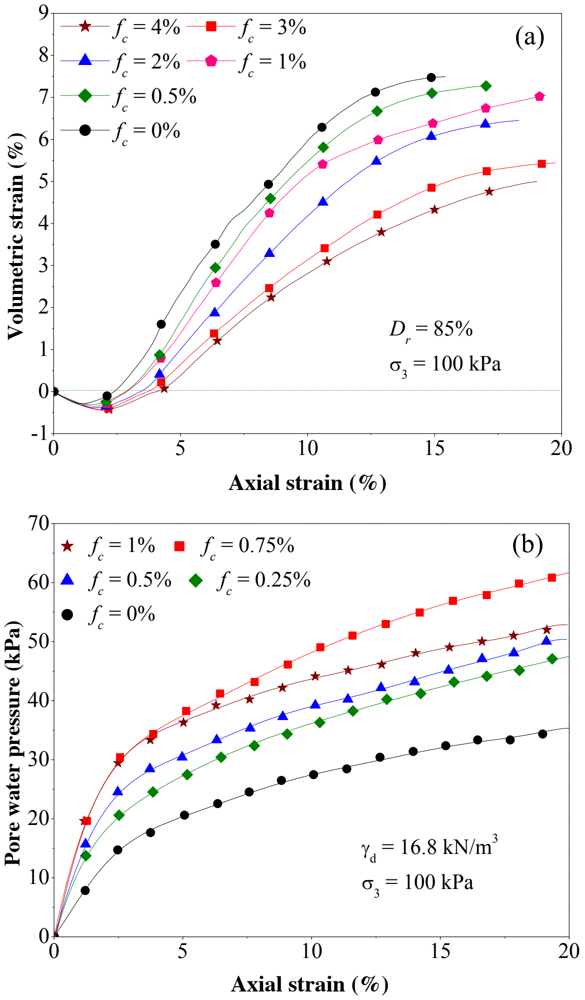

Figure 3. Effect of fibre content: (a) volumetric response of sandy soil; (b) pore pressure response of clayey soil.

From the pore pressure response curve of 0.75% fibre-reinforced clayey soil (Fig. 4b), it has been noted that there is small drop in positive pore water pressure with increasing dry unit weight of specimen. This reduction in positive pore water pressure also indicates that there is a decrease in the slope of positive pore pressure curve with increasing specimen dry unit weight. Thus, it can be inferred that with increasing compacted dry unit weight of specimen, the contraction behaviour decreases progressively. Also the reduction in pore pressure is small and is in close range, so the specimen contraction which will affect the deformation pattern will not differ that much, especially for closer dry unit weight, and same has been reflected in the specimen deformation patterns (Fig. 5) where the specimen bulging is comparable irrespective of the compacted dry unit weight of clay specimen.

Comparing the behaviour of sandy and clayey soils of varying compacted density, it can be seen that with variation of relative density the pattern of volumetric strain is different. Sand of 35% relative density shows pure contractive nature. With increasing specimen density to 65% and 85%, the sand undergoes initial contraction, followed by dilation at higher axial strain. However for the clayey soil specimens, there is continuous positive pore water pressure development at all dry unit weights in the tested range of axial strain, representing pure contractive nature of clay. Though the contraction behaviour decreases with increasing dry unit weight of specimen.

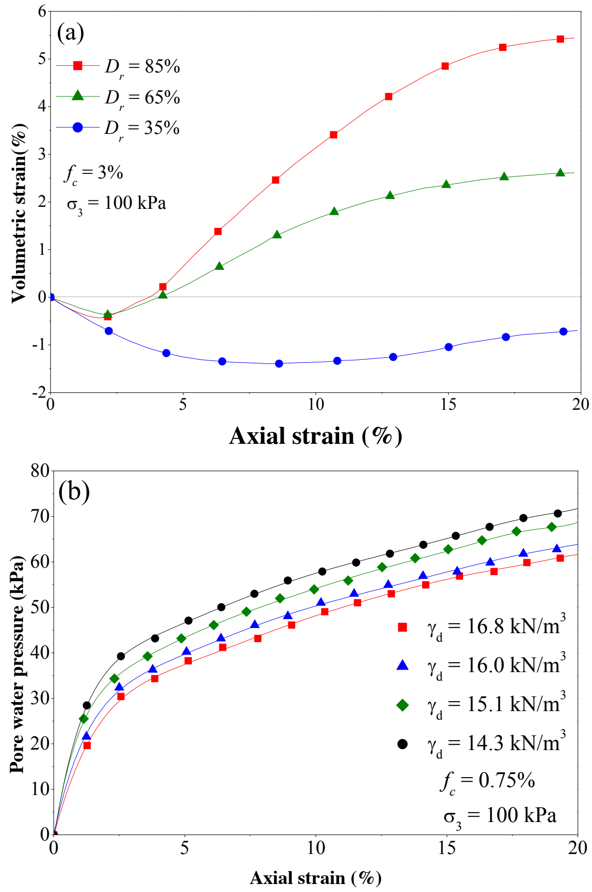

Figure 4. Effect of specimen density: (a) volumetric response of sandy soil; (b) pore pressure response of clayey soil.

3.3 *Comparison of Specimen Failure Modes*

The effects of relative density on the failure modes of unreinforced and fibre-reinforced sand (f_c = 3%) of varying relative densities are presented in Fig. 5. Unreinforced sand specimen of 35% relative density shows clear bulging failure (Fig. 5a). When fibres are added to this specimen (Fig. 5d), the bulging is controlled as the fibres suppress the lateral spreading. A pure shear failure plane can be seen across the specimen for the unreinforced sand of 65% relative density (Fig. 5b). This shear plane is found to be partially suppressed with fibre addition (Fig. 5e). The fibres within the specimen have stitched the developing shear zone, resulting in restriction of shear plane development. For the unreinforced sand of 85% relative density (Fig. 5c), a pure shear plane at failure can be noted. Fibre-reinforced sand of 85% relative density also undergoes shear failure with decreased shear zone, and one part of the specimen seems to have collapsed over the other half (Fig. 5f).

The influence of compacted specimen density on deformation modes of unreinforced and reinforced clay with 0.75% fibres is depicted in Fig. 6. There is noted to be clear bulging irrespective of dry unit weight for both unreinforced and reinforced clayey soil specimens. The same has also been replicated in the pore pressure response of reinforced clay where the difference in pore water pressure development is relatively low for specimens of varying dry unit weight (Fig. 4b).

Observing the deformation pattern of unreinforced and reinforced clay specimens, it can be seen that there is bulging in one part of the specimen of 16.8 kN/m^3 dry unit weight (Fig. 6a) which is noted to spread along the specimen length with inclusion of fibres (Fig. 6e). This indicates that fibres help in redistributing the stress to a larger part of the specimen. Also, the variation in bulging of unreinforced specimens with greater dry unit weights (Figs. 6b, 6c, 6d) and reinforced specimens of the same density (Figs. 6f, 6g, 6h) are comparable with reduction of bulging and its redistribution with fibre reinforcement. It has also been reported earlier that the bulging deformation is reduced with increasing fibre length (Patel and Singh 2019).

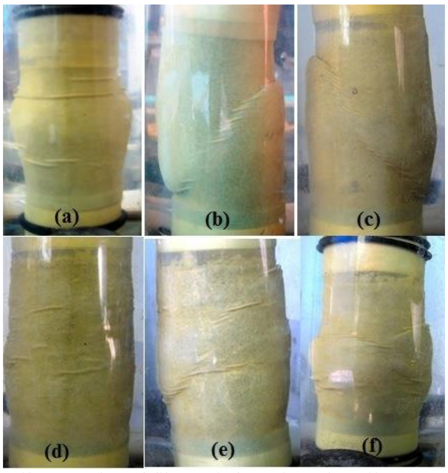

Figure 5. Failure modes of fibre-reinforced sandy soil.: (a) D_r = 35%, f_c = 0%; (b) D_r = 65%, f_c = 0%; (c) D_r = 85%, f_c = 0%; (d) D_r = 35%, f_c = 3%; (e) D_r = 65%, f_c = 3%; (f) D_r = 85%, f_c = 3%.

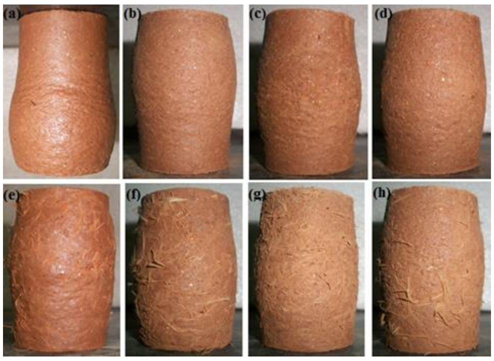

Figure 6. Failure modes of fibre-reinforced clayey soil: (a) f_c = 0%, γ_d = 14.3 kN/m^3; (b) f_c = 0%, γ_d = 15.1 kN/m^3; (c) f_c = 0%, γ_d = 16.0 kN/m^3; (d) f_c = 0%, γ_d = 16.8 kN/m^3; (e) f_c = 0.75%, γ_d = 14.3 kN/m^3; (f) f_c = 0.75%, γ_d = 15.1 kN/m^3; (g) f_c = 0.75%, γ_d = 16.0 kN/m^3; (h) f_c = 0.75%, γ_d = 16.8 kN/m^3.

3.4 *Comparison of Shear Strength Parameters*

The shear strength parameters (c and ϕ) of the present study have been calculated by plotting modified failure envelopes (p-q plots). For sandy soil, shear strength parameters were calculated at peak stress. For clayey soil, as it has been noticed earlier in stress-strain plot that no clear peak appears up to 20% axial strain, the stress corresponding to 10% axial strain was considered for calculating the shear strength parameters. The shear strength parameters calculated for sandy and clayey soil specimens are summarized in Table 1 and Table 2, respectively.
It has been found that inclusion of glass fibres significantly increases the shear strength parameters of both soils in term of induced cohesion and improved friction angle. The shear strength parameters are noted to increase continuously with increasing specimen compacted density for both soils. For sandy soil specimens, there is significance increase in both cohesion and friction angle values with increasing fibre content at any relative density or with increasing relative density at any fibre content (Table 1). The cohesion and friction angle values increase with fibre content and reach maximum values at 3% fibre content for all relative densities, whereas they increase continuously with compacted relative density at any fibre content.

Table 1. Shear strength parameters of reinforced sandy soil

f_c(%)	D_r = 35%		D_r = 65%		D_r = 85%	
	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)
0	20	32.7	26	35.0	30	37.0
0.5	59	35.3	65	37.8	72	38.5
1	74	36.5	77	39.1	89	40.0
2	94	37.3	100	40.0	117	41.3
3	120	38.3	132	40.4	145	42.4
4	115	37.8	122	40.2	140	42.1

For the unreinforced sand, the values of cohesion are 20, 26 and 30 kPa at 35, 65 and 85% relative densities, respectively. The corresponding friction angle values of unreinforced sand are 32.7, 35 and 37˚, respectively. With 3% glass fibre, the cohesion value reaches maximum to 120, 132 and 145 kPa, respectively and friction angle improves to 38.3, 40.4 and 42.4˚ for 35, 65 and 85% relative densities, respectively. In terms of fibre contribution which is the difference between the values of shear strength parameters of reinforced soil to that of unreinforced soil, the cohesion value has increased maximum by 100, 106 and 115 kPa and friction angle by 5.6, 5.4 and 5.4˚, respectively for 35, 65 and 85% relative densities when reinforced with 3% glass fibres.

In case of clayey soil, the maximum value of shear strength is with 0.75% fibre content for any dry unit weight (Table 2). The cohesion values of unreinforced clay are 28, 35, 40 and 45 kPa for 14.3, 15.1, 16.0 and 16.8 kN/m^3 dry unit weights, respectively. The corresponding friction angle values are 22.9, 23.7, 24.2 and 25.8˚, respectively. The cohesion value increases with addition of glass fibres and reaches maximum to 57, 60, 65 and 67 kPa with 0.75% fibres for the specimens of 14.3, 15.1, 16.0 and 16.8 kN/m^3 dry unit weights, respectively. The corresponding maximum friction angle values are 32.8, 34.0, 34.5 and 35.2˚, respectively. It can be noted that the corresponding fibre contribution to cohesion values are 29, 25, 25 and 22 kPa and to friction angle values are 9.9,10.3, 10.3 and 9.4˚, respectively.

Table 2. Shear strength parameters of reinforced clayey soil

f_c(%)	γ_d = 14.3 kN/m^3		γ_d = 15.1 kN/m^3		γ_d = 16.0 kN/m^3		γ_d = 16.8 kN/m^3	
	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)	c (kPa)	ϕ (˚)
0	28	22.9	35	23.7	40	24.2	45	25.8
0.25	40	25.6	45	26.9	48	29.8	56	30.4
0.5	49	29.3	54	30.7	56	31.6	62	33.3
0.75	57	32.8	60	34.0	65	34.5	67	35.2
1	58	31.6	59	32.2	64	33.2	66	33.2

Comparing the shear strength characteristics of reinforced sandy and clayey soils, it can be noted that there is greater contribution of glass fibres to cohesion value in sandy soil compared to that of clayey soil, and that there is higher contribution of the glass fibres to friction angle of the clayey soil than that of the sandy soil. It can be said that the improvement in the shear strength of the sandy soil is mainly due to increased induced cohesion value along with some enhancement of friction angle, whereas the improvement in shear strength parameters of the clayey soil is due to increase in both cohesion and friction angle values.

4 CONCLUSIONS

Following conclusions have been drawn from the present study:

- During shearing, clear peak appears for the reinforced sand irrespective of relative density with significant reduction of post-peak stress drop. However, no peak stress is found even up to 20% axial strain for the reinforced clay of any compacted density.
- Reinforced sand specimen of 35% relative density shows pure contractive nature. As the sand density increases (D_r = 65 & 85%), reinforced specimens show contraction at smaller strain and dilation at higher strain. The specimen dilation increases with fibre inclusion.
- Clay specimens undergo pure contraction, and the contraction further increases with increasing fibre content whereas it decreases with increasing dry unit weight.
- Inclusion of glass fibres reduces bulging in loose sand specimen (D_r = 35%) and the formation of shear plane in dense sand specimens (D_r = 65 & 85%), whereas glass fibres reduce and redistribute bulging in the clay specimens for all compacted states.
- Addition of glass fibres increases the shear strength of both the sand and clay, which rises with increasing fibre content and specimen density. The maximum shear strength improvement is achieved with 3% fibre content in the sandy soil and with 0.75% fibre content in the clayey soil.
- Shear strength improvement of the reinforced sand is predominantly due to increase in cohesion component with marginal friction angle increment, whereas it is always due to increase in both cohesion and friction angle of the reinforced clay.

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