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Research article

Shear strength of fibre reinforced cemented Toyoura sand

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Abstract: A series of consolidated drained and undrained tests are conducted on unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens with varying relative densities. Three different types of materials e.g., Toyoura sand, polyvinyl alcohol (PVA) fibres, and ordinary Portland cement (OPC) are employed in this study. Specimens in dimensions of 50 mm in diameter and height of 100 mm are prepared in a polyvinyl chloride (PVC) mold to a target dry density value, ρ_d = 1.40 g/cm^3 (Dr = 20%) and ρ_d = 1.489 g/cm^3 (Dr = 60%) of Toyoura sand using under-compaction moist tamping technique. Fibre reinforced cemented Toyoura sand samples were prepared with 10% moisture content by weight of sand-fibre-cement mixtures. The results on density variation shows that due to a better contact between sand-fibre interaction or sand-cement-fibre bonding and interaction for the denser specimens, a greater increase in shear strength is observed. However, the general effectiveness of fibre and cement additives alone and when mixed together also enhances the strength of unreinforced specimens for loose conditions based on the variation of fibre and cement contents. The results and findings in the current study can be used for the construction of economical and sustainable geotechnical infrastructures.

Keywords: shear strength; fibre reinforced sand; relative density; triaxial test; undrained

1. Introduction

The properties of soil can be enhanced using different products like synthetic fibre, metallic fibres, cement etc. [1]. Through the years, the practise of soil reinforcement has considered different types of fibres in laboratory investigations, ranging from plant roots [2], polyamide and steel fibres [3], polymer and polyethylene, carpet waste fibres [4], bamboo fibres [5], and coir fibres [6]. Nowadays, steel fibres are also of concern to improve properties of soil-cement mixture in concrete structures [7]. Further more they are used to enhance strength of soil but this enhancement is not comparable with any other type of fibre. On the contrary, Ghazavi and Roustaie [7] recommended polypropylene fibres (PP) instead of steel fibres in cold climatic condition because of freeze and thaw problems. Polypropylene fibres (PP) are preferred in cold climates because of their smaller unit weight (using PP fibres will decrease sample volume) as compared to that of steel fibres [8]. Hejazi [8] stated that now a days polyvinyl alcohol (PVA) fibre is replacing polypropylene (PP) fibre. Shrinkage resistance from heat, of PVA fibre is more as compared to those other fibers like nylon and polyester [9]. Michalowski and Cermak [10], performed a sequence of triaxial tests on different fibres in order to find their response in granular soils. It was found from the study that initial stiffness of the mixture was primary affected by fibres properties (e.g., fiber stiffness and roughness). It was also stated that using small quantity of steel fibres (let., 0.5% by volume) has eventually no major effect on mixture stiffness. Earlier research study concluded that using higher quantity of steel fibers in coarse sand does not effect soil stiffness [11]. Furthermore, steel fibres improvement effect is more than polyamide fibres because of a large interface friction angle of steel fibres. The past research on different types of fibres encourages us to perform further laboratory investigations on understanding the potential benefits of natural and artificial fibres.

The optimum content of fibre ranges from 0.5–6%, which is the most feasible weight fraction possible based on an asymptotic upper limit to strength gain. Tests have confirmed that increasing fibre quantity increase the ultimate strength of soil. Fibre content at one side improve shear strength of soil [1,2,12–15], while on other side researchers also observed reduction in post-peak response [2,16,17]. Some researchers also observed that volumetric compression at rupture increases [18,19]. It was found that if the fibre quantity is more, than higher volumetric deformation is recorded [20]. Previous study reported that with the use fibres up to a certain quantity (e.g. 2% by mass) shear strength of soil enhances, but above this threshold, soil porosity increases which further negate the strength increase [2]. Using fibre reinforcement peak and failure strengths of soil sample also increases. However, after a certain fibre quantity the strength increase seems to reach an asymptotic upper limit [2,16,21]. At large confining stresses, compressive strength of reinforced sand is directly proportional to fibre content. However, at low confining stress, this increase approaches an asymptotic upper limit [2,15,16]. Furthermore, it was also found by several researchers that enhancement quality of fibre depends on fibre length they stated that "higher the strength will be if longer the fibre length is" [1,3,13,22–24]. However, after a certain limit increasing fibre length won't affect the shear strength. It was stated that for better performance of fibre-soil interaction, its length would be at least one order of magnitude greater than the size of the grains [10]. When fibre are in stretched condition, tensile stresses are higher at the center and zero at the ends [10,15,21,25]. Shorter fibres will eventually slide at the sand particle while reaching its maximum tensile strength, however longer fibres can sustain enough strains so that fibres achieved their maximum tensile stresses [14].

Research with a slightly wider range (0–3%) on the short polyvinyl alcohol (PVA) fibres is limited, and needs further laboratory investigation to understand the potential benefits of fibre reinforcements. Fibre reinforcement technique is widely used in different civil engineering projects like slope stabilization, embankment construction, subgrade stabilization, and stabilization of thin veneers such as landfill covers. It is also considered as one of the best eco-friendly and economical, ground improvement techniques [26]. In practical projects most of the time these fibres are mixed randomly with soil, which does not bear good results for soil improvement. However, previous research study has confirmed that they require laboratory test also, in order to find the optimum content of fibres, type and their dimensions. [14]. Figure 1 shows the possible field applications (e.g., retaining walls, footing, dams etc) of fibre reinforced soils.

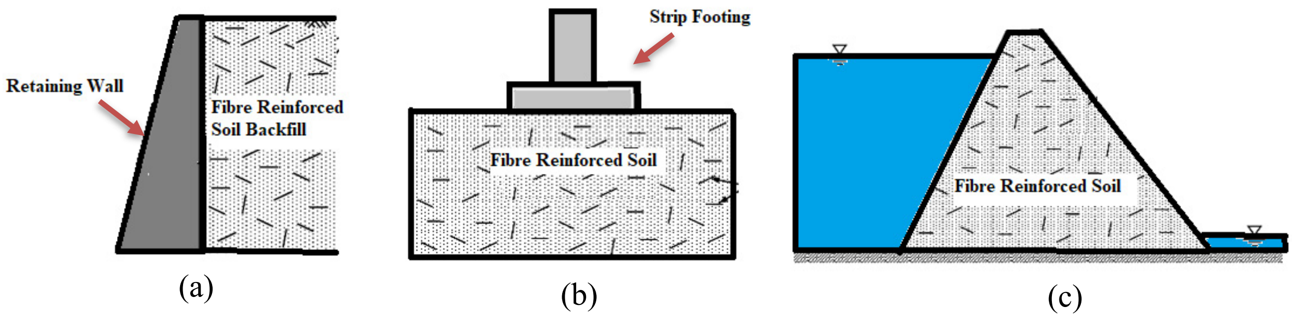


Figure 1. Applications of fibre reinforced soil: (a) A retaining wall, (b) A strip footing, (c) A check dam (small dam constructed across a drainage ditch, swale, or channel to lower the velocity of flow) modified from [26].

Mechanical properties of soil are also improved with the addition of cementitious material for soil stabilization. Using cement for enhancing the properties of soil is widely accepted by many researchers [27]. One of the distinctive property of cemented sands is their ability to support steep natural slopes [28]. Some researchers also used mixtures of sand and cement for better performance under concrete pavements [12]. Generally, cement content greatly affects the weak soil by increasing their ultimate shear strength. Static and dynamic strength of soil is also improved by increasing percentages of cement (e.g., 0–4% by weight). Several researchers have investigated the peak and post-peak stress-strain [27–39], curing conditions [40,41], microstructure [30,35,38,39], compression [35,38,39,42,43] behaviour of naturally and artificially cemented sands.

The use of cement and fibre is also preferred, for instantly enhancing the properties of top soil, in road and railway projects, when the site of granular soil is far away from construction site. Another use of reinforced fibre cemented sand, is enhancing the bearing capacity of low-budget building projects, for which solution of deep foundation might be expensive [44]. The soil stabilization and improvement techniques are used to enhance soil mechanical properties either with the add of cementing agents (like lime, Portland cement, asphalt, etc.) or fibre additives [45,46]. Artificial cementation is used for increasing the strength of weak soil, backfill soil of retaining walls, and sub-bases of railroads and roads. Although with the addition of cement content the strength and initial stiffness of soil increases, its compressibility also reduces [34,47]. However, on the other hand cement content increase the brittle behaviour of soil which would cause sudden failure without any preferable plastic deformation. In order to tackle this issue researchers, use fibres to reduce the brittle response of cemented soils [9]. A number of laboratory tests are also conducted, finding the effect of both cement and fibre on the mechanical behaviour of sandy soils [39,42,43,48]. In the previous literature, very little work has been done on the variation of relative density of fibre reinforced cemented Toyoura sand. Therefore, in this study drained and undrained behaviour of composite materials in triaxial compression loading conditions has been investigated.

2. Tested materials

In this study 3 different kinds of ingredients were studied, which are briefly discussed as below.

2.1. Toyoura sand

Toyoura sand is a famous Japanese, pacific costal sand, with a composition of 75% quartz, 22% feldspar, and 3% magnetite sand [49,50]. Toyoura sand particles have a uniformity co-efficient (Cu = 1.24), a minimum and maximum void ratio (e_{min} = 0.62, e_{max} = 0.95). Specific gravity test was performed on clean Toyoura sand according to ASTM standard [51] and the specific gravity value of 2.65 was observed. The specific gravity (Gs), like many silicate sands, ranges from 2.64–2.65 for pure Toyoura sand [39,42]. In Figure 2a grain size distribution of pure Toyoura sand is shown. Toyoura sand is an angular to sub-angular (see Figure 2b), fine grained and poorly graded sand, which is confirmed by its low co-efficient of uniformity and co-efficient of curvature [39,42,52], according to the classification of SP by the Unified Soil Classification System (USCS). Figure 2b shows SEM scan of pure Toyoura sand in order to show size, shape and texture of the particles [39].

2.2. Polyvinyl alcohol (PVA) fibres

Figures 2c,d shows picture of polyvinyl alcohol (PVA) fibres. It was found that PVA fibres are superior in chemical resistance, weather resistance, and tensile strength as compared to other synthetic fibres like propylene (PP). Therefore, the addition of PVA fibre enhances shear strength and ductility more effectively than any other fibre [9]. Properties of Polyvinyl alcohol (PVA) fibres are given in the Table 1.

Table 1. Properties of PVA fibres.

Properties	Values
Specific Gravity (G_s)	1.30
Length (mm)	12
Diameter (mm)	0.11
Young's Modulus (GPa)	28
Tensile Strength (MPa)	1200

2.3. *Ordinary Portland Cement Type-I (OPC-I)*

Ordinary Portland Cement Type-I (OPC-I) has been used as a cementing material. Table 2 Shows composition of OPC-I used in this research study having specific gravity of 3.15 [53].

Table 2. Composition of OPC-1 [53].

Component	Percentage
tricalcium silicate	63%
di-calcium silicate	12%
tri-calcium aluminate	5%
tetra-calcium alumino-ferrite	11%

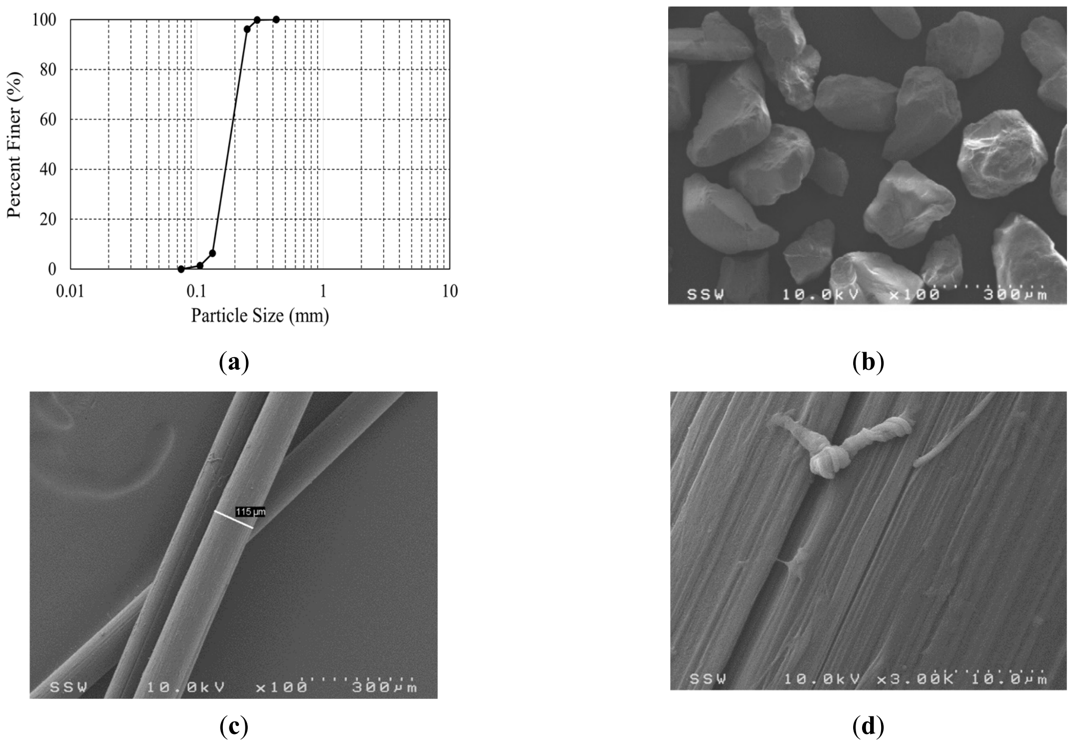


Figure 2. (a) Grain size distribution curve for Toyoura sand (b) Toyoura sand 100× optical zoom (c) PVA fibre 100× optical zoom (d) PVA fibre 3000x optical zoom [39].

3. Testing overview, sample preparation, testing apparatus

In the current study, monotonic triaxial consolidated drained (CID) and undrained (CIU) tests have been conducted in compression loading for both loose and dense states (20% and 60% relative density) of Toyoura sand using under-compaction moist tamping technique [54]. To understand the drained and undrained behaviour of unreinforced and fibre reinforced cemented Toyoura sand specimens, comparisons are made for samples with varying cement (0–3%), and fibre (0–3%) contents at 20% and 60% relative densities. The unreinforced and reinforced specimens were consolidated to a target mean effective stress, p' of 100 kPa to investigate the influence of each constituent and density of the composite material. Table 3 summarizes the testing program used to evaluate the stress-strain, and volumetric-axial strain behaviour of unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand in CID triaxial compression loading conditions at different densities.

Table 3. Consolidated drained (CID) compression tests to study the density variation.

Test No.	Test ID	Mean effective stress (p') (kPa)	Cement Content (%)	Fibres Content (%)	Silt Content (%)	Test Type C/E	Relative Density (%)
Pure Sand							
1	CD-C0F0M0-100	100	0	0	0	C	20
2	CD-C0F0M0-400	100	0	0	0	C	60
Cement Only							
3	CD-C3F0M0-100	100	3	0	0	C	20
4	CD-C4F0M0-100	100	4	0	0	C	20
5	CD-C3F0M0-100	100	3	0	0	C	60
Fibre Only							
6	CD-C0F0.5M0-100	50	0	0.5	0	C	20
7	CD-C0F1M0-100	100	0	1	0	C	20
8	CD-C0F1M0-100	100	0	1	0	C	60
9	CD-C0F3M0-100	100	0	3	0	C	20
10	CD-C0F3M0-100	100	0	3	0	C	60
Cement and Fibre							
11	CD-C3F1M0-100	100	3	1	0	C	20
12	CD-C3F1M0-100	100	3	1	0	C	60
13	CD-C3F2M0-100	100	3	2	0	C	20
14	CD-C3F3M0-100	100	3	3	0	C	20
15	CD-C3F3M0-200	100	3	3	0	C	60

*In test type(C/E) column "C" refer to Compression and "E" to Extension.

Table 4 summarizes the testing program used to evaluate the stress-strain, and pore pressure-axial strain of unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand in CIU triaxial compression loading conditions at varying densities. Samples in dimensions of 50 mm in diameter and height of 100 mm were prepared in a polyvinyl chloride (PVC) mold to a target dry density value, ρ_d = 1.40 g/cm3 (Dr = 20%) and ρ_d = 1.489 g/cm3 (Dr = 60%) of Toyoura sand using under-compaction moist tamping technique [54]. Fibre reinforced cemented Toyoura sand samples were prepared with 10% moisture content by weight of sand-fibre-cement mixtures. 10% initial moisture content was designed to mimic the work [39,48] from Fukuoka and Western University, who used a similar method for monotonic and cyclic triaxial specimen preparation. Samples were then cured for 3 days.

A unique test ID is used for the representation of a test i.e., CD-C0F0M0 represents consolidated drained test (CD) for cement (C) = 0%, fibre (F) = 0% and silt (M) = 0%. A GDS triaxial apparatus was employed to conduct consolidated drained (CD) compression triaxial tests as per accordance to ASTM [55] to investigate the behaviour of unreinforced, fibre-only, cement-only, and fibre-reinforced cemented Toyoura sand specimens. This system is a computer controlled, fully automated advanced GDS Triaxial Testing System (GDSTTS).

The GDS Standard Level Pressure/Volume Controllers (STDDPC) allow for pressure measurements to be resolved to 1 kPa, with an accuracy of ±1.5 kPa up to a maximum pressure of 2 MPa. Volume changes can be resolved to 1 mm^3 at an accuracy of <0.25% of the current measurement. A 15 kN load balanced internal load cell was installed providing an accuracy of ±1 N [56]. Figure 3 shows the failure patterns for pure sand, fibre reinforced sand and fibre reinforced cemented.

Table 4. Consolidated undrained (CIU) compression tests to study the density variation.

Test No.	Test ID	Mean effective stress (p’) (kPa)	Cement Content (%)	Fibres Content (%)	Silt Content (%)	Test Type C/E	Relative Density (%)
Pure Sand							
1	CU-C0F0M0-100	100	0	0	0	C	20
2	CU-C0F0M0-400	100	0	0	0	C	60
Cement Only							
3	CU-C3F0M0-100	100	3	0	0	C	20
4	CU-C3F0M0-100	100	3	0	0	C	60
Fibre Only							
5	CU-C0F1M0-100	100	0	1	0	C	20
6	CU-C0F1M0-100	100	0	1	0	C	60
7	CU-C0F3M0-100	100	0	3	0	C	20
8	CU-C0F3M0-100	100	0	3	0	C	60
Cement and Fibre							
9	CU-C3F1M0-100	100	3	1	0	C	20
10	CU-C3F1M0-100	100	3	1	0	C	60
11	CU-C3F3M0-100	100	3	3	0	C	20
12	CU-C3F3M0-200	100	3	3	0	C	60

*In test type(C/E) column “C” refer to Compression and “E” to Extension.

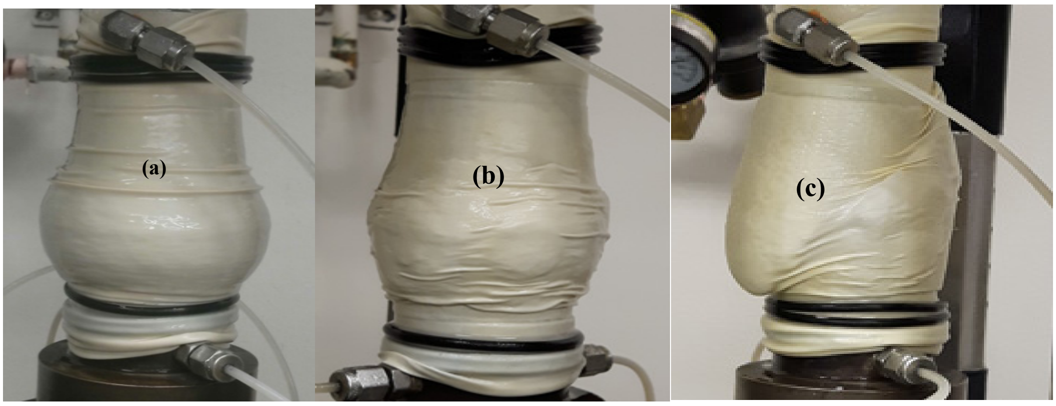
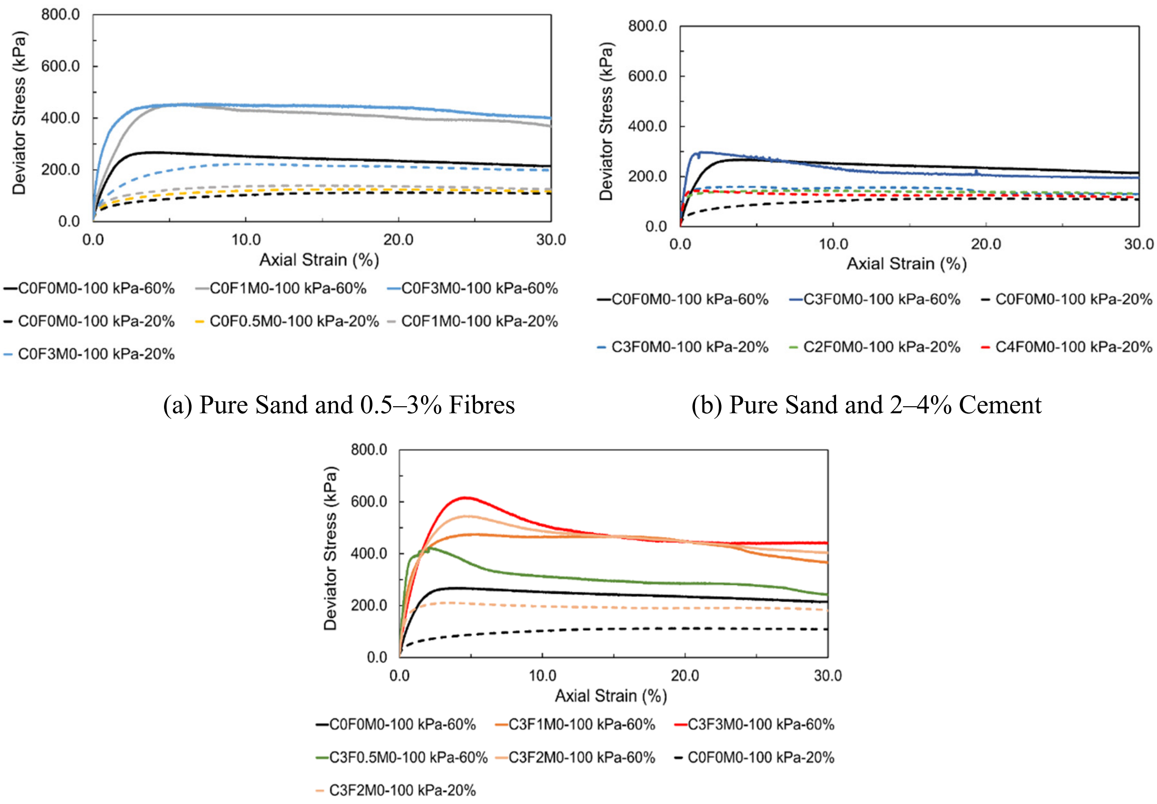


Figure 3. Failure patterns of a) Pure Toyoura sand (C0F0M0) b) Fibre reinforced sand (C0F1M0) c) Fibre reinforced cemented sand (C3F0.5M0).

4. Results and discussion

Figure 4 shows the typical measured deviator stress and axial strain response observed in CD compression tests conducted on the unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens at different densities. For the denser specimens (60%), the trend of the results shows typical behaviour of medium dense specimens with the absence of a significant stress peak. The unreinforced specimens reached a peak deviator stress (q_p) approximately within 4% axial strain (ε_a). For the cemented sand specimens, the peak deviator stress was reached at approximately 2–3% axial strain. However, for the fibre reinforced specimens the peak deviator stresses were observed within 6% axial strain. For the fibre reinforced cemented specimens, peak stresses were observed at approximately 8% strain. The reasons for the absence of significant peak for the cement, and fibre reinforced cemented specimens are most likely due to the relatively short duration of curing (e.g. 3 days) and use of low cement contents (0–3%). However, it was found that the peak and deviator stresses at critical state are noticeably increased by the inclusion of fibre and cement additives. No strain hardening could be seen in the cement, fibre and fibre reinforced cemented sand specimens as reported by previous researchers [38]. The peak drained strength increases with 1% fibre additive is 69% and with 3% fibre and 3% cement reinforced specimen is up to 131%. The drained strength increases at critical state for 1% fibre is 71% and with 3% fibre and 3% cement reinforced specimen is approximately up to 105%.

For the looser specimens (20%), strain hardening behaviour can be seen and the drained strength increase at critical state for 1% fibre additive is approximately 20% and with 3% fibre and 2% cement reinforced specimen is found to be 67%. In addition, it can also be seen that for cement additives alone only peak strength increase can be observed and almost no strength increase is found at critical state. It is evident from the results on density variation that due to a better contact between sand-fibre interaction (e.g., smaller void ratio and enhanced sand-fibre contact in dense state) or sand-cement-fibre bonding and interaction for the denser specimens, a greater increase in strength is observed. However, the general effectiveness of fibre and cement additives alone and when mixed together also enhances the strength of unreinforced specimens for loose conditions based on the variation of fibre and cement contents. This study on density variation supplements the work performed on liquefaction studies and effectiveness of fibre and cement additives previously studied at both the partner universities.



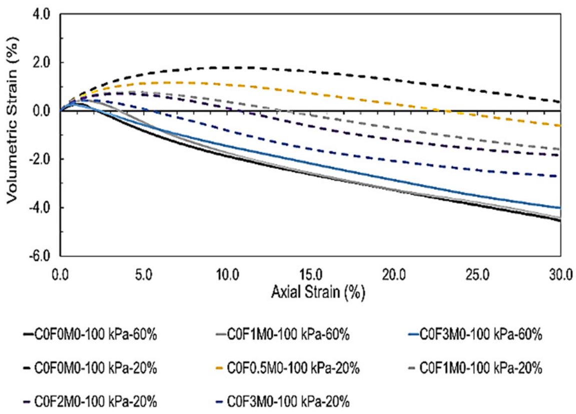
(a) Pure Sand and 0.5–3% Fibres

(b) Pure Sand and 2–4% Cement

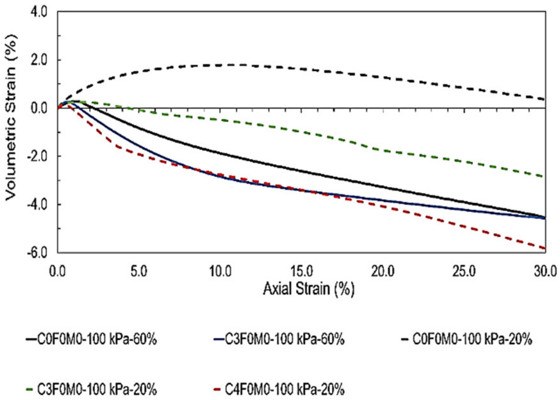
(c) Pure Sand, 3% Cement, and 0.5–3% Fibres

Figure 4. Deviatoric stress (q) versus axial strain (ε_a) curves from CID compression tests for unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens consolidated to mean effective stress(p') of 100 kPa at 20% and 60% relative densities.

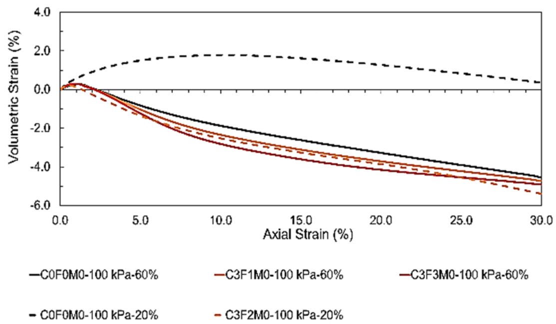
For the denser specimens (60%), the volumetric strain versus axial strain behaviour observed in the CID triaxial compression tests for unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens is shown in Figure 5. The unreinforced and reinforced specimens reveal classical responses for medium dense sand in compression at small strains (0–4%) followed by significant dilation as they reach medium to large strains (4–15%). However, for the looser samples (20%), unreinforced specimens show volumetric compression behaviour from low strains to critical state and significant increase in dilation can be seen for the fibre, cement, and fibre reinforced cemented Toyoura sand specimens. Similar results can also be seen for the denser specimens and previous studies on fibre reinforced [14] and fibre reinforced cemented sand specimens [37].



(a) Pure Sand and 0.5–3% Fibres



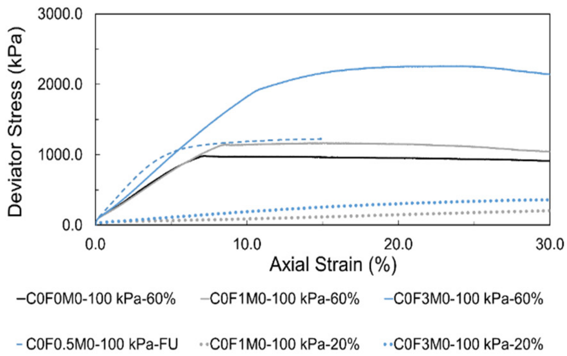
(b) Pure Sand and 3–4% Cement



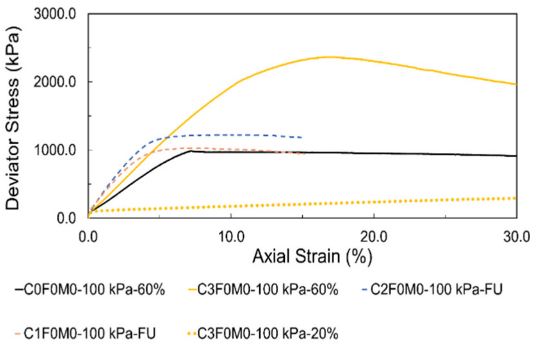
(c) Pure Sand, 3% Cement, and 1–3% Fibres

Figure 5. Volumetric strain (ε_v) vs axial strain (ε_a) curves from CID compression tests for unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens consolidated to mean effective stress(p') of 100 kPa at varying relative densities.

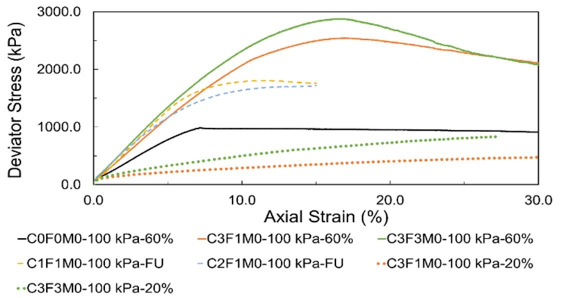
Figure 6 shows the measured deviator stress and axial strain response observed for the CIU compression tests conducted on the unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens. For the denser specimens (60%), the trend of the results shows the typical behaviour of a medium dense sand specimen with an absence of a significant peak, especially for unreinforced specimen and 1% fibre reinforced specimens. The unreinforced specimen and 1% fibre reinforced specimen reached to a peak deviatoric stress (qp) approximately within 7–9% axial strain (ε_a). However, for 3% fibre reinforced specimens the peak deviatoric stress are observed approximately within 20–25% axial strain. While, for cement reinforced, and fibre reinforced cemented specimens, peak stresses have been observed within 14–17% strain. The unreinforced specimen and 1% fibre reinforced specimen showed no noticeable peak, and only cement, and fibre reinforced specimens exhibited a relatively noticeable peak. In general, the peak strength and strength at critical state of reinforced specimens is observed to be significantly enhanced by the inclusion of fibres and cement additives. Overall, after reaching a peak deviatoric stress, strain softening behaviour has been found in almost every test specimen. In addition, it is found that the peak and deviatoric stresses at critical state have been increased by the inclusion of fibres and cement additives. The peak undrained strength increases in fibre reinforced cemented specimen with 3% cement and 3% fibre was found to be 193% and 143% with 3% cement additive. The undrained strength increases at critical state for the 3% fibre and 3% cement reinforced specimen was found to be 127% and 115% with 3% cement additive. For the looser specimens (20%), strain hardening behaviour can be seen and the undrained strength increase at critical state for 1% fibre additive is 15%, and with only 3% fibre additive, the peak strength increases by 103%. In addition, the increase in strength for 3% fibre and 3% cement reinforced specimen is found to be up to 380%. It is evident from the results on density variation that fibre, cement, and fibre + cement plays an important role in enhancing the strength of unreinforced Toyoura sand specimens in both dense and loose states. This increase in strength of loose and dense specimens might be attributed to a better sand-fibre interaction or sand-cement-fibre bonding and interaction in case of loose and dense specimens.



(a) Pure Sand and 0.5–3% Fibres



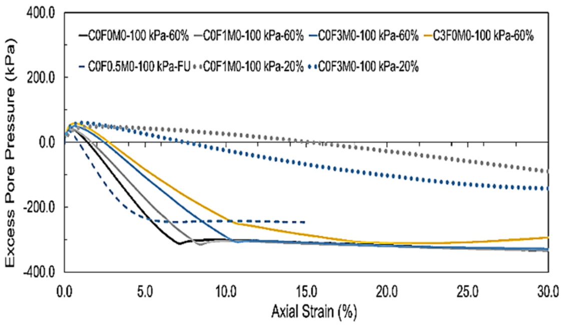
(b) Pure Sand and 1–3% Cement



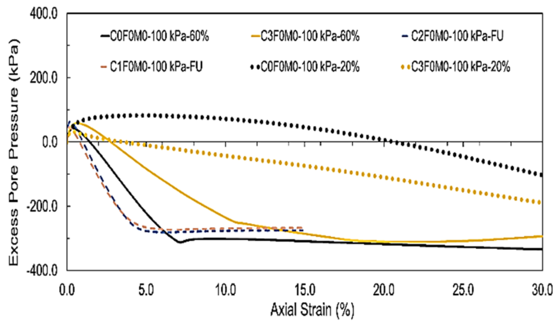
(c) Pure Sand, 1–3% Cement, and 1–3% Fibres

Figure 6. Deviatoric stress (q) versus axial strain (ε_a) curves from CIU compression tests for unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens consolidated to mean effective stress(p') of 100 kPa at varying relative densities.

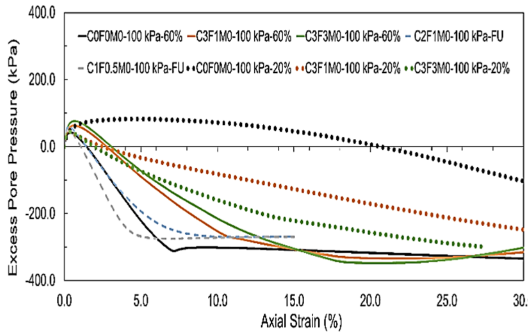
Figure 7 shows that in case of dense samples, excessive positive pore pressure (50 kPa) is observed for unreinforced Toyoura sand. With the addition of 0–3% PVA fibres, 0–3% cement, or a combination of both, same response (80 kPa) was also observed. However, when 0–3% fibres, 3% cement, or a combination of the both were added, lower negative excess pore pressure (−300 kPa) was observed. In case of loose sands, positive excess pore pressure was observed however with the addition of fibres and cement, the compression response changes and negative pore pressure increases, because of the increase in frictional resistance due to Cementitious particles.



(a) Pure Sand and 0.5–3% Fibres



(b) Pure Sand and 1–3% Cement



(c) Pure Sand, 1–3% Cement, and 0.5–3% Fibres

Figure 7. Excess pore pressure (Δu) vs axial strain (ε_a) curves from CIU compression tests for unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens consolidated to mean effective stress(p') of 100 kPa at varying relative densities.

5. Conclusion

To understand the mechanical behaviour at different densities in consolidated drained (CID) and undrained (CIU) triaxial loading conditions, a series of tests were conducted on unreinforced, fibre, cement, and fibre reinforced cemented Toyoura sand specimens with two relative densities: 20% and 60%. For the denser specimens (60%), it is shown that the peak drained strength and strength at critical state are noticeably increased by the inclusion of fibre and cement additives. No strain hardening could be seen in the cement, fibre and fibre reinforced cemented sand specimens. For the looser specimens (20%), strain hardening behaviour is shown. For the cement additives alone, only peak strength increase can be observed and almost no strength increase is found at critical state. For the denser specimens (60%), the peak undrained strength and strength at critical state of reinforced specimens is observed to be significantly enhanced by the inclusion of fibres and cement additives. For the looser specimens (20%), strain hardening behaviour can be seen and the undrained strength significantly increases with fibre and cement additives. It is evident from the results on density variation that due to a better contact between sand-fibre interaction (e.g., smaller void ratio and enhanced sand-fibre contact in dense state) or sand-cement-fibre bonding and interaction for the denser specimens, a greater increase in strength is observed. However, the general effectiveness of fibre and cement additives alone and when mixed together also enhances the strength of unreinforced specimens for loose conditions based on the variation of fibre and cement contents. This study on density variation supplements the work performed on liquefaction studies and effectiveness of fibre and cement additives previously studied at both the partner universities.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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