

Research on the failure behavior of cement- and fiber-reinforced sand under triaxial tensile loads

Research Article

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Abstract: The primary objective of this research is to investigate the failure behavior of sand treated with cement and fibers under triaxial tensile loading conditions. To achieve this, a new loading system and triaxial cell were developed for conducting tensile tests. The specimens included sand samples with 3 and 5% cement content (dry weight) and two types of polypropylene fibers with a length of 24 mm and diameters of 23 and 300 μm , incorporated at dosages of 0.0 and 0.5% (dry weight) of the sand–cement mixture. After a curing period of 7 days, the specimens were tested under direct triaxial tension at confining pressures of 100, 200, and 300 kPa under drained conditions. The stress–strain behavior, volumetric changes, and energy absorbed by the cement- and fiber-reinforced sand were analyzed and compared with data from other studies. The results showed that the addition of fibers led to a reduction in the peak deviator stress and an increase in the residual deviator stress of the cement- and fiber-reinforced sand, indicating a transition from brittle to ductile behavior. Additionally, a decrease in initial stiffness and stiffness at 50% of the maximum tensile stress was observed with the incorporation of fibers, with the effect becoming more pronounced as the fiber diameter increased. The energy absorbed by fibers with a diameter of 23 μm was lower compared to those with a diameter of 300 μm . The addition of fibers also influenced the strength parameters, resulting in a decrease in the cohesion intercept and an increase in the internal friction angle.

Keywords: Sand • Cement • Fibers • Triaxial loading

Nomenclature

σ'_1	major effective stress
σ'_3	minor principal stress
(C_C)	gradation coefficient
(C_U)	uniformity coefficient
(p')	mean stress
(q)	deviator stress
CC	cement-chemical
CP	cement-polymer
FC	fiber-cement
FT	fiber-treated
I_B	brittleness index
$q_{\max}$ and q_{res}	peak and residual deviator stress, respectively

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1. Introduction

In recent years, there has been a significant increase in the acceptance and use of cost-effective additives for problematic soils, leading to substantial developments in the construction of foundations over loose sands and soft soils. Over the past few years, various techniques have been applied to improve the mechanical properties of soils, including the injection of calcium oxide, cement, and tar. In modern times, new additives, such as nanomaterials and synthetic polymers, have brought significant advancements in the development of the physical and mechanical properties of cement–soil systems [1–3]. One of the primary issues in the design of geotechnical structures related to cement–soil systems is the tensile stress induced by bending moments, which manifests in these structures. After conducting dynamic experiments using centrifuge models and finite element analyses on grid-type walls, it was observed

that strong seismic events can cause tensile cracking in cement–soil walls due to bending. These observations highlight the importance of evaluating tensile behavior during the design process of cement-treated columns and grid-type walls [4, 5]. To prevent failure and weakness caused by cement-treated soil under tension, one proposed method is the use of new additives, such as synthetic fibers. Specifically, in the stabilization of cement-treated columns and the improvement of grid-type soils, commonly utilized to reduce construction costs, the bending failure under external loads in cemented soils constitutes a critical factor in the stabilization plan for these types of soils [6–10]. In centrifuge experiments conducted on cement-treated soil columns under consolidation loading, it was found that the tensile mechanism created by bending leads to bending failure in cement-treated columns due to consolidation loading. Soil stabilization has been achieved through the use of grid-type walls with cement as a method to reduce liquefaction. The performance of this method was validated in 1995 during the Hyogo-ken Nanbu earthquake [11]. Studies and analyses have shown that high-magnitude earthquakes increase tensile cracking at the corners of grid-type walls [12, 13]. To evaluate the reinforcement factors for these walls in cement–soil systems, dynamic centrifuge experiments were conducted, which show that strong movements are the primary cause of tensile cracking in cement–soil walls [14, 15]. The formation and propagation of cracks in materials containing cement highlight techniques that may be very useful in improving the behavior of cement-based composite materials. One such technique is the addition of synthetic fibers to the composite system, which are considered reinforcement elements that help reduce cracking [16]. Observations indicate that synthetic fibers not only directly control cracking but also improve the mechanical properties after cracking, such as fatigue and impact resistance [17, 18]. Cement-based soil stabilization has been widely applied in structural foundations, liquefaction protection methods, and in the construction of retaining walls during excavations [19, 20]. Numerous studies have been conducted in this field, most of which are based on the results of triaxial compression tests, which show that increasing the cement content in soil increases brittleness and deviatoric behavior up to the peak shear strength, and with increasing confining pressure, the behavior shifts toward softened deformation [21–23]. A study conducted by Namikawa and Koseki [24] showed that through numerical simulations of the three types of tests – direct tension, shear tension, and bending – it was concluded that direct tension testing provides more realistic results compared to the other methods [25]. To determine the failure criterion for

cement-treated soils under tension, experimental tests must be conducted to measure stresses under three-dimensional conditions. In 2017, Namikawa and Koseki conducted a study on the failure behavior of cement-treated soil under triaxial tension tests. Experimental results showed that the stress–strain relationship of drained triaxial tension tests at high pressure (around 400–500 kPa) is similar to low-pressure triaxial compression tests. This suggests that failure in cement-treated soils occurs in a shear manner [26, 27]. Various studies have examined the behavior of fiber-reinforced sand [28, 29], showing that the addition of fibers improves peak shear strength and enhances the ductile behavior of the soil. The combined effects of cement and fibers on the mechanical behavior of cemented sand have been studied by several research groups, including the work of Consoli et al. [10, 30], which shows that adding fibers to cemented soil increases both peak and residual shear strength and reduces residual dilation. This study is one of the few that examines the tensile strength of fiber-reinforced sand treated with cement. In all previous studies, the effect of confining pressures and direct tensile strength on cemented samples with added fibers has not been considered [31]. Ultimately, synthetic fibers are resistant to tensile failure and provide significant improvements in the ductility of composite materials [32, 33]. Therefore, the objective of this research is to investigate the failure of cement-treated columns and grid-type soils stabilized by cement–soil systems under dominant tensile stress. Additionally, the implementation of this system at greater depths and the evaluation of the effects of confining pressures are essential for such a study, utilizing triaxial testing. In this study, to enhance the tensile strength of the cement–soil system, polypropylene fibers were used. As demonstrated by Namikawa and Koseki [26], direct triaxial tension tests indicate that cement content and confining pressure significantly impact failure under tension and shear. In this study, by incorporating polypropylene fibers into the samples, a drained triaxial tension test was performed to evaluate failure under both tensile and shear stress, maximum and residual tensile strength, volumetric changes, and to determine the initial stiffness of the samples in relation to other variables, such as fiber diameter, confining pressure, and the percentages of fibers and cement on the deviatoric stress behavior with respect to axial deformation [26, 30].

2. Experimental procedure

The sand used in this study is uniform and sourced from a sample analyzed in Pristina. It was washed and dried prior

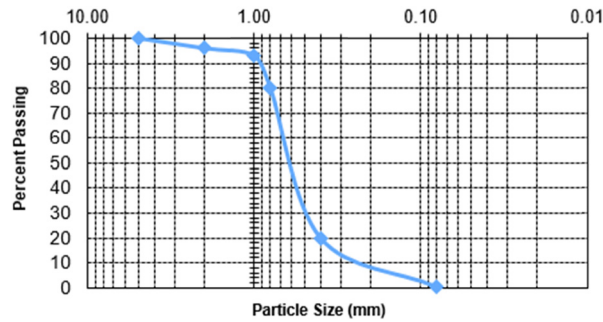


Figure 1. Gradation curve of the sand.

Source: From ref. [39].

to use. Figure 1 illustrates the characteristics of the sand, which has a uniformity coefficient (C_u) of 2.3 and a gradation coefficient (C_g) of 1, in accordance with ASTM standards [34]. Thus, this sand is classified as poorly graded, with the group symbol (sp). The cement used is Portland Pozzolana Type I, produced at the cement plant in Ardebil. The physical and mechanical properties of this cement are summarized in Table 1. To evaluate the effects of fiber diameter in these experiments, two types of polypropylene

fibers were used. In this study, two types of fibers with different diameters were applied. Both fibers have a specific gravity of 0.91 t/m^3 , a length of 24 mm, and a tensile strength of 400,000 kPa. Type I fiber has a thickness of 23 μm , while Type II fiber has a thickness of 300 μm . The macro-synthetic fibers are composed of refined olefin polymers, while the micro-synthetic fibers are made 100% from polypropylene. The main characteristics include the diameter, tensile strength, aspect ratio (length/diameter), and number per kilogram, which are detailed in Table 2.

Object	Range
Autoclave	0.2
Bliau	
Setting time (min)	
Initial	120
Final	180
Compressive strength (MPa)	
3 days	220
7 days	320
28 days	400

Table 1. Physical properties of the cement object.
Source: From ref. [39].

Typing	Fiber type I	Fiber type II
Material	Micro-synthetic	Macro-synthetic
Tensile strength	4,000,000	570,000–660,000 kPa
Diameter	23 μm	300 μm
Aspect ratio	600–1,200	30–120
Number per kg	<100,000,000	53,800
Color	Glossy	Gray

Table 2. Physical properties of the fiber.
Source: From ref. [39].

2.1 Sample preparation process

For each sample, the required amount of sand and cement was mixed with 10% kaolin clay and 20% distilled water. The cement weight was calculated to be 3 and 5% of the dry sand weight, while the fiber weight was set at 0 and 0.5% of the combined weight of the sand and cement, and was added evenly to the sand–cement mix. In the preparation phase, distilled water was first added to the clay, and after a homogeneous suspension was formed, this suspension was incorporated into the dry sand–cement mix. The clay served to prevent segregation of the sand particles, ensuring that less than 2% passed through a 200-mesh sieve to achieve a homogeneous mix [30].

In this study, the density method proposed by Ladd [35] was applied. The samples were organized into eight layers, and the composition of the soil was calculated and compacted for each layer until the required density was achieved. After this, the samples were combined into a cylindrical mold, as illustrated in Figure 2, using the vibration method, and then compacted. The height of the mold was 140 mm, with a diameter of 50 mm at the top and bottom, while the middle section had a diameter of 45 mm. The length of the sample with a thickness of 50 mm was 25 mm, while the section with a diameter of 45 mm had a length of 50 mm. The length of the section



Figure 2. Split cylindrical mold.

Source: From ref. [39].

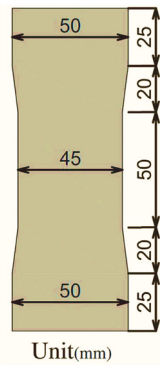


Figure 3. Specimen geometry.

Source: From ref. [39].

where the diameter changes from 50 to 45 mm was 20 mm. The geometry of the sample is shown in Figure 3. The samples were kept for 5 days under humid conditions after removal from the mold and were then placed in distilled water for 24 h to increase the saturation level. During the drained triaxial experiment, the samples underwent isotropic consolidation for approximately 1 day, ensuring that the total curing time reached 7 days. The uniaxial tensile strength (without protective pressure) of the provided samples was determined using the method mentioned above, with an additional day of curing, as shown in Table 3.

2.2 Experimental setup

The schematic diagram of the equipment used for the tensile test is presented in Figure 4. This equipment was originally designed by Koseki et al. [36], and in this study,

CC ^a	FC ^b	TF ^c	T_f (kPa)
3	0	—	44
3	0.5	I	41
3	0.5	II	39
5	0	—	104
5	0.5	I	95
5	0.5	II	90

^aCement content (%), ^bFiber content (%), and ^cfiber type.

Table 3. Summary of uniaxial tensile strength test results in the present study.

Source: From ref. [39].

modifications were made to the loading system, the pressure chamber, as well as to the deformation and volume change measurement systems. In this setup, the sample is placed between two holders, with gypsum serving as the adhesive material to fill the space between the sample and the holders, thus allowing the transmission of tensile forces during the loading process. The holders are connected to the top and bottom bases via spherical joints to prevent bending moments on the sample.

As mentioned earlier, the direct tensile test provides more realistic results compared to the tensile strength of cement-treated sand [33]. To minimize errors caused by friction on the support and the cover on the chamber, which uses a two-part sealing system, an o-ring was placed at the bottom and on the internal wall of the cover. The tensile force is measured using an external electronic force gauge, while axial displacement is monitored via a Variable Differential Transformer (LVDT). The cross-sectional area of the sample is modified according to the axial deformation. Volume changes are measured using a volumetric burette device, based on the negligible volume changes of the sample due to the tensile forces, while an applied back pressure is applied to this device. The image of the equipment used during the triaxial tensile test is shown in Figure 5. After placing in the chamber, the sample is surrounded by a latex membrane and saturated using either the double vacuum method or the dry placement method [37]. All samples reached saturation conditions by applying back pressures between 190 and 240 kPa. The Skempton B value for all experiments was at least 0.75 [39].

After the application of the back pressure, the triaxial pressure was consolidated for 24 h under isotropic pressure. Tensile stress was applied at values of 100, 200, and 300 kPa. The samples were then subjected to a drained loading condition with a very low loading rate of 0.005 mm/min. To prevent excessive pore pressure buildup during the loading, the loading rate was kept at minimal levels, and efforts were made to stabilize the pore pressure during the process.

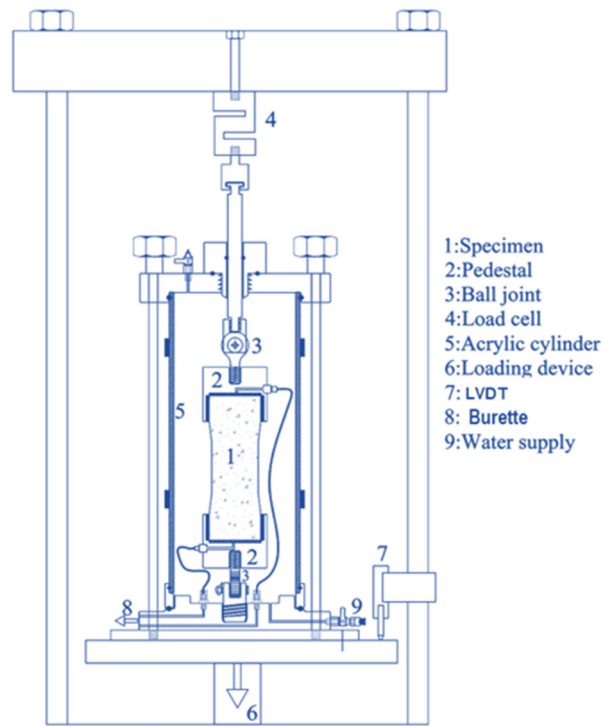


Figure 4. Schematic diagram of the triaxial tensile test device Tf (kPa).

Source: From ref. [39].



Figure 5. Triaxial tensile test device.

Source: From ref. [39].

3. Experimental results

This study examines the tensile behavior of cement-treated sand reinforced with fibers through direct triaxial tensile

tests. A detailed summary of these tests is presented in Table 4. In total, 23 experiments were conducted, some of which were repeated to ensure the validity of the results. Table 4 presents the values of the deviator stress (q) and the

CC	FC	TF	CP ^a	Deviatoric stress (kPa)		Mean stress (kPa)		Volumetric strain (%)		Axial state (%)	
				At failure	Residual state	At failure	Residual state	At failure	Residual state	At failure	Residual state
3	0	—	100	-196	-104	35	65	-0.037	-0.45	-0.41	-1.07
3	0	—	200	-277	-191	108	136	0.035	-0.86	-0.45	-1.32
3	0	—	300	-365	-278	178	207	0.029	-0.22	-0.49	-0.89
3	0	—	300	-364	-282	179	206	0.060	-0.10	-0.46	-0.73
3	0.5	I	100	-172	-160	43	47	-0.601	-1.61	-0.61	-0.51
3	0.5	I	200	-258	-240	114	120	-0.303	-1.21	-0.66	-2.18
3	0.5	I	300	-311	-293	196	202	-0.031	-1.35	-1.00	-3.26
3	0.5	I	200	-245	-222	118	126	-0.330	-1.45	-0.77	-2.33
3	0.5	—	100	-148	-123	51	59	-1.800	-1.80	-1.40	-4.50
3	0.5	—	200	-239	-192	120	136	-1.050	-1.43	-2.06	-4.39
3	0.5	—	300	-320	-292	193	203	-1.190	-1.60	-2.51	-1.76
5	0	—	100	-211	-95	30	68	-0.229	-0.66	-0.58	-1.01
5	0	—	200	-346	-164	85	145	-0.100	-0.63	-0.44	-1.25
5	0	—	300	-431	-240	156	220	-0.050	-0.53	-0.56	1.46
5	0	—	200	-316	-172	95	143	-0.090	-0.43	-0.42	-1.22
5	0	—	300	-450	-232	150	223	-0.050	-0.33	-0.56	-1.47
5	0.5	I	100	-186	-165	38	45	0.110	-1.62	-0.55	-3.02
5	0.5	I	200	-333	-313	89	96	0.120	-0.99	-0.38	-3.03
5	0.5	I	300	-406	-369	165	177	0.110	-1.06	-0.70	-5.54
5	0.5	II	100	-191	-157	36	48	-2.160	-2.68	-0.68	-9.97
5	0.5	II	200	-299	-267	100	111	-1.860	-2.00	-05.86	-11.56
5	0.5	II	300	-364	-328	179	191	-0.900	-1.80	-8.89	-12.09
5	0.5	II	200	-322	-256	93	115	-2.150	-3.10	-4.77	-7.20

Table 4. Summary of triaxial direct tension test results in the present study.

Source: From ref. [39].

mean stress (p'), which were calculated using equations (1) and (2):

$$q = \sigma'_1 - \sigma'_3, \quad (1)$$

$$p' = \frac{\sigma'_1 - 2\sigma'_3}{3}, \quad (2)$$

where σ'_1 represents the major effective stress and σ'_3 represents the minor principal stress. The tests were conducted using triaxial trials to assess the response of this material under varying loads and to identify variations in deviator stress (q) and mean stress (p'), which are crucial factors for understanding how the fiber-reinforced material reacts to tensile loads. The calculation of these values was performed using the above equations, which are based on the difference in the applied stress forces in different directions of the sample during the tests.

3.1 Failure mode

Figure 6 illustrates the impact of effective variables on the failure process and the increase in the frictional band width. It is observed that in both specimens without fibers, the failure surfaces are approximately oriented perpendicular to the applied tensile stress, suggesting that the failure mode could be of a tensile nature. In the case of increased confining pressure, this behavior is likely to transition from tensile failure to shear failure. The frictional bandwidth in all cement-treated samples increases due to the added fibers, and the fiber thickness also increases as a result of the localization of deformations. It is important to note that the fibers, when combined with cement, start to take effect after a certain displacement. In this context, in specimens with Type II fibers, the increase in surface contact with soil particles and the engagement of fibers with tensile forces leads

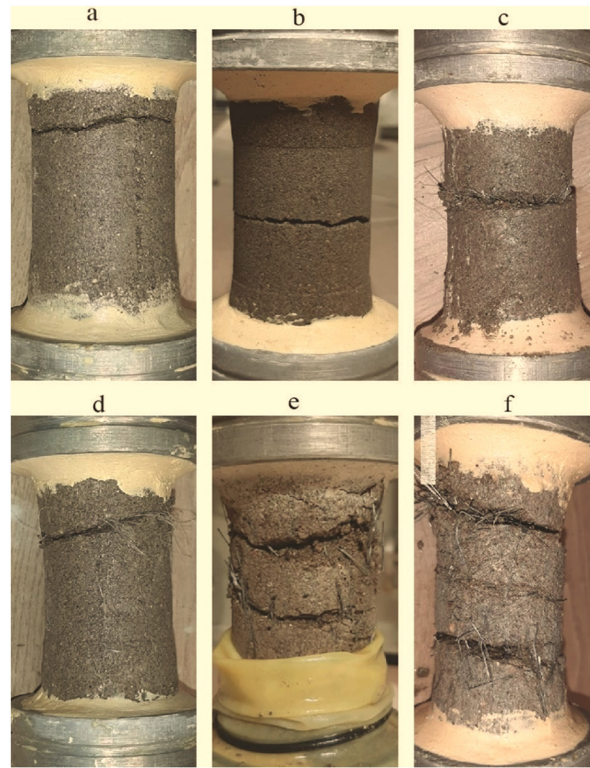


Figure 6. Fracture mode: (a) CP = 300 kPa, CC = 3.0%, and FC = 0.0%; (b) CP = 300 kPa, CC = 5.0%, and FC = 0.0%; (c) CP = 200 kPa, CC = 3.0%, and FT = TYPE I; (d) CP = 300 kPa, CC = 5.0%, and FT = TYPE II; (e) CP = 100 kPa, CC = 3.0%, and FT = TYPE II; and (f) CP = 200 kPa, CC = 5.0%, and FT = TYPE II.

Source: From ref. [39].

to their elongation. Moreover, according to the bonding content between the cement and fibers, other parts of the specimen experience tension, resulting in multiple fractures. In this type of failure, while the friction band has an angle, its width also increases. For Type II fibers, the friction band width decreases with increasing cement content and increases with increasing confining pressure. Therefore, it can be concluded that to fully utilize the maximum tensile capacity in cemented soils, it is necessary to not only increase the cement content but also the fiber diameter.

3.2 Stress-strain behavior and volume change

The stress-strain and volumetric strain-axial strain curves for all experiments are presented in Figures 7 and 8, which are based on the percentage of cement and fiber type. From these results, it can be concluded that the initial stress-strain relationship for all diagrams shows a similar curve. The failure type in cement-treated sand without fibers is similar for both 3 and 5% cement content. In these

specimens, after the initial hardening and deformation, the curve reaches a maximum at a strain of less than 0.5%, followed by an abrupt failure, illustrating brittle behavior. Essentially, the effects of the cement-bound structure include an initial hardening behavior, followed by an increase in plastic deformation, which ultimately results in material failure. This mechanical behavior of composite soils was discussed by Consoli et al. [39] under compression conditions. According to the nature of the fibers, the introduction of fibers in cement composites can reduce the tendency for brittle failure, and this effect is improved with the use of longer fibers. Similarly, Stacho et al. [40] showed that the addition of geogrids in granular materials reduces frictional strength and increases deformation. As illustrated in Figures 7 and 8, the addition of fibers results in a reduction of the peak for the fiber-containing specimens. A possible explanation for this phenomenon is that the increase in fiber length in the soil may result in more surface contact between the soil and fibers, thereby providing additional reinforcement due to the friction between the fibers and soil. Additionally, by adding polypropylene fibers along with cement, some of

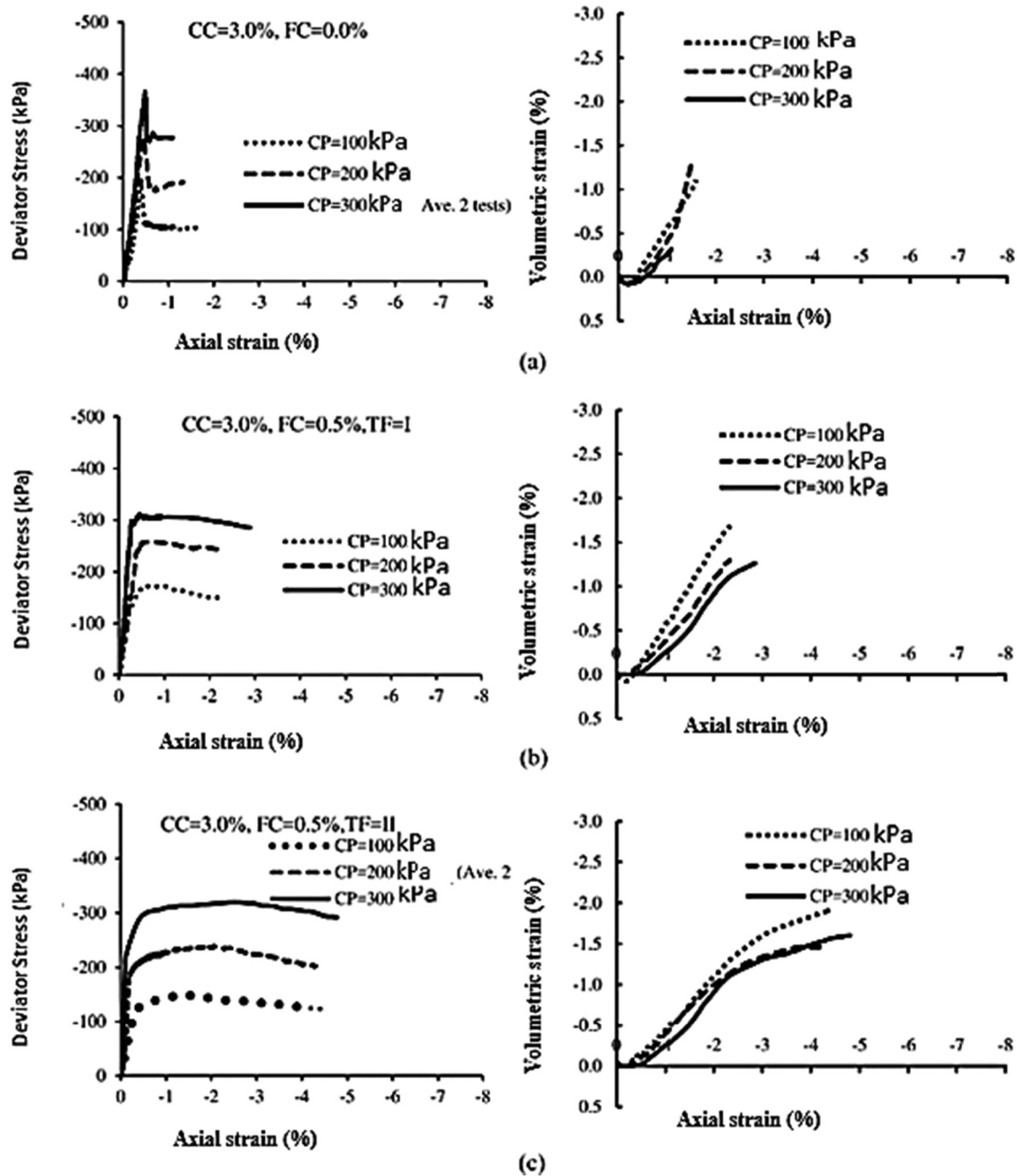


Figure 7. Stress-strain and volume change behavior with 3.0% cement: (a) FC = 0.0%; (b) FC = 0.5% and TF = I; and (c) FC = 0.5% and TF = II.

Source: From ref. [39].

the pores are filled with fibers instead of cement, leading to a reduction in the hardening effect of cement due to the decreased cement bonding between soil particles. The effect of fiber diameter, as shown in parts (b) and (c) of Figures 7 and 8, indicates that with an increase in fiber diameter, the brittleness caused by cement is reduced. In Figure 8(b), due

to the high cement bonding content in 5% cement and the low diameter of Type I fibers, the brittle behavior induced by cement has a relatively stronger effect, and the curve shows a peak similar to the fiberless specimens; after the sudden failure, the matrix-interface fibers engage, and the elastic fibers result in elongation and increased residual

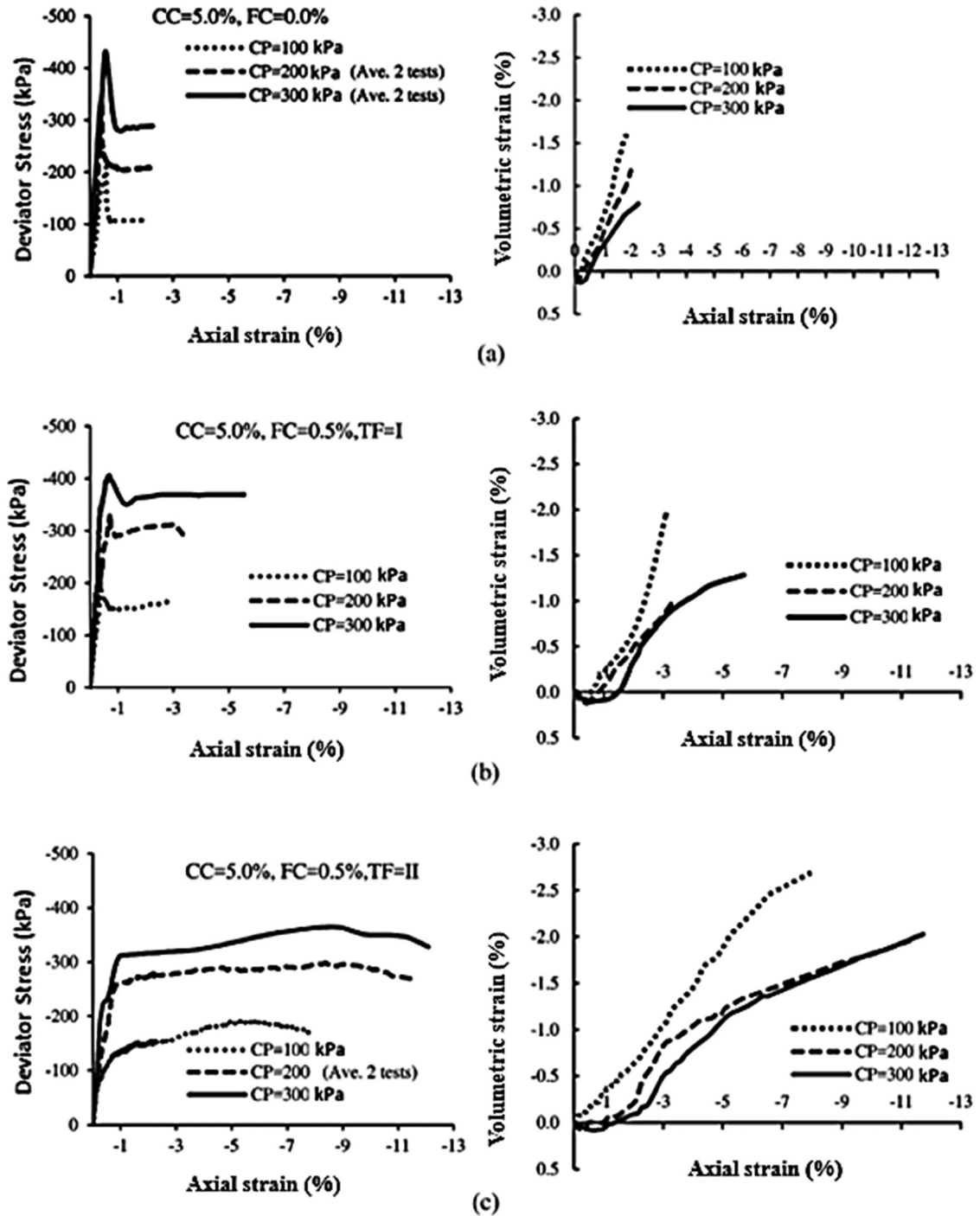


Figure 8. Stress-strain and volume change behavior with 5.0% cement: (a) FC = 0.0%; (b) FC = 0.5% and TF = I; (c) FC = 0.5% and TF = II. Source: From ref. [39].

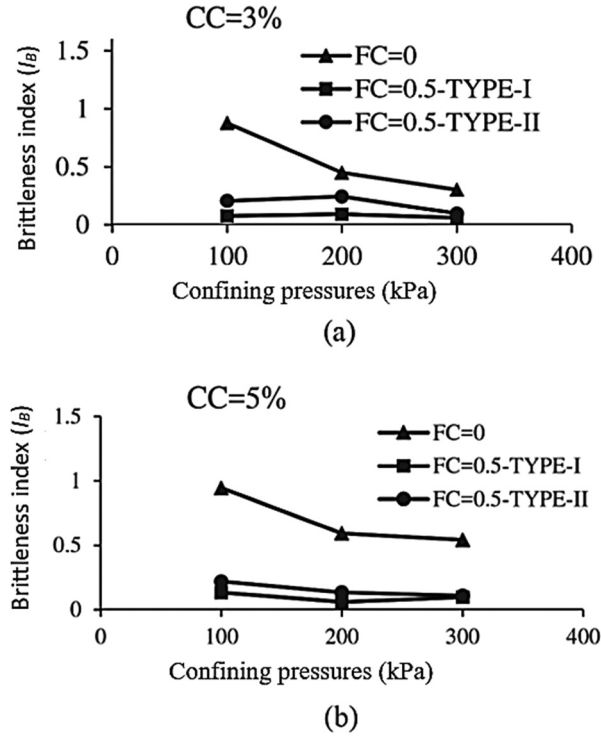


Figure 9. The effects of brittleness index versus confining pressure and type of fiber: (a) CC = 3.0% and (b) CC = 5.0%.

Source: From ref. [39].

strength. This failure mode was not observed in the thicker Type II fibers. Figure 8(c) shows that due to the localization of deformations at the point of sample failure and the coordinated support from both cement bonding sections and fiber engagement, the behavior becomes significantly more elastic.

The evaluation of the final residual stress shows that the presence of polypropylene fibers has a significant impact on improving the stability of cement-treated sand. As the diameter of the fibers increases, the residual stress also increases, following the increase in surface contact between the fiber and soil particles. This process leads to an improvement in the absorbed energy and an increase in the ductility of the cemented soil. In comparison to the sections related to volumetric strain behavior, it is observed that this increase is similar to axial strain behavior.

The higher the increase in cement content, fiber diameter, and confining pressure, the flatter the curves of volumetric strain become relative to axial strain. The brittleness index (I_B), defined by Consoli et al. [41], can serve as an indicator for assessing the stability and characteristics of treated materials. This index is described in equation (3) and is used to evaluate the impact of various factors such as cement content and the type of fibers used:

$$I_B = \frac{q_{\max}}{q_{\text{res}}} - 1. \quad (3)$$

In this context, $q_{\max}$ and q_{res} represent the peak and residual deviatoric stresses, respectively. The relationship between the brittleness index and the confining pressure in relation to the percentage of cement and type of fibers is illustrated in Figure 9. The data presented in these figures show that as the confining pressure increases, the brittleness index decreases, especially for sand treated with cement without fibers. This reduction is not significant when fibers are present.

In Figure 9(a), for sand with 3% cement and fibers, the brittleness index at a confining pressure of 100 kPa is lower than at 200 kPa, which is related to membrane rupture during testing. This phenomenon typically occurs due to the wide shear band at deformations exceeding 3%, focusing stress on the membrane at the location of the shear band. An important conclusion from this diagram is that the reduction in the brittleness index is more pronounced for fibers with larger diameters compared to those with smaller diameters. Therefore, it can be concluded that the two parameters, confining pressure and fiber type, contribute to the reduction in the brittleness index of cement-treated sand. Increasing both of these parameters, particularly the fibers,

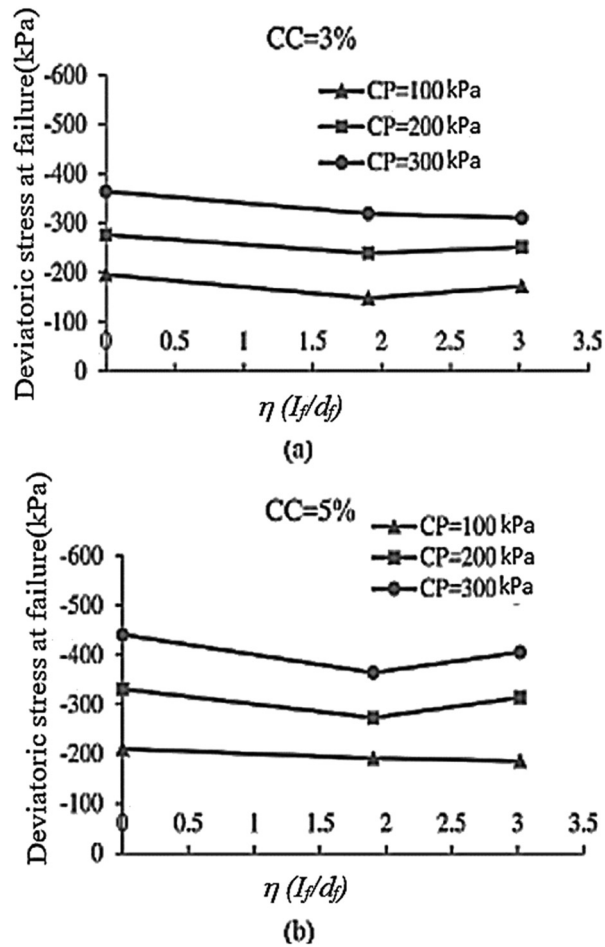


Figure 10. Changes in tensile strength against confining pressure and type of fiber: (a) CC = 3.0% and (b) CC = 5.0%.

Source: From ref. [39].

leads to a significant reduction in the brittleness of the materials.

Figure 10 illustrates the effects of peak deviator stress in relation to the logarithm of the aspect ratio of the fibers (the fiber length divided by the fiber diameter), thus examining the effect (Figure 11).

3.3 Stiffness

In determining the initial stiffness, as well as the stiffness at 50% of the maximum tensile stress, and the maximum tensile stress, the *secant stiffness* was used. Secant stiffness is defined as the slope of the line that connects the origin of the stress–strain curve to a specific point on this curve that corresponds to a particular stress or strain value. Figure 12(a) illustrates the variations in initial stiffness as a result of the fiber type and confining pressure for samples treated with

5% cement. From the data analysis, it is observed that the initial stiffness decreases with the addition of fibers, and this decrease is more pronounced when fibers with larger diameters are used. This phenomenon can be explained by the fact that, after the initial deformation, the polypropylene fibers cluster together to resist stresses that may arise. As a result, fibers with larger diameters contribute to lower loads and cause a more significant reduction in the stiffness of the cement-treated sand.

To compare the impact of fibers on stiffness under higher loading conditions, the *secant stiffness at 50% of the maximum tensile stress*, $E_{50\%}$, was evaluated. Figure 12(b) shows the changes in stiffness as a function of fiber diameter and confining pressure. As can be seen, the effect of fiber diameter on the reduction of stiffness at 50% of the maximum tensile stress is clearly evident. For fibers with larger diameters, increasing the diameter results in a reduction of 30–50% in both initial stiffness and stiffness

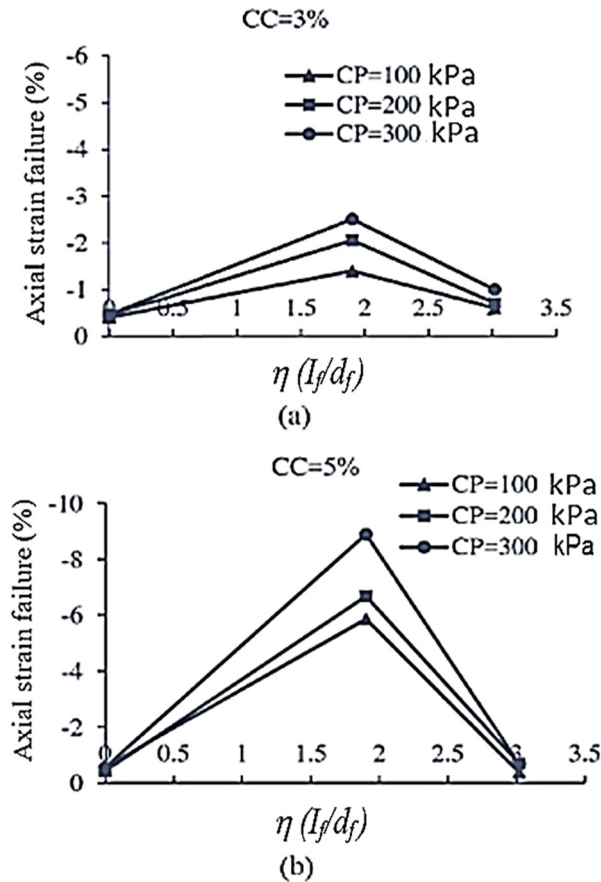


Figure 11. Axial strain changes in failure stress with changes in confining pressure and type of fiber: (a) CC = 3.0% and (b) CC = 5.0%. Source: From ref. [39].

at 50% of the maximum tensile stress, depending on the confining pressure. According to Figure 7(a) and (b), with an increase in confining pressure, both the initial stiffness and stiffness at 50% of the maximum tensile stress increase. Finally, it can be concluded that the addition of fibers leads to a reduction in the stiffness of cement-treated sand samples, reflecting a more ductile behavior of the material.

3.4 Energy absorption

In this study, to analyze brittle and ductile failure modes, the concept of toughness has been used, which represents the material's ability to absorb energy and transition into a plastic state before complete failure occurs. Under static experimental conditions, toughness is defined as the area under the stress-strain curve up to the failure point. The failure point is defined as the stress level reduced by 25%

from the peak stress [31]. During some experiments, where the membrane rupture does not reach the failure point, the remaining stresses after the event are considered as failure stress. Figure 13 shows the variations in energy absorption as a result of different variables, including the fiber diameter, confining pressure, and cement content. As shown in Figure 13, the energy absorbed for 5% cement is higher compared to 3% cement; furthermore, with an increase in confining pressure, the absorbed energy increases significantly. The effect of fiber diameter and confining pressure on energy absorption is quite pronounced in this diagram. As the confining pressure and fiber diameter increase, the energy absorption rate shows a noticeable increase compared to smaller diameter fibers, particularly for the 5% cement sample. This result can be interpreted considering that, with increasing confining pressure, the friction between the cement-treated soil particles and fibers increases. On the other hand, tensile forces enhance energy absorption due to the high tensile resistance

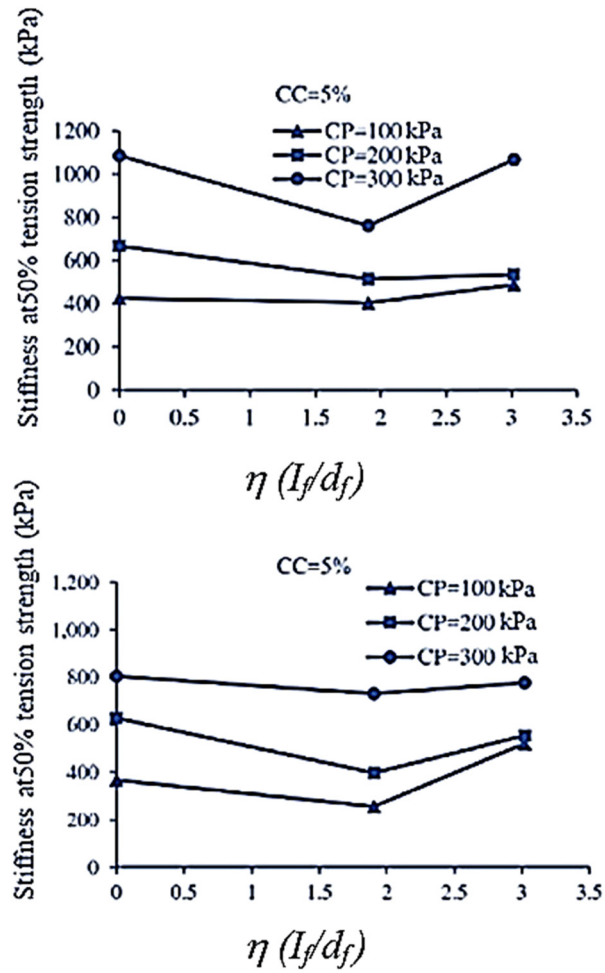


Figure 12. Changes in initial stiffness and stiffness at 50% tension strength of samples with 5% cement with changes in confining pressure and type of fiber.

Source: From ref. [39].

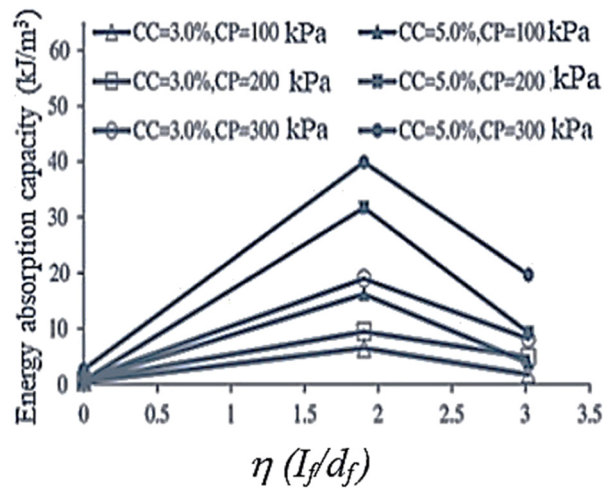


Figure 13. Changes in energy absorption up to failure point versus effects of fiber diameter.

Source: From ref. [39].

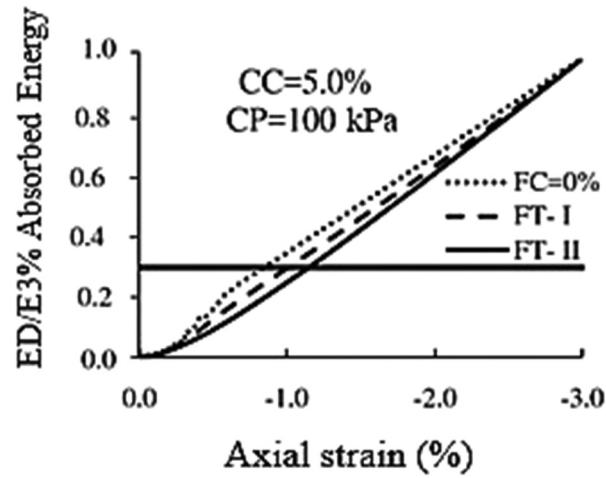


Figure 14. Changes in normalized absorbed energy compared to axial strain with the effect of fiber diameter.

Source: From ref. [39].

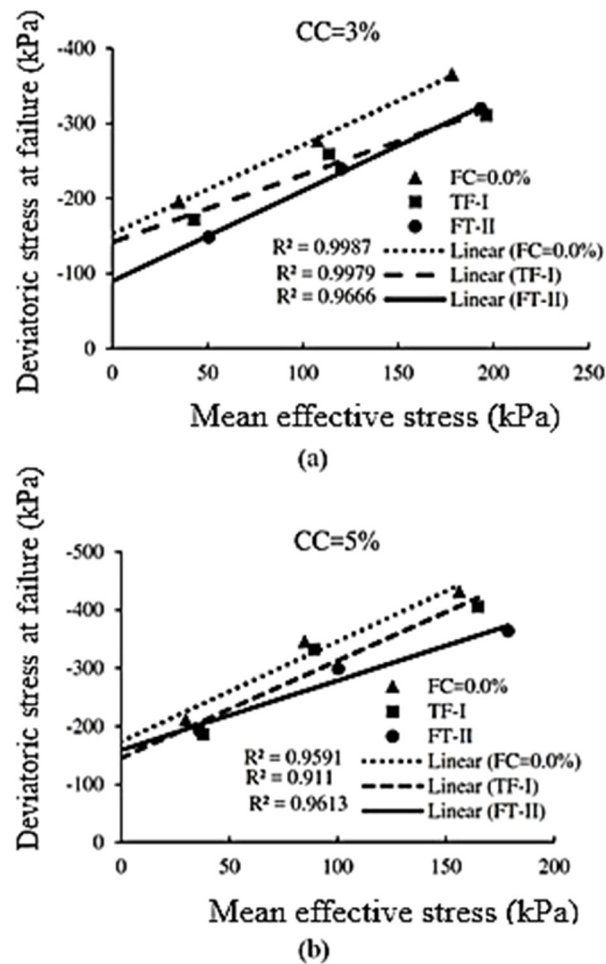


Figure 15. Failure envelopes for cement-treated sand reinforced with fibers compared to the percentage of cement: (a) CC = 3% and (b) CC = 5%.

Source: From ref. [39].

of the fibers. This effect becomes more pronounced as the fiber diameter increases, resulting in a greater aggregation of the cement-treated soil particles, which can more effectively withstand the applied tensile stress.

Meanwhile, the crack mode diagram, presented in Figure 6, shows that the overlapping of fibers along the length of the sample and its fracture from the weakest point has caused rapid fiber friction with the applied tensile stress. This friction leads to the propagation of the crack in other parts of the sample, causing a rapid distribution of failure in many parts of the sample, and consequently, maximum energy absorption. Figure 14 illustrates the effects of normalized energy absorption for each deformation, separated from the total absorbed energy at 3% deformation for a 5% cement content and confining pressure of 100 kPa. The slope of the fiber-free sample changes after 0.8% deformation and continues with a steady slope, indicating a higher rate of energy absorption at lower deformation levels. In contrast, for the fibered diagrams, the slope is more consistent, and as axial deformation increases, the absorbed energy increases proportionally.

Suppose a line parallel to the horizontal axis is drawn at any height in Figure 14; then, it can be concluded that the rate of energy absorption for each deformation is higher for fibers with larger diameters compared to those with smaller diameters, and both are higher than for the fiber-free sample. This section demonstrates how polypropylene fibers contribute to increasing the energy absorption capacity of cement-treated materials, reflecting a more ductile and elastic behavior of the material. Larger diameter fibers, along with increasing confining pressure, have a noticeable impact on increasing the absorbed energy, thereby improving the material's stability and performance under high loads.

3.5 Failure indicators and force parameters

Figure 15 presents the failure indicators derived from direct tension testing under triaxial conditions, which were calculated through linear regression. Although the

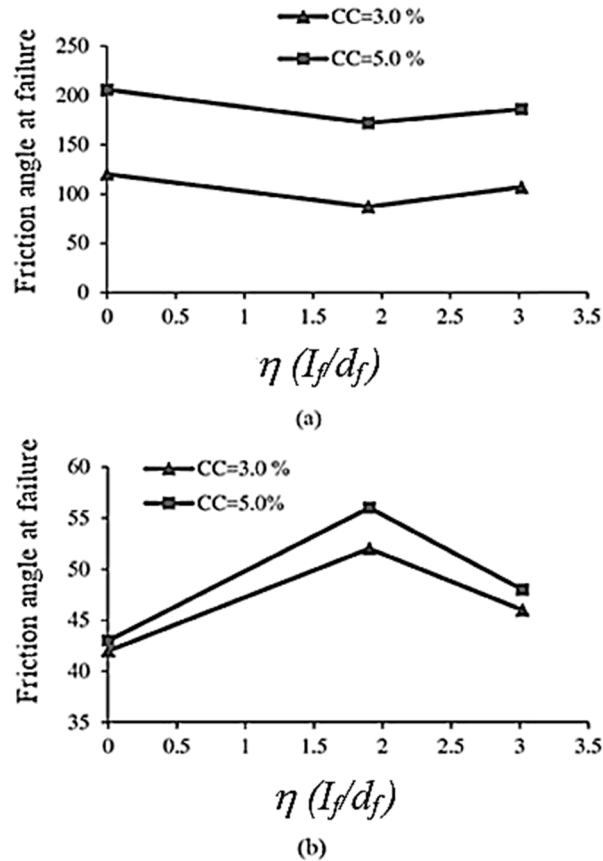


Figure 16. Changes in (a) the cohesion intercept and (b) internal friction coefficient compared to the fiber dimensional ratio.

Source: From ref. [39].

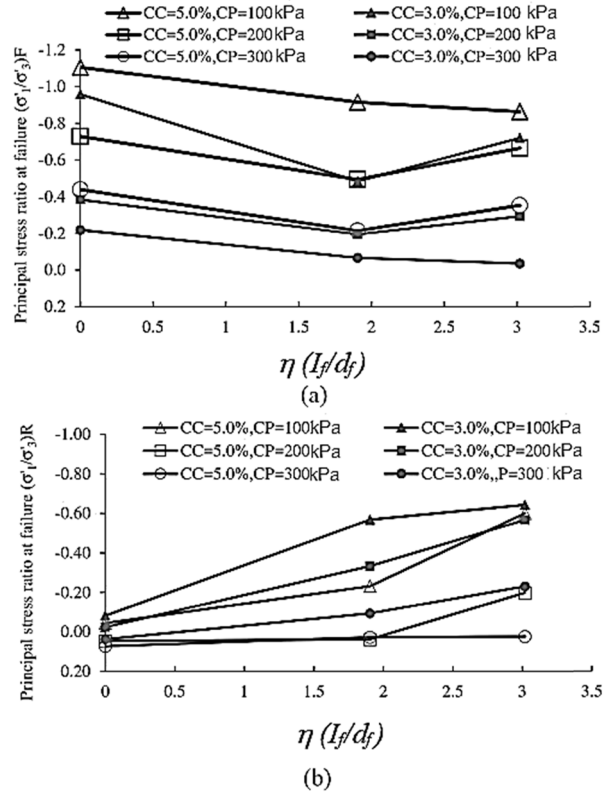


Figure 17. Changes in the main stress ratio in (a) peak stress and (b) residual stress.

Source: From ref. [39].

failure indicators may not always be linear for cemented and fiber-reinforced sand, the regression exceeding 90% suggests that they may provide an adequate estimate for the material parameters. By comparing the internal friction angle and the cohesion intercept for cemented sand with fibers of varying diameters, as shown in Figure 16, it can be concluded that the addition of fibers leads to a reduction in cohesion, with this effect being more pronounced for fibers with larger diameters. The cause of this decrease in cohesion factors may be linked to the weakening of the inter-particle bonds due to the presence of fibers, as well as the reduction in cement bonds after the fibers are added, which become weaker and impact cohesion negatively. As the fiber diameter increases, this effect becomes more significant, reaching up to a 15% reduction in cohesion for Type II fibers and up to 9% for Type I fibers. However, the addition of fibers results in an increase in the internal friction angle, and the larger the fiber diameter, the higher the angle. By analyzing the increase in the friction angle in Figure 16(b), it is observed that this parameter improves by more than 30% for fibers with diameters larger than 30%, whereas for fibers with diameters smaller than 11%,

the increase is more limited. It is also noteworthy that with an increase in the cement content, both force parameters of the soil, the friction angle and cohesion, show an increase.

Figure 17 shows the variations in the ratio of principal stress to failure stress and residual stress, in relation to changes in the dimensional ratio and the effects of cement percentage and confining pressure. With increasing confining pressure, the ratios of principal stress decrease for both failure stress and residual stress. However, with the addition of fibers, the ratio of principal stress to failure stress decreases, while the ratio to residual stress increases. The effect of cement content on the ratio of failure stress and residual stress is similar: both ratios increase with increasing cement content in the mixture.

4. Conclusions

Given the importance of the behavior of fiber-cement reinforced sand in engineering projects and its significant impact on the design of geotechnical structures,

particularly regarding the execution of direct tension tests under triaxial loading conditions, the results of this study offer substantial benefits to designers and geotechnical engineers, as follows. The analyses derived from Figure 6 indicate that the fracture point does not occur at a specific location along the sample, and that random fracture reflects the homogeneity of the sample preparation process through the vibration method. The addition of fibers causes changes in the fracture mode, shifting from a tensile fracture to a shear fracture. As the fiber diameter increases, the fracture mode transitions to a multiple shear fracture. The increase in the width of shear displacement is more pronounced with the addition of fibers, and the effect of increasing the fiber diameter and decreasing cement content is more significant than the influence of other parameters. The maximum tensile stress for fiber-reinforced samples is lower compared to cement-treated samples, but the residual stress and failure strain increased, thus shifting the material behavior from a brittle (fragile) state to a ductile (plastic) state. Additionally, the initial stiffness and stiffness at 50% of the maximum tensile stress reduced with the addition of fibers, particularly for fibers with larger diameters. The brittleness index evaluation has shown that fiber-reinforced samples exhibit lower stiffness compared to samples without fibers. Data on strength and energy absorption up to the failure point indicate that fiber-reinforced samples have a higher capacity for energy absorption compared to cement-treated samples. The effect of fibers with larger diameters is more pronounced compared to those with smaller diameters. However, it is important to emphasize that an increase in confining pressure and cement content leads to an increase in the rate of energy absorption, while increasing the fiber diameter has a more substantial effect on increasing the energy absorbed up to the failure point. The cohesion intercept in fiber-reinforced samples decreased due to a reduction in cement bonding, with a maximum decrease of 15% for Type II fibers and 9% for Type I fibers. At the same time, the internal friction angle showed an increase for cement-treated sand samples, reaching a maximum of 30% for Type 2 fibers and 11% for Type I fibers. Although the principal stress ratio decreases for maximum stress with the addition of fibers, this ratio significantly increases for residual stress, particularly when using thicker fibers.

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Author contributions

Hysen Ahmeti: Conceptualization of the study, data collection, statistical analysis, interpretation of results, and drafting of the initial manuscript. Ragip Behrami: Literature review, methodological support, language editing, and final revision of the manuscript. Both authors have read and approved the final version of the manuscript and agree with its content.

Conflict of interest statement

The authors declare that there are no conflicts of interest with this publication.

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