Arabian Journal of Geosciences (2022) 15:1679
https://doi.org/10.1007/s12517-022-10966-x

ORIGINAL PAPER

Check for updates

Experimental investigation of the mechanical behavior and engineering properties of sand reinforced with hemp fiber

Ali Vafaei[1] · Asskar Janalizadeh Choobbasti[1] · Reza Younesi Koutenaei[1] · Amir Vafaei[2] · MobinaTaslimi Paein Afrakoti[3] · Saman Soleimani Kutanaei[4]

Received: 4 January 2022 / Accepted: 22 October 2022 / Published online: 12 November 2022

Abstract

Tensile components are present in soil-based fibers that are dispersed randomly and are used to support tensile stress. The stabilization and shear strength of soil is increased through the application of fiber reinforcement, which imitates the reaction of tree roots. Human has used reinforced soil for the construction of various structures for a long time. Today, soil reinforcement is an effective and reliable means of increasing the strength and stability of soil masses. Previous studies were mainly focused on the behavior of soils reinforced with synthetic fibers and few studies were conducted on soils reinforced with natural fibers. Since natural fibers are abundant in nature, they seem to be economic options if their behavior can be stabilized. The present study investigated the behavior of soil reinforced with hemp fibers. Several static triaxial tests were carried out in this research to assess the resistive behavior of Babolsar sand reinforced with randomly distributed hemp fibers. Hemp fibers were mixed into the soil in amounts of 0.3, 0.6, and 0.9% by dry weight and with lengths of 6, 10, and 14 mm. Static triaxial tests were performed at confining pressure of 50, 100, and 200 kPa. Test results indicated that there was a considerable effect on the behavior of sand due to the presence of fibers. Moreover, the results of the examinations of hemp-reinforced sand revealed that fibers improved the shear strength parameters, peak strength, yield strain, and stiffness of the sand. Regarding the outcomes, adding 6 mm fibers to soil results in increases in peak strength ranging from 331% in the greatest condition (fiber weight ratio of 0.9% and 50 kPa confining pressure) to 21% in the lowest state (fiber weight ratio of 0.3% and 200 kPa confining pressure). The maximum and minimum strength increase ratios for 10 mm and 14 mm fibers occur under the same circumstances as for 6 mm fibers. Thus, the highest and minimum strength gains for 10 mm fibers are 499% and 39%, respectively. For 14 mm long fiber, these figures are 845% and 49%, respectively. It is worth mentioning that the internal friction angle in the case of unreinforced soil is equal to 43°. This value is equal to 49° for reinforced soil containing 0.3% of fiber with a length of 6 mm and in most cases reaches 57° for reinforced soil containing 0.9% of fiber with a length of 10 mm. The amount of cohesion of reinforced soil containing 0.3% of fiber with a length of 6 mm is equal to 65 kPa and in most cases for the sample of reinforced soil containing 0.9% of fiber and a length of 14 mm is 385 kPa.

Keywords Babolsar sand · Hemp fiber · Reinforced sand · Mechanical behavior · Static triaxial test

Introduction

Reinforcement of weak and unsuitable soils by adding elements such as fibers that strengthen tensile strength, to be used in slopes, roadbeds, and dams to create soil configuration with the desired engineering properties is called soil reinforcement. Fiber reinforcement on the one hand involves the direct use of fibers at random in a matrix such as soil and on the other hand, involves the use of fibers with a specific arrangement, such as the family of geosynthetics (Htut et al. 2019; Bascetin et al. 2020; Eker and Bascetin 2022; Yuxai et al. 2021; Zhang and Russell 2021).

Fiber-reinforced soil applications in geotechnical engineering

Improving soil behavioral properties should be consistent with functional aspects (Vafaei et al. 2022). In this section, practical aspects and practical examples of reinforced

Responsible Editor: Zeynal Abiddin Erguler

✉ Ali Vafaei
ali_vafaei1366@yahoo.com

Extended author information available on the last page of the article soils are presented. A review of research on reinforced soil shows that the use of fibers in geotechnical engineering can be divided into five categories: pavement, retaining walls, stability of the slope, foundation, and earthquake.

Pavement layers

In 1991, a team of US military engineers demonstrated the performance of fibers in improving stabilized soil layers in pavements. They found that the section containing 30 cm of fiber-reinforced silty sand increased the traffic volume by 33% compared to the unreinforced section. And in 2008, an example of the use of in situ soil mixed with hot-rolled cement and polypropylene fibers as a taxiway was also reported in Australia (Cabalar and Karabash 2015; Choobbasti et al. 2015; Consoli et al. 2017).

Retaining walls and stability of the slope

The use of reinforced soils with discrete fibers is considered a suitable solution for the reconstruction of failed soil slopes. Also, on slopes that have a high potential for erosion, the use of these materials reduces the rate of degradation. The use of reinforced soil on slopes as well as in the foreheads of walls reinforced with plate reinforcements reduces the possibility of failure and surface instability and thus reduces maintenance costs. On the other hand, reducing the slope angle reduces the volume of soil and space occupied. This idea is realized by adding fibers to the soil. For example, for a slope with a length of 1 km and a height of 10 m, increasing the slope angle from 20 to 30° reduces the volume of soil by 50,000 m^3 and the width of the slope by 10 m. Therefore, the use of these fibers saves cost and time and reduces environmental impact. Bahardavj and Mendel showed the positive effect of polypropylene fibers on the discussion of earthen roofing (Ghadakpour et al. 2021; Kutanaei et al. 2022).

Foundation engineering

One of the important applications of reinforced soils is related to the discussion of foundations on lands with inadequate bearing capacity. If the necessary financial resources are not available for the implementation of deep foundations, the discrete fibers are a good way to achieve bearing capacity. Also, in cases where the foundation suffers from asymmetric subsidence due to asymmetric loading or differences in soil properties, the use of fibers reduces the risk of failure. An example of the use of fiber-reinforced sand in foundation construction has been reported in Brazil. The method of deep mixing of soil with cement (cement soil column) is one of the common methods to increase the bearing capacity of soils in construction projects. In Thailand and Bangkok, for example, the use of deep-mixing cement has been considered by geotechnical engineers for decades. Although cementitious soil has considerable compressive strength, it does not have good tensile and flexural strength. When concrete columns are exposed to horizontal (lateral) loading (large embankments and lateral expansion phenomenon), weakness in flexural strength causes failure. For this purpose, engineers recommended the use of fibers in improved projects with a deep mixing method that has the possibility of horizontal loading (Choobbasti et al. 2018; Tang et al. 2016; Shen et al. 2021).

Earthquake engineering

Ductile behavior and high energy absorption of fiber-reinforced soils have made these materials useful materials for the construction of earthquake-resistant soil structures. The use of fibers in the construction of earthquake-resistant earthen structures in Japan has been reported by Makuuchi and Mines. Successful use of fibers in the construction of earth structures has also been reported by Leflive (Hejazi et al. 2012; Sahin et al. 2021; Zhao et al. 2020).

For the construction of stabilized pavement bases, canal linings, and support layers for shallow foundations, the enhancement of local soils with fibers and cement offers significant economic and environmental benefits, eliminating the need for a spoil area and the need to borrow materials from somewhere else. Previous studies have examined the shear strength of artificially cemented sandy soil (Choobbasti et al. 2014; Kutanaei and Choobbasti 2019). The addition of cement, according to the literature, increases dilatation and maximum shear strength. Additionally, by raising the confining pressure, soil cement's brittle nature is transformed into a more flexible one. (Choobbasti et al. 2015, 2018; Qu and Zhao 2016). With various forms of material, such as cemented sand, randomly distributed fibers are simply inserted. Improved isotropic strength is produced by randomly placed fibers (Jamei et al. 2013; Pino and Baudet 2015).

The behavior of reinforced soil has been studied by many researchers in recent decades. Applications of reinforced soil include embankment construction, reduction of cracks due to shrinkage and swelling in clay soils, and reinforcement of the substrate (Noorzad and Mirmoradi 2010; Noorzad and Fardad Amini 2014; Turk and Nehdi 2021). The use of discrete fibers to improve the engineering properties of soils has attracted the attention of many scientists around the world. The application of these methods in geotechnical work and further understanding of the benefits and limitations of these methods require further study. Many researchers performed several triaxial, unconfined, CBR, direct shear, flexural, and, tensile strength tests on reinforced soil samples. The results of these experiments showed that the addition of discrete fibers with random distribution improves the soil strength characteristics and changes the soil behavior from brittle to a more flexible state (Noorzad and Fardad Amini 2014; Malidarreh et al. 2018, Karimzadeh et al. 2022). In the following, some laboratory studies in this field are presented.

Gray and Ohashi (1983) based on the results of direct shear experiments, showed that reinforcement of the soil with discrete fibers increased the peak shear strength and limited the drop-in strength after the peak strength. Factors affecting the increase in strength are the amount, length, and modulus of fibers. In their study, no increase in the stiffness of the soil-fiber mixture was observed. Gray and Al-Refeai (1986) reported from triaxial experiments on reinforced sand that discrete fibers with random distribution increase the ultimate strength, but at small strains (less than 1%) cause a decrease in compressive stiffness. They also showed that fiber reinforcement increases the failure axial strain and, in most cases, reduces the drop in residual strength. Kumar et al. (2006) investigated the relationship between soil grain size and fiber strength. They found that finer sands had much higher fiber bond strengths, so they were less likely to fail due to slip conditions than coarser sands. Also, based on the triaxial experiment and static analysis, Yetimoglu and Salbas (2003) concluded that the presence of fibers increases the shear strength and decreases the drop in residual strength. Nataraj and McManis (1997) performed direct shear experiments on clay soils and sands reinforced with polypropylene fibers and found that the addition of fibers increased the angle of friction and cohesion and that the shear strength envelope of reinforced clay was slightly nonlinear. In addition, they found that the equivalent friction angle is slightly greater at low confining pressures than at higher confining pressures.

According to these investigations, the inclusion of fibers enhances the maximum shear strength of the sand and results in a more ductile behavior. The effects of effective stress (30, 60, 100, and 200 kPa), fiber (polypropylene) content, and fiber length on the mechanical behavior of fiber-reinforced soil were investigated by Diambra et al. (2010) using consolidate drained triaxial compression and extension. They concluded that as confining pressure, fiber content, and length increase and behavior becomes more ductile, so does the strain at failure. For the samples with 0.3%, 0.6%, and 0.9% of fiber, the relative improvement in internal friction angle was 9%, 18%, and 30%. In undrained ring shear experiments, Liu et al. (2011) looked into the static liquefaction resistance of saturated sand reinforced with polypropylene fibers. The findings demonstrated that the liquefaction potential was greatly decreased by the addition of fibers. The loose sample's residual shear strength significantly increases when fiber is added (72%, 100%, 71%, and 70% for 0.2%, 0.4%, 0.6%, and 0.8% of fiber). Gao and Zhao (2013) investigated how fiber orientations affected the behavior of fiber-reinforced sand. The findings demonstrated that in the triaxial test, fibers oriented in the horizontal direction greatly increased the shear strength parameters. By performing a series of ring shear tests at various normal stresses, Shao et al. (2014) evaluated the shear strength of Mississippi sands reinforced with polypropylene fiber. They claimed that the sand's shear strength metrics were significantly impacted by fiber inclusion. Cohesion and internal friction angle both rose by 700% and 32%, respectively. On fiber-reinforced cemented soil, Maher and Gray (1990) conducted static and dynamic triaxial compression and extension experiments. According to their findings, the inclusion of fibers increased the material's shear strength and energy absorption. Peak shear strength increases by 100 and 200%, respectively, for fiber contents of 0.2% and 3%. Polypropylene (PP) and polyester (PE) fibers' effects on the mechanical characteristics of soils stabilized with cement were studied by Consoli et al. in 2004. They discovered that while the deviatoric stresses at failure marginally decreased, the addition of Polypropylene fiber greatly enhanced the brittle behavior of cement-stabilized soils. In addition, whereas the presence of PP fiber significantly reduced the initial stiffness of samples, the inclusion of PE fiber only marginally altered it. Triaxial compression tests were performed by Consoli et al. (2010) to investigate the impact of fiber reinforcement (polypropylene fiber) on the mechanical characteristics of sand. Based on the percentage of fiber, cement content, and confining stress, they suggested polynomial equations to calculate residual and peak strength. To give an empirical equation for the prediction of the mechanical behavior of polypropylene fiber-reinforced cemented sandy soil, Kutanaei and Choobbasti (2015) conducted several unconfined compression experiments. Unconfined compression tests were performed by Yaghoubi et al. (2018) to examine the effects of cement and waste tire fiber addition on the mechanical properties of sand. They discovered that increasing cemented sand with 3% waste tire fiber boosted the unconfined compression strength by more than 25%.

The idea of using natural fibers as reinforcement elements has drawn a lot of attention due to the tensile strength of these materials, the availability of large quantities of these materials in regions where the fibers are produced from indigenous plants, as well as the environmental advantages of replacing natural materials with synthetic materials (Tang et al. 2012). Annual kenaf plants can reach heights of 1.5 to 3.5 m. Kenaf has a stem that is 1–2 cm in diameter with a woody base. Iran is one of several places in the globe where kenaf is grown. The manufacture of biodegradable polymers, textiles, paper, building materials, and biofuels are just a few of the businesses that employ kenaf fibers. For a full year, kenaf fiber was exposed to a natural weathering environment

(Akil et al. 2011). According to Akil et al. (2011), the following are the key benefits of employing Kenaf fibers over other types of fibers: low cost, low energy consumption, the most durable of all-natural fibers, and biodegradability.

Silveira et al. (2022) evaluated the effect of silica and polymer on the mechanical behavior of sand matrix reinforced with mentioned fibers. The result of their study indicated that both naturally occurring and surface-treated sisal fibers produced shear strength characteristics that were superior to those of unreinforced soil, promoting their long-term use in engineering projects like temporary landfills. Zhou et al. (2022) examined the liquefaction strength of calcareous sands reinforced with polypropylene fibers. The findings showed that calcareous sands' liquefaction resistance was increased along with their deformation and pore pressure accumulation rates by increasing fiber content and fiber length. When the fiber concentration was more than 0.8%, the risk of soil liquefaction might also be greatly decreased. Zhang et al. (2021) investigated the pore water pressure accumulation laws in sand reinforced with randomly distributed fibers through cyclic triaxial compression tests. The impacts of relative density, the ratio of cyclic stresses, fiber content, and fiber length were examined. The test findings demonstrated that adding fibers at random locations to the sand effectively delayed the buildup of pore water pressure and considerably boosted liquefaction resistance. In the study of Vakili et al. (2022) lignosulfonate was used as a binder and polypropylene (PP) fiber was used as a reinforcing material to protect the features of marl soils from the negative effects of freeze–thaw (F-T) cycles. The outcome has shown that freeze–thaw weathering changed the samples' stress–strain pattern from strain-softening to hardening behavior while also enhancing ductility behavior. It was found that applying lignosulfonate and PP fibers at the same time completely bonded soil particles and created interlocking zones around the fiber strands, which strengthened particle bonding. The Fourier transform infrared (FTIR) test findings also confirmed the creation of ionic bonds as a result of the presence of lignosulfonate in the marl soil and the space between the soil's mineral layers.

Considering all the cases discussed here, it is remarkable and very valuable to say that natural fibers such as hemp fiber have received very little attention; therefore, the present paper comprehensively deals with the behavior of reinforced soil with hemp fiber. It should be worth mentioning that particular, this study examines the various fiber content and different fiber lengths as well. Another significant point is that due to the availability and wide accessibility of hemp fibers, a comprehensive study of the behavior of sand reinforced with this type of fiber is very necessary. For example, the foundation of buildings in the village can be reinforced according to the mentioned characteristics of this type of fiber and also the lower price of the mentioned fiber compared to synthetic fibers.

The main objective of this study is to investigate the effect of reinforcement on stress–strain behavior, volumetric behavior, peak strength, stiffness of samples, and shear strength parameters. Studies have been done on fiber-reinforced sand thus far, although natural fibers and hemp fiber have received less attention. The mechanical behavior of Babolsar sand reinforced with hemp fiber is therefore the subject of a very thorough and comprehensive experimental research presented in this study. The innovation and novelty of this study is the examination of natural fiber by conducting very extensive experimental tests. In particular, in this study, the impact of the expressed parameters, especially the volumetric strain for natural fiber such as hemp fiber with static triaxial test has been observed. The findings and observations in this comprehensive study will be very useful and practical for civil-geotechnical engineers in various filed such as foundation, dam, slope, earthquake engineering, and pavements.

Experimental program

Numerous consolidated drained triaxial experiments were performed to evaluate the mechanical behavior of Babolsar sand reinforced with discrete randomly distributed hemp fibers. The various parameters of the experiments performed are as follows:

- Three different weight ratios of hemp fibers (0.3, 0.6, and 0.9%)
- Three different lengths of hemp fibers (6, 10, and 14 mm)
- Three different confining pressures (50, 100, and 200 kPa)

Materials

Babolsar sand

The sand used with the name Babolsar sand is taken from the shores of Babolsar city. The color of this type of sand is dark and its granulation is presented in Fig. 1. This type of sand is classified according to the Unified classification as part of the poorly-grained sand (SP) group. It should be noted that all experiments in this study were carried out according to the standard provided by the American Materials and Testing Association (ASTM). Accordingly, the sieving granulation test was performed according to the ASTM D422 standard and the soil classification test was performed according to the ASTM D2487 standard. The particles of this sand are semi-circular to semi-angular. The specific gravity of Babolsar sand is 2.78. ASTM D854 standard was

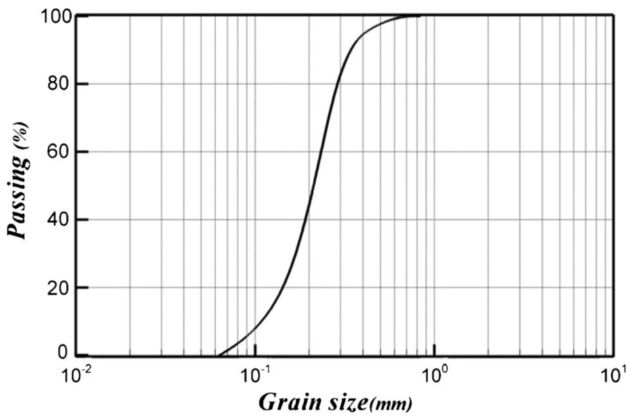

Fig. 1 Particle size distribution is related to the studied soil

Fig. 2 The hemp fiber is used in this study

used to determine the density of solid soil aggregates. A relative compaction test was used to determine the compaction characteristics of Babolsar sand. ASTM D4253 standard was used to determine the maximum specific gravity (corresponding to the minimum void ratio) and ASTM D4254 standard was used to determine the minimum specific gravity (corresponding to the maximum void ratio). All physical characteristics of Babolsar sand are presented in Table 1.

Hemp fiber

These fibers are widely cultivated in northern Iran and the Fars province. Hemp fiber needs a warm and humid climate to grow. The most important uses of hemp are in the production of products such as hemp and sackcloth, and its other applications are in horticulture, agriculture, and freight industries, especially to cover other objects, production of carpets, and rugs, home appliances, clothing, and shoes. New applications include the use of composites and even the form of geotextiles to prevent soil erosion and landslides. Hemp contains 17% lignin, 48 to 52% cellulose, and 7 to 10% water. The tensile strength of hemp is about 60 to 70 MPa, which is low compared to synthetic fibers (Akil et al. 2011). Figure 2 shows the hemp fibers used in this study. Hemp fibers are first cut to the desired lengths and then completely separated from each other. These fibers were mixed with 0.3%, 0.6%, and 0.9% by weight dry weight of the soil and with a length of 6, 10, and 14 mm in the soil.

Table 1 The physical characteristic of the base soil used in this study (the soil name is SP)

Characteristics	Value
$\gamma_{d,\min(\frac{KN}{m^3})}$	14.92
$\gamma_{d,\max(\frac{KN}{m^3})}$	17.64
e_{max}	0.81
e_{min}	0.53
Gs	2.78
Cu	2.13
Cc	1.32

Sample preparation

It should be considered that in most previous studies, the percentage of fiber used for soil reinforcement varied between 1 and 3%. The addition of fibers to the sand mixture decreases homogeneity. Adding a high percentage of fiber causes difficulty in the mixing process. Therefore, in this study, the fiber contents were 0.0%, 0.3%, 0.6%, and 0.9% by weight of the dry sand (Tang et al. 2007; Consoli et al. 2013; Consoli 2014).

One of the most important phases of experimental study is sample preparation. According to Ladd's (1978) procedure, samples for this investigation were prepared using the compaction technique. Dry sand and fiber cannot be combined because segregation occurs. To create samples of hemp fiber-reinforced sand, the necessary quantity of sand was first combined with 5% water, and then hemp fibers were added. An electric mixer was used for the mixing. The wet materials were placed in an oven to dry since all studies were conducted in a dry state. A tiny spoon was used to carefully pour the samples into a split mold.

It should be mentioned that in sandy soils, mixing was easier than in clayey soils. For this purpose, first water was mixed with soil, then fibers were added and mixed. The experiments of this study were performed in the dry state, the reason for adding water to the sand was that in granular soils due to lack of cohesion, the dry state, the fiber did not interact with the sand and separation occurred during mixing. Therefore, the first 5% of the dry weight of sand was added to that water, and then the fibers were gradually added to the soil and mixed. The reason for choosing a moisture content of 5% for the mixing operation was that in this percentage of moisture, there was the highest surface tension and the apparent cohesion resulting from this surface tension caused more sand and fibers to be involved and better mixing took place. A mixer was used for mixing. The materials were mixed with a mixer for 15 min until the resulting mixture was completely homogeneous.

As the specimen volume was identified, the weight of soil, water, and fibers was attained based on the specific dry weight considered for the soil and similarly the desired moisture content. The weight of the mixture ingredients was divided into 5 layers and the weight of each layer was determined. Reinforced specimens with a diameter of 52 mm and a height of 104 mm were organized. Specimens were completed with a specific dry weight of 80% of standard density. The quantity of mixture requisite for each layer was poured into a mold and then the specimen in each layer was compacted through static compaction. To avoid weak plates and appropriate joining between the layers, grooves up to 10% of the layer thickness were formed on the surface of the first and second layers. After that, because all experiments in this study were performed in a completely dry state, the samples were placed in an oven at 105° C for 24 h and then tested. This process was offered by Hamidi and Hooresfand (2013). At that time, the dimensions of the sample were precisely measured by a numerical caliper before the test. In calculating the average diameter of the specimen, the location of each quarter of the specimen diameter, and in calculating the height, the average of the specimen was three heights in location 120° of the specimen height was done. Figure 3 shows the various steps of specimen preparation.

Fiber is a flexible and ductile material. Ang and Loehr (2003), examined the size effect and found that for fibers with a length of 10, 15, 20, and 52 mm, no effect size effects were observed for the sample with a diameter of 70 mm (Ang and Loehr 2003). Consoli et al. in 2009, performed triaxial experiments with a fiber length of 23 and a sample of 50 mm-ratio of sample diameter to fiber length 2.1- (Consoli et al. 2009). Malidarreh et al. in 2018, carried out triaxial experiments with a fiber length of 15 and a sample of 38 mm-ratio of sample diameter to fiber length 2.2- (Malidarreh et al. 2018). Noorzad and Zarinkolaei (2015), performed triaxial experiments with a fiber length of 18 and a sample of 38 mm-ratio of sample diameter to fiber length 2.1- (Noorzad and Zarinkolaei 2015). All samples were prepared at a constant relative density of 80% because fiber-reinforced soil is used in high densities (pavement, slope, foundation) (Choobbasti and Kutanaei 2017; Haeri et al. 2000, 2005; Hamidi and Hooresfand 2013). Triaxial tests were carried out at confining pressures of 50 kPa (which simulated a low depth, such as pavement), 100 kPa (which simulated a medium depth, such as a foundation), and 200 kPa (simulating high depth: deep mixing). The range of pressures that we evaluated is that which typically happens in the majority of geotechnical structures. The confining pressure was determined following the practical loading conditions (Hamidi and Hooresfand 2013; Haeri et al. 2000, 2005).

Test equipment and procedure

The equipment used in this research to carry out the experiments is displayed in Fig. 4. Strain-controlled static triaxial tests were carried out using a triaxial scheme prepared by HEICO Company. The axial load on the sample was measured using a ring type of load cell. The essential parts of the organization were the actuator and load frame, water/air bladder, distribution panel, IMACS controller, triaxial cell, automatic volume change apparatus, and servo reservoir assembly. In this research, a triaxial device was equipped with a data control association. All data was transported with sensors to the control association. The control association transferred them to the software in the form of numbers. The axial displacement with the variety of 50 mm was measured with a displacement transducer and the load cell was applied to the axial load. The cylinder of the load cell

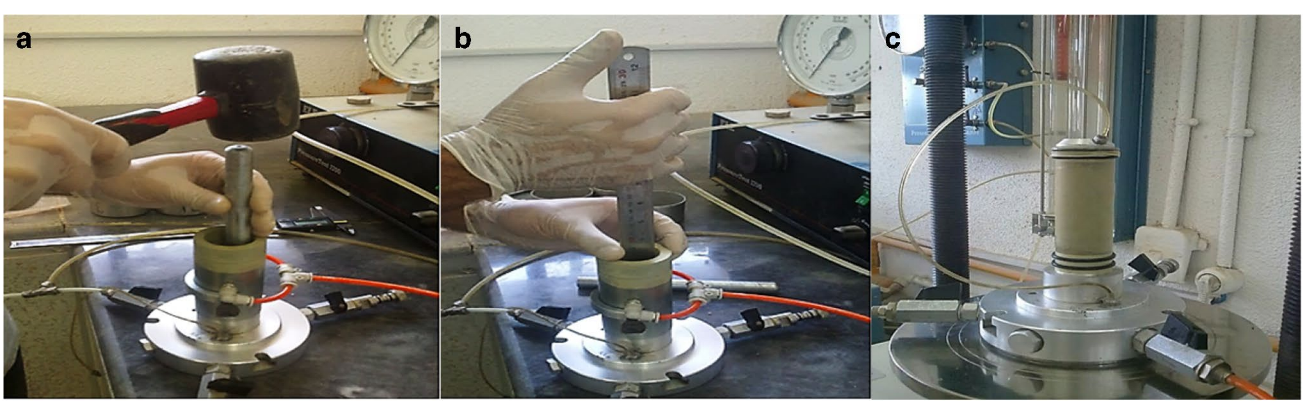

Fig. 3 Steps to prepare a specimen for experimental testing. **a** Compacting a layer of the specimen with a standard percussion. **b** Scratching the surface of the layer before pouring the next layer. **c** Static specimen made by suction

Fig. 4 Triaxial test equipment is used in this study

sustained pressure up to 1500 kPa and was experienced up to 2000 kPa. Axial load was controlled using a load cell with a size of 15 KN. The bladder IMACS controller delivered the required cell pressure, records data, and communication from transducers to the computer for exploring them. Several static triaxial tests were conducted in this study according to ASTM D7181. Strain-controlled consolidated drained triaxial tests were carried out with a strain rate of 0.02%.

Results and discussion

The results of these experiments are presented in the form of strength characteristics, i.e., peak strength, residual strength, failure axial strain, strength increase ratio, brittle index, and volumetric strain (Tables 2, 3, 4, and 5). The strength increase ratio is the ratio of the peak strength of reinforced specimens to unreinforced specimens. The brittle index is the ratio of the difference between peak strength and residual strength to peak strength, which indicates the ductility of the sample. The sample behavior is more ductile the closer this index is to zero.

The effect of reinforcement on stress–strain behavior

Stress–strain curves of unreinforced and reinforced sand (hemp) of Babolsar are determined. The stress–strain curves are plotted in Figs. 5, 6, and 7 for unreinforced and reinforced sand with various fiber contents of 0.3%, 0.6%, and 0.9%, various fiber lengths of 6 mm, 10 mm, and 14 mm, and at various confining pressures of 50 kPa, 100 kPa, and 200 kPa. Examination of the results shows that the presence of fiber increases the peak strength and failure strain

Table 2 Strength properties of reinforced and unreinforced sand (the length of hemp fiber is 6 mm)

Test no	Weight ratio of fibers (%)	Confining pressure (kPa)	Failure strain (%)	Peak deviatoric stress (kPa)	Residual strength (kPa)	Strength increase ratio	Brittle index	Volumetric strain (%)
1	0	50	3.6	252.74	173.95	1	0.31	9.8
2	0	100	4	528.19	350.42	1	0.33	8.7
3	0	200	4.2	1130.37	791.79	1	0.29	7.6
4	0.3	50	4.7	335.85	235.51	1.33	0.31	10.3
5	0.3	100	4.4	660.37	447.46	1.25	0.32	9.8
6	0.3	200	5.3	1365.84	849.91	1.21	0.38	8.8
7	0.6	50	5.2	710.57	414.82	2.84	0.42	9.5
8	0.6	100	5.2	1171.72	726.67	2.22	0.38	7.7
9	0.6	200	6.5	1817.22	1007.42	1.61	0.44	9.3
10	0.9	50	5.7	1088.12	540.21	4.32	0.51	9.1
11	0.9	100	5.7	1755.34	848.56	3.36	0.52	8.7
12	0.9	200	7.1	2573.22	1318.58	2.27	0.49	7.8

Table 3 Strength properties of reinforced and unreinforced sand (the length of hemp fiber is 10 mm)

Test no	Weight ratio of fibers (%)	Confining pressure (kPa)	Failure strain (%)	Peak deviatoric stress (kPa)	Residual Strength (Kpa)	Strength increase ratio	Brittle index	Volumetric strain (%)
1	0	50	3.6	252.74	173.95	1	0.31	9.8
2	0	100	4.1	528.19	350.42	1	0.33	8.7
3	0	200	4.2	1130.37	791.79	1	0.29	7.6
4	0.3	50	5.2	520.38	314.33	2.06	0.39	7.6
5	0.3	100	5.9	854.74	546.37	1.62	0.34	7.8
6	0.3	200	5.7	1570.73	997.53	1.39	0.36	7.2
7	0.6	50	6.1	921.03	528.05	3.61	0.43	7.9
8	0.6	100	6.2	1429.28	828.39	2.72	0.42	6.9
9	0.6	200	6.6	2089.88	1087.33	1.85	0.48	6.5
10	0.9	50	6.5	1510.88	718.45	6.12	0.52	6.8
11	0.9	100	6.4	2476.12	1150.18	4.69	0.53	6.5
12	0.9	200	7.2	3032.22	1488.61	2.71	0.51	5.9

Table 4 Strength properties of reinforced and unreinforced sand (the length of hemp fiber is 14 mm)

Test no	Weight ratio of fibers (%)	Confining pressure (kPa)	Failure strain (%)	Peak deviatoric stress (kPa)	Residual strength (kPa)	Strength increase ratio	Brittle index	Volumetric strain (%)
1	0	50	3.6	252.74	173.95	1	0.31	9.8
2	0	100	4.1	528.19	350.42	1	0.33	8.7
3	0	200	4.2	1130.37	791.79	1	0.29	7.6
4	0.3	50	5.9	914.09	548.35	3.62	0.41	9.5
5	0.3	100	5.2	1168.95	720.71	2.21	0.38	9.3
6	0.3	200	5.4	1690.78	917.78	1.49	0.46	7.4
7	0.6	50	6.5	1536.83	786.94	6.11	0.49	8.1
8	0.6	100	6.1	2002.62	993.12	3.79	0.51	7.1
9	0.6	200	5.7	2333.82	1132.96	2.06	0.52	6.6
10	0.9	50	7.1	2383.97	1006.73	9.43	0.58	8.2
11	0.9	100	6.5	3164.88	1377.41	6.22	0.56	7.2
12	0.9	200	6.3	3345.51	1541.21	2.96	0.54	6.1

of the specimens. Also, the addition of hemp fibers, unlike previous studies with synthetic fibers, does not reduce the drop-in strength after peak strength. These results are similar to the study conducted by Choobbasti et al. (2019a). Choobbasti et al. (2019b) performed triaxial experiments on clay reinforced with carpet fibers and showed that the addition of carpet fibers reduces the decrease in clay strength (resistance drop).

The reason for this is the low tensile strength of hemp fibers against synthetic fibers, so that failure in hemp-reinforced specimens occurs due to fibers failure and increases the strength drop after peak strength. It can be seen in the results that the presence of fibers increases the stiffness of the reinforced specimens. Since the stiffness of sandy soils is a function of confining pressure, this increase in confining pressure due to the presence of fibers increases the stiffness of the sample. This outcome is consistent with Choobbasti et al. (2019a). Choobbasti et al. (2019b) carried out reinforced triaxial experiments on drained sand reinforced with PVA fibers and showed that the stiffness of the reinforced soil depends on the density, confining pressure, and fiber contents.

Results show that the presence of fibers significantly increases the peak strength. For example, for a reinforced specimen with 6 mm long fibers under confining pressure of 100 kPa, the peak strength of the unreinforced specimen is from 528 to 660 kPa for reinforced sand with a weight ratio of 0.3%, to 1171 kPa for reinforced sand with a weight ratio of 0.6, and to 1775 kPa for reinforced sand with a weight ratio of 0.9%. Moreover, for a reinforced specimen with

Table 5 Shear strength parameters are based on the results of the static triaxial test on unreinforced sand and fiber-reinforced sand with hemp fibers

Soil FC = fiber content, FL = fiber length)	Friction angle (deg)	Cohesion (kPa)
Unreinforced	43	0
Reinforced (FC = 0.3%, FL = 6 mm)	49	9
Reinforced (FC = 0.6%, FL = 6 mm)	51	65
Reinforced (FC = 0.9%, FL = 6 mm)	56	100
Reinforced (FC = 0.3%, FL = 10 mm)	51	28
Reinforced (FC = 0.6%, FL = 10 mm)	52	95
Reinforced (FC = 0.9%, FL = 10 mm)	57	163
Reinforced (FC = 0.3%, FL = 14 mm)	46	129
Reinforced (FC = 0.6%, FL = 14 mm)	47	259
Reinforced (FC = 0.9%, FL = 14 mm)	50	385

10 mm long fibers under confining pressure of 100 kPa, the peak strength of the unreinforced specimen is from 528 to 854 kPa for reinforced sand with a weight ratio of 0.3%, and to 2476 kPa for reinforced sand with a weight ratio of 0.9%. In addition, the ratio of increasing resistance decreases with increasing circumferential pressure. These results are consistent with Kutanaei and Choobbasti's research (2016). Kutanaei and Choobbasti (2016) reported that the reduction in dilation due to the increase in confining pressure reduces the interaction of fibers and soil and thus reduces the efficiency of fibers in increasing strength.

Results show that the ratio of increasing the strength of a reinforced specimen with a weight ratio of 0.6% with a fiber length of 6 mm under a confining pressure of 50 kPa is 2.8, under a pressure of 100 kPa is 2.2, and under a pressure of 200 kPa is 1.6. Furthermore, the ratio of increasing the strength of a reinforced specimen with a weight ratio of 0.6% with a fiber length of 10 mm under a confining pressure of 50 kPa is 3.6, and under a pressure of 200 kPa is 1.85. These results are derived from Figs. 5, 6, and 7 as well as Tables 2, 3, and 4. The reason for this is a decrease in the interaction between the sand and the fibers with increasing confining pressure. Because sand under low confining pressures tends to increase in volume (dilation) due to shear, it will therefore engage more with the fibers. These outcomes are similar to the study performed by the published paper. (Choobbasti et al. 2019a; Ghadakpour et al. 2021).

The effect of reinforcement on volumetric behavior

In this section, the volumetric behavior of reinforced specimens with random distribution fiber is investigated. In the following, the results obtained in this study are presented about the volumetric behavior of the samples. According to the results and examination of Fig. 8, it is observed that during the initial shearing, the volume of reinforced and unreinforced sand decreases slightly (a positive sign of volumetric strain indicates an increase in volume or dilation). With increasing shear stresses in the samples, this behavior is reversed and they show an increase in volume. Increasing the confining pressure has caused a decrease, an increase in volume in unreinforced and reinforced sand samples with different weight ratios and lengths of hemp fibers. The presence of hemp fibers reduces the expansion (volume increase) in reinforced sand samples compared to unreinforced samples. As the weight ratio and string length increase, the amount of dilation decreases, which is not a very specific trend. The axial strain in terms of volumetric strain curves is plotted in Fig. 8 for unreinforced and reinforced sand with various fiber contents of 0.3%, 0.6%, and 0.9%, various fiber lengths of 6 mm, 10 mm, and 14 mm, and at various confining pressures of 50 kPa, 100 kPa, and 200 kPa. Koutenaei et al. (2021) reported similar results in reducing sandy soil dilation due to the addition of Kenaf fibers.

The effect of reinforcement on peak strength

According to the results, it can be said that in all cases, the peak strength of reinforced specimens compared to unreinforced specimens has increased. As the fibers' length and percentage increase, the peak strength increases dramatically. The following results have been observed with a detailed examination of Figs. 9 and 10. Reinforcements have two important characteristics, tensile strength and shear strength of the contact surface. Tensile strength is an important property. Because the reinforcer must be able to withstand the tensile pressures transmitted by the soil. But the most important parameter in the soil and reinforcing mechanism is the shear strength of the contact surface, which is responsible for transferring pressures from the soil to the reinforcing. Failure in reinforced soil occurs due to the gradual failure of reinforcing materials or the slipping of reinforcing materials in the soil mass.

Due to the low tensile strength of hemp fibers and their non-expandability compared to synthetic fibers, the strain required for their failure is created within the strain conditions of the test. Therefore, the peak tensile strength (tensile strength at failure) of hemp fibers is one of the main factors in increasing the peak strength of reinforced soil compared to unreinforced. However, a comparison of the increase in sample strength due to the addition of hemp fibers with technical texts that used synthetic fibers shows that hemp fibers had a relatively good increase in strength compared to synthetic fibers if they have lower tensile strength. Therefore, in this regard, another factor that can determine the peak strength of reinforced specimens due to the presence of hemp filaments is the angle of friction between the sand and the fibers. Because

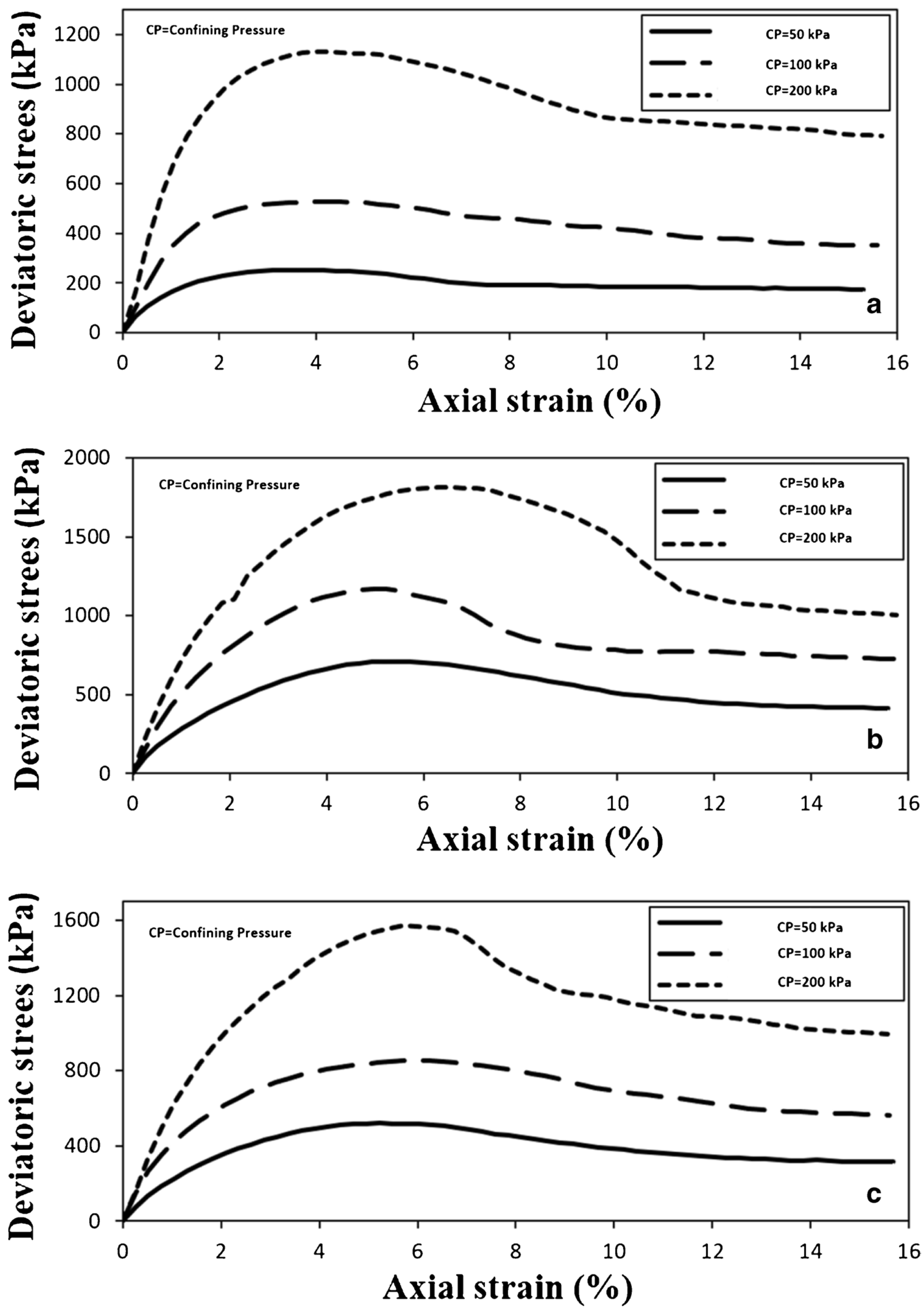

Fig. 5 The stress–strain curve for unreinforced and reinforced sand at various confining pressures of 50 kPa, 100 kPa, and 200 kPa. **a** Unreinforced soil. **b** Reinforced soil with a fiber content of 0.6% and fiber length of 6 mm. **c** Reinforced soil with a fiber content of 0.3% and fiber length of 10 mm

the larger this angle, the greater the shear stresses created between the sand and the fibers, and as a result the greater the tensile force in the fibers. The greater the tensile force generated in the fibers, the greater the strength due to their presence in the specimens. Ghadakpour et al. (2020) by conducting various experimental tests on kenaf fiber-reinforced cement sand, reported that the addition of hemp fiber increased compressive and tensile strength. However, fiber tires are more than compressive strength in improving tensile strength.

It can be said that with increasing fibers percentage, the process of increasing the peak strength is almost uniform and slightly increasing. However, for 10- and 14-mm fibers and fiber ratios of 0.9% compared to the reinforced samples with lower weight ratios, there is an increasing trend in increasing its strength. In the laboratory, while making the sample in a two-piece mold, it was observed that hammering the reinforced specimens into strands with higher lengths and a weight ratio of 0.9% is more difficult than all other specimens. Much harder hammer blows were needed

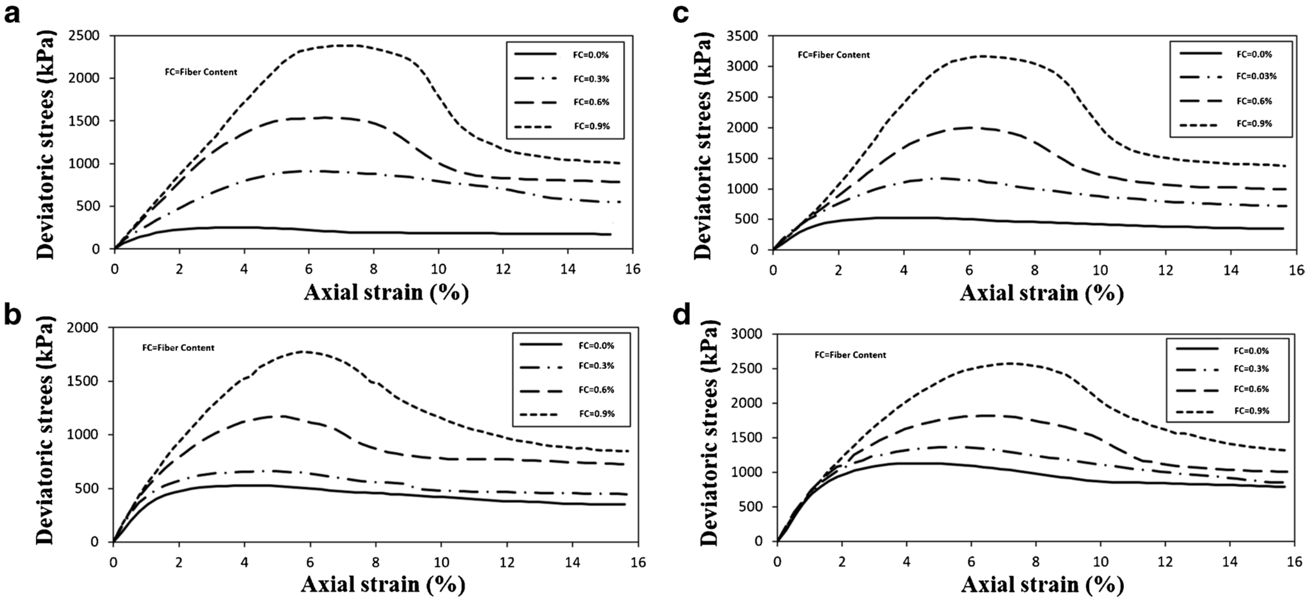

Fig. 6 The stress–strain curve for unreinforced and reinforced sand at various fiber contents of 0.3%, 0.6%, and 0.9%. **a** Unreinforced and reinforced soil with confining pressure of 50 kPa and fiber length of 14 mm. **b** Unreinforced and reinforced soil with confining pressure of 100 kPa and fiber length of 6 mm. **c** Unreinforced and reinforced soil with confining pressure of 100 kPa and fiber length of 14 mm. **d** Unreinforced and reinforced soil with confining pressure of 200 kPa and fiber length of 6 mm

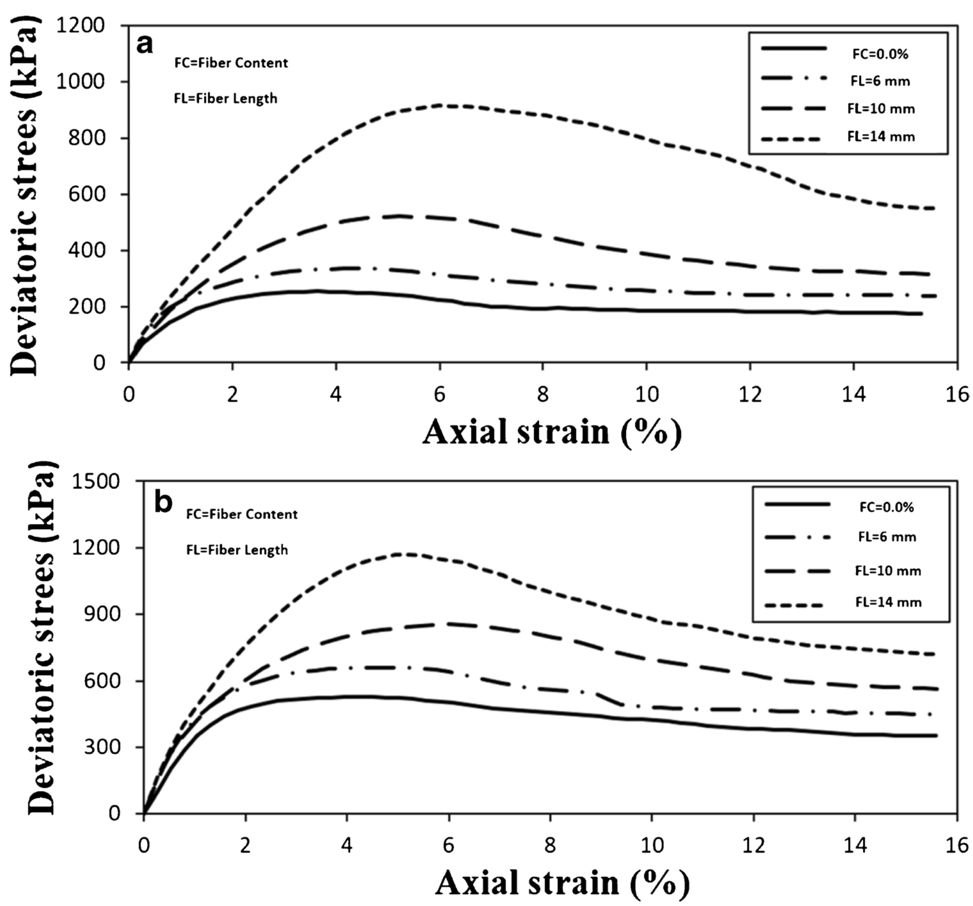

Fig. 7 The stress–strain curve for unreinforced and reinforced sand at various fiber lengths of 6 mm, 10 mm, and 14 mm. **a** Unreinforced and reinforced soil with confining pressure of 50 kPa and fiber content of 0.3%. **b** Unreinforced and reinforced soil with confining pressure of 100 kPa and fiber content of 0.3%

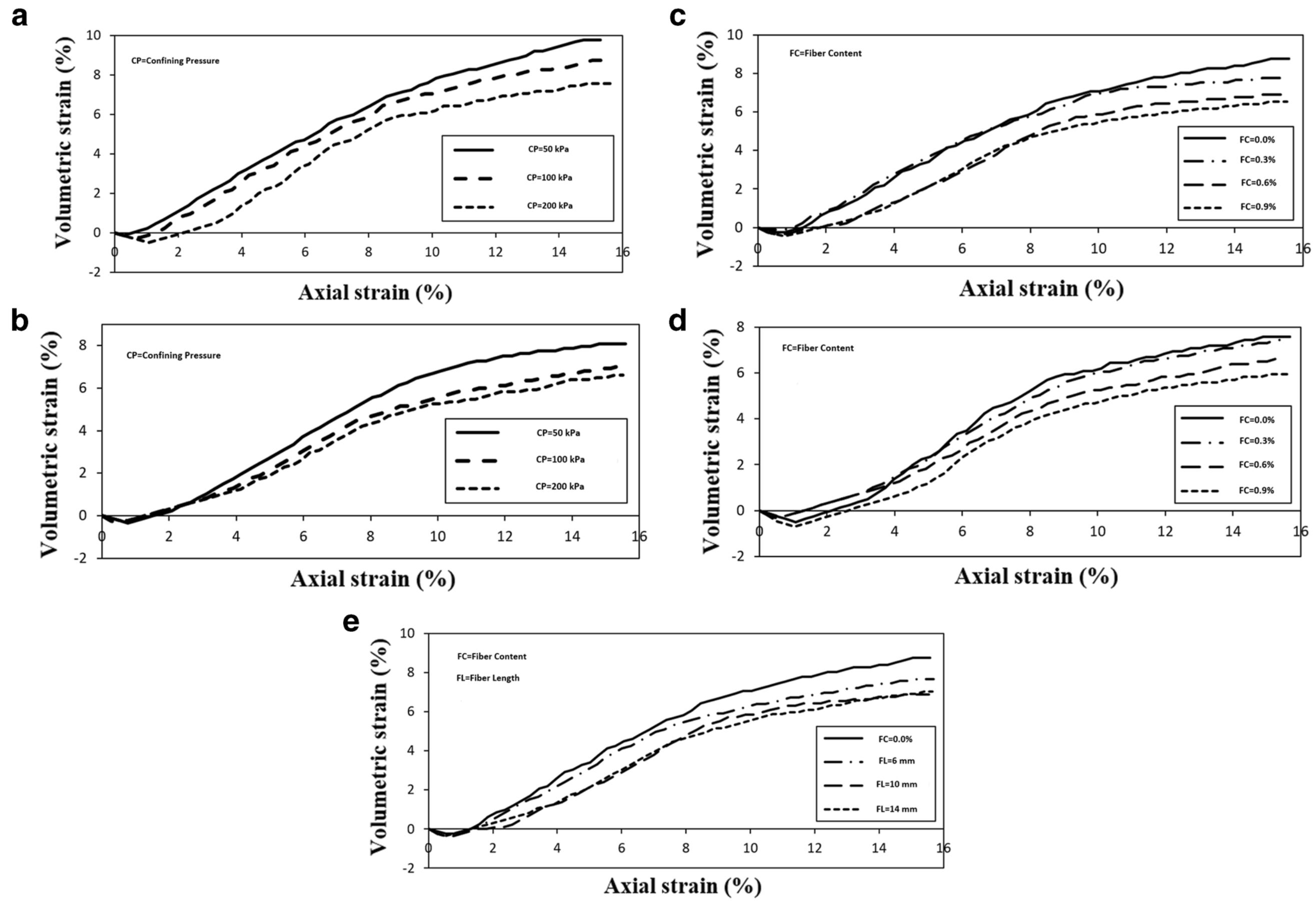

Fig. 8 The curve of axial strain in terms of volumetric strain for unreinforced and reinforced sand with the various fiber contents of 0.3%, 0.6%, and 0.9%, fiber lengths of 6 mm, 10 mm, and 14 mm, confining pressures of 50 kPa, 100 kPa, and 200 kPa. **a** Unreinforced soil with various confining pressures of 50 kPa, 100 kPa, and 200 kPa. **b** Reinforced soil with a fiber content of 0.6% and fiber length of 14 mm. **c** Unreinforced and reinforced soil with confining pressure of 100 kPa and fiber length of 10 mm. **d** Unreinforced and reinforced soil with confining pressure of 200 kPa and fiber length of 14 mm. **e** Unreinforced and reinforced soil with confining pressure of 100 kPa and fiber content of 0.6%

to achieve the desired density. Thus, at the end of the fabrication operation, in the resulting sample, which has hardly reached the desired density, the soil particles are more involved with the fiber body and a very strong and cohesive mass is in hand. In this specimen, the performance of the fiber increases significantly. This may be the reason for this increasing trend of peak strength in the mentioned samples. It can be concluded that by increasing the confining pressure, the effect of increasing the weight ratio and fiber length on increasing the peak strength decreases.

As the length of the fibers increases, the peak strength increases, which has a relatively uniform process of increasing strength. Here, the rate of increase for the fiber length is 14 mm. According to the results, it can be stated that with increasing the confining pressure, the peak strength increases, which is the amount of this increase in strength in the steps of increasing the confining pressure, decreases. Figure 10 shows the normalized strength (the ratio of the peak strength at the desired confining pressure to the peak strength at the confining pressure of 50 kPa). The point to be noted is that the slope of the normalized strength diagram is steeper as the confining pressure increases for smaller fiber lengths. This shows that with increasing pressure, the effect of increasing the length on increasing the maximum resistance decreases.

It can be seen from the results that at a constant fiber length and ratio, the strength increase ratio decreases with increasing confining pressure. The reason for this is that at high pressures, the unreinforced soil itself has high strength, and the addition of fibers to this soil increases the strength lesser than the soil, which is under less confining pressure and has lower strength. Another factor that can be effective in this case is that with increasing pressure, the tendency to dilation decreases and, as a result, the involvement of sand and fibers due to the increase in sand volume, which is one of the positive factors in the interlocking of soil grains and

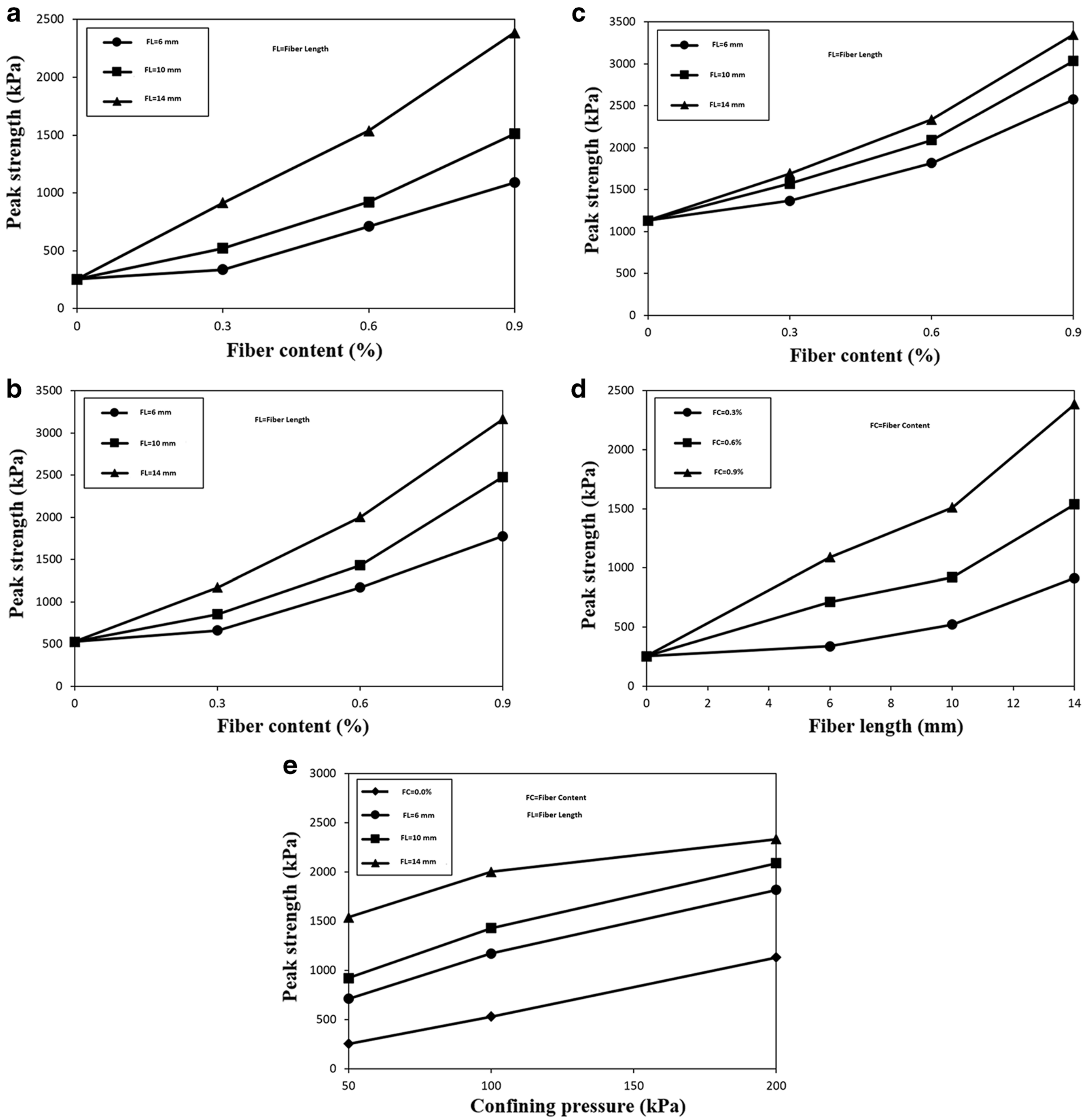

Fig. 9 The curve of peak strength for unreinforced and reinforced sand with the various fiber contents of 0.3%, 0.6%, and 0.9%, fiber lengths of 6 mm, 10 mm, and 14 mm, confining pressures of 50 kPa, 100 kPa, and 200 kPa. **a** Reinforced soil with confining pressure of 50 kPa in terms of various fiber content. **b** Reinforced soil with confining pressure of 100 kPa in terms of various fiber content. **c** Reinforced soil with confining pressure of 200 kPa in terms of various fiber content. **d** Reinforced soil with confining pressure of 50 kPa in terms of various fiber lengths. **e** Unreinforced and reinforced soil with various confining pressures

fibers, is reduced. It can be seen that the addition of 6-mm fibers to the soil, in the highest case (fiber weight ratio of 0.9% and 50 kPa confining pressure) causes a 331% increase in peak strength and the lowest state (fiber weight ratio of 0.3% and 200 kPa confining pressure) increases the peak strength by 21%. For 10- and 14-mm fibers, the maximum and minimum strength increase ratios occur in the mentioned conditions for 6-mm fibers. Thus, for 10-mm fibers, the maximum and minimum strength increases are 499% and 39%, respectively. These values are 845% and 49% for 14-mm-long fiber, respectively. These results were obtained from a detailed study of Figs. 9 and 10. These outcomes

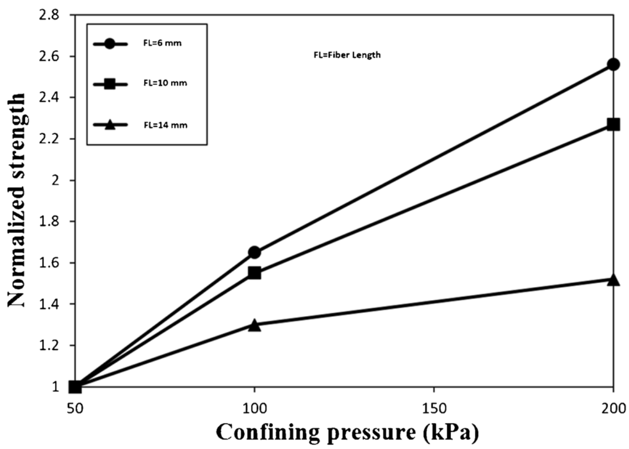

Fig. 10 The curve of normalized strength for reinforced sand with a fiber content of 0.6% and various confining pressures of 50 kPa, 100 kPa, and 200 kPa and fiber lengths of 6 mm, 10 mm, and 14 mm

agreed with the study performed by the published paper (Choobbasti et al. 2019b).

The effect of reinforcement on failure strain

Due to the low tensile strength of hemp fibers and their non-expandability compared to synthetic fibers, the strain required for their failure occurs within the test strain conditions. Therefore, the peak tensile strength (tensile strength at failure) of hemp fibers is one of the main factors in increasing the peak strength of reinforced soil compared to unreinforced. Therefore, the tensile strength of hemp fibers has been a determining factor in the failure of specimens. In this study, the addition of hemp fibers caused an increase in failure strain compared to unreinforced samples. However, this increase in failure strain is less than the increase in failure strain due to the addition of synthetic fibers because synthetic fibers have better tensile properties than hemp fibers.

According to Fig. 11, it can be seen that the addition of fibers to the soil increases the failure strain. It seems that the flexibility of hemp fibers in comparison with sand grain materials is effective on the flexibility of sand reinforced with hemp fiber and increases the axial strain in its failure compared to that of unreinforced sand. Also, with increasing the weight ratio of the fiber, the failure strain continues with a relatively decreasing trend. However, at 100 and 200 kPa pressures, the failure strain of fiber length by 14 mm is reduced in all string weight ratios, compared to the fiber length of 10 mm. For example, the failure strain for a sample with a weight ratio of 0.9% of hemp fiber with a length of 10 mm at a confining pressure of 200 kPa is equal to 7.2%, which is a 71% increase compared to the failure strain of unreinforced sand by 4.2%. These results are similar to the study performed by other researchers (Ghadakpour et al. 2021).

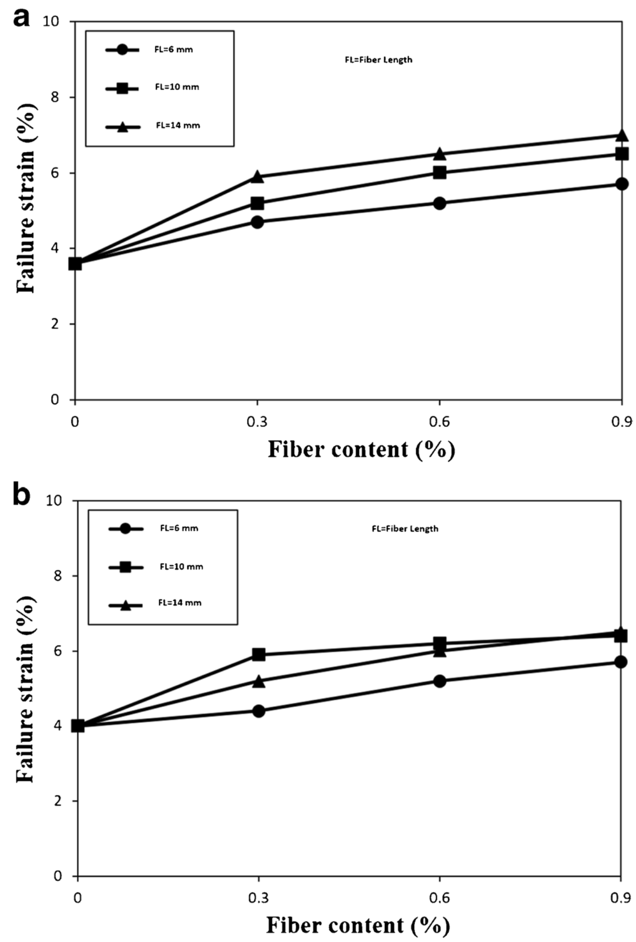

Fig. 11 The curve of failure strain for reinforced sand with the various fiber contents of 0.3%, 0.6%, and 0.9%, fiber lengths of 6 mm, 10 mm, and 14 mm, confining pressures of 50 kPa, and 100 kPa. **a** Configure pressure of 50 kPa. **b** Configure pressure of 100 kPa

The effect of reinforcement on residual strength

Residual strength is the resistance that the soil shows after failure, and usually, a strain resistance of 15% is considered a residual strength. The lower the strength drop after the peak strength, the soil retains much of its strength after failure and deformation, and the less damage is done to the structure built on it. According to the technical texts, adding fibers to the reinforced soil reduces the drop-in strength after peak strength. This behavior shows that the presence of fibers causes more flexibility in the behavior of reinforced samples compared to unreinforced samples. The reason for this is that the presence of fiber prevents the creation of a shear band in the samples. The formation of the shear band is the cause of strength drop after peak strength in unreinforced sand samples. The reason for this can also be explained by the fact that when the specimens are loaded, the fibers act like bridges, and this action of theirs increases the soil strength to high deformation. However, the results of the present study on hemp fibers show that after peak strength, a sudden drop in the stress–strain curve occurred. The reason for this is the low failure strain in hemp fibers. In other words, due to the low tensile strength of hemp fibers, the strain required for their failure is created within the strain conditions of the experiment, and a sharp drop in the stress–strain curve of reinforced specimens is seen. This point is one of the main weaknesses of hemp fibers against synthetic fibers with high tensile strength.

It is clear that with increasing the weight ratio and the length of the fiber, the residual strength increases, but the rate of decrease in strength also increases with increasing the weight ratio and the length of the fiber. For this reason, the brittle index was previously defined as an indicator to show the degree of soil ductility. This index is the ratio of the difference between the peak strength and the residual strength to the peak strength. The closer this index is to zero, the more ductility the sample behavior is. According to Fig. 12, it is clear that with increasing the weight ratio and fiber length, the value of the brittle index increases and causes the behavior of the reinforced sample to be more brittle than the unreinforced sample. Ghadakpour et al. (2019) testified that the rate of decrease in cementitious soil strength decreases dramatically with the increasing percentage of PVA fibers.

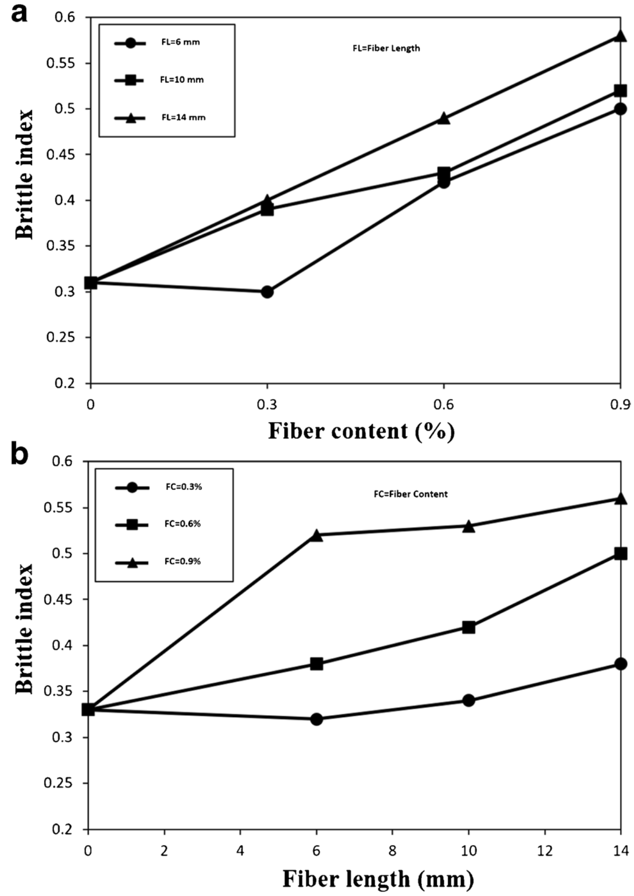

Fig. 12 The curve of the brittle index for reinforced sand with various fiber contents of 0.3%, 0.6%, and 0.9%, fiber lengths of 6 mm, 10 mm, and 14 mm, confining pressures of 50 kPa, and 100 kPa. **a** Configure pressure of 50 kPa. **b** Configure pressure of 100 kPa

The effect of reinforcement on stiffness

Stiffness is one of the factors affecting the behavior of soils that controls the rate of deformation and settlement under loading.

As shown in the stress–strain diagrams, the addition of hemp fibers to the sand has increased the stiffness of the reinforced specimens. According to Fig. 13, it is clear that by increasing the weight ratio and the length of the hemp fiber, the stiffness (sequence modulus) corresponding to the pear deviatoric stress (linear slope that in the deviatoric stress diagram in terms of axial strain, connects the origin of the coordinates to the point corresponding to the peak deviatoric stress) increases, which is almost increasing in stiffness. Results also show that with increasing confining pressure, the stiffness corresponding to the peak deviatoric stress increases. Kutanaei and Choobbasti (2017) stated that a decrease in the tendency of lateral deformations due to the addition of fibers caused an increase in soil stiffness.

The effect of reinforcement on the failure envelope

In this section, by presenting the failure envelope, the effect of discrete fibers with random distribution on soil strength parameters (φ and C) is investigated (Table 5). It should be noted here that the cohesion created by the act of reinforcement in non-cohesive materials was defined as "apparent cohesion." In general, the improvement of soil strength properties or shear strength due to reinforcement in the failure envelope is obvious. As shown in Fig. 14 and also according to the results, by adding the fibers to the sand, the failure envelope moves up and to the right. This upward trend continues with the increase in fiber content. Results also show that the strength properties increase with the addition of fibers to unreinforced sand. This upward trend continues with the increase in fiber content. Koutenaei et al. (2021) stated similar consequences regarding soil strength parameters according to the addition of Kenaf fibers in sandy soils. It is noteworthy that in this study, only one type of soil and only Babolsar sand were studied. Different types of soil can be used in future projects, and the effect of durability can be studied and investigated for reinforced soil as well.

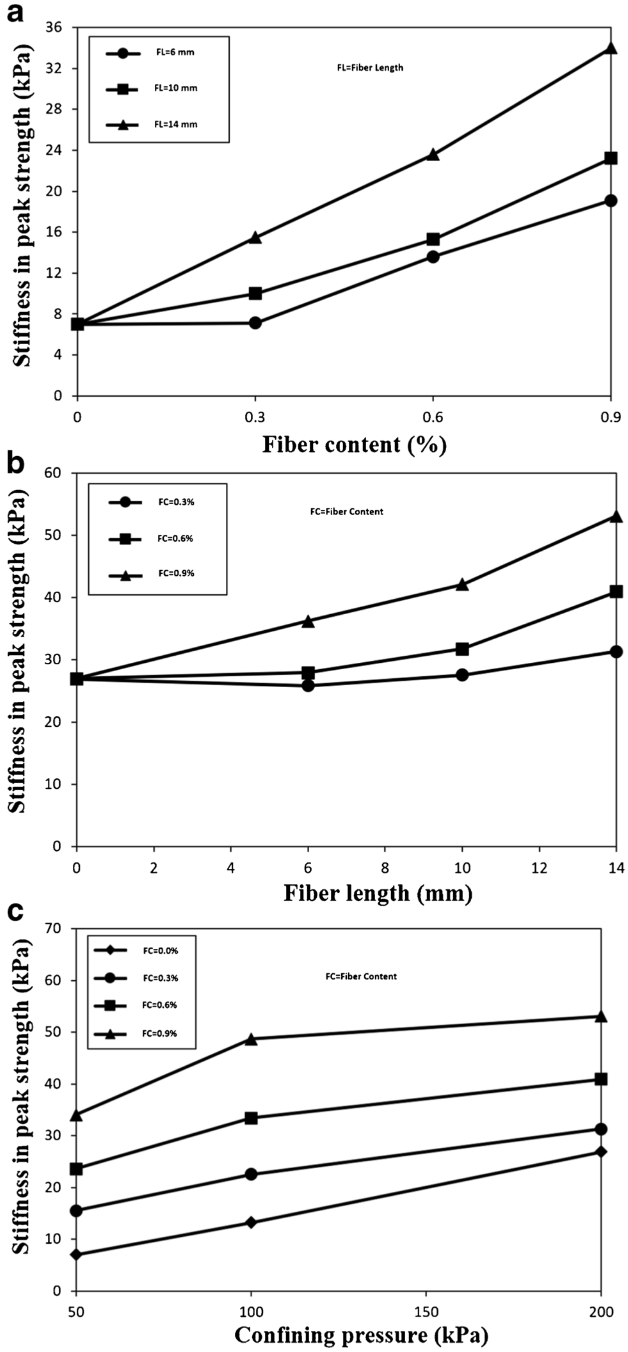

Fig. 13 The curve of stiffness in peak strength for unreinforced and reinforced sand with the various fiber contents of 0.3%, 0.6%, and 0.9%, fiber lengths of 6 mm, 10 mm, and 14 mm, confining pressures of 50 kPa, 100 kPa, and 200 kPa. **a** Configure pressure of 50 kPa. **b** Configure pressure of 200 kPa. **c** Fiber length of 14 mm

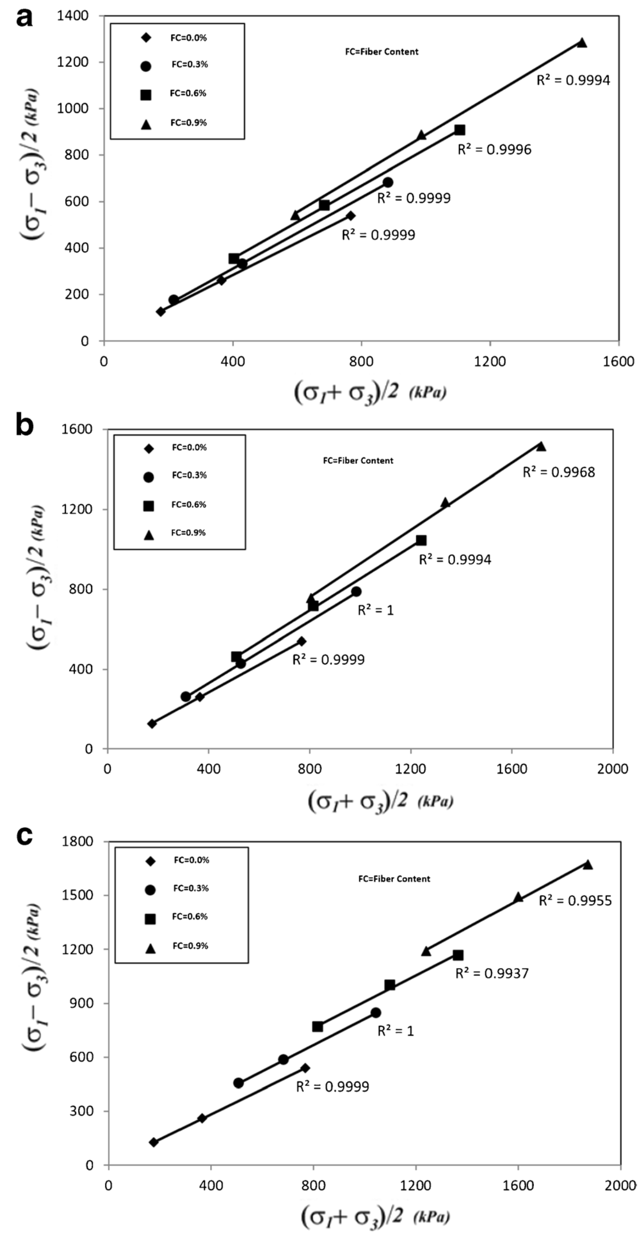

Fig. 14 The failure envelope for unreinforced and reinforced sand with various fiber contents of 0.3%, 0.6%, and 0.9%, fiber lengths of 6 mm, 10 mm, and 14 mm. **a** The fiber length of 6 mm. **b** The fiber length of 10 mm. **c** The fiber length of 14 mm

Conclusion

In this study, several triaxial experiments were performed on Babolsar sand reinforced with natural fibers to investigate the stress–strain properties and how various factors affect the behavior of materials. Enhancing soil behavior should be aligned with functional considerations and real-world instances. The usage of fibers in geotechnical engineering can be applied in the five categories of pavement, retaining walls, slope stability, foundations, and earthquake, according to a thorough analysis of this research on reinforced soil. So far, no extensive study has been done on the behavior of sand reinforced with hemp fiber, and the results of this research will be of great help to civil and geotechnical engineers.

The resistive behavior of Babolsar sand reinforced with randomly distributed hemp fibers was examined in this study using several static triaxial tests. Hemp fibers with lengths of 6, 10, and 14 mm were incorporated into the soil at percentages of 0.3, 0.6, and 0.9% by dry weight. At confining pressures of 50, 100, and 200 kPa, static triaxial tests were conducted.

The summary of the results is as follows:

The results show that adding 6-mm fibers to soil enhances peak strength by 331% under the best conditions (fiber weight ratio of 0.9% and 50 kPa confining pressure) and by just 21% under the lowest conditions (fiber weight ratio of 0.3% and 200 kPa confining pressure). The optimal content of fiber is around 0.9%.

For 10-mm and 14-mm fibers, the maximum and minimum strength increase ratios occur under the same conditions as for 6-mm fibers. Thus, for 10-mm fibers, the maximum and minimum strength improvements are 499% and 39%, respectively. These percentages are 845% and 49%, respectively, for fiber that is 14 mm long. The optimal length of fibers is around 14 mm.

It is important to note that unreinforced soil has an internal friction angle of 43°. For reinforced soil containing 0.3% fiber with a length of 6 mm, this value is equal to 49°, and for reinforced soil including 0.9% fiber with a length of 10 mm, it often reaches 57°. A sample of reinforced soil with 0.3% fiber and a length of 6 mm has a cohesion of 65 kPa, whereas a sample with 0.9% fiber and a length of 14 mm typically has a cohesion of 385 kPa.

In every instance, the peak strength is increased by mixing hemp fibers with sand. Peak strength considerably rises as the fibers' length-to-weight ratio increases. Peak resistance rises along with the confining pressure as it rises, and as the confining pressure rises, it decreases.

The effect of increasing the weight ratio and length of the fiber on enhancing the peak strength decreases as the confining pressure is raised in sand samples reinforced with hemp fibers. The dilatation can be reduced by mixing hemp fibers with unreinforced sand, but it is unclear how this reduction is achieved.

Hemp fibers are added to unreinforced sand, increasing the failure strain. Additionally, the failure strain rises as the weight ratio does as well. However, compared to synthetic fibers with high tensile strength, the increase in failure strain brought on by the inclusion of hemp fibers is less. Since hemp fibers have low tensile strength and their failure strain occurs under the experiment's strain settings.

Due to their low tensile strength, hemp fibers have some disadvantages over synthetic fibers, including the tendency to fail under strain under experimental conditions. Due to this flaw, the sample's strength abruptly decreased after reaching peak strength, and the brittleness index of reinforced samples increased in comparison to unreinforced sand.

The stiffness has been improved by mixing hemp fibers with unreinforced sand. With more confining pressure, stiffness also gets stiffer. The failure envelope shifts up and to the right as the fibers are added to the sand. With a rise in the weight ratio of the fiber, this rising trend continues.

Data availability All data, models, and code generated or used during the study appear in the submitted article.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Akil H, Omar MF, Mazuki AAM, Safiee SZAM, Ishak ZM, Bakar AA (2011) Kenaf fiber reinforced composites: a review. Mater Des 32(8–9):4107–4121. https://doi.org/10.1016/j.matdes.2011.04.008

Ang EC, Loehr JE (2003) Specimen size effects for fiber-reinforced silty clay in unconfined compression. Geotech Test J 26(2):191–200. https://doi.org/10.1520/GTJ11320J

Bascetin A, Adiguzel D, Eker H, Odabas E, Tuylu S (2020) Effects of pozzolanic materials in surface paste disposal by pilot-scale tests: observation of physical changes. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-020-02892-w

Cabalar AF, Karabash Z (2015) California Bearing Ratio of a sub-base material modified with tire buffings and cement addition. J Test Eval 43(6):1279–1287. https://doi.org/10.1520/JTE20130070

Choobbasti AJ, Kutanaei SS (2017) Microstructure characteristics of cement-stabilized sandy soil using nanosilica. J Rock Mech Geotech Eng 9(5):981–988. https://doi.org/10.1016/j.jrmge.2017.03.015

Choobbasti AJ, Tavakoli H, Kutanaei SS (2014) Modeling and optimization of a trench layer location around a pipeline using artificial neural networks and particle swarm optimization algorithm. Tunn Undergr Space Technol 40:192–202. https://doi.org/10.1016/j.tust.2013.10.003

Choobbasti AJ, Vafaei A, Kutanaei SS (2018) Static and cyclic triaxial behavior of cemented sand with nanosilica. J Mater Civ Eng 30(10):04018269. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002464

Choobbasti AJ, Kutanaei SS, Ghadakpour M (2019a) Shear behavior of fiber-reinforced sand composite. Arab J Geosci 12(5):1–6. https://doi.org/10.1007/s12517-019-4326-z

Choobbasti AJ, Samakoosh MA, Kutanaei SS (2019b) Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers. Constr Build Mater 211:1094–1104. https://doi.org/10.1016/j.conbuildmat.2019.03.306

Choobbasti AJ, Vafaei A, Kutanaei SS (2015) Mechanical properties of sandy soil improved with cement and nanosilica. Open Eng 5(1). https://doi.org/10.1515/eng-2015-0011

Consoli NC (2014) A method proposed for the assessment of failure envelopes of cemented sandy soils. Eng Geol 169:61–68. https://doi.org/10.1016/j.enggeo.2013.11.016

Consoli NC, Montardo JP, Donato M, Prietto PDM (2004) Effect of material properties on the behavior of sand–cement–fibre composites. Ground Improv 8(2):77–90. https://doi.org/10.1680/grim.8.2.77.36370

Consoli NC, Vendruscolo MA, Fonini A, Dalla Rosa F (2009) Fiber reinforcement effects on sand considering a wide cementation range. Geotext Geomembr 27(3):196–203. https://doi.org/10.1016/j.geotexmem.2008.11.005

Consoli NC, Bassani MAA, Festugato L (2010) Effect of fiber-reinforcement on the shear strength of cemented soils. Geotext Geomembr 28(4):344–351. https://doi.org/10.1016/j.geotexmem.2010.01.005

Consoli NC, Consoli BS, Festugato L (2013) A practical methodology for the determination of failure envelopes of fiber-reinforced cemented sands. Geotext Geomembr 41:50–54. https://doi.org/10.1016/j.geotexmem.2013.07.010

Consoli NC, Nierwinski HP, da Silva AP, Sosnoski J (2017) Durability and strength of fiber-reinforced compacted gold tailings-cement blends. Geotext Geomembr 45(2):98–102. https://doi.org/10.1016/j.geotexmem.2017.01.001

Diambra A, Ibraim E, Wood DM, Russell AR (2010) Fibre reinforced sands: experiments and modeling. Geotext Geomembr 28(3):238–250. https://doi.org/10.1016/j.geotexmem.2009.09.010

Eker H, Bascetin A (2022) Influence of silica fume on mechanical property of cemented paste backfill. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2021.126089

Gao Z, Zhao J (2013) Evaluation on failure of fiber-reinforced sand. J Geotech Geoenviron Eng 139(1):95–106. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000737

Ghadakpour M, Janalizadeh Choobbasti A, Soleimani Kutanaei S (2019) Investigation of the deformability properties of fiber reinforced cemented sand. J Adhes Sci Technol 33(17):1913–1938. https://doi.org/10.1080/01694243.2019.1619224

Ghadakpour M, Choobbasti AJ, Kutanaei SS (2020) Investigation of the Kenaf fiber hybrid length on the properties of the cement-treated sandy soil. Transp Geotech 22:100301. https://doi.org/10.1016/j.trgeo.2019.100301

Ghadakpour M, Fakhrabadi A, Choobbasti AJ, Kutanaei SS, Vafaei A, Taslimi MPA, Eisazadeh N (2021) Effect of post-construction moisture condition on mechanical behavior of Fiber-reinforced-cemented-sand (FRCS). Geomech Geoeng 1–13https://doi.org/10.1080/17486025.2021.1980230

Gray DH, Al-Refeai T (1986) Behavior of fabric-versus fiber-reinforced sand. J Geotech Eng 112(8):804–820. https://doi.org/10.1061/(ASCE)0733-9410(1986)112:8(804)

Gray DH, Ohashi H (1983) Mechanics of fiber reinforcement in the sand. J Geotech Eng 109(3):335–353. https://doi.org/10.1061/(ASCE)0733-9410(1983)109:3(335)

Haeri SM, Noorzad R, Oskoorouchi AM (2000) Effect of geotextile reinforcement on the mechanical behavior of sand. Geotext Geomembr 18(6):385–402. https://doi.org/10.1016/S0266-1144(00)00005-4

Haeri SM, Hamidi A, Tabatabaee N (2005) The effect of gypsum cementation on the mechanical behavior of gravely sands. Geotech Test J 28:180–190. https://doi.org/10.1520/GTJ12574

Hamidi A, Hooresfand M (2013) Effect of fiber reinforcement on triaxial shear behavior of cement treated sand. Geotext Geomembr 36:1–9. https://doi.org/10.1016/j.geotexmem.2012.10.005

Hejazi SM, Sheikhzadeh M, Abtahi SM (2012) A simple review of soil reinforcement by using natural and synthetic fibers. Constr Build Mater 30:100–116. https://doi.org/10.1016/j.conbuildmat.2011.11.045

Htut ZM, Azhar MM, Chao KC (2019) Evaluation of the relationship between swelling pressures determined by consolidation-swell test and constant volume test. 7th Asia-Pacific Conference on Unsaturated Soils (AP-UNSAT 2019), 7(2), 250–255. https://doi.org/10.3208/jgssp.v07.039

Jamei M, Villard P, Guiras H (2013) Shear failure criterion based on experimental and modeling results for fiber reinforced clay. Int J Geomech 13(6):882–893. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000258

Karimzadeh AA, Leung AK, Fardad AP (2022) Energy-Based Assessment of Liquefaction Resistance of Rooted Soil. J Geotech Geoenviron Eng 148(1):06021016. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002717

Koutenaei RY, Choobbasti AJ, Kutanaei SS (2021) Triaxial behavior of a cemented sand reinforced with Kenaf fibres. Eur J Environ Civ Eng 25(7):1268–1286. https://doi.org/10.1080/19648189.2019.1574607

Kumar A, Walia BS, Mohan J (2006) Compressive strength of fiber-reinforced highly compressible clay. Constr Build Mater 20(10):1063–1068. https://doi.org/10.1016/j.conbuildmat.2005.02.027

Kutanaei SS, Choobbasti AJ (2015) Mesh-free modeling of liquefaction around a pipeline under the influence of trench layer. Acta Geotech 10(3):343–355. https://doi.org/10.1007/s11440-015-0381-0

Kutanaei SS, Choobbasti AJ (2016) Triaxial behavior of fiber-reinforced cemented sand. J Adhes Sci Technol 30(6):579–593. https://doi.org/10.1080/01694243.2015.1110073

Kutanaei SS, Choobbasti AJ (2017) Effects of nanosilica particles and randomly distributed fibers on the ultrasonic pulse velocity and mechanical properties of cemented sand. J Mater Civ Eng 29(3):04016230. https://doi.org/10.1061/(ASCE)MT.1943-5533.000176

Kutanaei SS, Choobbasti AJ (2019) Prediction of liquefaction potential of sandy soil around a submarine pipeline under earthquake loading. J Pipeline Syst Eng Pract 10(2):04019002. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000349

Kutanaei SS, Choobbasti AJ, Fakhrabadi A, Ghadakpour M, Vafaei A, Taslimi MPA (2022) Application of LRBF-DQ and CVBFEM Methods for Evaluating Saturated Sand Liquefaction around Buried Pipeline. J Pipeline Syst Eng Pract 13(1):04021077. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000625

Ladd R (1978) Preparing test specimens using under compaction. Geotech Test J 1(1):16–23. https://doi.org/10.1520/GTJ10364J

Liu J, Wang G, Kamai T, Zhang F, Yang J, Shi B (2011) Static liquefaction behavior of saturated fiber-reinforced sand in undrained ring shear tests. Can Geotech J 29:462–471. https://doi.org/10.1016/j.geotexmem.2011.03.002

Maher MH, Gray DH (1990) Static response of reinforced with randomly distributed fibers. J Geotech Eng 116(11):1661–1677. https://doi.org/10.1061/(ASCE)0733-9410(1990)116:11(1661)

Malidarreh NR, Shooshpasha I, Mirhosseini SM, Dehestani M (2018) Effects of reinforcement on mechanical behavior of cement treated sand using direct shear and triaxial tests. Int J Geotech Eng 12(5):491–499. https://doi.org/10.1080/19386362.2017.1298300

Nataraj MS, McManis KL (1997) Strength and deformation properties of soils reinforced with fibrillated fibers. Geosynth Int 4(1):65–79. https://doi.org/10.1680/gein.4.0089

Fardad Amini R, Fardad AP (2014) Liquefaction resistance of Babolsar sand reinforced with randomly distributed fibers under cyclic loading. Soil Dyn Earthq Eng 66:281–292. https://doi.org/10.1016/j.soildyn.2014.07.011

Noorzad R, Mirmoradi SH (2010) Laboratory evaluation of the behavior of a geotextile reinforced clay. Geotext Geomembr 28(4):386–392. https://doi.org/10.1016/j.geotexmem.2009.12.002

Noorzad R, Zarinkolaei STG (2015) Comparison of mechanical properties of fiber-reinforced sand under triaxial compression and direct shear. Open Geosci 7(1):547–558. https://doi.org/10.1515/geo-2015-0041

Pino LFM, Baudet BA (2015) The effect of the particle size distribution on the mechanics of fiber-reinforced sands under one-dimensional compression. Geotext Geomembr 43:250–258. https://doi.org/10.1016/j.geotexmem.2015.02.004

Qu J, Zhao D (2016) Stabilizing the cohesive soil with palm fiber sheath strip. Road Mater Pavement Des 17(1):87–103. https://doi.org/10.1080/14680629.2015.1064010

Sahin DD, Isik E, Isik I, Cullu M (2021) Artificial neural network modeling for the effect of fly ash fineness on compressive strength. Arab J Geosci. https://doi.org/10.1007/s12517-021-09120-w

Shao W, Cetin B, Li Y, Li J, Li L (2014) Experimental investigation of mechanical properties of sands reinforced with discrete randomly distributed fiber. Geotech Geol Eng 32(4):901–910. https://doi.org/10.1007/s10706-014-9766-3

Shen Y, Tang Y, Jie Y, Li MP, Wen T (2021) An experimental investigation on strength characteristics of fiber-reinforced clayey soil treated with lime or cement. Constr Build Mater 294 (123537). https://doi.org/10.1016/j.conbuildmat.2021.123537

Silveira MV, Ferreira WDS, Casagrande MDT (2022) Effect of surface treatment on natural aging and mechanical behavior of sisal fiber–reinforced sand composite. J Mater Civ Eng 34(6) https://doi.org/10.1061/(ASCE)MT.1943-5533.0004237.

Tang CS, Shi B, Gao W, Chen F, Cai Y (2007) Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotext Geomembr 25(3):194–202. https://doi.org/10.1016/j.geotexmem.2006.11.002

Tang C, Shi B, Cui Y, Liu C, Gu K (2012) Desiccation cracking behavior of polypropylene fiber-reinforced clayey soil. Can Geotech J 49(9):1088–1101. https://doi.org/10.1139/t2012-067

Tang CS, Wang DY, Cui YJ, Shi B, Li J (2016) Tensile strength of fiber-reinforced soil. J Mater Civ Eng 28(7):04016031. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001546

Turk K, Nehdi ML (2021) Flexural toughness of sustainable ECC with high-volume substitution of cement and silica sand. Constr Build Mater 270:121438. https://doi.org/10.1016/j.conbuildmat.2020.121438

Vafaei A, Choobbasti AJ, Kutanaei SS, Taslimi MPA (2022) The presence of colloidal nano silica in sandy soils: a review. Arab J Geosci 15:582. https://doi.org/10.1007/s12517-022-09908-4

Vakili AH, Salimi M, Lu Y, Shamsi M, Nazari Z (2022) Strength and post-freeze-thaw behavior of a marl soil modified by lignosulfonate and polypropylene fiber: an environmentally friendly approach. Constr Build Mater (332) 127364https://doi.org/10.1016/j.conbuildmat.2022.127364

Yaghoubi M, Shukla SK, Mohyeddin A (2018) Effects of addition of waste tyre fibers and cement on the engineering behavior of Perth sand. Geomech Geoeng 13(1):42–53. https://doi.org/10.1080/17486025.2017.1325941

Yetimoglu T, Salbas O (2003) A study on shear strength of sands reinforced with randomly distributed discrete fibers. Geotext Geomembr 21(2):103–110. https://doi.org/10.1016/S0266-1144(03)00003-7

Yuxai B, Jin L, Yujun C, Xiao S, Zezhuo S, Qi C (2021) Mechanical behavior of polymer stabilized sand under different temperatures. Constr Build Mater 290 (123237). https://doi.org/10.1016/j.conbuildmat.2021.123237.

Zhang J, Yang Z, Yang Q, Li G, Liu J (2021) Pore water pressure model for sands reinforced with randomly distributed fibers based on cyclic triaxial tests. Soil Dyn Earthq Eng (148) 106812.https://doi.org/10.1016/j.soildyn.2021.106812

Zhang X, Russell AR (2021) Liquefaction Potential And Effective Stress Of Fiber-Reinforced Sand During Undrained Cyclic Loading. J Geotech Geoenviron Eng 147(7):04021042. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002530

Zhao M, Liu G, Zhang C, Guo W, Luo Q (2020) State-of-the-Art of colloidal silica-based soil liquefaction mitigation: an emerging technique for ground improvement. Appl Sci 10(1):15. https://doi.org/10.3390/app10010015

Zhou, Chen JF, Peng M, Zhu Y (2022) Liquefaction behavior of fiber-reinforced calcareous sands in unidirectional and multidirectional simple shear tests. Geotext Geomembr (50) 794-806https://doi.org/10.1016/j.geotexmem.2022.04.003

Authors and Affiliations

Ali Vafaei[1] · Asskar Janalizadeh Choobbasti[1] · Reza Younesi Koutenaei[1] · Amir Vafaei[2] · MobinaTaslimi Paein Afrakoti[3] · Saman Soleimani Kutanaei[4]

Asskar Janalizadeh Choobbasti
asskarjanali@gmail.com

Reza Younesi Koutenaei
rezayounesik@gmail.com

Amir Vafaei
amir_vafaei92@yahoo.com

MobinaTaslimi Paein Afrakoti
mobinataslimi16@gmail.com

Saman Soleimani Kutanaei
samansoleimani16@yahoo.com

[1] Department of Civil Engineering, Babol Noshirvani University of Technology, P.O. Box: 484, Babol, Iran

[2] Department of Civil Engineering, Sharif University of Technology, P.O. Box, Tehran 11155-4313, Iran

[3] K. N. Toosi University of Technology, P.O. Box, Tehran 15875-4416, Iran

[4] Department of Civil Engineering, Islamic Azad University, Ayatollah Amoli Branch, P.O. Box: 678, Amol, Iran