sciendo

Studia Geotechnica et Mechanica, 2025; 47(1): 48–64

Original Study

Open Access

Kheira Boutouba, Ismail Benessalah*, Ahmed Arab, Ahmed Djafar Henni

A Study of the Effect of Combined Cement and Fibre on Shear Strength Response of Chlef Sand

https://doi.org/10.2478/sgem-2025-0005
received January 10, 2024; accepted January 13, 2025.

Abstract: Soil reinforcement remains a vital task of a geotechnical engineer. There are a few support strategies for counting sands considered in this field that are strengthened by combined hydraulic binder (such as cement) and/or fibres. The behaviour of such mixtures (sand–cement and sand–cement–fibre mixtures) in terms of direct shear response has been subject to a lot of controversy in the literature. The base material used in the framework of this study is Chlef sand (taken from Chlef Valley, Algeria), mixed with cement and reinforced with synthetic fibres and considering the use of a direct shear device. , mixed with cement and reinforced with synthetic fibres. The types of fibres in terms of the materials used in the manufacture as well as their length and physical characteristics can improve the stress/strain response of sands. Laboratory results show that the shear strength response of sand–cement mixture increases the shear strength of this last and that it was observed with the addition of cement to the sand. The tests done on the mixtures of sand and cement and on fibre-reinforced mixtures showed better strength compared with just sand or cemented sand alone. Adding fibre to the mixture improved the soil's ability to withstand shear forces. As the threshold value, the fibre content should be at least 0.15% in order to make a noticeable improvement in the mechanical properties. This increase in shear strength is noticed accompanied by a limitation in the samples' contractiveness.

Keywords: soil reinforcement, fibres, sand-cement mixtures, direct shear test, contractiveness

***Corresponding author: Ismail Benessalah,** Laboratory of Materials Sciences and Environment, University Hassiba Benbouali University of Chlef, 02000 Chlef, Algeria, E-mail: i.benessalah@univ-chlef.dz; ORCID: 0000-0002-9456-8339

Kheira Boutouba, Ahmed Arab, Laboratory of Materials Sciences and Environment, University Hassiba Benbouali University of Chlef, 02000 Chlef, Algeria

Ahmed Djafar Henni, LSGR Laboratory, University Hassiba Benbouali of Chlef, 02000 Chlef, Algeria

1 Introduction

As roads and factories are built in big cities, the base on which they are built is often not strong nor easy enough to take care of. Composite foundations such as deep soil mixing piles are commonly used in high-speed railway constructions to make natural foundations stronger and easier to maintain [1-2]. Using fibres to make weak soils stronger is a new method that civil engineers are very interested in. This method, which aims to make soil stronger by adding fibres, involves stabilisation of a sloping soil [3], construction of embankments with soils of low strength, reduction of formation of cracks when clay layers shrink or expand [4], mechanical stabilisation of flexible roads [5], use of airstrip pavement base layers [6-7], improvement of bearing capacity [8] and protection against surface soil erosion. In addition, using small separate fibres can make the soil stronger in all directions without creating weak spots. The construction of fibre-reinforced soils is easily achieved and can be stabilised simply by combining soil with fibres such as cement, lime, calcium sulphate, fly ash and silica fume [9]. A study was carried out by Zaimoglu and Yetimoglu [10] to investigate the behaviour of fine-grained soil reinforced with fibre inclusion. They observed that unconfined compressive stress, cohesion intercept and the California bearing ratio (CBR) index increase with the addition of fibres. They also noted that shear strength was not significantly affected by fibre reinforcement. The way soil mixed with fibres behaves has been a popular subject of study for the past 20 years. Many scientists have studied how fibre-reinforced sand works [11-13], and some experimental results have shown that the addition of fibres to soil mass improves the strength of the composite sand, especially when the relative size of the fibres and grains satisfies certain criteria [14-15].

On the other hand, treatment of poor-quality soil with cement is one of the most commonly used techniques for soil stabilisation. The process of adding a substance called hydraulic binder to make soils stronger involves mixing cement evenly with the soil and water. This helps reinforce the soil in specific areas. A study was carried out by Sun et al., [16], who were interested in examining the effect of a few parameters on the mechanical behaviour of cemented embankments based on Aeolian sand, in particular the water to cement ratio, the Aeolian sand content, the ash content of fly ash and the Portland cement content, as well as different curing times. The results of their microstructural analyses revealed that the studied parameters can affect the properties of cemented paste backfill materials. Another study performed by Lu et al., [1] investigated how cement mixed with soil and sisal fibre behaves under pressure, as well as the water flow, by conducting several tests. The results of the tests showed that mixing fly ash and sisal fibre made the cemented soil much resistant. They also found that adding sisal fibre made the soil less likely to allow water to pass through. Other research has examined how glass fibres and cement kiln dust can be used to make a silty soil more stable [17], considering how long and heavy the fibres are in cement and fibres. The strength of the ground was tested using the CBR test. The results of the lab test showed that the proposed technique can help improve the ground and make low-traffic roads better. It can also be used as a way to get rid of waste in an environment-friendly way. A subsequent study realised by Shen et al., [18] tested how adding lime or cement to clayey soil with fibres affected the soil's strength. They did experiments to see how much lime or cement should be added to get the best results. In particular, they conducted a series of consolidated undrained triaxial compression tests and unconfined compressive strength tests and found how strong the cement gets compared with lime when a certain amount of fibres is added. They also found that the polyester fibre contribution was with a peak strength, considering 0.2% fibre content for plain soil and lime-treated soil, while for lime-treated soil specimens the fibre contribution has been recorded for a threshold of 0.1% fibre content. They also found that plain soil and lime-treated soil followed the same increase trend when the polyester fiber content increased from 0% to 0.2%, While for lime-treated soil specimens, peak values can be observed when the fiber content was 0.1%.

In this paper, we present a contribution supported by an experimental programme to study the behaviour of sandy soils reinforced by combining two inclusions, namely the cement as the binder and synthetic fibres (glass fibres or polypropylene fibres). Conducting a direct shear test will allow for better understanding and will help evaluate the contribution of each inclusion to the shear strength behaviour of the mixtures under study. This study considered different parameters, namely the initial relative density (Dr = 20%, 50% and 80%), the pressure on the materials (normal stress), how much cement was used (2.5%, 5%, 75% and 10% content), the fibre content (0.15% and 0.30% content) and how long the materials were allowed to dry (7 days).

2 Experimental programme and test procedures

2.1 Tested materials

2.1.1 Sand

A series of tests of the sandy soil from the Chlef area (Figure 1a) were conducted, specifically tests where we applied a direct shear box. The soil was first dried in an oven set to a temperature of 105°C. The soil was then passed through a sieve of 2 mm in size. The sand in Chlef is round in shape and made up of quartz and some carbonates. The particles are usually isometric. Figure 1b shows a close-up view of the sand using a scanning electron microscope. The main characteristics of the soil can be found in Table 1. Figure 2 presents the grading distribution of the materials used. The literature shows many studies [19-28] have been carried out to study the behaviour of Chlef sand.

2.1.2 Cement (the binder)

The cement used in this study is a cement from the Chlef region, CEM II/A42.5, which is manufactured by ECDE (Entreprise des Ciments et Dérivés d'Ech-Cheliff). It has a density of 3.1 and a specific surface of 3298 cm^2/g. The cement used 8% silica fume, according to the EN13263-1 standard, with a density of 2.4 and a specific surface of 22 m^2/g. The chemical properties of the silica fume and the cement are shown in Table 2. The soil and the cement mixture are put into a mixer for 2 minutes while adding the right amount of water [25].

2.1.3 Fibres

Several research studies [28, 32] have found that the use of fibres in geotechnics is a cost-effective and efficient way to enhance the strength of the soil, as well as its other properties. In our study, we chose two types of fibres characterised by their tensile strength and rigidity: glass fibres and polypropylene fibres. The mixtures used a fibre content of 0.15% and 0.3%, respectively.

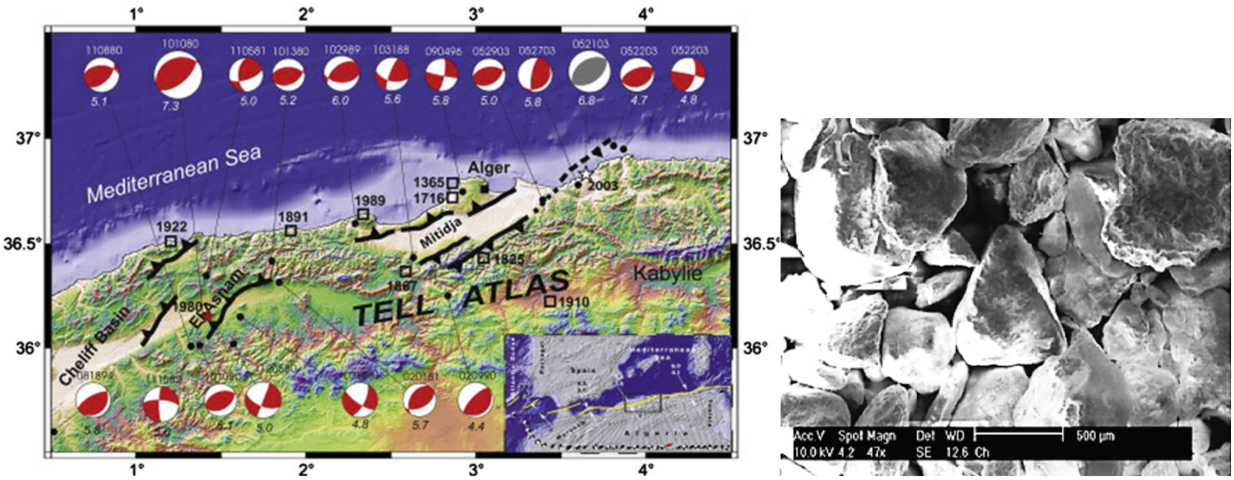

Figure 1: Chlef sand under study: (a) situation of Chlef (formerly El Asnam) region [42] and (b) sand visualised using a scanning electron microscope [21].

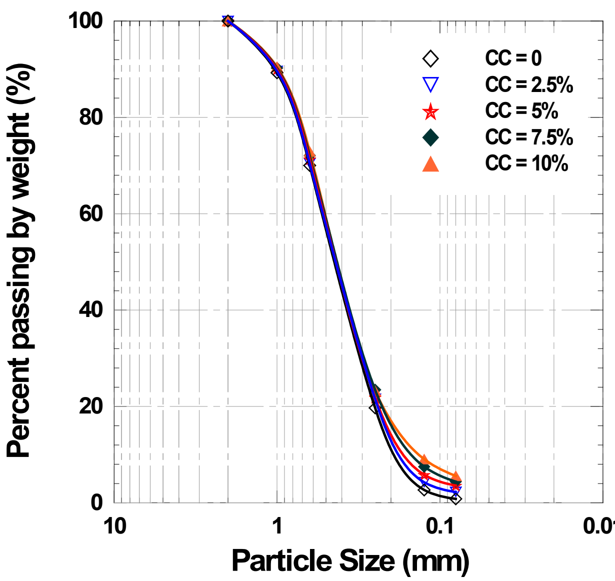

Figure 2: Size distribution of the particles of the tested materials [25]. CC, cement content.

Table 1: Physical characteristics of Chlef sand.

Materials used	CC (%)	G_s	D_{50} (mm)	C_U	C_{CURV}	e_{min}	e_{max}
Chlef sand	0	2.7	0.45	2.34	1.39	0.582	0.873

CC, cement content.

Table 2: Chemical and mineralogical compositions of the cement [25].

CEM II/A 42.5			
Chemical compositions (%)		**Mineralogical compositions (%)**	
SiO_2	20.58	C_3S	57.79
Al_2O_3	4.90		
Fe_2O_3	4.70	C_2S	20.47
CaO	62.8		
SO_3	2.28	C_3A	7.20
MgO	0.53		
K_2O	0.42	C_4AF	11.49
Na_2O	0.12		
Free lime	2.17		

- **Glass fibres:** The glass fibre used in this study is in the form of a complex fabric cut in the form of masts called Woven-Roving. The material is made by a company in Chlef, Algeria called ENPC, and it is used to seal the hulls of small boats and fishing boats. Details on its physical and mechanical properties can be found in Table 3.
- **Polypropylene fibres:** The use of polypropylene fibres in the field of soil improvement remains all the same as with its virgin state. In the following work, we will test the effect of polypropylene fibres on the behaviour of the physicomechanical characteristics of sand reinforced with such fibre, the main characteristics of which are included in Table 3.

Figure 3 illustrates the different samples used during our tests, namely Chlef sand alone (a), II/A 42.52 cement (b), glass fibres (c), polypropylene fibres (d),

Table 3: Physicomechanical characteristics of the glass fibres used [29].

Name	Unit	Glass fibres	Polypropylene fibres
Colour	–	White	White
Width	mm	0.12	0.03
Thickness	mm	0.013	–
Specific gravity	–	2.62	0.96
Specific weight	g/m²	300	–
Tensile strength	MPa	2500	500–750
Poisson coefficient	–	0.35	–
Shear modulus	GPa	29.2	–
Young modulus	GPa	73	2.9–3.8

2.2 Testing programme

Direct shear tests were done to examine, on the one hand, the effect of two types of fibres (glass fibres and polypropylene fibres) on the sand's mechanical behaviour, and on the other hand to compare the results between the fibre-reinforced sand and the fibre-reinforced cemented sand, emphasising the binary effect of the two inclusions (cement and fibres). The fibres used were randomly distributed in the box while injecting a fibre content equivalent to $\rho_f = 0.15\%$ and $\rho_f = 0.3\%$ for the two types of fibres, with a cement content of 2.5%, 5%, 7.5% and 10%. The size of the shear box used in our study was

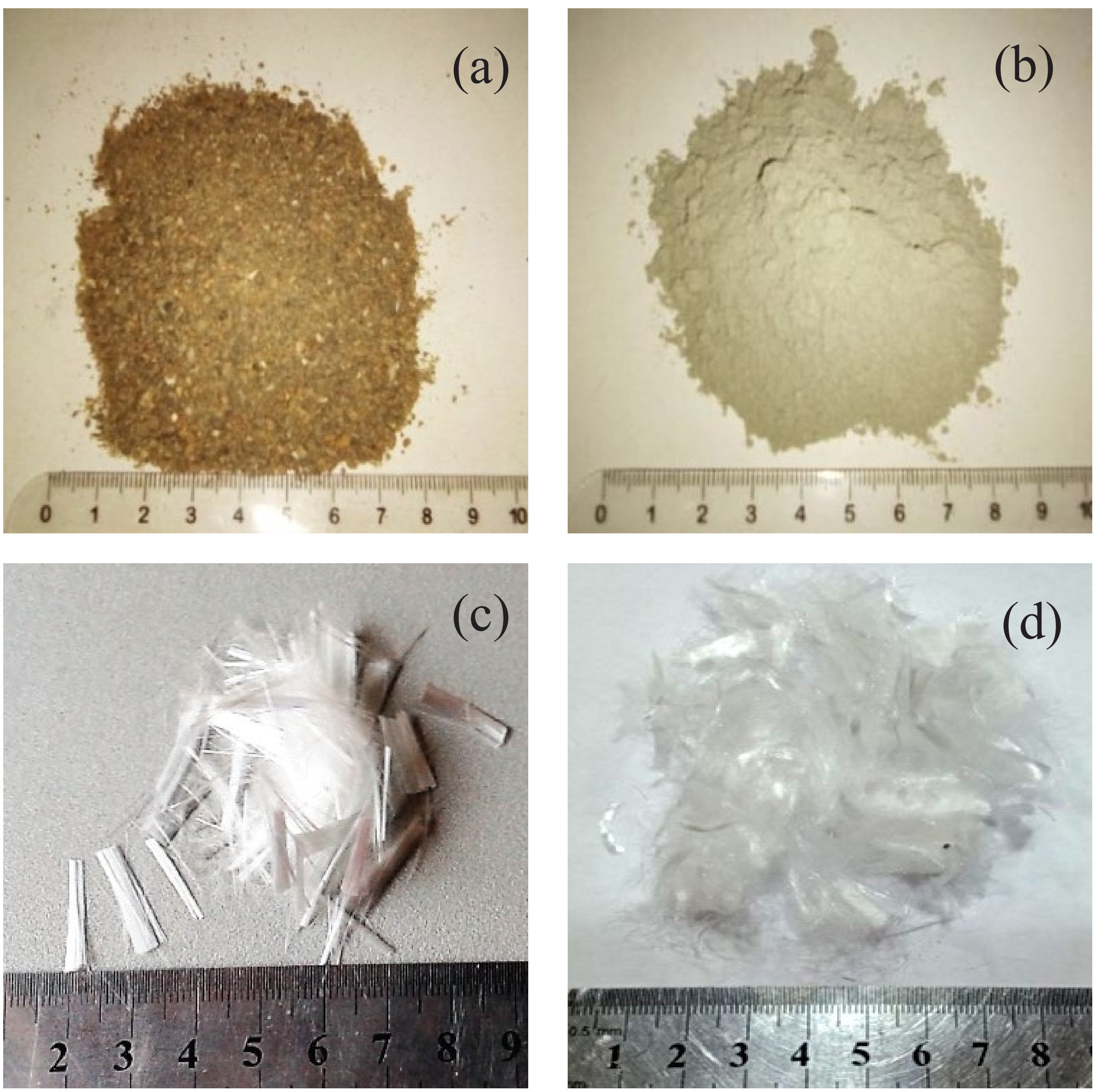

Figure 3. Materials used: (a) sand, (b) cement, (c) glass fibres and (d) polypropylene fibres.

60 × 60 × 20 mm. The experiments were done at a rate of 1 mm/min, while the samples were consolidated and sheared under a constant normal stress of 100 kPa, 200 kPa and 300 kPa during all stages of the test. This was done according to the ASTM D3080 standard [30]. These test parameters were also used by Nougar et al., [31] and Benessalah et al., [32]

2.3 Sample preparation

The study was realised based on a combination of sand, cement and fibre. The amount of fibre in the mixture is either 0.15% or 0.3%, depending on the dry state. The mixture was also tested considering a sample with wet damage with a water content of 10%. The relative density, which characterises the compactness of the composite material. This parameter (Dr) is calculated considering the maximum and minimum void ratios Dr = $(e_{max} - e)/(e_{max} - e_{min})$, being fixed in order to consider two types of samples: one with medium relative density (Dr = 50%) and the other with high relative density (Dr = 80%).

Majority of the laboratory tests on granular soils, such as clean sand and gravels, are performed on reconstituted specimens, as obtaining samples of these materials in their undisturbed or natural state is very difficult due to the lack of 'cohesion'. Various sample preparation methods have been developed based on the moisture condition of the soil (e.g., dry, moist and wet), the method of soil placement (e.g., pluviation, spooning or flowing) and the medium through which the soil is placed (e.g., air or water). On the other hand, according to Vaid [40] and Kuerbis and Vaid [41], the water pluviation method is one of the popular methods for sample preparation. Pluviation in water has been shown to resemble the alluvial deposition process because the fabric that ensues upon water pluviation has been found to be similar to that of the naturally deposited alluvial and hydraulic fill sands [42].

There are two sample preparation methods adapted in this study, emphasising their effect on the behaviours of the mixtures under study: (1) samples prepared by wet tamping, using an initial water content of 10%; and (2) samples prepared by dry funnel pluviation, which has regular structure without macropores.

The samples were consolidated and sheared under normal stresses (σ_n = 100 kPa, 200 kPa and 200 kPa). The time it took to prepare the sample and for the cement to harden was about 1 hour, after which the samples were kept in a room at a temperature of around 26°C, give or take 2°C, for 7 days. The humidity in the room was about 90%.

The average amount of cement and fibre was measured as a percentage of the weight of dry sand. This measurement was determined by the following equation:

$$\rho_f = \frac{M_f}{M_S} \times 100(\%) \qquad (1)$$

where ρ_f is the fibre content, *Mf* is the weight of the fibres and *Ms* is the weight of the grain sand.

The average cement content (CC) is defined as the percentage of the dry mass of sand (*msand*), according to the following equation [25]:

$$C = \frac{m_{cement}}{m_{sand}} \times 100(\%) \qquad (2)$$

Each sample was prepared in three layers. The mass of each layer was determined according to the value of the initial relative density using Eq. 3.

$$m_s = (V_T \times \gamma_s)/(1+e_{\max}(1\text{-}D_r)+D_r \times e_{\min}) \qquad (3)$$

Each layer was poured into the mould and then compacted manually; 25 strokes were done until the desired height for the dense tests was obtained [25]. The initial water content used for sample preparation in our study was calculated according to Eq. 4.

$$w = \frac{m_W}{m_S} \times 100(\%) \qquad (4)$$

where *mW* and *mS* represent the water mass and the dry mass of the sand–cement mixtures, respectively.

Figure 4 shows samples of the fibre-cemented sand, prepared considering 0% and 10% water content and 0.3% fibre content.

3 Results and discussion

The shear stress that develops in the fibre-reinforced sand mobilises the tensile strength in the fibres via friction at the fibre–sand interface. The maximum shear strength occurs either at the onset of the greatest mobilisation between the sand and the reinforcing surface or in case of ruptures by traction in the fibre. The amount of pull on a fibre in the shear plane depends on various factors,

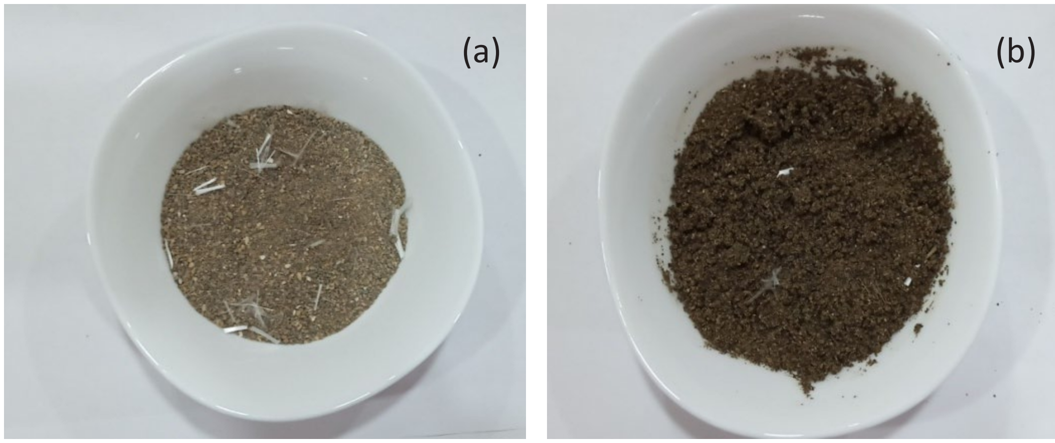

Figure 4: Sample preparation: (a) fibre-reinforced mixtures: dry state; and (b) fibre-reinforced mixtures: wet state with a water content of 10%.

such as fibre length and diameter, fibre content, how stiff or flexible the fibre is, the angle it is positioned at, how rough or smooth the fibre's surface is, the shape and size of the sand particles, how the sand interacts with the fibre, and how tightly packed the samples are at the beginning. Variables tested that determine how strong the connection is between the materials include how the samples are prepared, how much pressure is applied and the size of the fibres compared with the mould. The results of the test show how much force is needed to make the materials slide horizontally and how much the materials move vertically when pushed horizontally. These tests were done using mixtures that had two different amounts of fibres (0.15% and 0.30%). The results were then compared with the mixtures without fibres. The specimens tested were consolidated and sheared under three different normal stresses: 100 kPa, 200 kPa and 400 kPa. This was analysed to determine the effect of fibres on the stress/strain behaviour, volume change behaviour and shear strength parameters.

3.1 Glass fibre-reinforced sand

3.1.1 Stress/strain behaviour

The stress/strain response of fibre-reinforced sand was tested by a direct shear device. The object was made to shear or break in a specific horizontal direction. However, it might not have been the least strong plan within the sample. There are different amounts of stress on the shear surface. Usually, stress measurements are taken by averaging the measurements from the whole surface. The force applied to the soil that causes it to shear represents how strong the soil is.

The shear stress variation versus the horizontal displacement curves obtained for glass fibre-reinforced sand (with fibre content of 0.15% and 0.3%), considering three different initial relative densities (20%, 50% and 80%) and emphasising that the samples were consolidated and sheared under a normal stress of 100 kPa, are shown in Figure 5. The results indicate the efficiency of including fibres. It was found that, for all fibre contents, shear stress increases significantly, with the shear strength at the end of the test reaching a value of 80 kPa for the unreinforced sand and values of 88 kPa and 103 kPa for the glass fibre-reinforced sand, with 0.15% and 0.3% fibre content, respectively, and with a relative density of 50% and a normal stress of 100 kPa (Figure 5b). This means an improvement in shear strength of 10% and 29% for a fibre content of 0.15% and 0.3%, respectively. A similar improvement was also obtained for the other initial relative densities.

3.1.2 Maximum shear strength

Figure 6 presents the effect of the initial relative density on the behaviour of glass fibre-reinforced sand. The samples were reinforced with a fibre content of 0.15% and 0.3% in their dry state, consolidated and sheared under a normal stress of 100 kPa and considering three initial states of relative density (loose, medium dense and dense). It can be seen that the maximum resistance of the materials under study is indeed affected by the initial density state on which the samples were prepared. The improvement is less significant compared with the samples prepared at loose density. Figure 6 also shows the lines obtained directly by plotting the shear strength as a function of fibre content at different relative densities or the measured shear stress at 2-mm horizontal displacement. (The

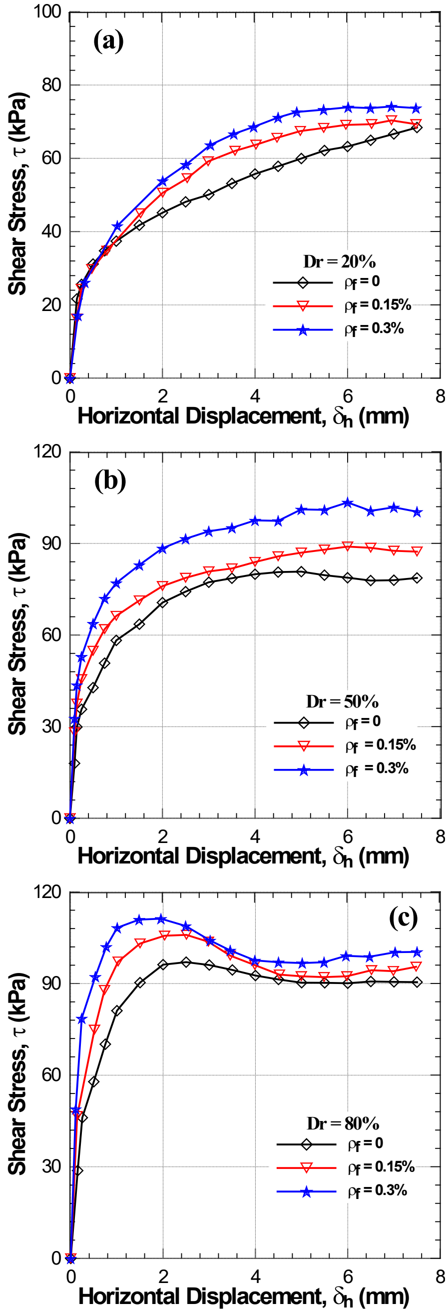

Figure 5: Effect of glass fibre content on sand shear strength (σ_n = 100 kPa): (a) Dr = 20%, (b) Dr = 50% and (c) Dr = 80%. Dr, relative density.

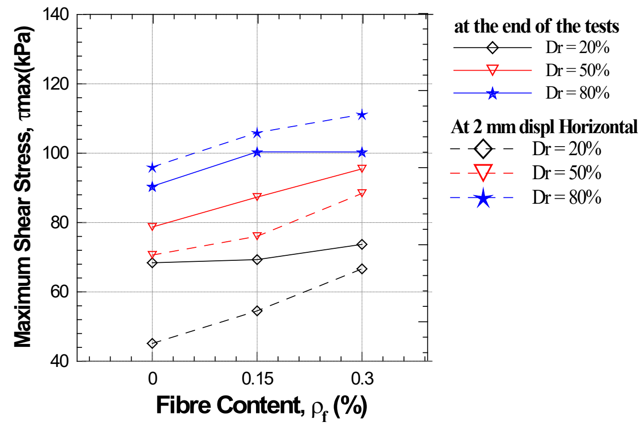

Figure 6: Effect of relative density on shear strength in glass fibre-reinforced sand. Dr, relative density.

same values of shear strength have been picked at this horizontal displacement by Aouali et al. [28] and at the end of the test approximately 7 mm.) The results show that the shear strength of the sand increases with an increase in fibre content and that the density as well as the line at the end of the tests increase considerably with that of the 2-mm horizontal displacement. The maximum shear strength for almost all loose and medium relative density specimens was reached at the end of the tests, whereas at high density the maximum shear strength was reached with a horizontal displacement of about 2 mm, followed by a residual resistance up to the end of the test.

3.1.3 Effect of glass fibres on volumetric change

Figure 7 shows the shear strength response in terms of vertical displacement as a function of shear displacements (horizontal displacement); the sand was reinforced and prepared considering different initial densities and was consolidated and sheared under a normal stress of 100 kPa. The tests indicate that the presence of fibres consistently inhibits the tendency to expand in fibre-reinforced sand for all density states under investigation. The decrease in contractiveness phase is more noticeable in samples with low density (loose state). With increasing relative density, the trend in variations of vertical displacement with horizontal displacement remains the same, but the dilatancy increases for all mixtures under study. This observed increase in dilatancy is due to the ductile nature of the sand–fibre mixture. The results found are in good agreement with those found by Boutouba et al., [25] and Benessalah et al., [32].

3.2 Polypropylene fibre-reinforced sand

3.2.1 Stress/strain behaviour

Shear strength versus shear displacement curves for unreinforced and polypropylene fibre-reinforced soil samples are shown in Figure 8. An unreinforced sample was made to establish the base strength of the sand

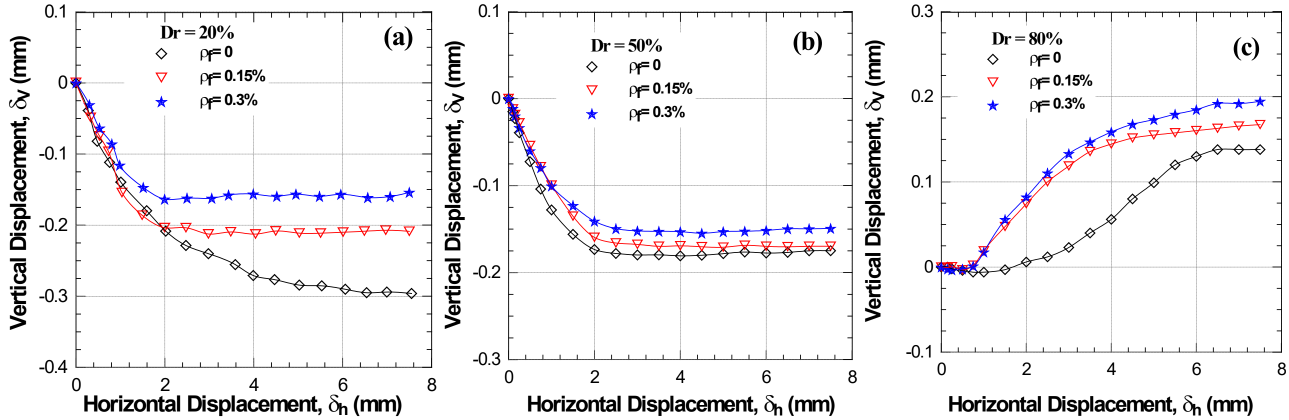

Figure 7: Effect of glass fibre content on vertical displacement (σ_n = 100 kPa): (a) Dr = 20%, (b) Dr = 50% and (c) Dr = 80%. Dr, relative density.

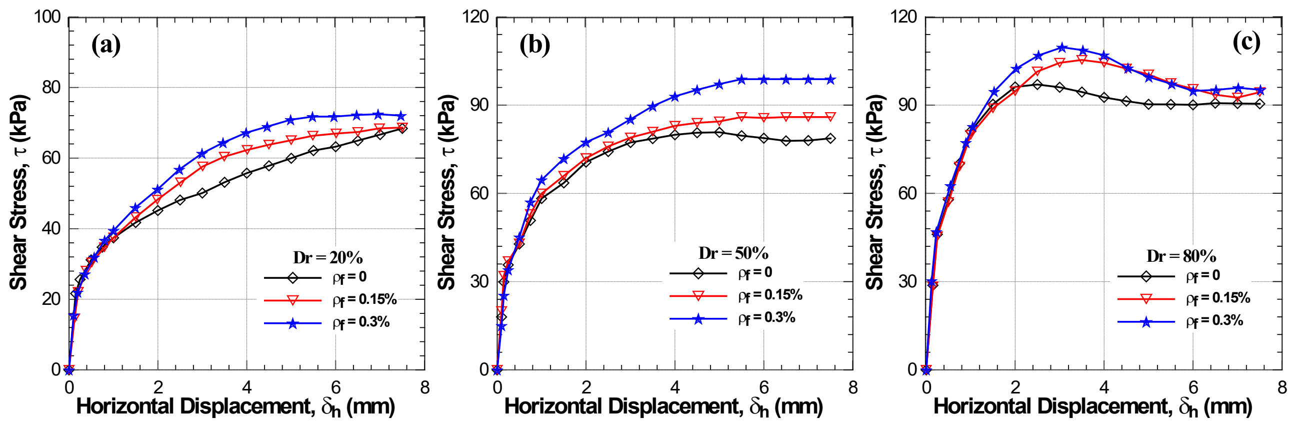

Figure 8: Effect of polypropylene fibre content on sand shear strength (σ_n = 100 kPa): (a) Dr = 20%, (b) Dr = 50% and (c) Dr = 80%. Dr, relative density.

alone so that the change in strength due to addition of polypropylene fibres could be estimated. The specimen had a polypropylene fibre content of 0.15% and 0.3% by the soil's dry weight and the fibre length used was 1 cm. This length of fibre has been used in the literature by Aouali et al., [28] and Benessalah et al., [32]. In the present analysis, the samples were consolidated and sheared under a normal stress of 100 kPa and a relative density of 20%, 50% and 80%. The results showed that the strength/strain behaviour was significantly affected by the inclusion of polypropylene fibres. For all the tested fibre-reinforced mixtures, the maximum strength increases with the inclusion of polypropylene fibres and with increasing fibre content.

3.2.2 Effect of polypropylene fibres on volumetric change

The volumetric deformation behaviour of sand reinforced with polypropylene fibres is shown in Figure 9. It can be observed that the behaviour is similar to sand that has not been strengthened. In simpler terms, fibre-reinforced sand is more likely to contract or compress than sand without reinforcement. However, samples with a high relative density reinforced with polypropylene fibres have a tendency to expand after a horizontal displacement of 2.5 mm and until the end of the test.

3.3 Comparison of contributions between glass fibres and polypropylene fibres

The results of the comparison between the two reinforcement techniques (glass fibres and polypropylene fibres) include shear stress and the vertical displacement versus horizontal displacement of soil samples consolidated and sheared under a normal stress of 100 kPa and prepared considering different density states, namely loose (Dr = 20%), medium dense (Dr = 50%) and dense (Dr = 80%). These graphs were analysed to compare the

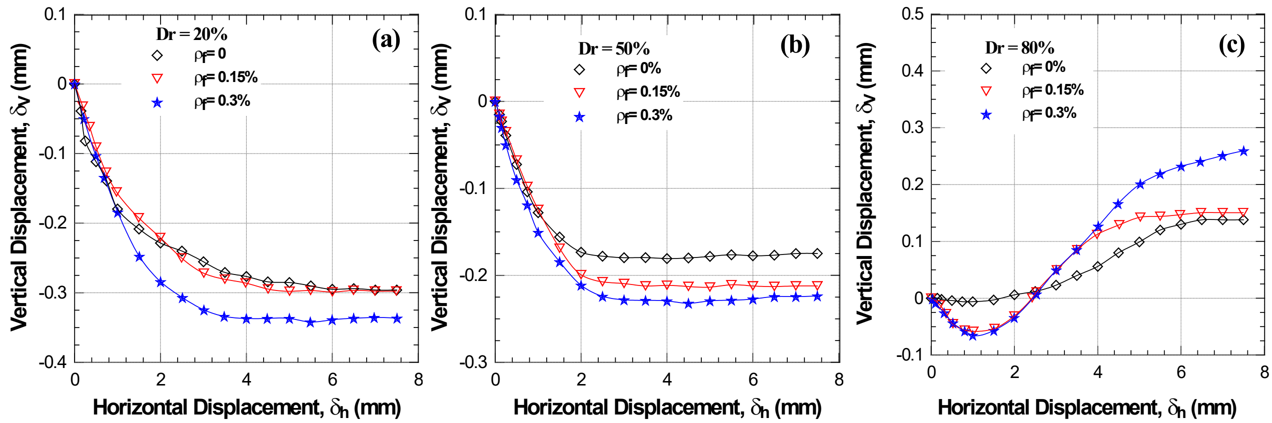

Figure 9: Effect of polypropylene fibre content on vertical deformation of sand (σ_n = 100 kPa): (a) Dr = 20%, (b) Dr = 50% and (c) Dr = 80%. Dr, relative density.

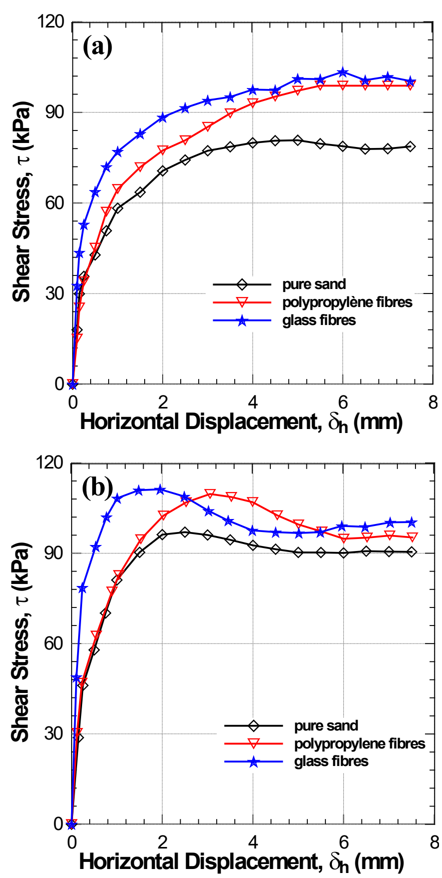

Figure 10: Comparison between glass fibres and polypropylene fibres and their effect on stress/strain curves (σ_n = 100 kPa and ρ_f = 0.3%): (a) Dr = 50% and (b) Dr = 80%. Dr, relative density.

effect of the two types of fibres on stress/strain behaviour, volumetric changes and the increase in maximum shear strength.

3.3.1 Stress/strain behaviour

Curves showing the variation in shear strength with horizontal displacement are shown in Figure 10 for unreinforced and fibre-reinforced Chlef sands (glass fibres and polypropylene fibres) with a fixed fibre content of 0.3% and an average relative density of 50% and 80% (Figures 10a and 10b, respectively). These curves are representative of the typical behaviour of the samples tested with other different types of fibres. The results presented indicate increase in strength of the fibre-reinforced sample, which was more remarkable with the inclusion of glass fibres compared with polypropylene fibres. The general shape of the stress displacement curves of the glass fibre-reinforced sample was similar to that of the polypropylene fibre-reinforced sample at medium density (Figure 10a), except for an increase in the slope of the stress/strain curve for small displacements. Where the relative density is high (note that the sample reinforced with glass fibres reaching its maximum value has a horizontal displacement of less than 2 mm) and for the samples reinforced with inclusion of polypropylene fibres, the maximum resistance reached up to 3 mm of horizontal displacement, which means that the glass fibres have better contributions to improving the time for which the shear strength reaches its maximum values.

3.3.2 Maximum shear strength

The increase in maximum shear stress as a function of fibre content is illustrated in Figure 11 for sands reinforced with different types of fibres (glass fibres and polypropylene fibres). The results indicate that the maximum shear stress

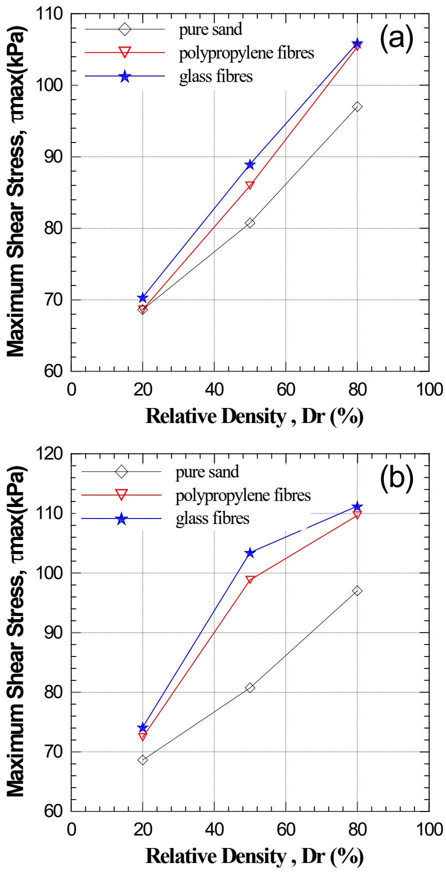

Figure 11: Effect of different fibre types on maximum shear strength: (a) fibre content = 0.15% and (b) fibre content = 0.3%.

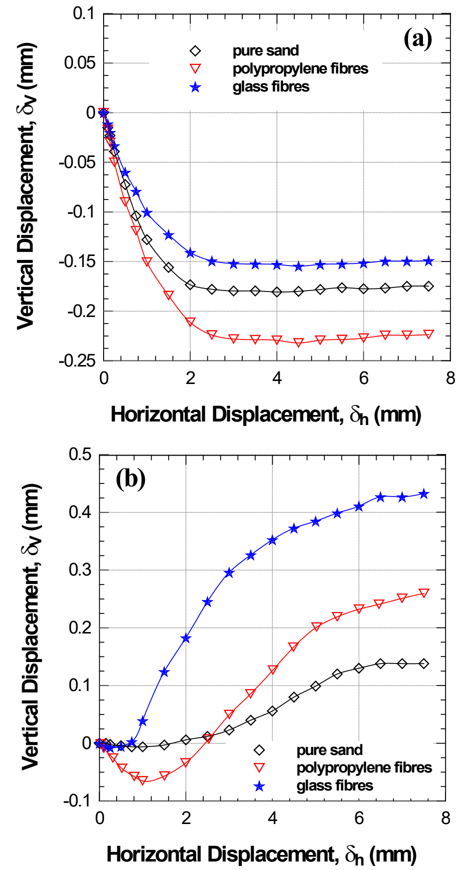

Figure 12: Comparison between glass fibres and polypropylene fibres in terms of variations in vertical displacements (σ_n = 100 kPa and ρ_f = 0.3%): (a) Dr = 50% and (b) Dr = 80%. Dr, relative density.

of the sand–fibre composite increases approximately linearly with fibre content. It is evident in Figure 11a that the maximum shear strength of sand reinforced with 0.15% glass fibre content has a higher maximum strength compared with that of the unreinforced soil and that reinforced with polypropylene fibres. Moreover, with an increase in fibre content (0.3%; Figure 11b), the maximum strength of the soil increased and the gap between glass fibre and polypropylene fibre reinforcement becomes clearer.

3.3.3 Contribution of fibre type to volumetric change

The results of the tests performed to determine variations in vertical displacements observed during shearing of samples that were consolidated and sheared under a normal stress of 100 kPa and prepared with medium and dense states are shown in Figure 12. The results indicate an increase in the contractiveness of the sand sample reinforced with polypropylene fibre (Figure 12a). On the other hand, the sample reinforced with glass fibres shows a decrease in contractiveness at a medium relative density state (Dr = 50%). Figure 12b illustrates that the glass fibre-reinforced samples exhibited more dilatant character compared with polypropylene fibres, taking into consideration the sample's high density state (Dr = 80%). In general, adding elements with tensile properties, such as fibres, to the soil affects the soil's elasticity, and therefore specimens fail at higher axial strain. Therefore, the addition of glass fibres has a double advantage of increasing the resistance and also increasing the ductility (greater dilatant character) of the soil.

3.4 Behaviour of glass fibre-reinforced cemented sand

The idea of using glass fibres as reinforcement for sandy materials represents certain vulnerabilities in the search for mechanical performance in the field of geotechnical engineering (stability of slopes, liquefaction of saturated sands, etc.) and has enabled several researchers to opt for

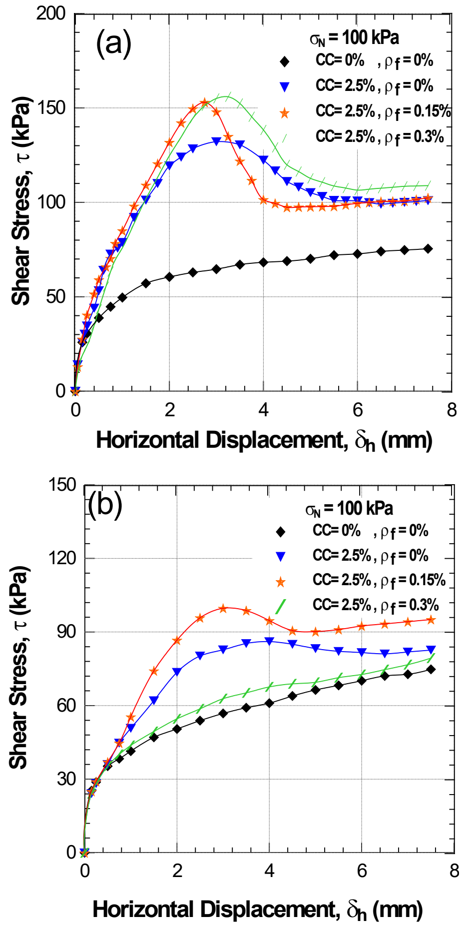

Figure 13: Effect of glass fibre content on shear strength of fibre-cemented sand (CC = 2.5%, σ_n = 100 kPa, w = 10%): (a) Dr = 80% and (b) Dr = 50%. CC, cement content; Dr, relative density.

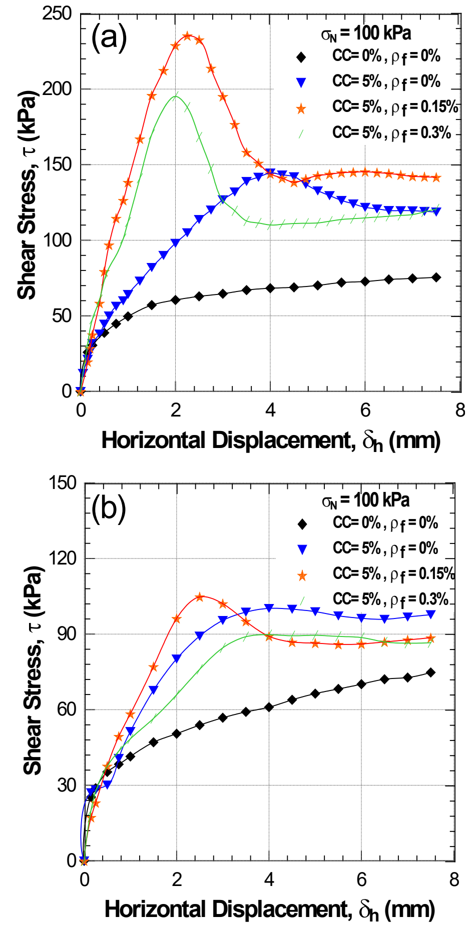

Figure 14: Effect of glass fibre content on shear strength of fibre-cemented sand (CC = 5%, σ_n = 100 kPa, w = 10%): (a) Dr = 80% and (b) Dr = 50%. CC, cement content; Dr, relative density.

this type of reinforcement in order to ensure the rigidity and cohesion of a new composite, and by this ensuring a high intrinsic quality of glass fibres. The absence of a potential weakness plane was mentioned in the research of Ateş [33] as one of the main advantages of randomly distributed fibers in the soil. . Fibre reinforcement increases peak and residual strength and modifies the brittle behaviour of cemented soil to become more ductile [34]. In what follows, we study the effect of glass fibre content on sand–cement mixtures.

3.4.1 Strength characteristics of fibre-reinforced cemented sand

Figure 13 shows the evolution of shear stress as a function of the horizontal displacement for samples sheared using a direct shear device with a cement content of 2.5% and a glass fibre content varying from 0.15% to 0.3% (by dry weight). The samples were prepared considering an initial density state of 50% (medium dense) and 80% (dense). Another parameter was carried out in this analysis of cemented sand, a curing period of 7 days before shearing, which has also been used by Boutouba et al., [25]. There is therefore a significant increase in shear stress when the fibre content increases, established by peak values of 95 kPa at a relative density of 50% and 152 kPa at a relative density of 80%, respectively, highlighting initial conditions fixed at a fibre content of 0.15% and a normal stress of 100 kPa on which the samples were consolidated and sheared. This observation is clearer in the sample with a cement content of 5% (Figure 13). As shown in Figures 13 and 14, the overall behaviour of the cemented soil is considerably affected by the inclusion of glass fibres. This can be attributed to the physical interaction between the cemented soil particles and the transfer of stress due to the high tensile fibres (2500 MPa), which results in an increase in the strength of the cemented soil

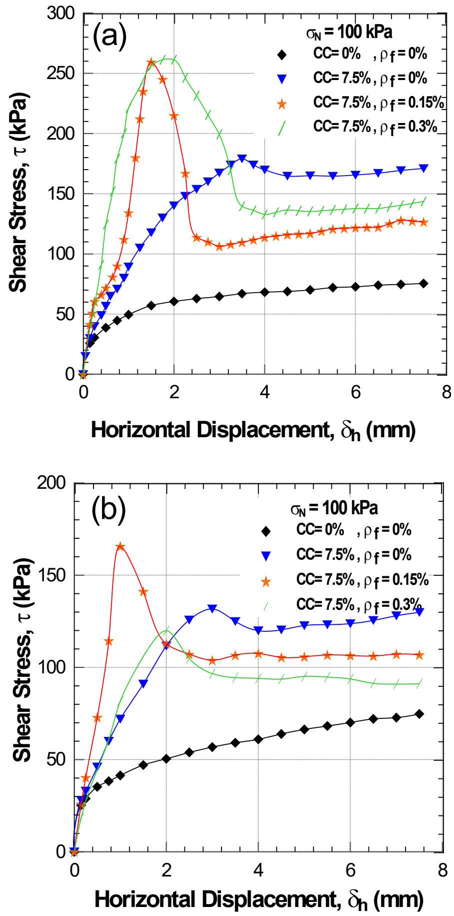

Figure 15: Effect of glass fibre content on shear strength of cemented sand (CC = 7.5%, σ_n = 100 kPa, w = 10%): (a) Dr = 80% and (b) Dr = 50%. CC, cement content; Dr, relative density.

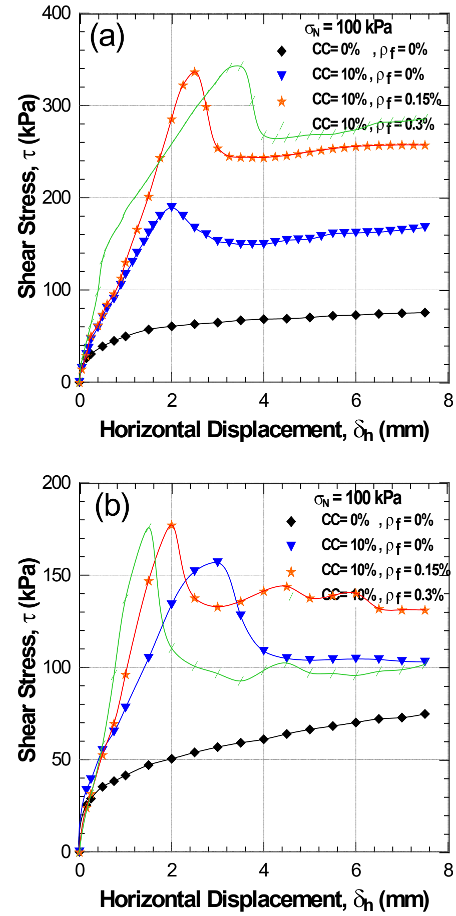

Figure 16: Effect of glass fibre content on shear strength of cemented sand (CC = 10%, σ_n = 100 kPa, w = 10%): (a) Dr = 80% and (b) Dr = 50%. CC, cement content; Dr, relative density.

and improvement in its mechanical behaviour. This seems in perfect agreement with the results found by Malidarreh et al., [35].

For the cemented sand samples (CC = 7.5%) without fibre inclusions and considering a high relative density (Dr = 80%), the maximum shear strength took a value of 178 kPa (Figure 15a), compared with the fibre-reinforced cemented sand (CC = 7.5%), where the maximum shear stress took values of 259 kPa and 261 kPa with 0.15 and 0.30 fibre content, respectively. It must also be noted that shear strength was more considerable in the case of fibre-reinforced cement sand with 10% cement content, where it took values of 336 kPa and 342 kPa for 0.15 and 0.30 fibre content, respectively, and considering the same initial relative density (Dr = 80%) (Figure 16b).

We also note that the treatment of the cemented soil with glass fibre content of 0.15% leads to a shear strength that increases for all cement contents. On the other hand, when the fibre content is increased to 0.3%, the increase in strength is almost negligible. Based on the results, it can be said that increasing the cement content and the fibre content increases the peak shear strength of the fibre-cemented soil. It is observed that the maximum shear stress of the sample depends on the fibre content as well. In addition, a fibre content of 0.15% demonstrated a more remarkable increase in shear stress compared with a fibre content of 0.3%. Our results are in good agreement with those found by Aouali et al., [28], who observed a fibre contribution threshold of around 0.20% fibre content.

It can therefore be concluded that the samples reinforced by combining cement and fibre exhibit maximum shear strength with 0.15% fibre content better than that observed on samples with 0.30% fibre content. It can also be said that the fiber content of 0.15% indicates a threshold contribution of glass fiber inclusions to improve the shear strength of the cemented sand under study.

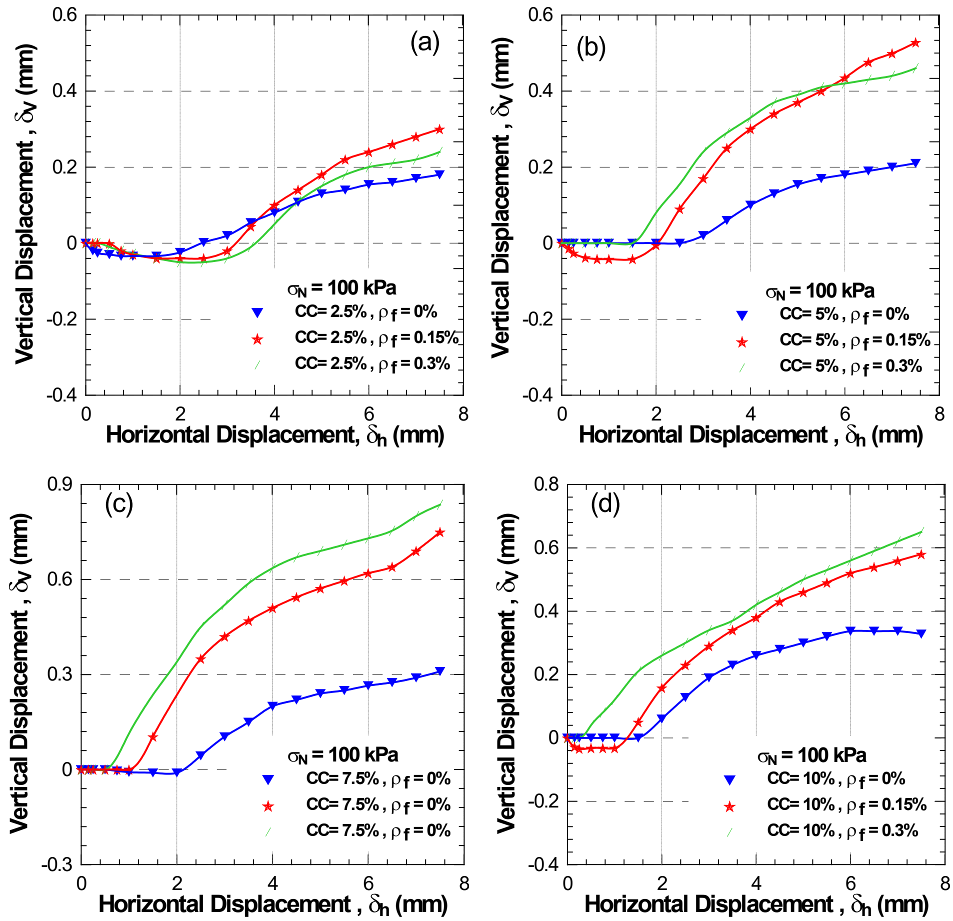

Figure 17: Effect of glass fibre content on vertical displacement of cemented sand (σ_n = 100 kPa, w = 10%, Dr = 80%): (a) CC = 2.5%, (b) CC = 5%, (c) CC = 7.5% and (d) CC = 10%. CC, cement content; Dr, relative density.

3.4.2 Volumetric change of fibre-reinforced cemented sand

Figure 17 illustrates the variations in vertical displacement versus horizontal displacement during shear testing of cemented samples (CC = 2.5%, 5%, 7.5% and 10%). The tests were also reinforced by inclusion of glass fibres with a percentage by weight of 0.15% and 0.3%. The samples were prepared considering a high initial relative density (Dr = 80%) and an initial water content of 10%. They were consolidated and sheared under a normal stress of 100 kPa. It is noted here that the dilatant character of the samples reinforced with fibres proved to be greater than of the samples cemented alone. This change in volume is directly linked to the fibre content, which also leads to an improvement in the dilatant character of the mixtures reinforced with 0.15% fibre content compared with that observed for samples reinforced with 0.30% fibre content. The volumetric change curves (the variation of the vertical displacement provoqued a volumetric change because the dimensions of the shear box plan were fixed at 60 × 60 mm) clearly indicate that the glass fibres significantly limited the contractiveness of the samples at different relative densities under study. This behaviour is interesting because it contradicts the results reported by Ahmad et al., [9] and Michalowski and Čermák [15], which support the idea that fibres generally inhibit the soil's dilatancy. These results, however, are in agreement with those found by other studies ([28], [32], [34]). The results suggest that the volumetric response represented by the dilatant character of the soil–cement samples reinforced with fibre inclusion could be a consequence of an apparent densification of the composite matrix resulting from the mechanism of interaction between the fibre mesh and the cemented soil particles. As shown in Figure 17, it was also found that the presence of fibres systematically increases the tendency for dilatation of fibre-reinforced cemented sands for all sand–cement mixtures and the increase in dilatancy is as observed as the cement content increase.

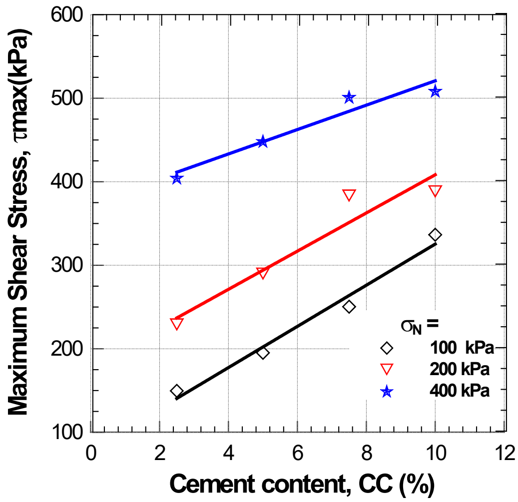

Figure 18: Variation in maximum shear strength according to cement content (Dr = 80%, ρ_f = 0.15%). Dr, relative density.

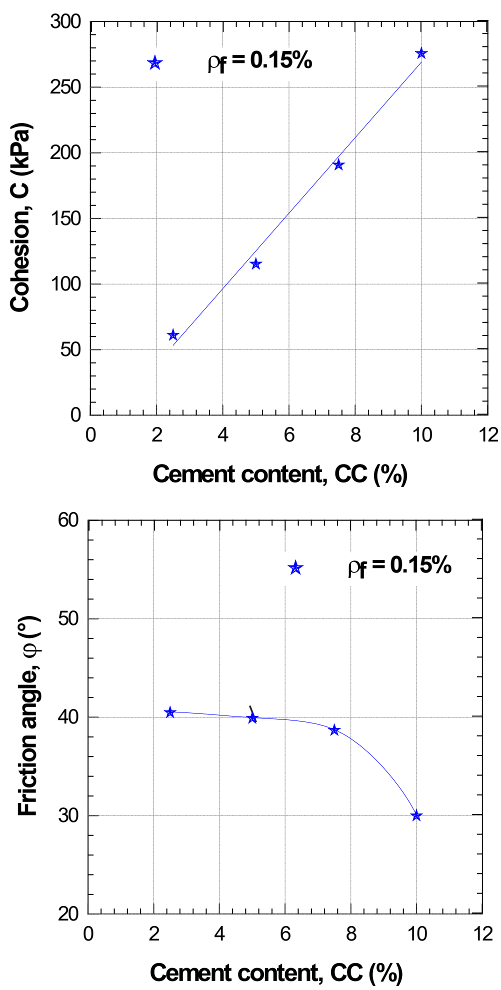

Figure 19: Effect of cement content on glass fibre-reinforced sand–cement mixtures (Dr = 80%): (a) variation in cohesion and (b) variation in internal friction angle. Dr, relative density.

3.4.3 Maximum shear strength of fibre-reinforced cemented sand

Figure 18 visualises the variation in maximum shear strength (τ_{max}) according to the cement content of the sand–cement mixtures, reinforced with inclusion of ρ_f = 0.15% glass fibre content. The maximum shear strength increases with increasing cement content. The results obtained show a quasilinear correlation between the variation of the maximum shear strength and the cement content within the fibre-reinforced sand–cement mixtures. This phenomenon of increasing shear strength can be attributed to the interaction between the different particles of the sand and cement and also to their connection with fibre mesh, which consequently ensures an improvement in the mechanical behaviour of the composite block. The various correlations between the values of maximum shear strength according to the content of cement and considering a fix reinforcement inclusion of 0.15% fibre content and also an initial dense state (Dr = 80%) are given by the following relations:

τ_{max} = 24.646 CC + 78.919 (σ_n = 100 kPa), R^2 = 0.97

τ_{max} = 22.857 CC + 179.75 (σ_n = 200 kPa), R^2 = 0.91

τ_{max} = 14.595 CC + 374.89 (σ_n = 400 kPa), R^2 = 0.93

3.4.4 Variation of mechanical characteristics

The internal friction angle is sometimes used to indicate improvement in soil strength. As noted, there have been some controversies in the literature about variations in internal friction angle when cemented sand is reinforced with fibres. Studies [36-37] have reported that the internal friction angle was affected, while some [38-39] reported the opposite, that is, cemented sand is in no way affected either by fibre addition or other secondary additions. The cohesion values obtained in samples containing different cement contents and reinforced with two fibre contents (0.15% and 0.3%) and considering two initial relative densities (Dr = 50% and 80%) are presented in Figure 19a. It is noted that cohesion (c) increases significantly when the cement and fibre contents increase. The variation in this cohesion follows a quasilinear manner.

Figure 19b illustrates the evolution of the friction angle according to variations in cement content. The results show that, for a fibre inclusion of 0.15%, the internal friction angle shows a relative decrease within the range of 40° (CC = 2.5%) and 38° (CC = 7.5%); when the cement content increases up to 7.5%, the internal friction angle drops sharply beyond this cement content (CC = 7.5%) and this is for a relative density of 80%. All that can be concluded from this is that in the samples reinforced with fixed fibre content (0.15%) and with different cement contents, the internal friction angle marks a sudden drop beyond a percentage of cement equivalent to 7.5%, showing loss of cement efficiency in sand–cement–fibre mixtures around a value of 7.5% cement content. This confirms the criteria of the GTR standard (Guide des Terrassements Routiers), which prohibits treatment with cement beyond 9% cement content.

4 Conclusion

In this paper, we highlight a study carried out in a laboratory characterising a variety of samples composed of sand from Oued Chlef (Algeria), treated with different cement contents (CC = 0%, 2.5%, 5%, 7.5% and 10%) and reinforced with inclusion of glass fibres (or polypropylene fibres) with variable content (ρ_f = 0%, 0.15% and 0.30%). The composite materials were tested using a direct shear device, where they were consolidated and sheared in general under a fixed normal stress (σ_n = 100 kPa). The intrinsic parameters that were taken into consideration during our interpretations mainly included the shear stress, the cohesion, the angle of internal friction, the volumetric change and the initial relative density of the composite sand–cement–fibre mixtures. The following are the main conclusions drawn from this study:

- The inclusion of glass fibres and polypropylene fibres with fibre content ranging from 0.15% to 0.3% in Chlef sand samples, prepared considering different relative densities, increased the shear strength and the dilatant character of the fibre-reinforced sand as well as the maximum shear strength.
- Glass fibres can effectively improve the shear strength of Chlef sand treated with cement. Sand resistance behaviour improved with the addition of fibres. Fibre type and fibre content are factors that affect the shear strength and contractiveness/dilatancy of the samples. Glass fibres are more effective than polypropylene fibres in improving the mechanical behaviour of sand.
- The addition of fibres to cemented sand causes a substantial increase in the internal friction angle up to an optimum cement content of 7.5%, beyond which it marks a particularly sharp drop. On the other hand, the cohesion increases considerably with the inclusion of fibre content and cement content.
- It is also concluded that a 0.15% glass fibre content indicates a threshold for the fibre to contribute to improved shear strength and behaviour of the sand–cement mixtures under study.
- It is suggested that future studies consider other cements to compare our results with and to provide more understanding on how the sand–cement mixtures behave. .

Acknowledgement

The authors would like to thank the reviewers for their constructive and detailed comments. The tests were performed at the Laboratory of Soil Mechanics at UHBC University of Chlef and at the Laboratory of Materials Sciences and Environment (LSME). The authors express their gratitude to all who assisted in the preparation of this paper.

Conflicts of interest

The authors declare that they have no conflict of interest.

Funding

The present study was financially supported by the General Directorate for Scientific Research and Technological Development (DGRSDT).

Availability of data and materials

Not applicable.

References

[1] Lu, L., Liu, C., Qu, S., & Zhang, M. (2022). Experimental study on the mechanical and hydraulic behaviour of Fibre-Reinforced cemented soil with fly ash. Construction and Building Materials, 321, 126374.

[2] Porbaha, A., Shibuya, S., &Kishida, T. (2000). State of the art in deep mixing technology. Part III: geomaterial characterization. Proceedings of the Institution of Civil Engineers-Ground Improvement, 4(3), 91-110.

[3] Gregory, G. H., & Chill, D. S. (1998). Stabilization of earth slopes with fiber reinforcement. In Proc., 6th Int. Conf. on Geosynthetics (pp. 1073-1078). International Geosynthetics Society.

[4] Ziegler, S., Leshchinsky, D., Ling, H. I., & Perry, E. B. (1998). Effect of short polymeric fibers on crack development in clays. Soils and Foundations, 38(1), 247-253.

[5] Choubane, B., Robert, K., &Armaghani, J. (2001). Full-scale laboratory evaluation of polypropylene fiber reinforcement of subgrade soils. Transportation Research Record (TRB), 01-2157.

[6] Webster, S. L., &Santoni, R. L. (1997). Contingency airfield and road construction using geosynthetic fiber stabilization of sands (Vol. 97, No. 4).US Army Engineer Waterways Experiment Station.

[7] Tingle, J.S., Webster, S.L., & Santoni, R.L. (1999). Discrete Fiber Reinforcement of Sands for Expedient Road Construction. (1999). Discrete fiber reinforcement of sands for expedient road construction. Published 1 March 1999. Engineering, Environmental Science. DOI:10.21236/ADA362057

[8] Tang, C., Shi, B., Gao, W., Chen, F., &Cai, Y. (2007). Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotextiles and Geomembranes, 25(3), 194-202.

[9] Ahmad, F., Bateni, F., &Azmi, M. (2010). Performance evaluation of silty sand reinforced with fibres. Geotextiles and geomembranes, 28(1), 93-99.

[10] Zaimoglu, A.S., Yetimoglu, T. (2012). Strength Behavior of Fine Grained Soil Reinforced with Randomly Distributed Polypropylene Fibers. Geotech Geol Eng 30, 197–203 (2012). https://doi.org/10.1007/s10706-011-9462-5

[11] Gray, D. H., &Ohashi, H. (1983). Mechanics of fiber reinforcement in sand.Journal of geotechnical engineering, 109(3), 335-353.

[12] Murray, J. J., Frost, J. D., & Wang, Y. (2000). Behavior of a sandy silt reinforced with discontinuous recycled fiber inclusions. Transportation research record, 1714(1), 9-17.

[13] Consoli, N. C., Rotta G. V., and Prietto. P. D. M. (2002). Influence Of Curing Under Stress On The Triaxial Response of Cemented Soils. Geotechnique 52(5): 382–384.

[14] Zornberg, J. G. (2002). Discrete framework for limit equilibrium analysis of fibre-reinforced soil. Géotechnique, 52(8), 593-604.

[15] Michalowski, R. L., &Čermák, J. (2003). Triaxial compression of sand reinforced with fibers. Journal of geotechnical and geoenvironmental engineering, 129(2), 125-136.

[16] Sun, Q., Zhang, J. & Zhou, N. (2018). Early-Age Strength of Aeolian Sand-Based Cemented Backfilling Materials: Experimental Results. Arabian Journal for Sciences Engineering 43, 1697–1708 (2018). https://doi.org/10.1007/s13369-017-2654-4

[17] Gul, N., & Mir, B. A. (2023). Performance evaluation of silty soil reinforced with glass fiber and cement kiln dust for subgrade applications. Construction and Building Materials, 392, 131943.

[18] Shen, Y. S., Tang, Y., Yin, J., Li, M. P., & Wen, T. (2021). An experimental investigation on strength characteristics of fiber-reinforced clayey soil treated with lime or cement. Construction and Building Materials, 294, 123537.

[19] Arab A. (2009) Monotonic and cyclic behaviour of silty sand, C. R. Mecanique 337 (2009) 621–631

[20] Arab A., Sadek M., Belkhatir M., Shahrour I. (2014). "Monotonic preloading Effect on the Liquefaction Resistance of Silty Sand: a Laboratory Study". Arabian Journal for Sciences Engineering. 2014. 39:685–694. DOI 10.1007/s13369-013-0700-4

[21] DjaferHenni A, Arab A, Belkhatir M, Hamoudi SA, Khelafi H (2013) Undrainedbehavior of silty sand: effect of the overconsolidation ratio. Arab J Geosci. doi:10.1007/s12517-011-0365-9

[22] Benessalah, I., Sadek, M., Villard, P., and Arab, A. (2022). Undrained triaxial compression tests on three-dimensional reinforced sand: effect of the geocell height. European Journal of Environmental and Civil Engineering, 26(5), 1694-1705.

[23] Benessalah, I., Arab, A., &Meziane, E. H. (2021). Intergranular void ratio and undrained monotonic behavior of Chlef sand containing low plastic fines. Acta Mechanica, 232(4), 1621-1640.

[24] Meziane, E. H., Benessalah, I. & Arab A. (2022). An insight into the liquefaction resistance of sand using cyclic undrained triaxial tests: Effect of the relative density and the loading amplitude.Acta Geotechnica Slovenica 18(2). 44-55. https://doi.org/10.18690/actageotechslov.18.2.44-55.2022

[25] Boutouba, K., Benessalah, I., Arab, A., &Henni, A. D. (2019). Shear strength enhancement of cemented reinforced sand: role of cement content on the macro-mechanical behavior. Studia Geotechnica et Mechanica, 41(4), 200-211.

[26] Merabet, K., Benessalah, I., Chemmam, M., & Arab, A. (2020). Laboratory study of shear strength response of Chlef natural sand: Effect of saturation. Marine Georesources & Geotechnology, 38(4), 461-467.

[27] Della, N., Belkhatir, M., Arab, A., Canou, J., &Dupla, J. C. (2015). Undrained monotonic response and instability of medium-dense sandy soil. Marine Georesources & Geotechnology, 33(6), 487-495.

[28] Aouali, N., Benessalah, I., Arab, A., Ali, B., & Abed, M. (2019). Shear strength response of fibre reinforced Chlef (Algeria) silty sand: laboratory study. Geotechnical and Geological Engineering, 37(2), 1047-1057.

[29] Bouaricha, L., Henni, A. D., & Lancelot, L. (2017). A laboratory investigation on shear strength behavior of sandy soil: effect of glass fiber and clinker residue content. Studia Geotechnica et Mechanica, 39(4), 3-15.

[30] ASTM D3080. : Standard test method for direct shear test of soils under consolidated drained conditions, American Society for Testing and Materials, West Conshohocken, (2005).

[31] Nougar, B., Brahimi, A., Bouri, D. E., Arab, A., Benessalah I. (2019). Laboratory investigation into the effect of fines plasticity on the mechanical behavior of sand/fines mixtures. Transportation Infrastructure Geotechnology 8(3).438-451.

[32] Benessalah, I., Arab, A., Villard, P., Sadek, M., &Kadri, A. (2016). Laboratory study on shear strength behaviour of reinforced sandy soil: effect of glass-fibre content and other parameters. Arabian Journal for Science and Engineering, 41, 1343-1353.

[33] Ateş, A. (2016). Mechanical properties of sandy soils reinforced with cement and randomly distributed glass fibers (GRC). Composites Part B: Engineering, 96, 295-304.

[34] Sadek, S., Najjar, S., &Abboud, A. (2013). Compressive strength of fiber-reinforced lightly-cement stabilized sand. In Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

[35] Malidarreh, N. R., Shooshpasha, I., Mirhosseini, S. M., &Dehestani, M. (2018). Effects of reinforcement on mechanical behaviour of cement treated sand using direct shear and

triaxial tests. International Journal of Geotechnical Engineering, 12(5), 491-499.
[36] Al-Refeai, T. O. (1991). Behavior of granular soils reinforced with discrete randomly oriented inclusions. Geotextiles and Geomembranes, 10(4), 319-333.
[37] Michalowski, R. L., & Zhao, A. (1996). Failure of fiber-reinforced granular soils. Journal of geotechnical engineering, 122(3), 226-234.
[38] Di Prisco, C., & Nova, R. (1993).A constitutive model for soil reinforced by continuous threads. Geotextiles and Geomembranes, 12(2), 161-178.
[39] Wu, T. H., Beal, P. E., &Lan, C. (1988). In-situ shear test of soil-root systems. Journal of Geotechnical Engineering, 114(12), 1376-1394.
[40] Vaid, P.Y., Sivathayalan, S., Stedman, D.: Influence of specimen reconstituting method on the undrained response of sand. Geotech. Test. J. 22, 187–195 (1999)
[41] Kuerbis, R., Vaid, Y.P.: Sand sample preparation—the slurry deposition method. Soils Found 28, 107–118 (1988)
[42] Della, N., Belkhatir, M., Arab, A., Canou, J., &Dupla, J. C. (2014). Effect of fabric method on instability behavior of granular material. Acta Mechanica, 225(7), 2043-2057.