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Research Article

Mechanical behavior of sandy soil reinforced with naturals and synthetics fibers: A laboratory study

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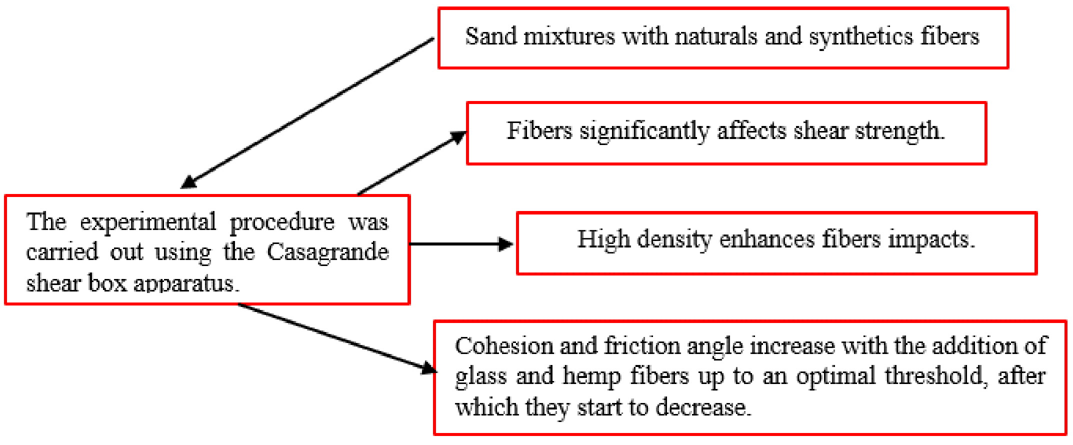
Graphical abstract:



Highlights:

- Fibers significantly impacts shear strength and internal friction angle of sand mixtures.
- Shear strength increases with glass fibers up to 0.5%, then decreases with higher content.
- Shear strength increases with hemp fibers up to 0.75%, then decreases with higher content.

- Higher relative density (RD=80%) shows a greater effect of fibers on mechanical behavior.

Abstract: This paper presents a laboratory study of the effect of naturals (hemp fibers) and synthetics fibers (glass fibers) on the mechanical behavior of sandy soil (natural Chlef sand). A series of shear direct tests were carried out on medium dense (RD= 50%) and dense (RD= 80%) Chlef samples sand with different naturals and synthetics content fibers ranging from 0, 0.25, 0.5, 0.75 and 1% and under three normal stress of 50, 100 and 200 kPa. The test results show that the addition of fibers has a significant effect on the shear strength of the sand-fiber mixture, however, this shear strength increases with the increase of the fibers content, the normal stress applied and the relative density until up an optimal fibers content of 0.5% for the glass fibers and 0.75% for the hemp fibres. Beyond these optimal fibres content, the shear strength decreases. The internal friction angle and the cohesion are significantly influenced by the fibres content.

Keywords: Sand, shear strength, fibers content, relative density, mechanical behavior, sand–fiber mixture.

Abbreviation:

γ_s: Sand specific gravity

D_{10}: Effective diameter

D_{50}: Average diameter

Cu: Coefficient of uniformity

Cc: Coefficient of curvature

e_{max}: Maximum void ratio

e_{min}: Minimum void ratio

σ_n: Normal stress

IP: Plasticity index

τ: Shear strength

τ_{max}: Maximum shear stress

RD: Relative density

φ: Internal friction angle

C: Cohesion.

ΔH: Horizontal displacement

ΔV: Vertical displacement

FC: Fibers content

Sr: Reinforcement coefficient

1. Introduction

Recently, experts in geotechnical engineering have become interested in earth reinforcement using synthetic materials. Currently, a trusted and efficient method for improving the strength and stability of soil is the use of conventional geosynthetic materials (geotextile, geogrid, fiber, etc). In particular, the application of randomly spaced fibers is considered a viable technique of soil reinforcement that improves the soil mass's resistance close to the surface, where effective strength is lowest, and so aids in soil stability (Noorzad and Zarinkolaei, 2015). Indeed, shear stress of granular soils is one of the recommended aspects in the geotechnical engineering field to analyze stability problems such as deep foundations and embankments (Wang et al., 2013), particularly at the bottom of the circular failure surface beneath the embankment, as schematically illustrated in Fig. 1. This conceptual representation follows the failure mechanisms discussed by Day et al. (2016).

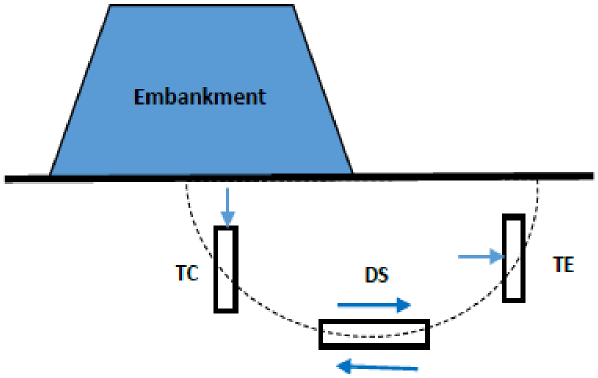


Figure 1. Conditions of shear in the failure surface under embankment: TC: triaxial compression, DS: direct shear and TE: triaxial extension (Redrawn and adapted from Day et al., 2016).

Numerous studies show that the shear strength of sand increases with the increase in fiber content in the soil (Gray et al. 1986, Michałowski et al. 2003, Romero et al. 2003, Consoli et al. 2007, Chen et al. 2008, Eldesouky et al. 2016). However, other studies have studied the effect of addition of natural or artificial fiber content (Ranjan et al. 1994, Sivakumar et al. 2008, Sadek et al. 2010, Harikumar et al. 2015). Tests results indicate that the shear strength of reinforced sand increases while the loss of post-peak strength is reduced with the presence of the fibres. Similar tests results were found by Al-Refeai (1991, Diambra et al. 2010). Praveen Kumar et al. (2006) based on direct shear and triaxial test conducted on small and large samples of randomly distributed fibers reinforced sand shows the percentage increase in the strength of sand is more at 50% relative density compared to 70% relative density. According to (Ibraim et al. 2010, Liu et al. 2011), the inclusion of reinforcement fibers reduced the risk of liquefaction potential. Michalowski (1997) and Consoli et al. (2009) reported that the increase of the shear strength of sand increases with the length and the diameter of the fibers and of the grain shape of the sand. Latha and Murthy (2007) by performing a series of triaxial tests on polyester fibers reinforced sand with a mean diameter D_{50} of 0.7 mm, C_u of 3.54 and a relative density of 70%. Thrie tests results showed that the shear strength of sand was not improved by the addition of the fibers reinforcement.

Gray and Ohashi (1983) performed a series of direct shear tests on dry sand reinforced with natural, synthetic, and metallic fibers. Their findings showed that natural and synthetic fibers were more effective reinforcing agents than metallic ones. Similarly, Consoli et al. (2002) conducted triaxial tests on homogeneous fine sand (D_{10} = 0.16 mm, C_u = 1.9, C_c = 1.2) with a 70% relative density and reinforced with polyethylene terephthalate fibers. The results showed that, whereas peak and residual strengths improved dramatically with fiber addition, stiffness remained largely unchanged. Similar findings were reported by Shewbridge and Sitar (1989), Murray et al. (2000), and Maher and Gray (1990). In contrast, Yetimoglu and Salbas (2003) discovered that fiber insertion had no significant influence on peak shear strength or internal friction angle, but did result in a modest drop in shear stiffness and an increase in residual strength.

Numerous studies have shown that both natural and synthetic fibers can improve soil characteristics and promote long-term soil stabilization. Zafar et al. (2023) found that incorporating natural and synthetic fibers considerably enhances CBR values, compressive strength, and swelling resistance, indicating their potential as long-term soil stabilization approaches. Similarly, Senol (2012) conducted early studies on the effect of fly ash and polypropylene fibers on CH-type soft soils, demonstrating that incorporating 10-15% fly ash and 0.5-1% polypropylene fibers improves mechanical behavior, increases shear strength, and converts soil from brittle to ductile. Building on these findings, Navagire et al. (2025) investigated Indian black cotton soils and discovered that stabilization with polypropylene fibers significantly improves the engineering capabilities of clayey formations. Their findings showed a considerable decrease in swelling pressure and a notable rise in California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) values. Gümüşerand Şenol Şenol (2014) found that fiber length (6, 12, 19 mm) and fiber content (0.5-2%) with 10-15% fly ash have a significant impact on geotechnical properties, improving soil strength and ductility. This highlights the environmental and practical benefits of fiber-reinforced soft soils. In this connection, Araya-Letelier et al. (2019) conducted a thorough experimental mechanical-damage assessment of earthen mixes reinforced with micro polypropylene fibers, emphasizing the fibers vital role in improving post-cracking toughness and energy absorption capacity. The role of natural fibers has also been thoroughly investigated. Siouta et al. (2024) found that treated hemp fibers serve as a long-lasting and environmentally friendly reinforcement, increasing flexural and tensile strength in sustainable construction applications.

Medina-Martinez et al. (2022) demonstrated the benefits of introducing bamboo, jute, coir, palm, rice husk, and sawdust fibers into expansive soils, which improved shear strength and bearing capacity in a cost-effective and environmentally friendly manner. Furthermore, recent advancements by Paul et al. (2025) investigated hybrid stabilization methods, such as the combination of microbial-induced calcite precipitation (MICP) and natural jute fibers, which was found to significantly reduce the shrink-swell potential and enhance the strength of expansive soils. Karimah et al. (2021) evaluated the fundamental properties of natural fibers, highlighting their low density, high strength-to-weight ratio, and the impact of fiber composition and microstructure on mechanical performance, emphasizing their importance in long-term soil stability. Similarly, synthetic fibers have demonstrated effectiveness in geotechnical applications. Mishaal and Aldaad (2023) reviewed synthetic fiber and plastic-waste reinforcements, showing significant im-provements in mechanical properties, particularly shear strength. Alcan and Çelik (2023) found that reinforcing sandy soils with various fibers, such as glass, basalt, mac-romesh, and hybrid combinations, improves bearing capacity and reduces settlement. PIV analysis confirmed more uniform stress distribution and reduced localized deformations. These findings highlight the expanding importance of fiber-reinforced soils, not just for strength augmentation, but also in the larger context of environmental engineering and the circular economy. Furthermore, the fiber contents used in this investigation, ranging from 0% to 1%, are consistent with those published in the literature, ensuring both scientific comparability and practical applicability (Zafar et al., 2023; Siouta et al., 2024).

While previous studies have extensively explored soil reinforcement with varied inclusions, the majority of study has focused on generic sand types or specialized clayey soils. This research fills the gap by focusing on the mechanical response of natural Chlef sand, a regional soil with distinct geomorphological features. In this work, we sought to give a direct comparison of synthetic fibers (glass fibers) and natural fibers (hemp fibers) in order to assess their relative effectiveness in improving sand stiffness and shear strength. Unlike earlier studies, this study investigates the interaction between these two types of reinforcement across a wide range of compaction states (RD = 50% and 80%) and various normal stresses (50, 100, and 200 kPa). This study shows a key ideal fiber content for each kind, revealing fresh information about the mechanical limits of fiber effectiveness. the paper is organized as follows: Section 1 includes an introduction and a literature review; section 2 describes the experimental program and the qualities of the materials employed; and section 3 summarizes and discusses the key experimental findings. Section 4 specifies the study's limitations and scope, and section 5 concludes with a summary of the findings, the final conclusions, and recommended future work for this research field.

2. Experimental programs

2.1. *Tested materials*

2.1.1. Soil

In this laboratory investigation, testing were performed on natural Chlef sand (Algeria) with 0.8% low-plasticity silt (Ip = 5.81%) (Fig. 2). The particle size distribution curve of natural Chlef sand is shown in Figure 3. Many researchers have made considerable use of this sand (for example, Brahim et al. 2019, Krim et al. 2017, Brahim et al. 2018, Bouri et al. 2019, Boutaraa et al. 2020, Krim et al. 2021, Nougar et al. 2021, Bouri et al. 2021, Nougar et al. 2022, Brahimi et al. 2022, Bouri et al. 2023, Bouri et al. 2024). Table 1 summarizes the geotechnical features of this sand.

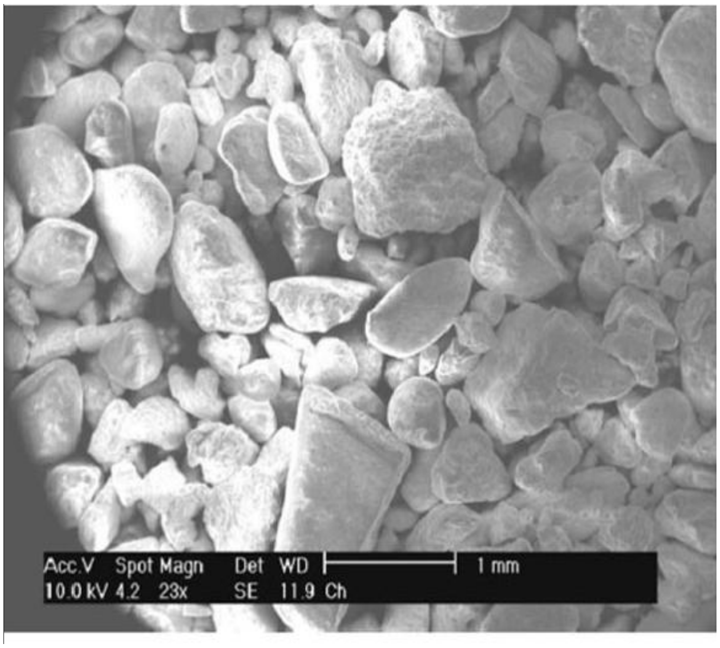


Figure 2. Microscopic view of natural Chlef sand.

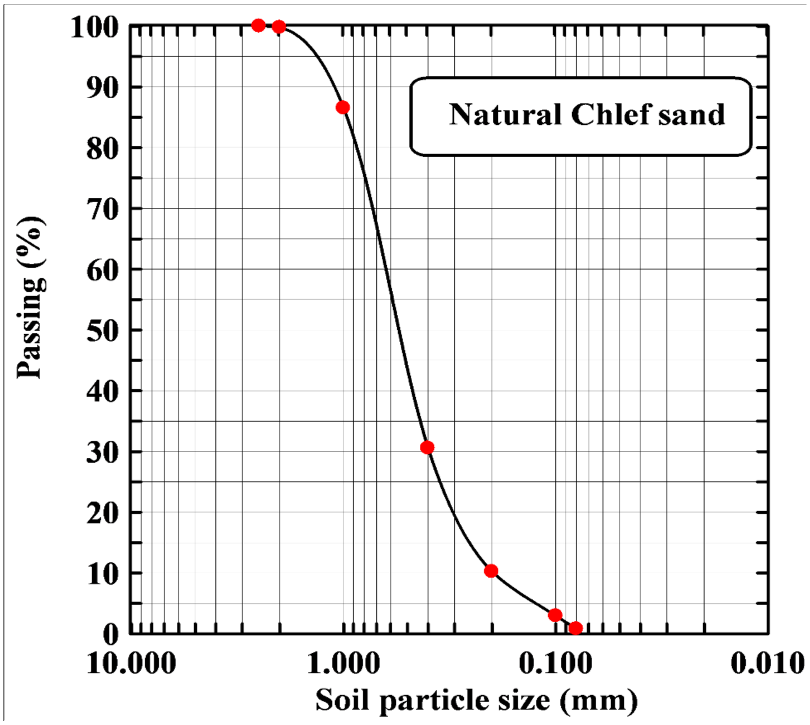


Figure 3. Grain size distribution curve of the natural Chlef sand.

Table 1. Physical properties of natural Chlef sand.

Properties	Natural Chlef sand
Specific weight of solids, γ_s (g/cm^3)	2.67
Minimum void ratio, e_{min} (.)	0.66
Maximum void ratio, e_{max} (.)	0.81
Effective diameter, D_{10} (mm)	0.20
Mean diameter , D_{50} (mm)	0.55
Uniformity coefficient, C_u (.)	3.25
Coefficient of curvature, C_c (.)	1.23
Plasticity index of fines element, IP (%)	5.81
Particles shape	Rounded

2.1.2. Fibers

The fibers utilized in this investigation are glass and hemp, both with a circular cross-section and a length of 12 mm. The diameters of glass and hemp fibers are 18 µm and 35 µm, respectively (Fig. 4). Glass fibers are synthetic materials with good soil reinforcing properties (Al-Refeai et al. 2015, Maher et al. 1990, Consoli et al. 1998, Mujah et al. 2013, Bouaricha et al. 2019). In contrast, hemp fibers are natural, eco-friendly materials with great tensile strength that have traditionally been used in the building industry to reinforce gypsum plasterboard. Recently, these natural fibers have been the focus of substantial geotechnical reinforcement research (Ghavami et al. 1999, Prabakar et al. 2002, Mattone et al. 2005). Table 2 summarizes the physical and mechanical parameters of both fiber types.

Figure 4. Views of the used fibers: (a) glass fibers, (b) hemp fibers.

Table 2. Physical and mechanical properties of used fibers.

Properties	Glass fibers	Hemp fibers
Specific density (g/cm^3)	2.62	0.96
Length (mm)	12	12
Diameter (mm)	18	35
Tensile strength (MPa)	485	550
Young modulus (MPa)	73000	19000

2.2. *Samples preparation*

To investigate the effect of fibers on the behavior of natural Chlef sand, a series of direct shear tests were performed on both unreinforced and fiber-reinforced samples with fiber contents ranging from 0 to 1%, for two relative densities: medium dense (RD = 50%) and dense (RD = 80%), under normal stresses of 50, 100, and 200 kPa.

The tests were performed using a square direct shear box 60 x 60 mm2 with an initial sample thickness of 25 mm. The experimental procedure involved two phases. The first concerns the preparation of reinforced sand samples; while the second phase consisted of carrying out tests on the shear box. The sample preparation was carried out by first determining the weight of the sand and fibers for the mixture. The fibers content (Fc) added, is defined as a percentage of dry weight of sand:

$$F_c\,(\%) = \left(\frac{\mathrm{W_f}}{\mathrm{W}_s}\right)\mathrm{x}100 \tag{1}$$

where: Wf and Ws are the weight of fibers and dry sand, respectively.

The sand is dried and then manually mixed with fibers. To fabricate samples, the dry deposition method was used. To obtain the two relative densities, the sample was deposited in three layers. Each layer was compacted to obtain the dense state (RD = 80%), however, for the medium density (RD = 50%), the material is lightly compacted. The test consists of placing the sample in the shear box and subjecting it to a vertical load N and a horizontal force T which gradually increases until failure. The direct shear test allowed measuring the peak and residual shear resistance and the vertical displacement corresponding to every applied normal stress according to an imposed shear plane. All the tests were conducted at constant displacement rate of 1.00 mm/min according to (ASTM-D3080, 2005). The shear stress was recorded as a function of horizontal displacement up to an average shear strain of 7.5 mm.

3. Results and discussion

In this part, the variation of the shear strength and the vertical displacement versus the horizontal displacement and the stress path obtained from direct shear tests are presented in order to analyse the effect of the fibers content on the mechanical behaviour of the Chlef sand before and after its reinforcement under different applied normal stress for two relative densities.

3.1. *Effect of fibers content on the maximum shear strength (τ_{max})*

3.1.1. Medium dense state (RD= 50%)

Figure 5 shows the impact of natural and synthetic fiber content on shear strength (τ) and horizontal displacement (ΔH) in medium dense soil (RD = 50%) under normal stress of 100 kPa. Fiber levels ranged from 0 to 1%. As fiber concentration rises, shear stress increases with horizontal displacement (ΔH) until it reaches an ideal value for each fiber type. The maximum shear strength values for glass fiber-reinforced samples under constant normal stress of 100 kPa were 73.3, 84.78, 91.72, 82.58, and 78.94 kPa for Fc = 0%, 0.25%, 0.5%, 0.75%, and 1%, respectively (Fig. 5a). For hemp fiber-reinforced samples (Fig. 5b), shear strength increased dramatically, with values of 73.3, 84.52, 96.14, 120.17, and 83.53 kPa for the same fiber contents. Hemp-reinforced composites have increased stiffness due to stronger and more flexible fibers, which improve particle bonding and stress distribution.

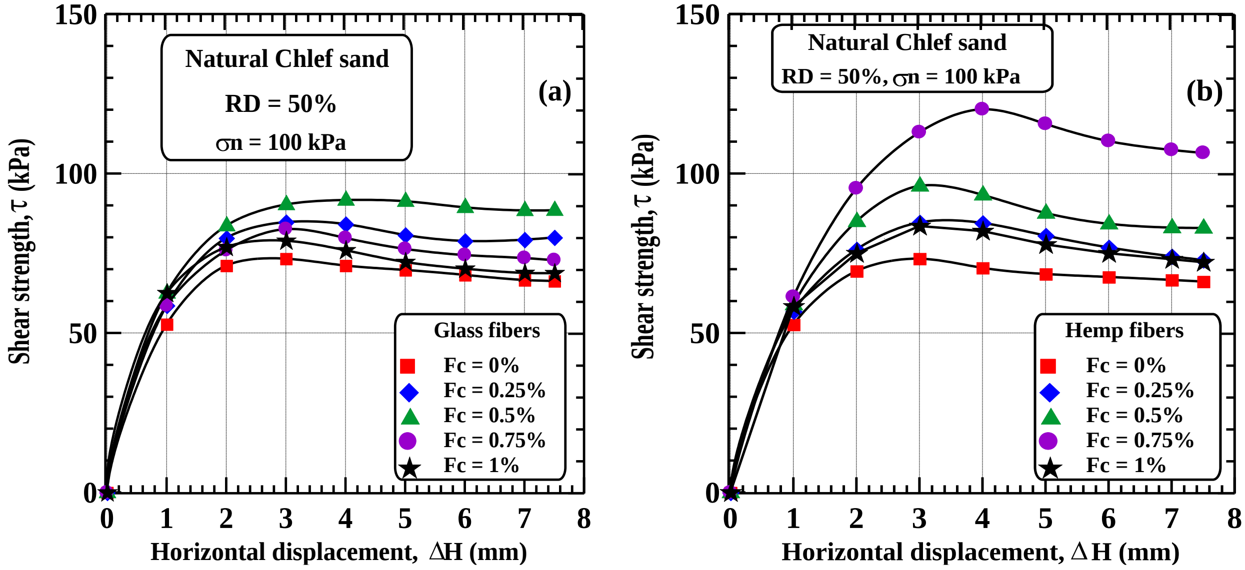


Figure 5. Effect of fibers content on shear strength (σ_n = 100 kPa, RD = 50%):
Shear strength (τ) - Horizontal displacement (ΔH), a) glass fibers, b) hemp fibers.

Figure 6 shows the connection between vertical displacement (ΔV) and horizontal displacement (ΔH) in both unreinforced and fiber-reinforced samples. The experimental results show that, whereas sand-fiber combinations have a slightly stiffer initial reaction, the inclusion of fibers greatly reduces the sand's dilatancy. Specifically, raising fiber content above a given level encourages increased contractive activity. This transition from dilatancy to contraction is most likely due to soil matrix dilution and fiber rearrangement during shearing. At greater concentrations, the creation of fiber clusters (or'soft pockets') disrupts grain-to-grain interlocking, increasing the composite's initial void ratio. Under normal and shear pressures, these clusters tend to compress, which overrides thick sand's characteristic dilative response. As a result, the presence of too many fibers results in a more compressible structure, as confirmed by the findings of Liu et al. (2019), who discovered that fiber winding and clumping impeded effective particle bonding.

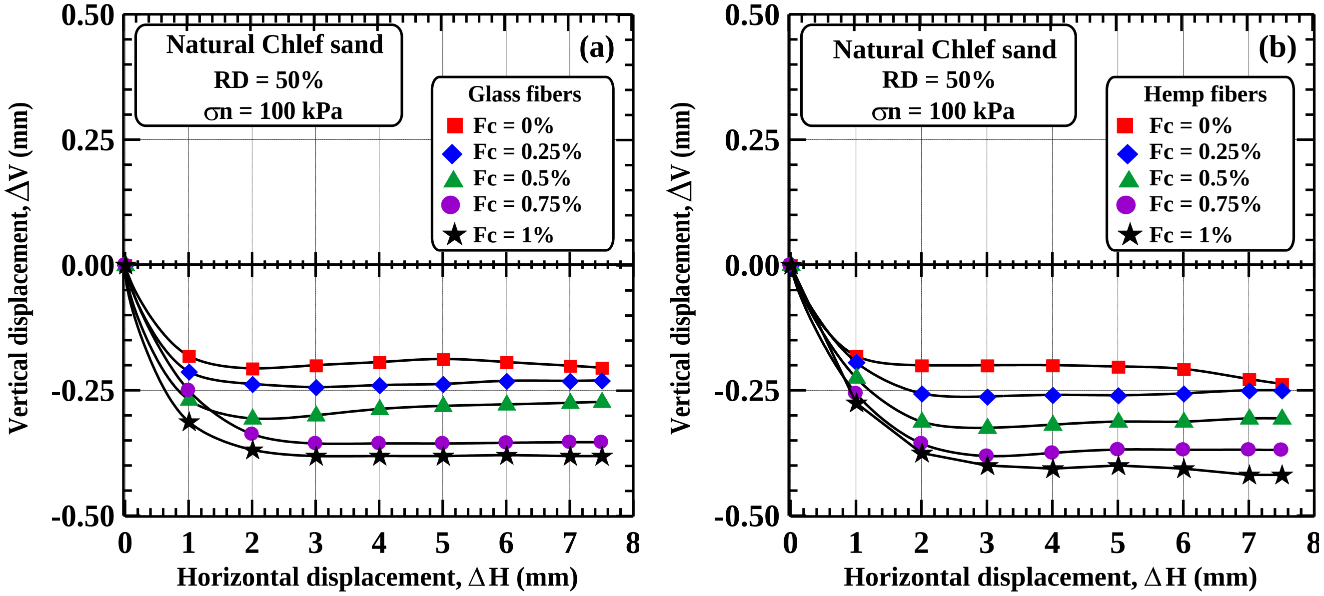


Figure 6. Effect of fibers content on displacements (σ_n = 100 kPa, RD = 50%):
Shear strength (τ) - Horizontal displacement (ΔH), a) glass fibers, b) hemp fibers.

Figure 7 shows how peak shear strength (τ_{max}) varies with fiber content (Fc) and normal stress (σ_n) in medium-dense sand reinforced with glass and hemp fibers. The findings show that (τ_{max}) initially increases with both fiber concentration and normal stress. However, this enhancement is limited by an optimum fiber content (OFC), after which any additional reinforcement reduces shear resistance. This degradation is mostly caused by soil matrix saturation, in which abundant fibers enhance fiber-to-fiber contact while inhibiting grain-to-fiber interlocking.

Notably, hemp fibers regularly beat glass fibers under most testing situations. This greater performance is most likely owing to hemp fibers' higher surface roughness and natural shape, which increases interfacial friction and mechanical interaction with sand particles. Unlike the comparatively flat surface of synthetic glass fibers, the uneven roughness of natural hemp fibers allows for more effective mobilization of tensile resistance during shearing, resulting in higher reinforcing efficacy in medium-dense soil settings.

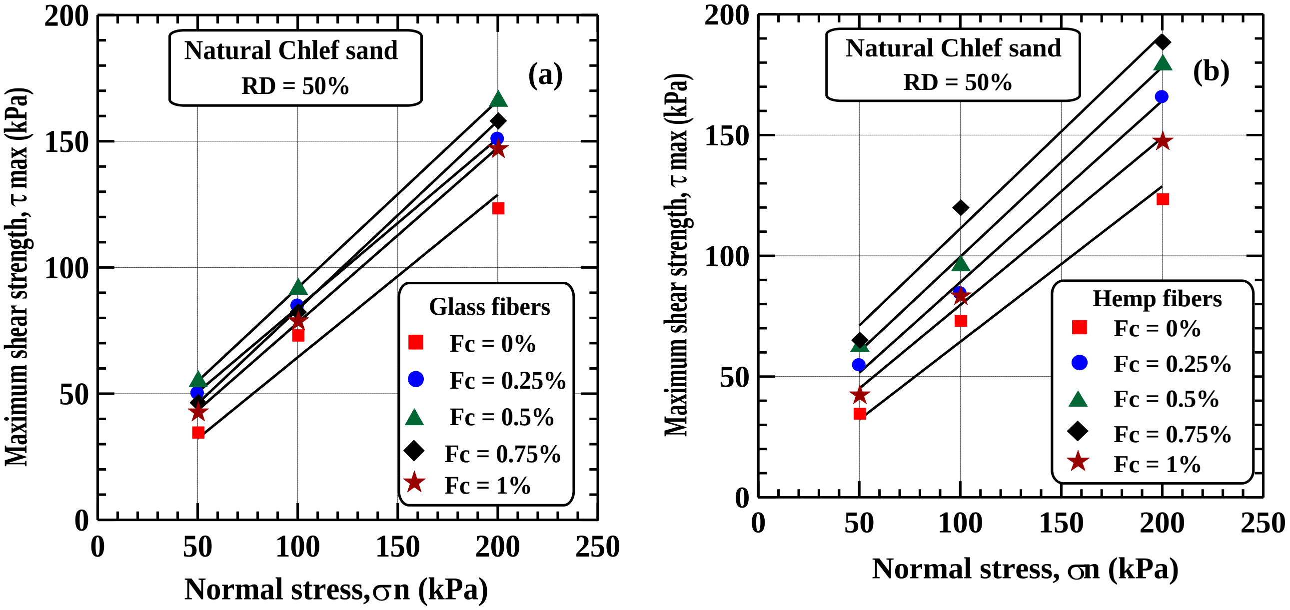


Figure 7. Variation of maximum shear strength (τ_{max}) versus fibers content (Fc) and normal stress (σ_n) in the medium dense state (RD = 50%): a) glass fibers, b) hemp fibers.

3.1.2. Dense state (RD= 80%)

Figure 8 shows the shear strength (τ) vs horizontal displacement (ΔH) of unreinforced and dense samples (RD = 80%) reinforced with glass and hemp fibers under 100 kPa. Shear strength generally increases with fiber concentration until it reaches a peak, after which it declines to a lower residual value. The maximum shear strength of glass fibers at Fc = 0.25%, 0.5%, 0.75%, and 1% was 94.67, 108.14, 84.67, and 80.41 kPa, respectively (Fig. 8a). Hemp fibers had maximum shear strengths of 94.67, 109.44, 126.25, and 90.44 kPa (Fig. 8b). Hemp fibers outperform glass fibers because they are more flexible, generating an internal cohesive network that increases overall shear strength and reduces localized failures.

Figure 9 shows the vertical displacement (ΔV) vs horizontal displacement (ΔH) for dense samples. The initial contraction phase is followed by dilatation. This contraction-dilation phenomenon is more prominent in hemp-reinforced soils due to their higher stiffness and fewer weak surfaces than glass fibers.

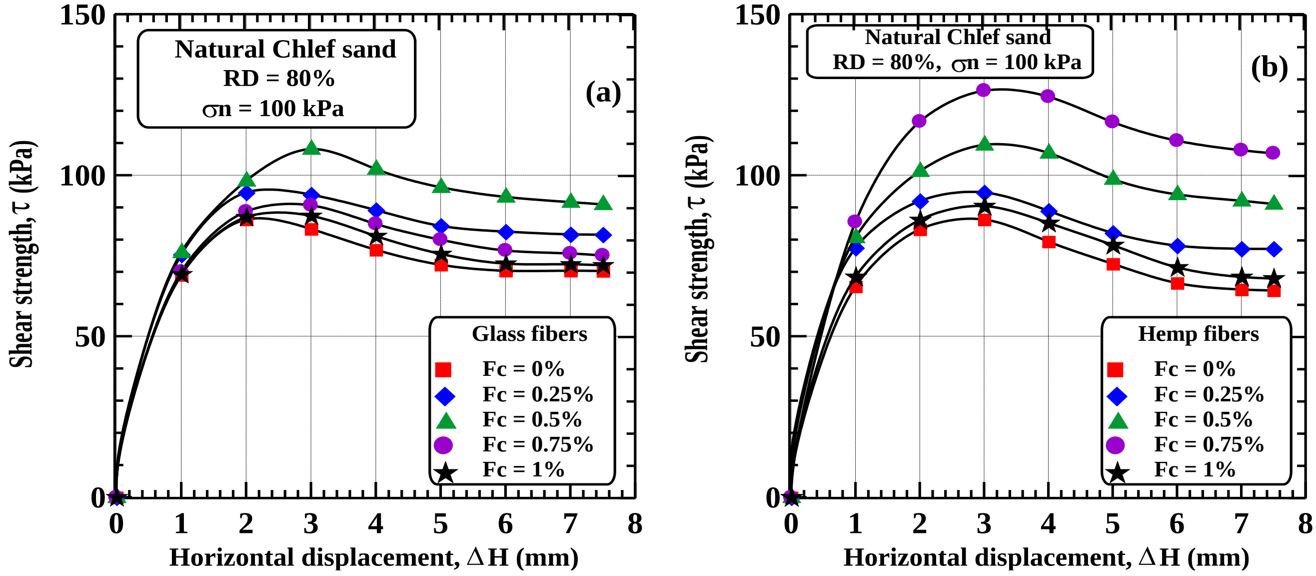


Figure 8. Effect of fibers content on shear strength (σ_n = 100 kPa, RD = 80%):
Shear strength (τ) - Horizontal displacement (ΔH), a) glass fibers, b) hemp fibers.

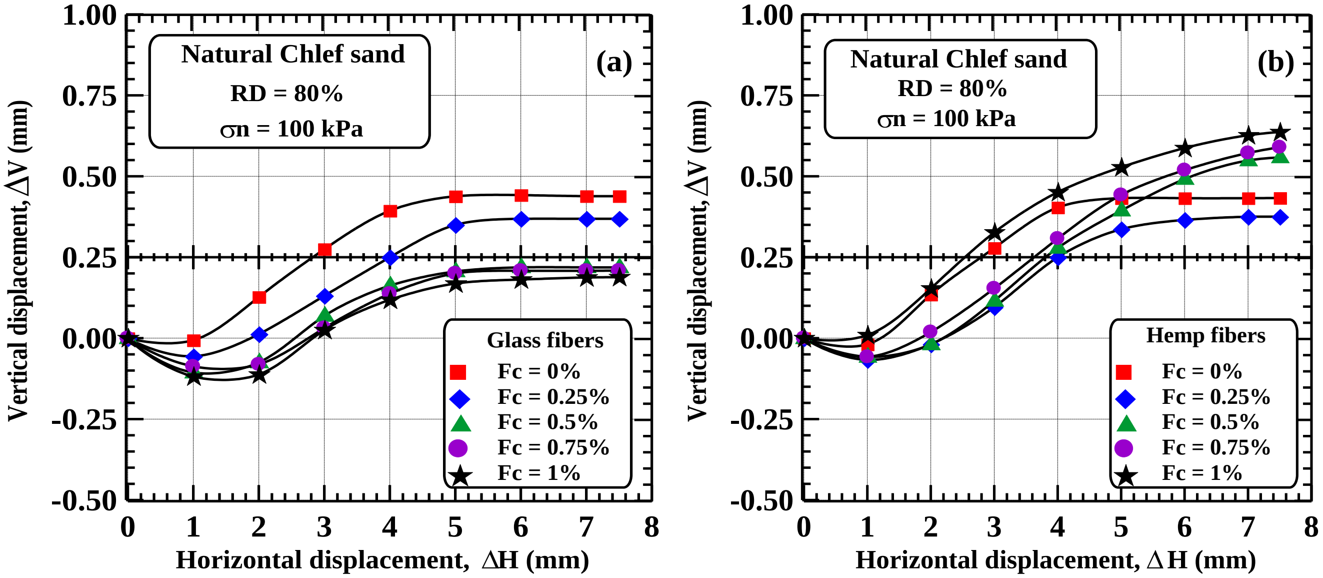


Figure 9. Effect of fibers content on displacements (σn = 100 kPa, RD = 80%):
Vertical displacement (ΔV) - Horizontal displacement (ΔH), a) glass fibers, b) hemp fibers.

Figure 10 shows the relationship between peak shear strength (τmax) and normal stress (σn) in dense sand samples. For glass fibers with an optimal fiber content of Fc = 0.5%, the peak shear strength values were 62.78, 108.14, and 183.32 kPa for normal stresses of 50, 100, and 200 kPa, respectively. Hemp fibers with Fc = 0.75% had higher τmax values of 74.58, 126.25, and 193.11 kPa.

These findings highlight the synergistic effects of fiber shape, reinforcement ratio, and initial packing density. The greater performance of hemp fibers is principally due to their larger aspect ratio and surface imperfections, which allow for more uniform stress redistribution and reduce the creation of preferential failure planes. Furthermore, the thick condition of the sand improves reinforcing efficiency by creating a stronger confinement effect on the fibers. In dense soil, greater particle-to-fiber contact pressure causes a more effective mobilization of fiber tensile strength, resulting in a significant increase in total bearing capacity and shear resistance as compared to medium-dense soil.

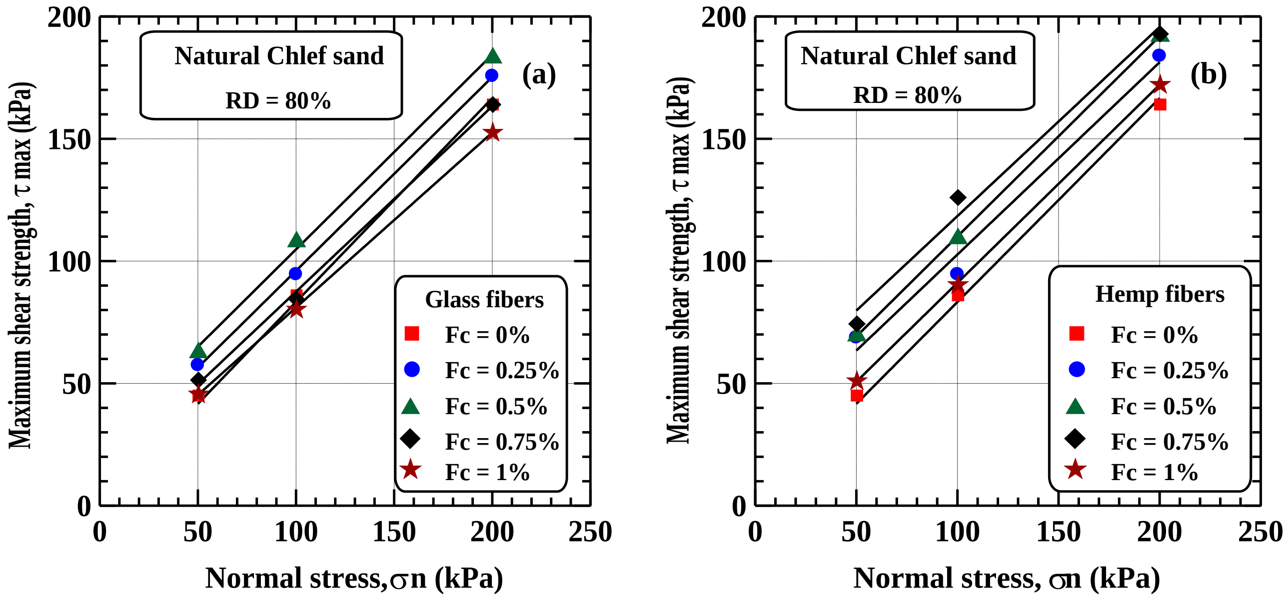


Figure 10. Variation of the maximum shear strength (τ_{max}) versus fibers content (F_c) and normal stress (σ_n) in the dense state (RD = 80%): a) glass fibers, b) hemp fibers.

3.2. *Effect of fibers content on the cohesion (c)*

Figure 11 shows the variation of cohesion (c) versus fibers content varying from 0% to 1% in the medium dense and dense state. From this figure, it can be seen an effective improvement of the reinforced sand with fibers distributed in randomly manner, indicating high values of the cohesion obtained by to the inclusion of fibers in the soil. This figure indicates also the existence of an initial cohesion due to the presence of weakly plastic fine clays fines. For the medium dense state, for the unreinforced and reinforced sand with glass fibers, the cohesion is 9.62, 16.78, 17.95, 9.31 and 8.72 kPa. For the hemp fibers, the cohesion is 9.62, 16.17, 20.7, 31.03 and 30.27 kPa; these values vary according to the fibers content (F_c = 0, 0.25, 0.5, 0.75 and 1%) respectively. For the dense state, the cohesion varying from12.38 kPa for unreinforced sand to 25.19 kPa for reinforced sand with glass fibers and until 49.29 kPa for sand reinforced with hemp fibers. The results show better mechanical performance in the dense state than those obtained in the medium dense state.

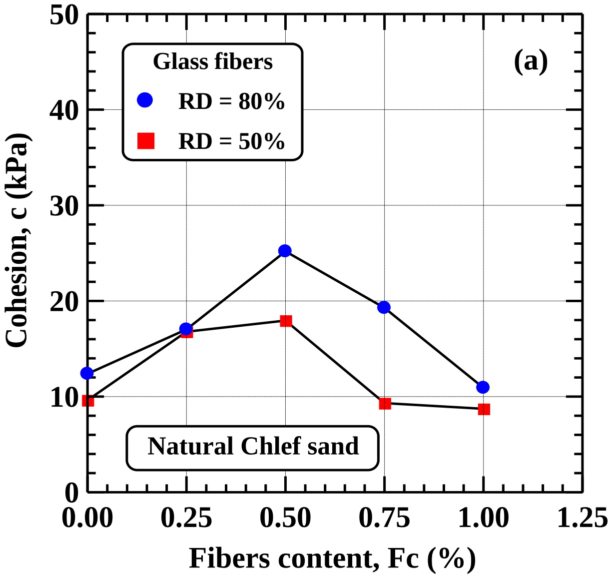


Figure 11. Variation of cohesion (c) versus fibers content (F_c) (RD = 50%, RD = 80%): (a) glass fibres, (b) hemp fibres.

3.3. *Effect of fibers content on the internal friction angle (ϕ)*

Figure 12 shows the variation of the internal friction angle (ϕ) with the fibers content (F_c) for the two types of fibers in medium dense and dense state. The results obtained indicate a significant increase in the angle of internal friction (ϕ) with the increase in the fraction of the fibers up to an optimal value of fibers content of 0.5% for glass fibers and 0.75% for hemp fibers. Once this value is reached, the internal friction angle decreases for the two types of fibers in the medium dense and dense state. For the medium dense sand, the internal friction angle for sand reinforced sand with glass fibers is 29.91°, 35.75°, 42.46°, 42.51° and 39.82°. For the second type (hemp fibers), the internal friction angle is 29.91°, 42.63°, 45.21°, 46.01° and 23.38° for the fibers content of 0%, 0.25%, 0.5%, 0.75% and 1%, respectively. The same observations are noted for the sand reinforced in the dense state. However, the internal friction angle in the dense state is very important and greater than that obtained in the medium dense state.

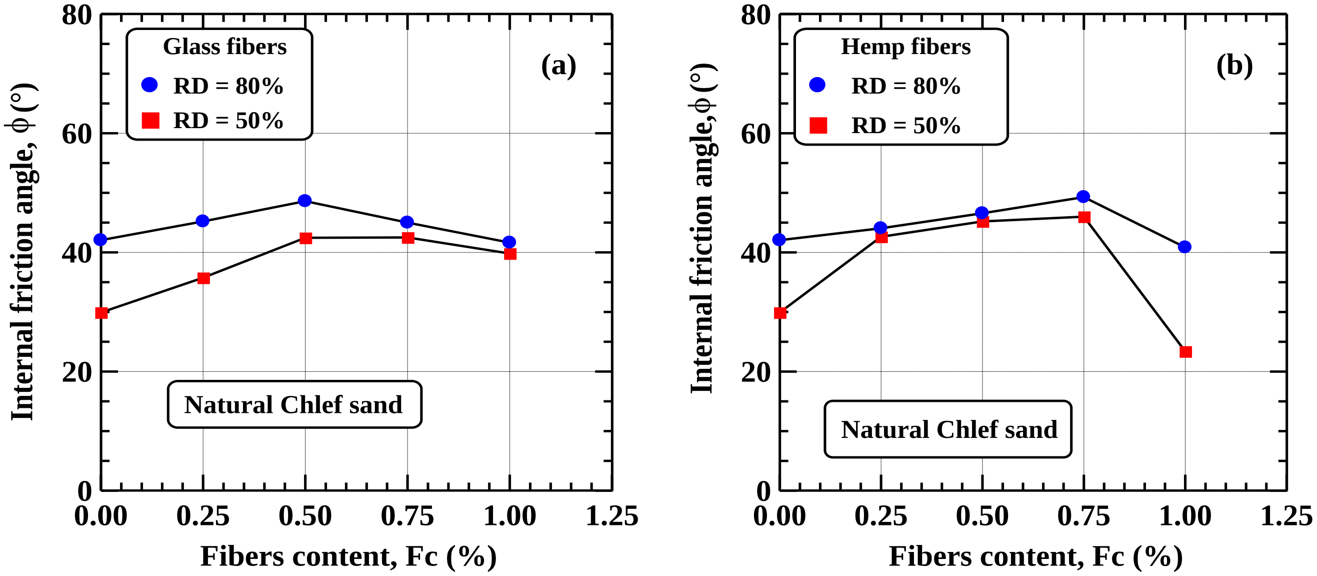


Figure 12. Variation of internal friction angle (ϕ) versus fibers content (F_c) (RD = 50%, RD = 80%): a) glass fibers, b) hemp fibers.

3.4. *Effect of fibers content on the reinforcement coefficient (Sr)*

In order to evaluate the effect of fibers reinforcement on the shear strength of sand, the shear strength ratio (S_r), defined by (Zhang et al. 2006) is introduced according to the following relationship:

$$S_r = \frac{(\tau_{max})^r}{(\tau_{max})^{nr}} \qquad (2)$$

where:

$(\tau_{max})^r$: Maximum shear strength of reinforced sand.
$(\tau_{max})^{nr}$: Maximum shear strength of unreinforced sand.

Figure 13 and 14 show the variation of the coefficient of reinforcement (S_r) or the shear strength ratio for reinforced sand to that of unreinforced sand at medium dense and dense state under different normal stresses (σ_n = 50, 100, 200kPa). In the medium dense state, it can be seen that the shear strength ratio increases with the increase with the fibers content until an optimal value of fibers specific fibers to each of type fibers and decreases with the increase of the normal stress (Fig. 13).

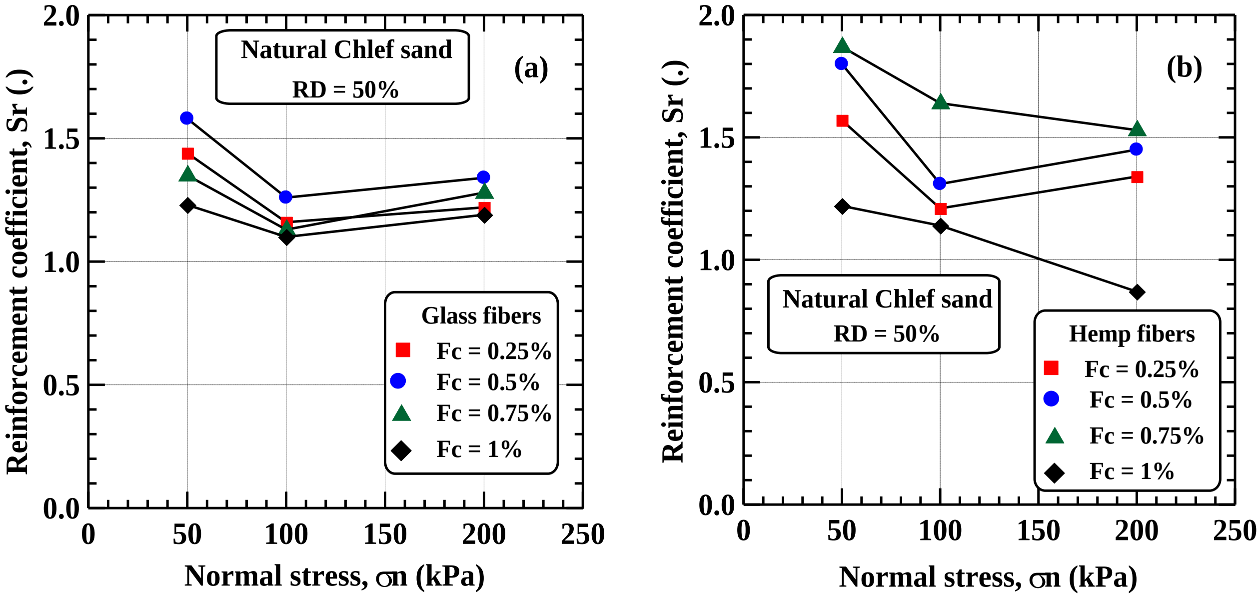


Figure 13. Variation of the reinforcement coefficient (S_r) versus fibers content (F_c) (RD = 50%): (a) glass fibers, (b) hemp fibers.

In the dense state (Fig. 14), the results show that the strength ratio (S_r) of the fiber-reinforced sand increases proportionally with fiber concentration until it reaches an ideal value unique to each fiber type. Low normal stress (σ_n = 50 kPa) results in the highest reinforcement efficiency (S_r) values. This phenomena can be scientifically explained as dilatancy-induced confinement. At low normal loads, thick sand has a high tendency to dilate; however, the presence of fibers prevents this expansion, thereby raising the local confining pressure surrounding the fibers. This contact increases interfacial friction and enables for more effective mobilization of the fibers tensile resistance. As normal stress increases, the fibers' relative contribution decreases as shear behavior is more dominated by the primary mineral friction of the sand particles. These results are similar with the observations made by Bouaricha et al. (2017) and Suchit et al. (2020).

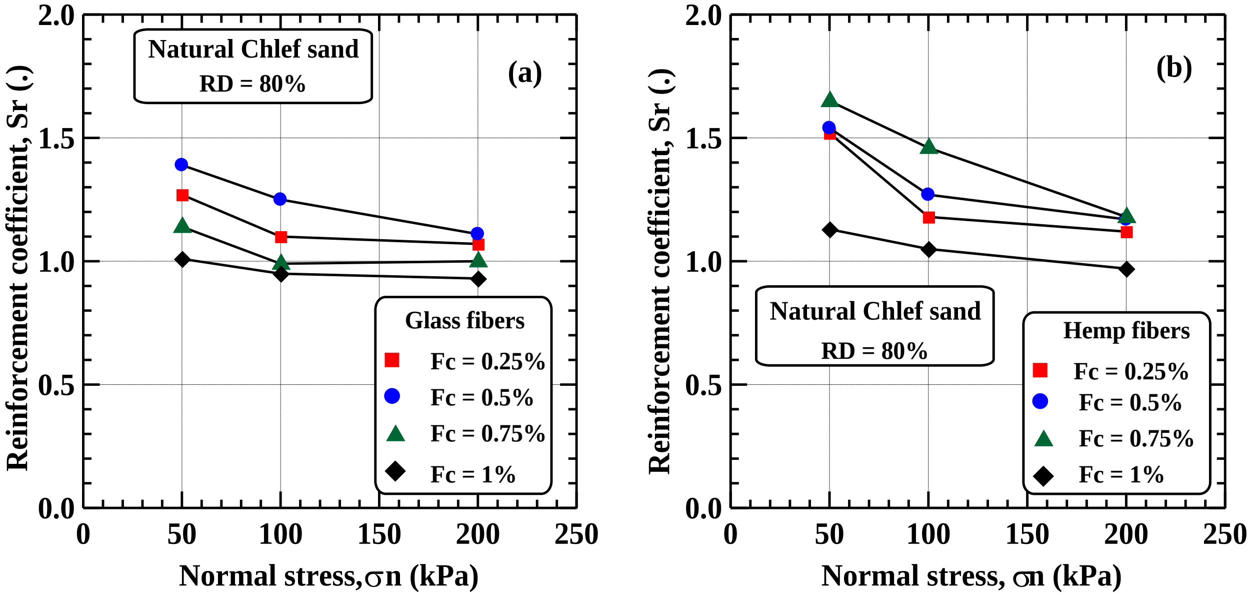


Figure 14. Variation of the reinforcement coefficient (Sr) versus fibers content (Fc) (RD = 80%): (a) glass fibres, (b) hemp fibres.

3.5. *Effect of type of fibers on shear strength (τ) and vertical displacement (ΔV)*

Figure 15 shows the variation shear strength (τ) versus horizontal displacement (ΔH) carried out on unreinforced and reinforced samples with two types of fibers under a normal stress (σ_n = 100 kPa) at a medium dense and dense state. It can be seen from this figure that the shear strength of sand increases significantly for each type of fibers. However, the maximum shear strength obtained for samples reinforced with hemp fibers is greater than the samples reinforced with glass fibers. The samples reinforced with glass and hemp fibers and subjected to a normal stress (σ_n = 100 kPa) recorded the optimal values of 91.72 kPa and 120.17 kPa, respectively (Fig. 15a). In Fig. 15b, it can be noted the same observations as those observed in figure 15a of the shear strength carried out on samples in the medium dense state and the maximum shear strength obtained in the dense state is 108.14 and 126.25 kPa, for samples reinforced with glass and hemp fibers, respectively. It can be noted from the recorded values that the reinforcement with hemp fibers seems more rigid than the glass fibers due to the high difference in the resistance between the two types of fibers.

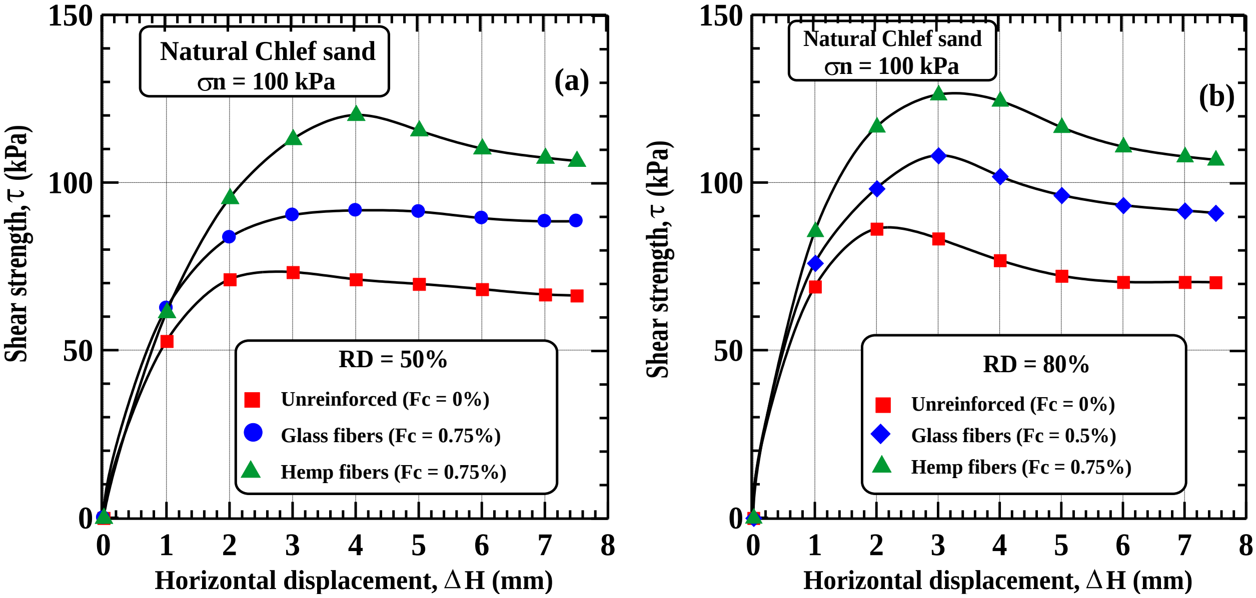


Figure 15. Variation of shear strength versus type of fibers content (σ_n = 100 kPa): Shear strength (τ) - Horizontal displacement (ΔH), a) RD = 50%, b) RD = 80%.

Figure 16 shows the vertical displacement (ΔV) vs horizontal displacement (ΔH) of both unreinforced and fiber-reinforced sand. The results show that the introduction of glass and hemp fibers causes largely contractive behavior in medium-dense samples (RD = 50%) (Fig. 16a). In contrast, in the dense state (RD = 80%), the reinforced samples show an initial contractive phase followed by a dilatancy phase (Fig. 16b). Notably, the dilatancy phase is significantly reduced in reinforced specimens, particularly those containing glass fibers.

This action can be scientifically explained by interrupting the grain-rolling mechanism. In dense sand, fibers operate as a physical restraint, preventing sand particles from overriding one another (dilatancy). This suppression is more evident with glass fibers, most likely due to their higher stiffness than hemp, which creates a more rigid boundary condition within the soil matrix. The initial contractive phase in dense samples is further intensified by fiber-induced void compression and fiber rearrangement during the early phases of shearing, which somewhat offsets the dense sand's intrinsic dilative propensity.

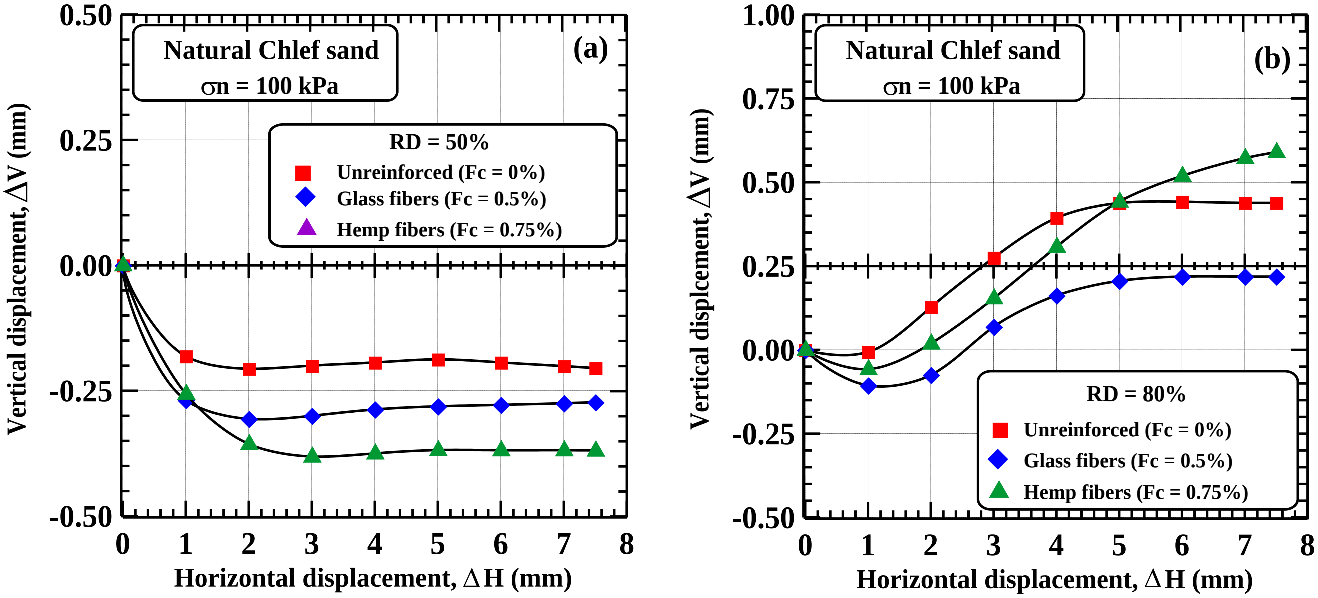


Figure 16. Variation of displacements versus type of fibers (σ_n = 100 kPa): Vertical displacement (ΔV) - Horizontal displacement (ΔH), a) RD = 50%, b) RD = 80%.

3.6. *Effect of the type of fibers on the maximum shear strength (τ_{max})*

Figure 17 illustrates the variation of maximum shear strength (τ_{max}) versus types of fibers (glass and hemp) and normal stress (σ_n) for samples prepared in the medium dense and dense state. It can be seen from this figure that the maximum shear strength increases linearly for each type of used fibers. However, it is noted that the values recorded with hemp fibers show better performance than those obtained with glass fibers at a medium dense state. The unreinforced and reinforced samples with glass and hemp fibers in a medium dense state (Fig. 17a) are characterized by the following values: 34.81, 73.28 and 123.67 kPa for the unreinforced samples; 55.06, 91.97, 166.19 kPa for the samples reinforced with glass fibers and 65.25, 120.25 and 188.69 kPa for the samples reinforced with hemp fiber for normal stresses of 50, 100 and 200 kPa, respectively. In a dense state (Fig. 17b), the values of the maximum values of the shear strength are 45.25, 86.25 and 164.25 kPa, for unreinforced samples; 62.78, 108.14 and 183.32 kPa for the samples reinforced with fibers glass and 74.58, 126.25 and 193.11 kPa for the samples reinforced with hemp fiber. From the obtained values, we can note that in the dense state, the maximum shear strength of the samples reinforced with hemp fibers is greater than those of the samples reinforced with fiber glass; this is due to the improvement of the contact between from hemp fibers to grains of sand.

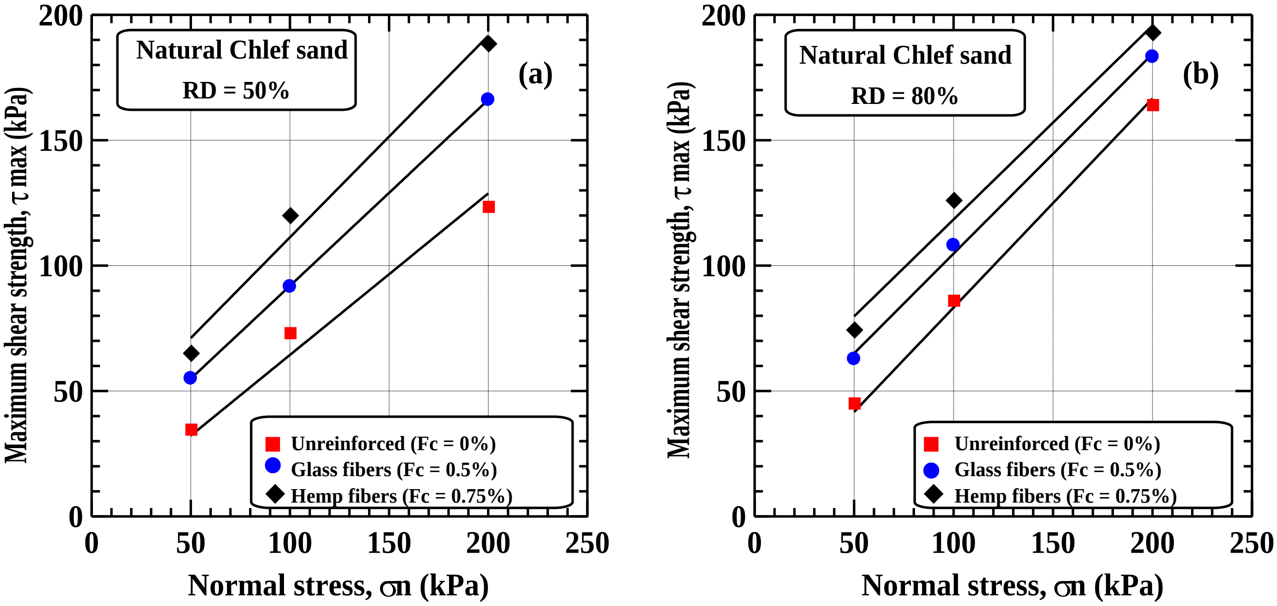


Figure 17. Variation of the maximum shear strength (τ_{max}) versus type of fibers (F_c) and normal stress (σ_n): Maximum shear strength (τ_{max}) - Normal stress (σ_n), a) RD = 50%, b) RD = 80%

3.7. *Effect of type of fibers on cohesion (c)*

Figure 18 shows the variation of the cohesion versus type of fibers in the medium dense and dense state. The tests results indicate that there is a significant increase in the cohesion with the increase of the fibers content for the medium dense state and dense state for the two types of fibers. In the medium dense state (RD = 50%), the cohesion increases from 9.62 kPa (F_c = 0%) to 17.95 kPa for sand reinforced with glass fibers for a fibers content of F_c = 0.5%. For the second type of fiber (hemp), the cohesion reaches a value of 31.03 kPa for a fibers content of F_c = 0.75% (Fig. 18a). For the dense state, the cohesion increases from 12.38 kPa for the unreinforced sand (F_c = 0%) to 25.19 kPa for the reinforced sand with fiber glass (F_c = 0.5%), while for the sand reinforced with hemp fibers, the cohesion increases from 12.38 kPa (F_c = 0%) to 49.29 kPa (F_c = 0.75) (Fig. 18b). We note better mechanical performances in the dense state than those obtained in the medium dense state. From these test results, a clear improvement of the sand reinforced with fibers content is observed, indicating high cohesion obtained from each type of fiber studied. However, it is clear that the cohesion obtained from the samples reinforced with hemp fibers are significantly higher than those of the samples reinforced with glass fibers for the two relative densities (RD = 50% and 80%).

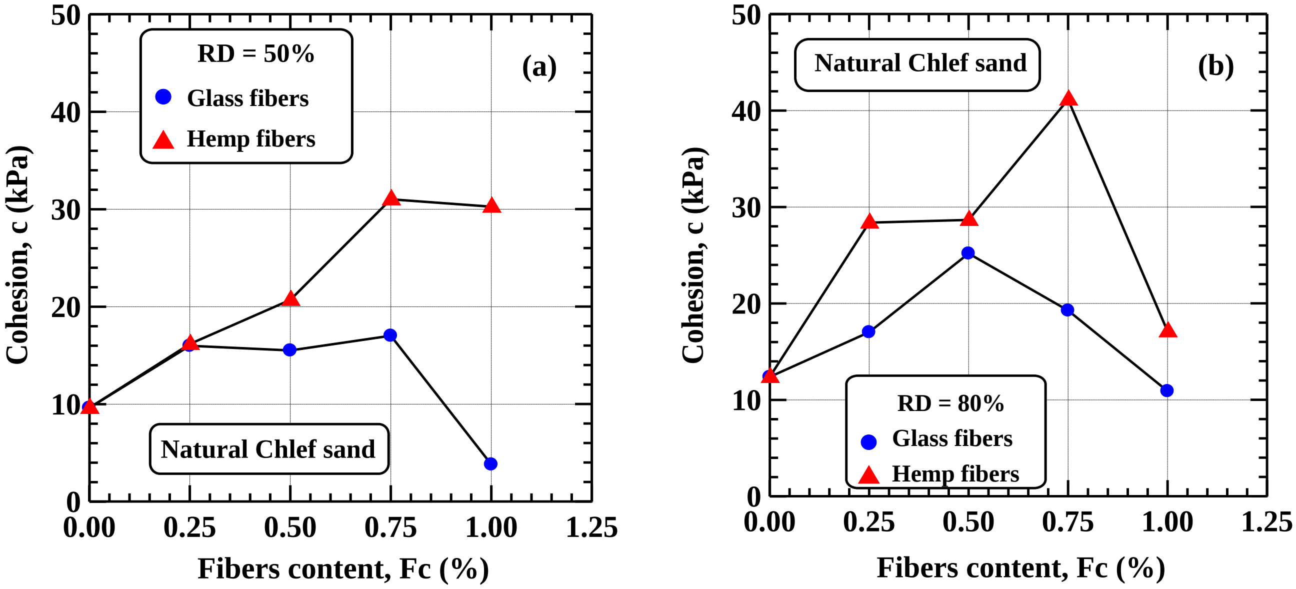


Figure 18. Variation of cohesion (c) versus fibers content (F_c): a) RD = 50%, b) RD = 80%.

3.8. *Effect of type of fibers on the internal friction angle (ϕ)*

Figure 19 shows the variation of friction angle (ϕ) versus fibers content (F_c) for the two types of fibers in the medium dense and dense state. The obtained results indicate that there is a significant increase in the internal friction angle (ϕ) with the increase of the fibers content for the two relatives densities for the two types of fibers.

It is noted that for medium dense sand, the internal friction angle is between 29.91° for unreinforced sand to 42.46° for reinforced sand with fibers glass at an optimal fibers content of $F_c = 0.5$ %. For the second type (hemp fibres), the internal friction angle increases to 46.01° for an optimal fibers content of $F_c = 0.75\%$ (Fig. 19a). However, the values of the internal friction angle recorded for the Chlef sand in the dense state vary between 42.06° for the unreinforced sand until 48.61° for the sand reinforced with glass fibers and until 49.29° for the sand reinforced with hemp fibers for an optimal fibers content of $F_c = 0.5\%$ and 0.75%, respectively (Fig. 19b).

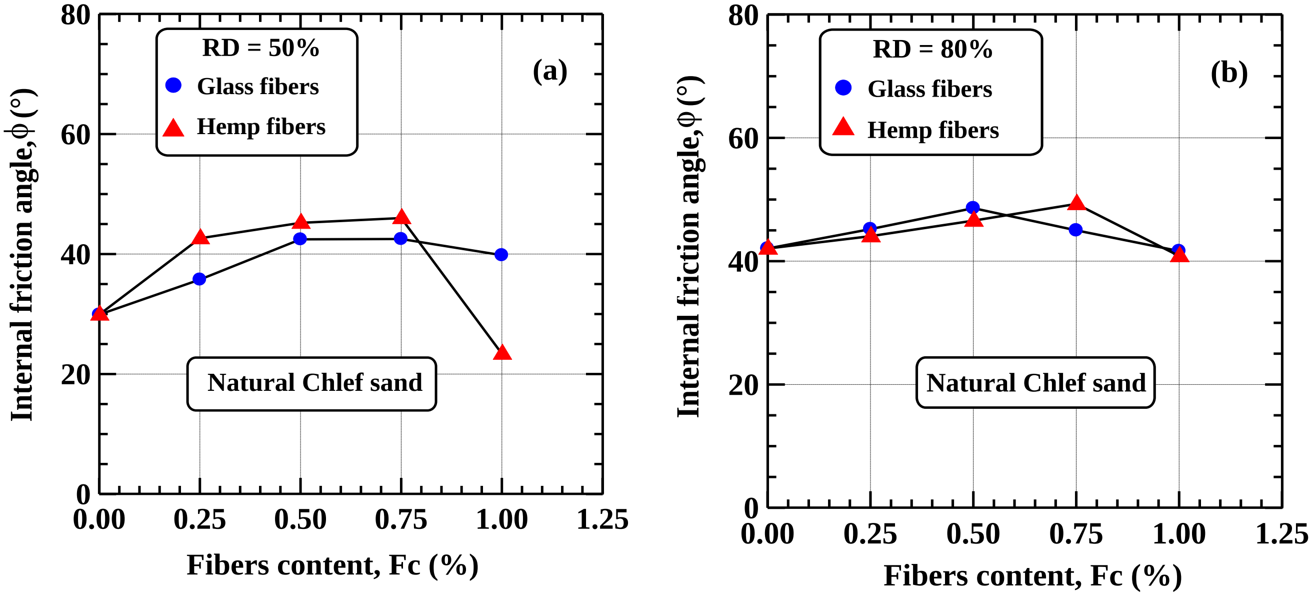


Figure 19. Variation of internal friction angle (ϕ) versus fibers content (F_c): a) RD = 50%, b) RD = 80%.

3.9. *Effect of type of fibers on the reinforcement coefficient (Sr)*

Figure 20 shows the variation in shear strength ratio for reinforced to unreinforced sand in medium dense and dense state under different normal stresses (σ_n = 50, 100 and 200 kPa). At the medium dense state (Fig. 20a), there is a significant difference in the shear strength ratio for the samples reinforced with hemp fibers compared to those reinforced with glass fibers. The shear strength ratio (S_r) is 1.58, 1.26 and 1.34 for the fibers glass. For the hemp fibers, the shear strength ratio is 1.87, 1.64 and 1.53 for normal stresses (σ_n = 50, 100, 200 kPa) respectively. In the dense state (Fig. 20b), we note that the difference in the shear strength ratio for the samples reinforced with hemp fibers compared to those reinforced with glass fibers and less important. It can be noted that the shear strength ratio of the samples reinforced with glass fibers are higher than those reinforced with the hemp fibers.

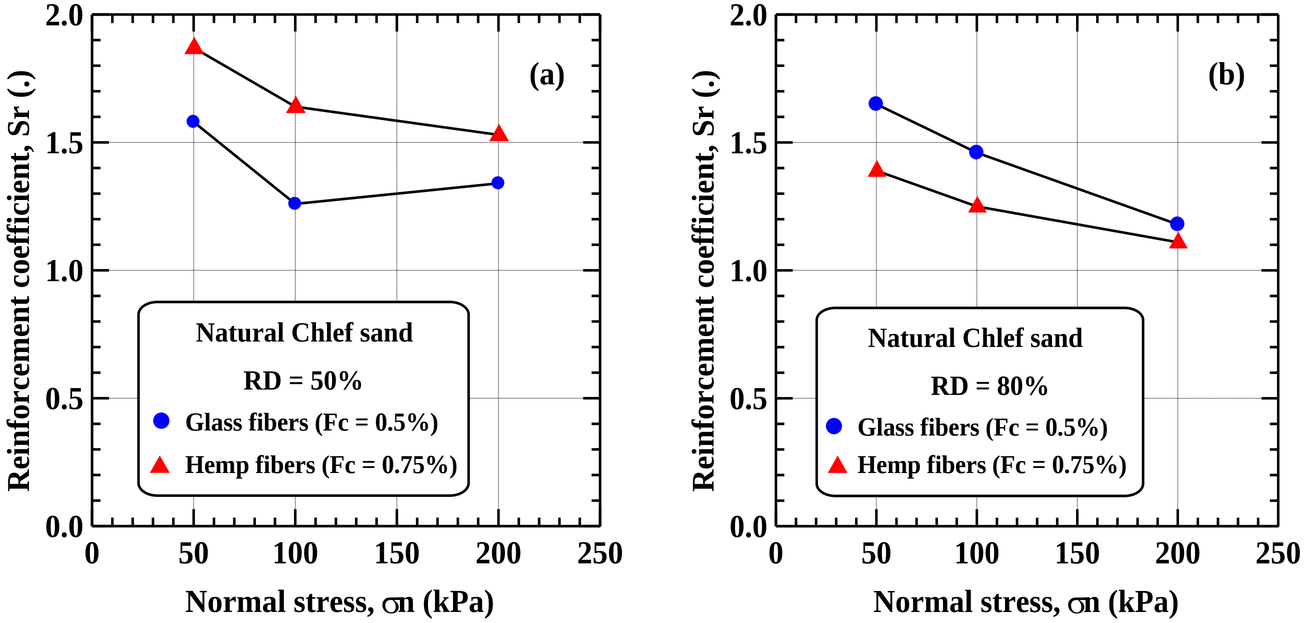


Figure 20. Variation of the reinforcement coefficient (S_r) versus fibers content (F_c): RD = 50%, b) RD = 80%.

3.10. *Effect of normal stress (σ_n) and relative density (RD) on the maximum shear strength (τ_{max})*

Figure 21 illustrates the variation of maximum shear strength (τmax) versus fibers content (Fc) of unreinforced and reinforced Chlef sand under three normal stresses (σn= 50, 100 and 200 kPa) and at a medium dense (RD= 50%) and dense state (RD= 80%) for two different types fibers. There is a significant increase in shear strength with the increase in the relative density and normal stress. This behavior is expected because the fiber reinforcement mechanism is purely frictional. Increasing the relative density or the normal stress pushes the sand grains and fiber inclusions closer together, resulting in a larger interfacial contact area.

This increases friction, promotes plastic deformation, and hence increases the strength of the sand-fiber mixture (Liu et al. 2011). Our test results are consistent with those reported in the literature by Prabakar et al. (2002). Hemp fibers have a higher tensile strength (550 MPa) than glass fibers (485 MPa), which accounts for their improved performance in soils. Hemp fibers can absorb higher stress before breaking, allowing for more effective stress transfer between soil particles, minimizing localized deformations, and enhancing the soil's overall shear strength.

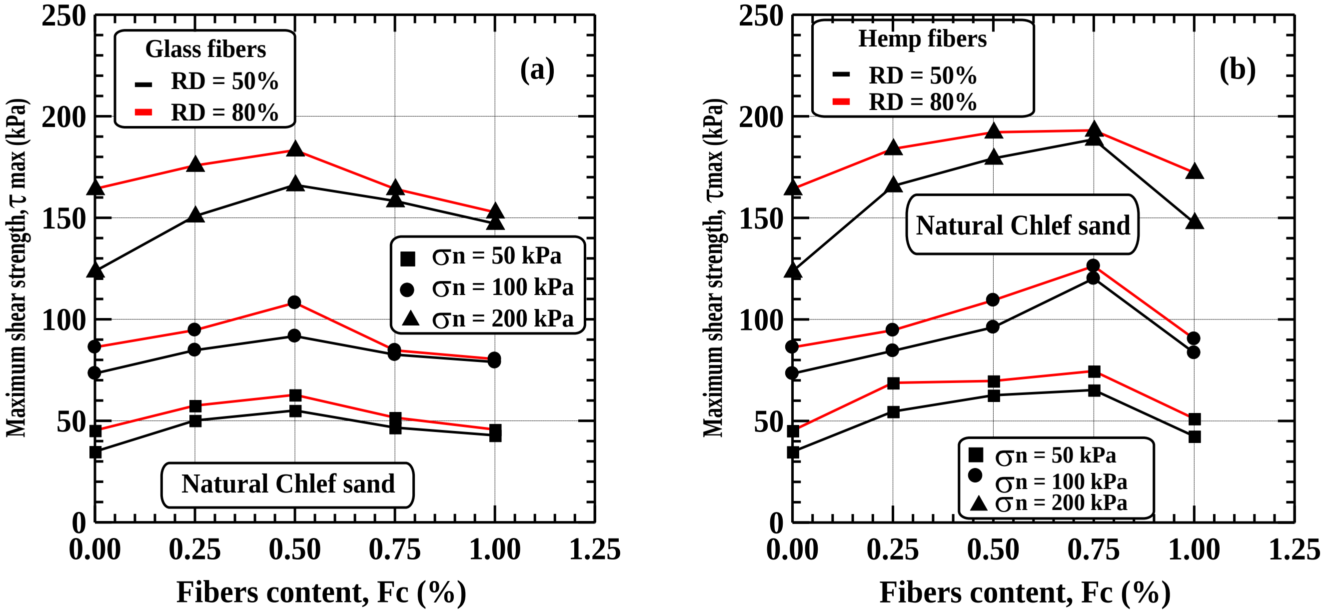


Figure 21. Variation of maximum shear strength (τ_{max}) versus fibers content (F_c) (σ_n = 50, 100 and 200 kPa, RD= 50%, RD= 80%): (a) glass fibers, (b) hemp fibers.

4. Limitations of the study

Although the shear box dimensions (60 mm × 60 mm) are compatible with ASTM requirements, the impact of particle size on specimen representativeness cannot be ignored completely. Given that the greatest grain size was approximately 2 mm, the ratio of specimen size to particle size met the required requirement (at least 6-10 times greater), minimizing but not completely eliminating the potential scale effect. Another restriction is the hand mixing process used to prepare the sand-fiber combinations. Manual mixing may result in non-uniform fiber dispersion within the soil matrix, thereby introducing variability in test results. Although efforts were made to guarantee homogenous blending, some degree of variation in fiber orientation and dispersion is unavoidable and should be considered when interpreting the results.

5. Conclusion

This paper presents a laboratory study of the effect of naturals and synthetics fibers content, the relative density and the applied normal stress on the mechanical behavior of natural Chlef sand. A series of direct shear tests were carried out on medium (RD = 50%) and dense (RD = 80%) samples of fiber-sands varying from 0 to 1% under three applied normal stresses of 50, 100 and 200 kPa. Based on the experimental data and the tests results obtained from this study, the following conclusions can be drawn:

1. The inclusion of the fibers in the soil leads to an increase in the shear strength of the soil for the two types of fibers much more the natural fibers (hemp).
2. The increase in relative density leads to an increase in soil strength. Indeed, it has been found that dense samples are stronger than medium samples.
3. The increase in the applied normal stress leads to an improvement in the behavior of soil samples (increase in shear strength for reinforced samples, internal friction angle and cohesion).
4. The addition of fibers in percentage improves the mechanical characteristics of the soil. However, the internal friction angle and the cohesion increase considerably with the increase in the fibers content (Fc) in the sand until an optimal value.
5. In further studies
    a. Long-term Durability and Microstructure: Evaluate natural hemp fibers' durability and resilience to biodegradation in a Chlef sand matrix over extended periods. Furthermore, microstructural investigations, such as Scanning Electron Microscopy (SEM), are required to better understand the bonding mechanisms and interface interaction of natural and synthetic fibers with sand particles.
    b. Future research should investigate the performance of fiber-reinforced mixes under dynamic and cyclic loading conditions to model seismic effects, notably in the Chlef region. Furthermore, moving from laboratory shear tests to numerical modeling (FEM/DEM) and full-scale field applications would help to validate these findings for geotechnical design and infrastructure projects.

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

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Conflicts of interest: The authors declare that they have no conflict of interest.

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