Innovative Infrastructure Solutions (2023) 8:40
https://doi.org/10.1007/s41062-022-01011-7

TECHNICAL PAPER

Numerical and experimental study on the effect of fiber reinforcement on the shear strength and hydraulic conductivity of Chlef soil

Abdelkader Brahimi[1,2] · Djamel Eddine Bouri[1] · Zohra Boutaraa[1] · Benali Nougar[1] · Abdellah Krim[1] · Mohammed Chemmam[1] · Ahmed Arab[1]

Received: 22 December 2021 / Accepted: 25 November 2022 / Published online: 3 December 2022

Abstract

This paper examines the effect of fiber content and relative density (RD) on the hydro-mechanical behavior of Chlef sand. The hydro-mechanical behavior of the sand-fiber mixture was evaluated by 45 permeability tests and 30 direct shear tests in the laboratory. Tests were performed on reconstituted specimens at different relative densities (RD = 15, 50 and 70%) and at different commercial polypropylene fiber contents (0, 0.25, 0.50, 0.75 and 1%). The results indicate that adding polypropylene fibers reduces the hydraulic conductivity (k) in the range of 0% to 0.5% and then increases in the range of 0.5% to 1%. In addition, higher relative density (RD) values in the mixtures increase hydraulic conductivity (k). The results also show that shear strength, cohesion c, and friction angle φ are improved in the range of 0% to 0.5% and then increased in the range of 0.5% to 1%. The finite element method was used to simulate the drained behavior of the sand. The aim is to obtain a simple soil model from a numerical analysis to represent the studied material's drained behavior.

Keywords Shear strength · Hydro-mechanical behavior · Fibers content · Sand–fiber mixture · Modeling

List of symbols

G_s	Sand specific gravity
D_{10}	Effective diameter
D_{50}	Average diameter
C_u	Coefficient of uniformity
C_c	Coefficient of curvature
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
σ_n	Normal stress
τ	Shear strength
RD	Relative density
R^2	Coefficient of determination
DF	Diameter of polypropylene fibers
LF	Length of polypropylene fibers
φ	Internal friction angle
E	Young's modulus
C	Cohesion
Ψ	Dilatation angle
ν	Poisson's ratio
E_{50}^{ur}	Stiffness modulus
E_{oed}^{ur}	Oedometer modulus
γ_{unsat}	Unsaturated volume weight
γ_{unsat}	Saturated volume weight
ΔH	Horizontal displacement
ΔV	Vertical displacement
f	Fibers content
k	Hydraulic conductivity

✉ Abdelkader Brahimi
a.brahim@centre-univ-mila.dz

[1] LsmE Laboratory of Materials Sciences and Environment, Univ. UHBC Hassiba Benbouali of Chlef, 02091 Chlef, Algeria

[2] Civil Engineering and Hydraulics Department, University Center of Mila, Institute of Science and Technology, Mila, Algeria

Introduction

Sandy soils are often used in the design of the road layers' structure, embankments, ground constructions, deep foundations (bridges) and retaining walls due to their high availability, ease of use in all projects and cost-effectiveness. However, in many projects, improving soil properties for use as a construction material has been considered a challenging task. The primary goal is to increase the shear resistance, improve hydraulic conductivity and/or the soil stability and reduce the project cost considering the environmental advantages of the available local materials [2, 3, 30, 32, 36, 44].

Numerous studies have been conducted to evaluate the mechanical behavior of sandy soils, which are affected during shear by several factors such as sample preparation method, particle size and shape, packing density, confining pressure, stress history, pre-shear or fines content ([4, 6, 18–20, 23–25, 49, 51, 52]). However, research focused on the hydro-mechanical behavior of sand-fiber mixtures is limited.

Several authors have evaluated the effect of adding fiber content to soil on hydraulic conductivity. Junjun et al. [46] indicated that the hydraulic conductivity value of sand is lower than that of soil mixed with fiber content. Junjun et al. [46] developed a new model to predict the soil water retention curve (SWRC) and water permeability of soils mixed with lignocellulose fibers. This model considers the void ratio change by incorporating the air void from fibers. Bordoloi et al. [21] reported that soil reinforced with coir fibers gives five times the compressive strength compared to pure soil.

In addition, some studies have addressed soil improvement by plant roots [37, 46, 53, 54]. However, plant roots do not always enhance the hydraulic properties of soil-fiber mixtures and are still unclear. The majority of sand-related problems involve heaving and shrinkage. Indeed, the primary purpose of soil-polypropylene fiber mixtures as hydraulic barriers in waste containment systems is to impede flow [14]. Other researchers have reported that particle size distribution characteristics can affect the soil's hydraulic conductivity. Cherif Taiba et al. [31], Cronican and Gribb [33] and Belkhatir et al. [18, 19] evaluated the hydraulic conductivity of granular soil. Their results indicate that the hydraulic conductivity decreases proportionally with the effective diameter (D_{10}) and mean grain size (D_{50}).

Improving the mechanical properties of locally available soils by adding cementitious materials such as cement and lime is very common. Fibers have attracted considerable interest in soil mechanics [11–13, 43, 45]. Garg et al. [21] and Junjun et al. [14] showed that increasing the fiber content in the soil increases its hydraulic permeability. Divya et al. [34] showed that the hydraulic conductivity of a silt–clay mixture mixed with different percentages of fibers (0, 0.25, 0.5, and 0.75%) decreases up to fiber content of 0.25%, increasing beyond 0.25% up to 0.75%. Abdi et al. [1] found that the hydraulic conductivity of the soil increases proportionally to fiber content from 1 to 8%.

Other studies have shown the benefit of adding polypropylene and glass fibers to address its contribution to soil mechanical behavior ([14, 22, 27, 28, 47]) found that adding geotextile increases the performance of Chlef liquefied sand. Gao and Zahao [39] and Shao et al. [56] showed that the shear strength of granular soil, cohesion, and friction angle increase with the addition of polypropylene fibers. Baig Moghal et al. [14] reported that the soil hydraulic conductivity increases with the increase in the fiber fraction from 0.2 to 0.6%.

This study evaluates the hydro-mechanical behavior of Chlef sand using the permeability and direct shear box apparatus. The addition of polypropylene fibers in a fraction of 0 up to 1% on hydraulic conductivity is also evaluated. The effect of fiber content on Chlef soil hydro-mechanical behavior is investigated on hydraulic conductivity and shear strength to establish a relationship between them and determine if there is a relationship between strength and permeability. The numerical simulation performed aims to determine the drained behavior of Chlef sand to simulate direct shear tests using the Hardening Soil model.

Experimental programs

Tested materials

The tests were carried out on Chlef sand. Specific gravity for natural sand is $G_s = 2.65$ [ASTM D854-83]. 2002, Maximum and minimum void ratios were determined according to the recommendations of [ASTM D 4253-00]. 2002, and [ASTM D 4254-00]. 2002. Table 1 summarizes different characteristics of Chlef sand, such as the diameters (D_{10} and D_{50}) and the uniformity coefficient (C_u). Figure 1 shows the particle size distribution curve, while Fig. 2 shows the polypropylene fibers (Sika) used in this study. Table 2 lists the physical and mechanical characteristics of this material.

Samples preparation

A total of 45 permeability tests were performed using the permeameter device (Fig. 3). The samples were tested with a variable percentage of polypropylene fiber (0, 0.25, 0.5, 0.75, and 1%) (Fig. 4) and under three vertical loads (50, 100, and 200 kPa) and three relative densities (RD = 15%, 50%, and 70%). The sample was placed in a cylindrical mold. The sample saturation was obtained by filling a basin

Table 1 Physical properties of Chlef sand

Composition	Chlef Sandy soil
Specific weight of solids, γs (g/cm^3)	2,67
Maximum void ratio (e_{max})	0,854
Minimum void ratio (e_{min})	0,535
Effective diameterD_{10} (mm)	0,225
average diameter D_{50} (mm)	0,61
Uniformity coefficient (Cu)	3,38
Coefficient of curvature (Cc)	0.968
USCS classification	SP
Plasticity index of fine element (%)	6.32

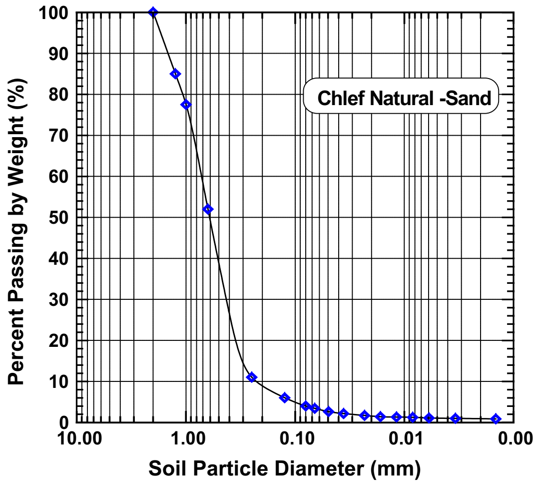

Fig. 1 Particle size distribution curve of Chlef natural sand

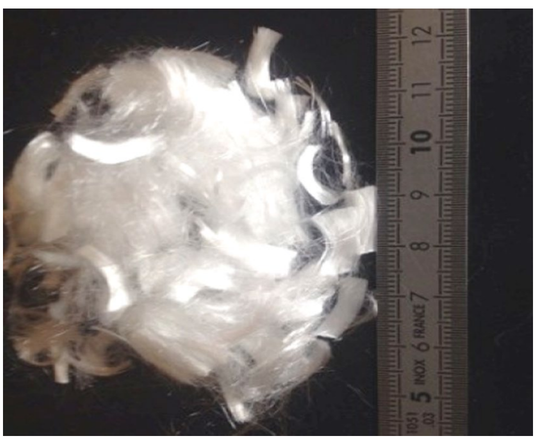

Fig. 2 Polypropylene fibers (Sika) used in this study

Table 2 Physical and mechanical properties of the used polypropylene fibers (SIKA)

Properties	Type of reinforcement
Diameter DF (mm)	0.018
Length LF (mm)	12
Aspect ratio (length/diameter) LF/DF	666
Density	0,91
Specific area (m^2/kg)	250
Tensile strength (MPa)	300–400
Elastic modulus (MPa)	6000–9000

Fig. 3 Permeability apparatus used in this study

Fig. 4 Chlef sand mixed with polypropylene fibers (Sika)

Fig. 5 Direct shear test device

where the test tube was placed gradually with distilled water and remained submerged for at least 24 h. The water was then allowed to flow through the soil with maintaining a constant pressure (50, 100 and 200 kPa), and hydraulic conductivity was measured when the outflow rate became constant.

Next, 30 direct shear tests were carried out using a square direct shear box (60 × 60 mm^2) device (Fig. 5) on sand-fibers mixtures (0, 0.25, 0.5, 0.75 and 1%) under three normal stresses (σ_n = 50, 100 and 200 kPa) and two relative densities (RD = 15% and 50%) using Air-Pluviation method, without initial water content w = 0%. The tests were carried out according to [ASTM standards D3080]. 2005. For medium dense state (RD = 50%) samples were prepared in four layers by compacting a known mass of the studied materials in the direct shear box to reach the target void ratio; the initial sample height was 20 mm [24]. However, loose samples (RD = 15%) do not require layer preparation to avoid grain compaction, so the funnel was used to obtain them [28].

Numerical simulation and boundary conditions

Over the past twenty years, the finite element method (FEM) has gained much popularity in the field of geoengineering and design and has been used in several studies ([16, 17, 29, 40–42]). In this study, the direct shear test was modeled using Plaxis 2D. The plane strain (2D) test was simulated using 15 node elements, with volume and interface elements. The geometric model reproduces the real dimensions of the shear box (60 × 60 × 20) mm. Concerning the two upper and lower box dimensions, an interface was created between the two.

The initial conditions require the generation of the initial water pressure and the initial effective stress. In this case, the pore water pressure was equal to zero since the test was carried out in a drained condition, whereas the calculation of the effective stress was done automatically by Plaxis. The model's boundary conditions were determined similarly to the experimental method. In the upper box, horizontal and vertical displacements are allowed, while all displacements in the lower box are blocked. The constant normal load condition was created by applying a uniformly distributed normal stress at the level of the top of the specimen, and horizontal shear displacement along is created to allow the horizontal displacement of the upper box (Fig. 6).

The HSM model was used for numerical simulation. This model was derived from the Duncan and Chang [35] hyperbolic model because it considers hyperbolic formulations to be adapted to all types of soils. The model is based on the Mohr–Coulomb parameters (Poisson's modulus "ν," Friction angle "φ," Cohesion "c" and Dilatation angle "ψ") and stiffness parameters (Oedometer reference modulus " E_{50}^{ref}" and stiffness reference modulus " E_{oed}^{ref}") (Table 3).

Results and discussion

Effect of relative density and vertical stress on the hydraulic conductivity (k) of reinforced sand

Figure 7a, b and c shows the variation in the hydraulic conductivity versus relative density for samples prepared using the Air-Pluviation method. The sand–fiber mixture samples were reconstituted in the laboratory at three initial relative densities (RD = 15%, 50% and 70%). It can be observed that the loose samples (RD = 15%) give a larger value of hydraulic conductivity (k) than the medium dense (RD = 50%) and dense sample (RD = 70%), respectively. This finding can be attributed to the loose specimen's lower compaction and a

Table 3 Parameters of HSM model used in numerical simulation for the medium dense state (RD = 50%)

Parameters	Values	Unit
Ψ	14.62	
ν	0.3	–
Φ	44.62	°
C	1	kPa
γ_{sat}	21	KN/m^3
E_{50}	5100	kPa
γ_{unsat}	18	KN/m^3
E_{oed}	6666.66	KN/m^2

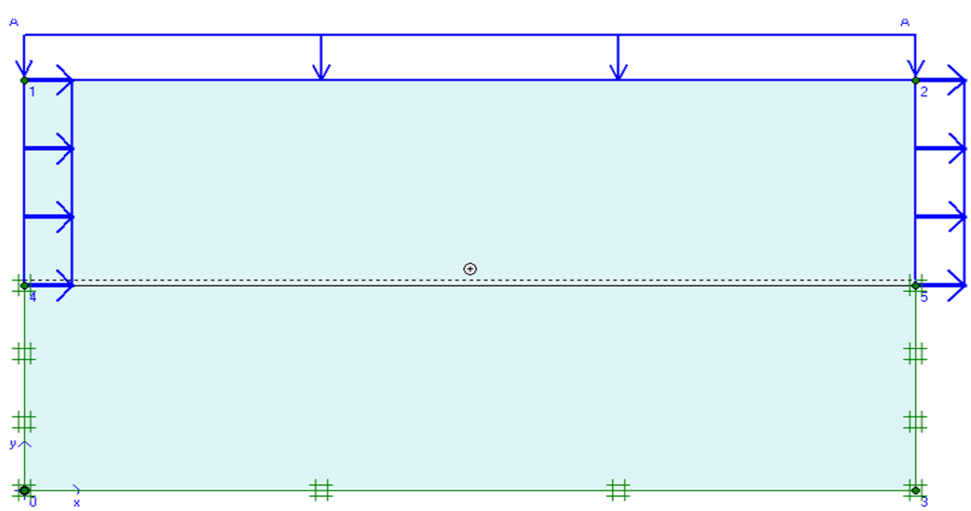

Fig. 6 Boundary condition of the performed model

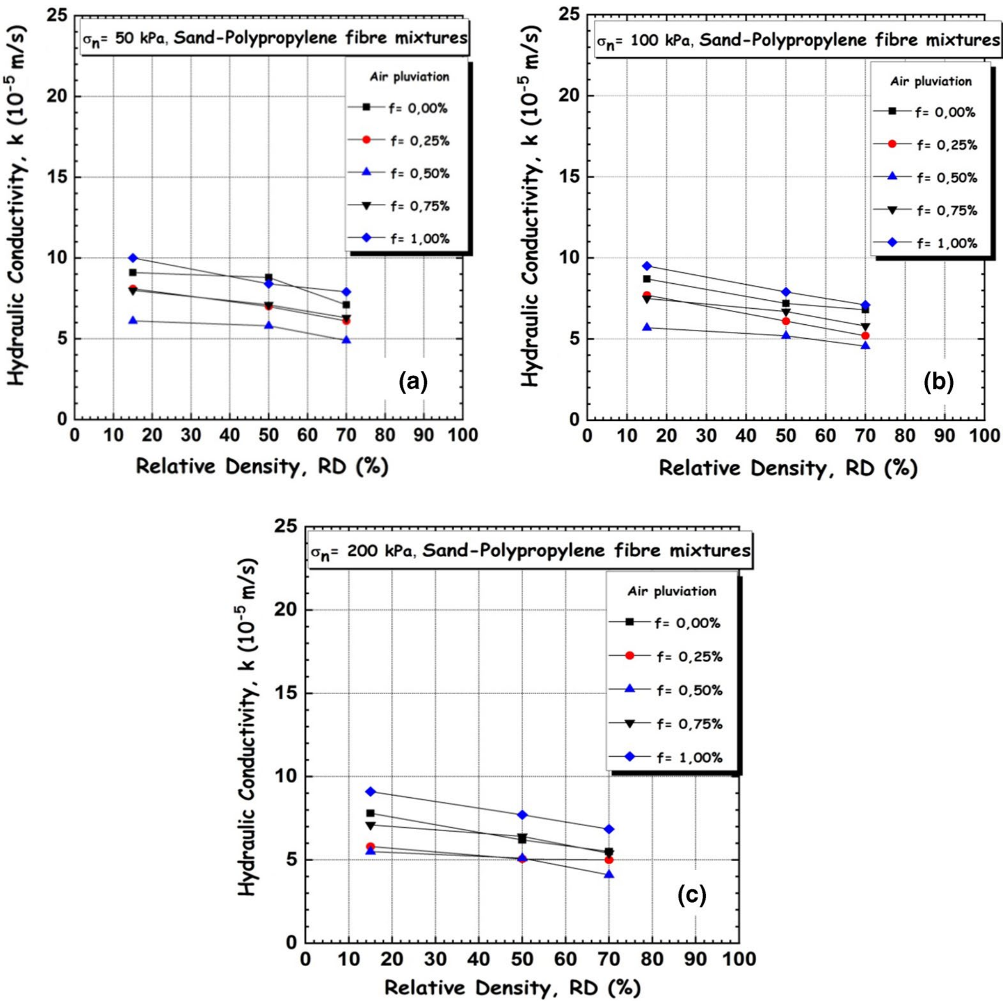

Fig. 7 Effect of relative density on the hydraulic conductivity (k) of reinforced sand, (air pluviation method: w = 0%), **a** $\sigma_n = 50$ kPa, **b** $\sigma_n = 100$ kPa, **c** $\sigma_n = 200$ kPa

higher void ratio. It can also be noted that the vertical stress increase from 50 to 200 kPa reduces the soil's hydraulic conductivity value. Moreover, the increase in the normal stress decreases the hydraulic conductivity (k) of both unreinforced and reinforced sand. Indeed, samples prepared under vertical stress of 200 kPa give greater hydraulic conductivity values than those prepared under vertical stress of 100 and 50 kPa.

These results can be attributed to the increase in the intergranular forces between the sand grains, which increase proportionally to the normal stress from 50 up to 200 kPa and the relative density from 15 up to 50% and from 50 up to 70%, which will decrease the void ratio between these grains. Similar observations were made by Yixian et al. [57] on fiber-reinforced soil. The authors reported that a high relative density causes a further increase in the effective contact area between soil particles and fiber. Belkhatir et al. [18, 19] indicated that increasing the relative density from RD = 20 to RD = 90% decreases the hydraulic conductivity (k) and the decrease in the void ratio decreases the value of the hydraulic conductivity (k). Thus, it can be noted that the relative density positively affects the soil's hydraulic behavior. In the same way, the relative density has a similar effect as the vertical stress to improve the soil's hydraulic behavior.

Effect of polypropylene fiber on the hydraulic conductivity (k) of sandy soil

The fiber content influence on Chlef soil was studied by varying fiber contents (0.25%, 0.50%, 0.75% and 1%). Figure 8a, b and c shows the hydraulic conductivity (k) variation versus polypropylene fiber content. It can be noted that the hydraulic conductivity (k) decreases inversely to the polypropylene fiber amount by up to 0.5% and decreases with a further increase in polypropylene fiber by up to 1%. The decreases of hydraulic conductivity (k) up to 0.5% can be explained by the fact that the friction angle between the

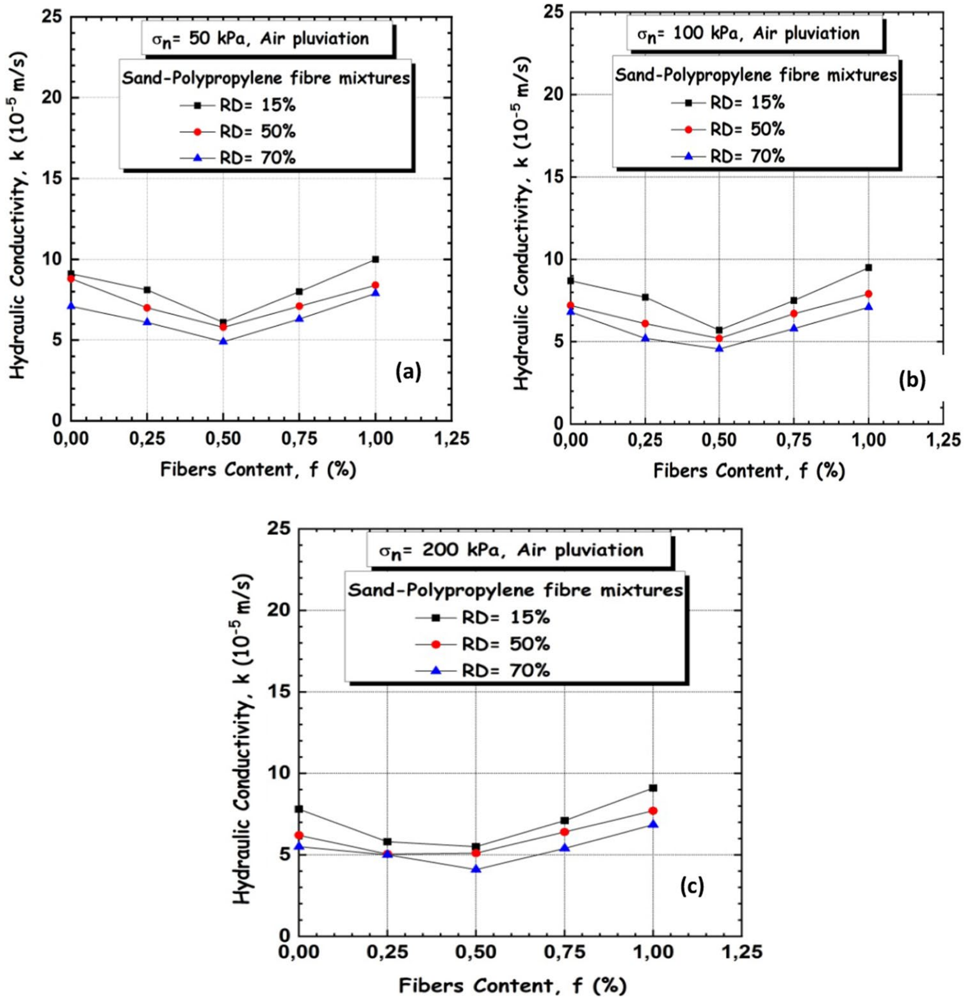

Fig. 8 Effect of polypropylene fiber content on the hydraulic conductivity (k) of reinforced sand, (air pluviation method: w = 0%), **a** $\sigma_n = 50$ kPa, **b** $\sigma_n = 100$ kPa, **c** $\sigma_n = 200$ kPa

sand grains increases beyond 0.5% of the polypropylene fiber and then decreases up to 1%. Thus, it causes an increase in the hydraulic conductivity (k) up to 1% of polypropylene fiber content.

Shao et al. [56] indicated that the increase in the polypropylene fiber increases the friction angle due to the mobilization of friction between the soil particles and fibers. In this study, the transition fiber content is 0.5%. Before this limit, the fibers contribute to the increase in the friction angle, which increases the shear strength and decreases the hydraulic conductivity (k), whereas for fiber content values greater than 0.5%, the friction angle decreases, reducing the shear strength and increasing the hydraulic conductivity (k).

Effect of fiber content on the mechanical behavior of sand

Loose samples (RD = 15%)

Figure 9a and b presents the effect of polypropylene fiber on the mechanical behavior of loose sand (Dr = 15%). The results indicate a consistent amelioration in the maximum shear stress proportional to the increase in the fiber content up to 0.5% and a reduction with a further increase in the fiber content up to 1%. Thus, it can be noted that the addition of fiber content increases the shear strength compared to unreinforced soil. The other fiber fractions (0.25, 0.75, and 1%) give a lower shear strength value than that obtained from 0.5%. Similar observations were made by Kumar et al. [48]. In this study, all samples show stabilization of shear strength for horizontal displacement greater than 5 mm. Figure 9b shows the vertical displacement versus the horizontal one, and it can be observed that increasing the polypropylene fiber content in the sand decreases the contracting phase. These results indicate that the presence of polypropylene fiber consistently decreases the tendency for contractancy [5].

Medium dense samples (RD = 50%)

Figure 10a and b shows the effect of polypropylene fiber content on the mechanical behavior of the medium dense

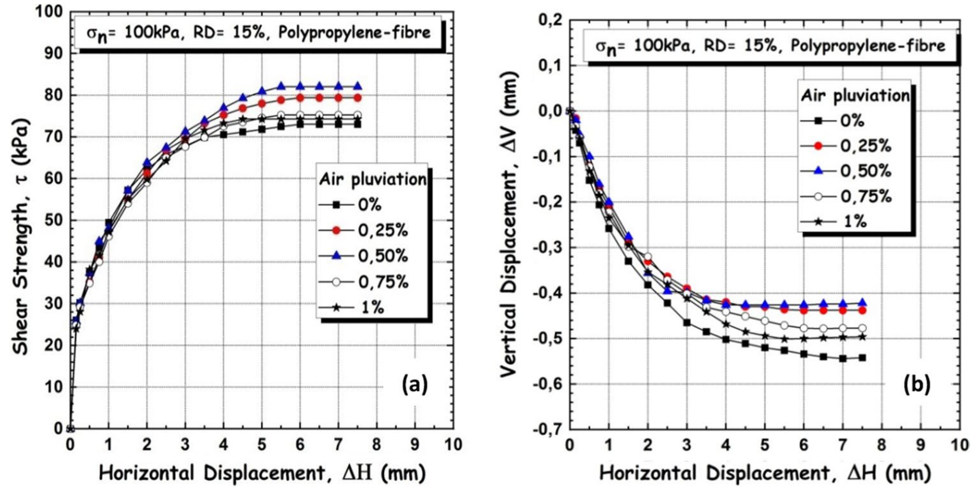

Fig. 9 Effect of polypropylene fibers on the mechanical behavior of loose state samples: **a** variation in the shear strength versus horizontal displacement, **b** variation in vertical displacement versus horizontal displacement

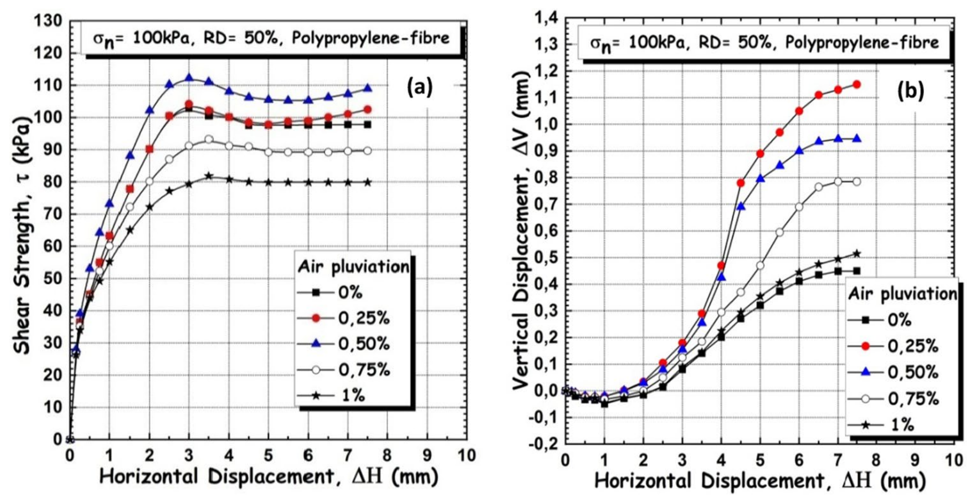

Fig. 10 Effect of polypropylene fibers on the mechanical behavior of medium dense samples: **a** variation in the shear strength versus horizontal displacement, **b** variation in vertical displacement versus horizontal displacement

sand (RD = 50%). This result indicates that the maximum shear strength increases proportionally to the fiber content up to 0.5% and decreases with a further increase in polypropylene fiber up to 1%. Figure 10a shows that all sample resistance increases up to a corresponding deformation value between 3 and 3.5 mm, then this resistance tends to decrease to a minimum value. Figure 10b illustrates the sample vertical displacement versus the horizontal one. It can be seen that the increase in the polypropylene fiber in the medium dense sand decreases the contractancy phase and increases the dilatancy phase. These results are in perfect agreement with those reported by Anagnostopoulos et al. [5].

Mohr–Coulomb failure line

Figure 11a and b shows the effective Mohr–Coulomb envelopes corresponding to the unreinforced sand samples and those reinforced with different fiber contents. The relationship connecting the maximum shear strength ($\tau_{\max}$) to the normal stress (σ_n) for different fiber content (0, 0.25, 0.5, 0.75, and 1%) can be written according to the following expression:

$$\tau_{\max} = \sigma_n . tg\phi + c \tag{1}$$

where c and φ are the cohesion and the internal friction angle, respectively.

These results indicate that adding fiber increases the slope of the failure line compared to that of unreinforced samples. It can be noted that the 0.5% reinforced samples have the greater value of the failure slope for both relative densities, i.e., 0.778 for the loose sample (RD = 15%) and 1.056 for the medium dense sample (RD = 50%).

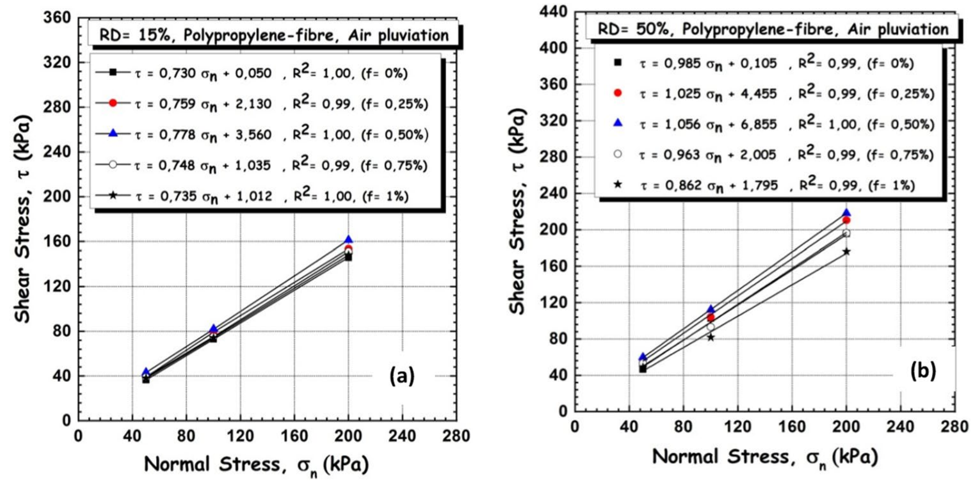

Fig. 11 Intrinsic curves equation $\tau = \sigma.\text{tg}\ \Phi + c$: **a** loose samples "RD = 15%", **b** medium dense samples "RD = 50%"

Effect of polypropylene fiber on the mechanical characteristics

Figure 12a and b illustrates the resulting drained shear strength parameters c and φ. It can be observed that the cohesion and the friction angle increase proportionally to the polypropylene fiber content up to 0.5% and decrease with further increase up to 1%. According to Gao and Zhao [39] and Shao et al. [56], this increase in the friction angle for the fiber content of less than 0.5% is most probably associated with the mobilization of friction between the sand grains and fibers. It can also be deduced that the friction angle decreases for fiber content greater than 0.5% reducing the friction between the sand grains. Furthermore, according to Kumar et al. [48] and Shao et al. [56], cohesion increases due to the sand ductility increase through the stretching of fibers. It is noted that the medium dense samples have greater values of cohesion and friction angle than the loose samples due to the difference in compaction between the two relative densities.

Effect of relative density, normal stress, and polypropylene fibers content on the mechanical behavior and hydraulic conductivity

Figure 13a and b shows the variation in the maximum shear strength as a function of the polypropylene fiber content. The results indicate that the maximum shear strength increases proportionally to fiber content until 0.5% and then decreases beyond this percentage. Moreover, it can be observed that the increase in the normal stress induces an increase in both maximum shear strength and hydraulic conductivity. Note that, samples with high shear strength values present low hydraulic conductivity values favorable to the studied sand.

Thus, it can be noted that hydraulic behavior relates to mechanical behavior. The hydraulic conductivity decreases with the increase in the shear strength of the samples. For example, in Fig. 13b, the sample with a fiber content of 0.5% and a density of 50% under normal stress of 200 kPa has a hydraulic conductivity value of $5.1.10^{-5}$ m/s and, therefore, a shear strength greater than 210 kPa. While in the

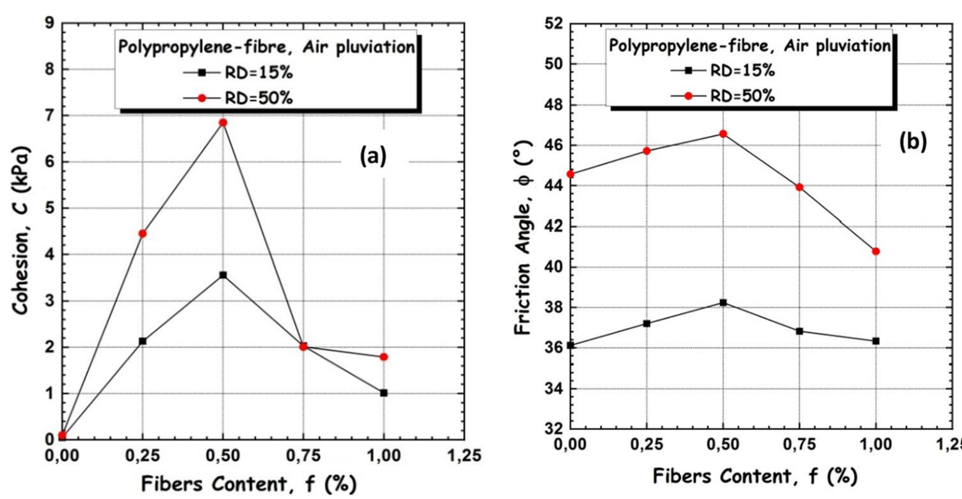

Fig. 12 Effect of polypropylene fiber content on the mechanical behavior of Chlef sand, (air pluviation method): **a** variation in the cohesion, **b** variation in the friction angle

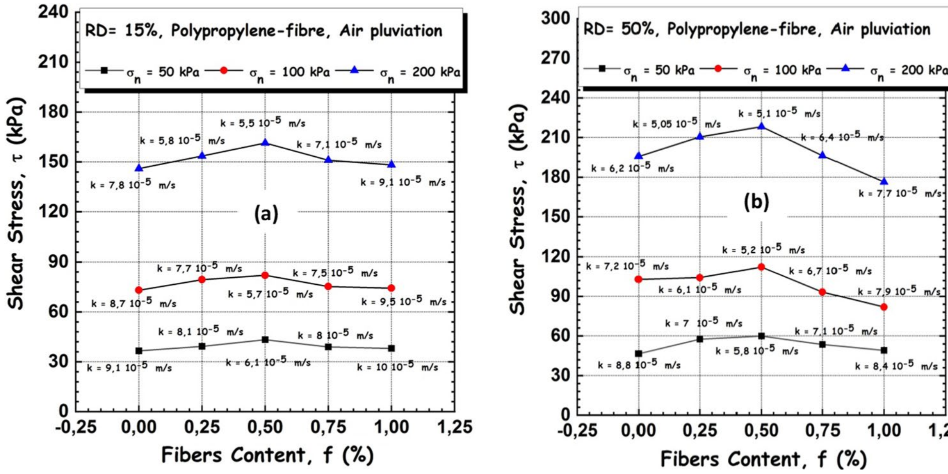

Fig. 13 Effect of normal stress and hydraulic conductivity on the mechanical behavior of the reinforced sand samples, (air pluviation method): **a** RD = 15% and **b** RD = 50%

same condition, the sample with a fiber content of 1% has a hydraulic conductivity value equal to $7.7.10^{-5}$ m/s and, therefore, a shear strength of less than 180 kPa.

Numerical simulations results

The numerical study was carried out to predict the experimental drained behavior of Chlef sand in a loose state (RD = 15%) and medium dense state (RD = 50%) in-plane strain conditions by implementing numerical computations via Plaxis software. A simple hardening soil model implanted in Plaxis was used. The aim is to predict the drained behavior of loose and medium dense samples by exploiting the experimental results and to satisfactorily reproduce the shear strength behavior of sandy soil. According to Fig. 14, the numerical simulation results are in good agreement with those obtained from laboratory tests. Thus, HSM well predicted the peak resistance in laboratory tests on dense samples. The curves of the shear strength versus horizontal displacement are almost identical.

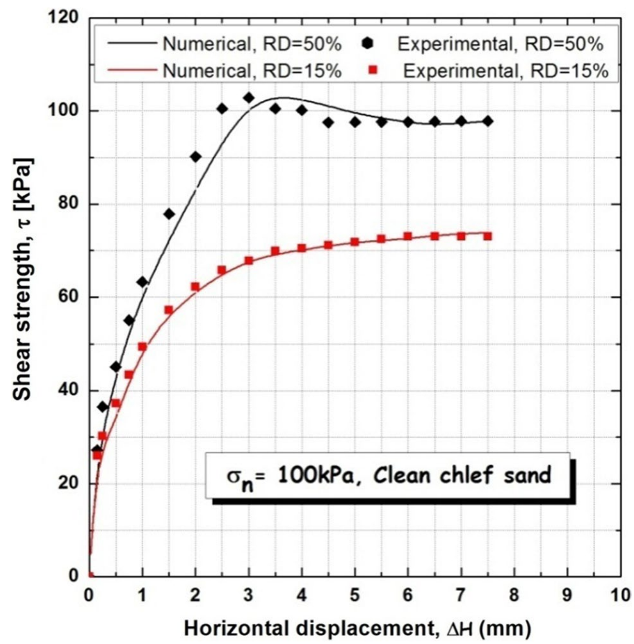

Fig. 14 Numerical simulation of drained behavior of Chlef sand

Conclusions

This paper provided a numerical and experimental study of the hydro-mechanical behavior of Chlef sand by mixing it with contents of polypropylene fibers (f = 0, 0.25, 0.50, 0.75, 1%), reconstituted with three relative densities (RD = 15, 50, 70%) and subjected to three initial normal stresses (σ_n = 50, 100 and 200 kPa). In the first part of the experiment, the effect of the relative density, vertical stress, and polypropylene fiber content on the hydraulic conductivity of the studied sand was examined. Afterward, the effect of polypropylene fibers' relative density and content on shear strength was evaluated. It can be noted that the relative density and the vertical stress affect the hydraulic conductivity of the soil. The results indicate that loose samples (RD = 15%) have greater hydraulic conductivity than medium dense and dense samples (RD = 50% and 70%), and increasing the vertical stress from 50 to 200 kPa decreases the value of the hydraulic conductivity.

The increase in the polypropylene fiber content for a fraction less than 0.5% positively affects the hydraulic conductivity (decrease in hydraulic conductivity), whereas it increases again for a fiber fraction greater than 0.5%. This behavior can be attributed to the decrease in friction angle between the sand grains beyond 0.5% of the polypropylene fiber content and then increases up to 1%, which causes a decrease in the hydraulic conductivity up to this content. Furthermore, the increase in the fiber content from 0 up to

1% increases the shear strength compared to that of unreinforced samples. The other fiber fractions (0.25, 0.75, and 0.1) have a lower value of shear strength than 0.5%. The presence of polypropylene fiber consistently increases the tendency for dilatancy and reduces the contractancy phase.

The cohesion and the friction angle increase proportionally with an increase in the polypropylene fiber content up to 0.5% and decrease with a further increase in the polypropylene fiber up to 1%. These mechanical parameters were improved after the relative density augmentation from 15 to 50%. Thus, it is worth noting that numerical simulation using the finite element method and HSM model can predict the drained behavior of Chlef sand in their loose (RD = 15%) and medium dense states (RD = 50%). This model provided an acceptable first approximation of the behavior of Chlef sandy soil.

Therefore, it can be concluded that increased density improves the hydro-mechanical response of soils in terms of hydraulic conductivity and shear stress behavior. Polypropylene fiber significantly affected hydro-mechanical behavior and showed positive effects in the 0 to 0.5% range. Furthermore, the numerical simulation results indicate that the HSM model has a good estimation to obtain stress developments for a real geotechnical project.

Acknowledgements Chlef university authors thank the reviewers for their detailed remarks. Tests were performed in the Laboratory of Material Sciences and Environment (LsmE) at UHBC University of Chlef.

Author contributions AB contributed to conceptualization, methodology, writing—original draft, investigation. DEB contributed to methodology, conceptualization, Writing. ZB contributed to writing—review and editing. BN contributed to data curation, conceptualization. AK contributed to supervision, methodology. MC contributed to data curation, conceptualization. AA contributed to conceptualization, supervision, methodology.

Funding Direction Générale de la Recherche Scientifique et du Développement Technologique.

Data availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interest We declare that we have no financial and personal relationships with other person or companies that can inappropriately affect our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the paper.

Consent for publication Not applicable.

Ethics approval Not applicable.

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