

Shear behavior of sandy soil reinforced with plastic waste fibers

Benathmane Baghdir^a, Younes Abed^b, Zine El Abidine Laidani^c

^a NEIGE Laboratory, Civil Engineering Department, Blida 1 University, Blida, People's Democratic Republic of Algeria, e-mail: baghdir_benathmane@univ-blida.dz, **corresponding author**, ORCID iD: <https://orcid.org/0000-0001-5754-2925>

^b NEIGE Laboratory, Civil Engineering Department, Blida 1 University, Blida, People's Democratic Republic of Algeria, e-mail: younes_abed_gce@yahoo.fr, ORCID iD: <https://orcid.org/0000-0003-1305-086X>

^c Geomaterials and Civil Engineering Laboratory, Civil Engineering Department, Blida 1 University, Blida, People's Democratic Republic of Algeria, e-mail: laidani_z@univ-blida.dz, ORCID iD: <https://orcid.org/0000-0002-8502-9819>

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Abstract:

Introduction/purpose: The issue of plastic pollution represents a significant global challenge that demands urgent action. Current initiatives focus on employing technical solutions to incorporate non-biodegradable plastics into the construction of buildings and road pavements.

Methods: This paper presents a series of direct shear tests aimed at highlighting the benefits of using recycled fibers, specifically in terms of shear strength performance. The tests examined reinforced sand with varying fiber contents of 0.2, 0.4, 0.6 and 0.8%, applied to both low- and medium-density sand.

Results: The results indicate that samples prepared through dry deposition exhibited significantly higher shear strength compared to those prepared using wet deposition. Additionally, the increase in shear strength was closely related to the quantity of fiber content used.

Conclusion: In conclusion, utilizing plastic waste as reinforcement offers two solutions to pressing environmental issues: it enhances soil reinforcement and helps reduce the impact of waste.

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Key words: shear test, sandy soil, plastic waste, cohesion, friction angle, sustainability.

Introduction

The north of Algeria is known for significant geological and geomorphological risks induced by earthquakes, including phenomena such as soil erosion, ground rupture, liquefaction, and landslides. Soil liquefaction is among the leading causes of structural damage in saturated loose sand deposits during earthquakes. During the Zemmouri earthquake ($M_w = 6.8$) of May 21, 2003, the city of Boumerdes, located in northern Algeria, was severely affected, and significant liquefaction was observed in the region (Bourenane et al., 2018).

Several solutions have been proposed in order to overcome this problem. Various soil improvement techniques, such as soil reinforcement and stabilization, have brought very satisfactory results in many cases (Arasan et al., 2015). Soil reinforcement is provided using different processes and materials, such as geosynthetics and fibers (Bader and Szilagyi, 2023; Zhou et al., 2024). The reinforcement of soils with fibers has undergone considerable development in recent years (Kumar et al., 2015; Szypcio et al., 2023). The fibers are generally introduced into the soil in a random way. There are at least two advantages to using randomly distributed fiber as reinforcement. First, discrete fibers are simply added and mixed randomly with soil as cement, lime, or other additives. Second, the distributed fibers overcome the problem of potential weakness that can develop parallel to the oriented reinforcement (Prabakar & Sridhar, 2002). Implementing the recycling process is necessary to make this achievable, provided that the material is ready to be effectively reused (Shukla et al., 2009; Horodytska et al., 2020). From an ecological point of view, the use of these wastes in civil engineering projects could avoid burying or burning them while avoiding the use of other expensive materials (Maurya and Kumar, 2014; Jigheh and Rasulifard, 2016; Abbaspour et al., 2018; Al-Ghazawi and Zboon, 2021; Ahmed, 2023).

Reinforcing the soil using strips of raw waste plastic bottles is an alternative method to improve the geotechnical properties of the subgrade road and the stability of the constructed embankment (Kanwar and Shukla, 2020; Hameed et al., 2021; Festugato et al., 2022). This new soil-reinforcing technology can actually be used to reduce the amount of plastic waste, which helps protect the environment (Jalal and Hassan, 2021). There are low-cost plastic recycling methods that provide aggregates and fibers for use in concrete and flexible pavements

(Belmokaddem et al., 2020). In recent years, polymers have been used in the form of fibers for various geotechnical engineering applications, including soil improvement (Kurniawan & Anouzla, 2025).

Polymer-based fibers are usually added to soil to improve its strength parameters. These fibers are coating agents capable of filling the voids between the soil grains and reinforcing the soil fabric (Monkul, 2021). In addition, these fibers can be mixed with other binding materials in the soil, such as fly ash, lime, or cement, to increase the shear and compressive strength of the soil (Tingle et al., 2007). Several earlier research studies were carried out by adding synthetic polymer-based fibers to soils and soil-cement mixtures and subjecting those materials to strength tests such as unconfined compression and direct and triaxial shear tests (Javani et al., 2019; Kholghifard and Amini Behbahani, 2022; Lv et al., 2021; Hamza et al., 2022).

Gray and Ohashi (1983) showed that the incorporation of fibers into the tested soil improved the soil shear resistance and compression significantly. In recent years, this area has seen significant advances in civil engineering practice and geotechnical engineering in particular. For example, Souadeuk and Boudaoud (2021) studied the effect of mixed soil-sand-cement columns with or without polypropylene (PP) fibers. The experimental results of consolidated drained (CD) tests proved that the fibers mixed with the soft soil are effective in improving the mechanical properties of the studied soil. Yasmine and Zeineddine (2022) indicated that 1% of polypropylene fibers (12mm and 18mm) mixed with cement content (0, 3, and 6%) and sand through the consolidated drained triaxial test increased both the cohesion and friction angle of sands. A study by Correia and Rocha (2021) showed the effects of recycled polypropylene (R-PP) fibers on compacted clayey lateritic soil at different compaction degrees. The results of the tests indicated that using fibers improved the shear stress-strain behavior of the composites and soils compacted at different degrees of compaction.

This research focuses on studying the shear behavior of sandy soil from the Zemmouri region reinforced with waste plastic fibers recovered from plastic packaging for application in embankment reinforcement or foundations. A series of direct shear tests were carried out to assess the optimum content of plastic waste fibers to improve the mechanical properties of the sand. Several parameters related to the mechanical properties, including dry density and water content, were also examined and discussed.

Materials and methods

To investigate the effect of fiber content on shear strength, a direct shear testing program was conducted. This type of testing was chosen due to its simplicity and suitability for testing. The direct shear testing was carried out according to the NF EN ISO 17892-10 standard (2018). Several specimens with varying fiber content and relative density for the dry and wet states were prepared for testing, as shown in Table 1.

Table 1 – Summary of the table tests

Groups	Normal stress (kPa)	Relative Density	Fibre content (%)	Water Content (%)
A1	50, 100, 200	25%	0, 0.2, 0.4, 0.6, 0.8	0
A2	50, 100, 200	25%	0, 0.2, 0.4, 0.6, 0.8	4
B1	50, 100, 200	49%	0, 0.2, 0.4, 0.6, 0.8	0
B2	50, 100, 200	49%	0, 0.2, 0.4, 0.6, 0.8	4

Materials

• Sand

The soil used in this investigation was collected from Zemmouri City, northern Algeria. Quartz is mainly present in this sand, along with carbonate materials. According to the USCS, the sand is classified as poorly graded with little or no fines (SP). The sand particles are sub-rounded and generally anisometric, ranging from 0.08 to 2 mm. The samples were taken from the bank-liquefied layer in the deposit areas at a depth of 3.00m. The grain size distribution and physical properties of the tested sand are presented in Figure 1 and Table 2, and the minimum and maximum void ratios presented in Table 2 were determined according to ISO 14688-1 specifications.

Figure 1 illustrates the particle-size distribution of the studied soil, indicating significant variability in grain size across the sample.

Table 2 – Physical properties of the used sand

Sand properties	Standard test specifications	Value
Mean grain size, D_{50} (mm)	ISO 14688 1	0.51
Maximum diameter, D_{max} (mm)	ISO 14688 1	2
Uniformity coefficient, C_u	ISO 14688 1	2.21
Coefficient of curvature, C_c	ISO 14688 1	0.83
Classification	USCS	SP
Mean specific gravity, G_s	ISO 14688 1	2.64
Maximum void ratio, e_{max}	ISO 14688 1	0.51
Minimum void ratio, e_{min}	ISO 14688 1	0.79

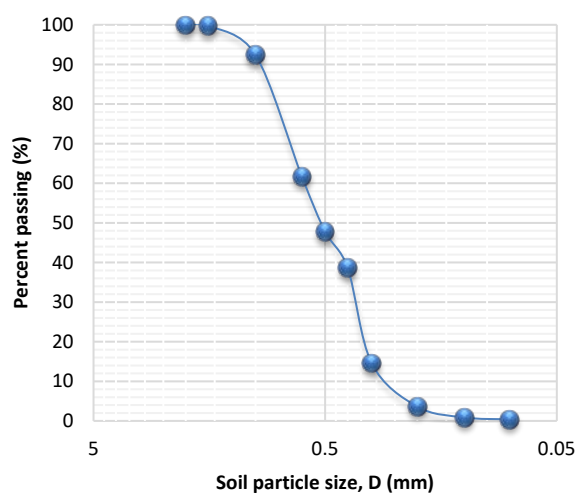


Figure 1 – Grain size distribution of Zemmouri sand

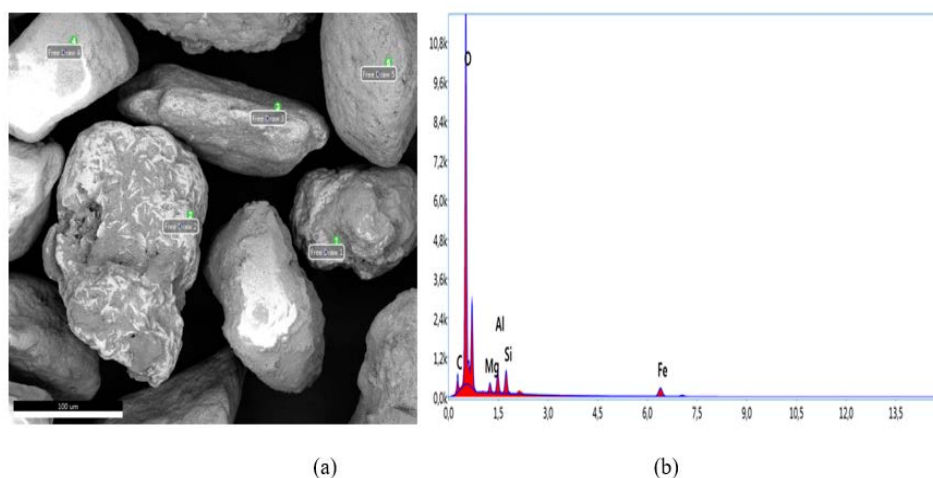


Figure 2 – (a) SEM images of sandy soil; (b) EDX spectrum of sand

Scanning Electron Microscopy (SEM) was employed to characterize the microstructure of dried sand samples. As shown in Figure 2 (a), the particles are predominantly angular to sub-angular, exhibiting rough and irregular surfaces.

An Energy Dispersive X-ray (EDX) system coupled with the SEM was employed to determine the elemental composition at various distinct

points. As illustrated in Figure 2 (b), the EDX spectrum is dominated by Si and O peaks, confirming a silica-rich composition. The presence of Al, Mg, Ca, and Fe is likely associated with aluminosilicates and accessory mineral phases.

- **Fiber**

The study utilized recycled yoghurt pots fiber with an average length of 10 to 18 mm and a diameter of 1 to 3 mm as shown in Figure 3. The fiber was composed of a polypropylene-based polymer with an average density of 1.02 g/cm³. For the experiment, the weight of the fiber content was varied between 0% and 0.8%, with 0.2% increments. This range was selected based on previous studies demonstrating that the optimum fibre content for reinforced soils was between 0.5% and 1%. These earlier studies include (Consoli et al., 2005; Eldesouky et al., 2015; Peddaiah et al., 2018).



Figure 3 – Recycling fibers

Sample preparation and test procedure

Twelve unreinforced samples and forty-eight reinforced samples incorporating recycled fibers were used in this study, totaling sixty samples for the Direct Shear Test (DST).

Figures 4 (a) and 4 (b) show the Zemmouri sand and the recycled yogurt pot fibers, respectively, prior to the mixing procedures. Two types

of sample preparation have been used in Figure 5: dry specimens and wet specimens characterized by a water content of 4%. All tests were done on loose and medium relative densities. A small direct shear test apparatus with dimensions of 60×60 mm was used with a sample thickness of 25mm. Sample preparation was first conducted by determining the mixture's required mass of sand and fiber.

The concentration of fibers (F_c) included in a composite is defined as a percentage of the dry mass of sand. Based on the hypothetical equations assumptions, we assume the weight and content of sand used to obtain a fiber reinforced with a volume (V) and a void ratio (e_0) equal to those for an unreinforced specimen (Anagnosopoulos et al., 2013). In this case, a particular soil mixture is changed by replacing a portion of a total solid with another component with a lower density, such that the entire solid mass remains unchanged (Michalowski, 2002; Özkul and Baykal, 2007).

$$F_c (\%) = \frac{W_f}{W_s} \times 100 \quad (1)$$

Where W_f and W_s are fiber and dry sand masses, respectively. The samples were manually prepared by adding and mixing the oven-dried sand with fibers as shown in Figure 5. Special attention was paid during sample preparation to ensure a similar level of mixture for all the samples tested.

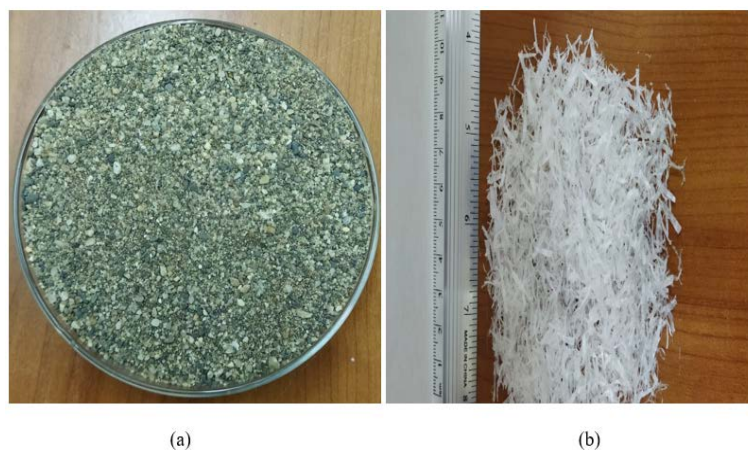


Figure 4 – Materials used in this study: (a) Zemmouri sand; (b) recycled fiber

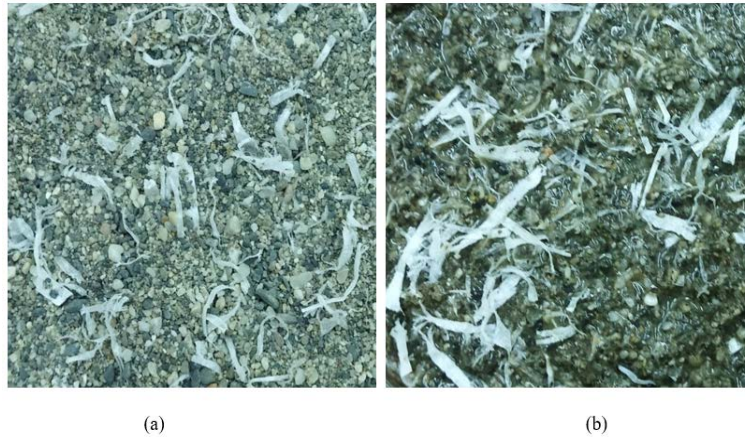


Figure 5 – Samples preparation for (a) dry specimens; (b) wet specimens

Results and discussions

Sixty conventional shear box tests were conducted for wet and dry sand at different fiber contents. We assume here that the fibers are uniformly distributed and randomly oriented in the sand. The fibers are considered one-dimensional elements, and they can be deformed or slipped into the matrix (sand).

Effect of fiber content

Through a series of direct shear tests, this study examines the impact of fiber content on the mechanical behavior of Zemmouri sand. Parameters including dry density, normal stress, and water content were evaluated to determine how fiber reinforcement influences the sand's shear response. The results for fiber contents ranging from 0% to 0.8% are presented and compared against findings for unreinforced, dry sand.

- *Loose sample ($D_r=25\%$)*

Test results for loose samples ($D_r=25\%$) distinctively illustrate the impact of fiber content on both the shear strength evolution and the intrinsic failure envelope. In Figure 6a, the variation of shear strength-displacement relationship of a sand-fiber mixture under different normal stresses is shown. A proportional increase in shear strength was observed during the test period until it was constant after 5 mm of horizontal displacement. It can be seen that the initial tangential stiffness of the matrix fiber-sand was the same for all tests, indicative of a stiffer sand-fiber matrix, while the final stable value of shear strength increased

proportionally with fiber content. It is evident that the addition of fiber has accelerated the development of shear strength. For volumetric fiber contents of 0.2 and 0.4%, peak strength was reached after 2.5 mm of horizontal displacement; this event is significant at the 0.4% fiber content. Additionally, an increase in residual shear strength was observed for samples reinforced by fibers in this case of relative density and specimen preparation (dry samples).

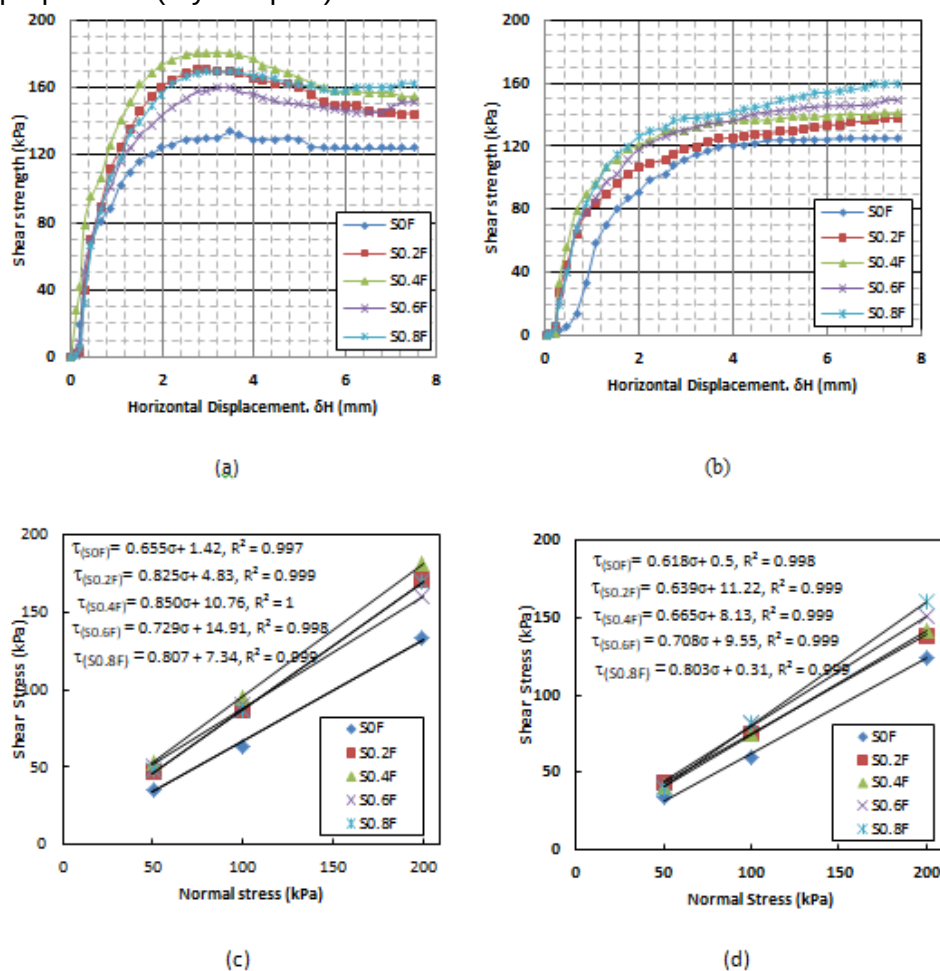


Figure 6 – Effect of fiber content on shear strength, normal stress of 200KPa and average density $Dr=25\%$: (a) variation of shear strength of dry sand versus horizontal displacement δH (mm); (b) variation of the shear strength versus horizontal displacement δH (mm) with a water content $W= 4\%$; (c) intrinsic curves of dry sand; (d) intrinsic curves of wet sand with ($w=4\%$)

The two figures showed a significant difference (Figures 6a and 6b). Figure 6b illustrates the variation of shear strength of wet sand versus horizontal displacement; the shear stress increases with increasing fiber content at the same applied normal stress, showing practically the same behavior. The results indicate that the reinforcement with recycled fiber improved the interlocking force of sand particles while increasing the shear stress. Moreover, shear strength improvement is essentially governed by the movement of fibers and their interaction with sand particles. The intrinsic curves shown in Figures 6c and 6d reveal that all reinforced specimens exhibit higher shear strength than the unreinforced sand. For dry sand, the friction angle slope values for varied fiber contents, specifically 0.2%, 0.4%, 0.6%, and 0.8%, were 0.82, 0.85, 0.72, and 0.80. Compared to Figure 6d, the friction angle slope varied to 0.63, 0.66, 0.70, and 0.80, respectively, for sand with 4% water content.

The interlocking force of fibers with sand particles produces the mobilization of tensile strength at higher strains in the shear plane. Several studies have demonstrated that increasing volumetric fiber content improves shear strength (Michalowski, 2002; Özkul and Baykal, 2007; Sadek et al., 2010; Yu et al., 2021; Hasanzadeh and Shooshpasha, 2023). In the mechanics of stress transfer in composites reinforced with short fibers, the applied stresses are first transferred to the matrix material (the shape of sand supported the applied stress afterwards), then to the fibers through the fiber ends and the surfaces of the fibers near the fiber ends. Figure 7 explains the mechanism of fiber-reinforced sand. As a result of a normal stress application on the fiber-reinforced sand, the soil particles at the sand-fiber interface may have a heading of rotation, and the fiber in tension may undergo plastic deformation at the sharp angles or boundaries of the particles.

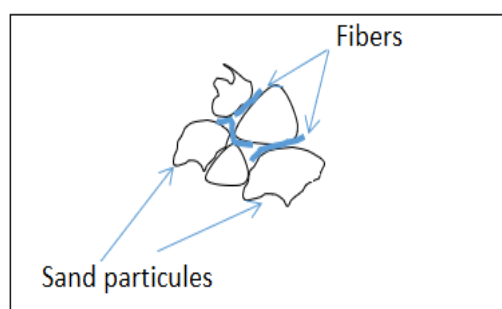


Figure 7 – Incorporating fiber reinforcement mechanisms into sandy soil materials

- *Medium dense sample (Dr=49%)*

In the shear stress versus horizontal displacement curves shown in Figures 8a and 8b, for a normal stress of 200 kPa in medium density, the specimens without reinforcement exhibit slightly higher initial stiffness compared to those with reinforcement. Additionally, shear strength increases across all fiber contents for dry sand, as the fibers create voids within the matrix. The shear peak resistance of fiber-reinforced sand is greater than that of unreinforced sand due to enhanced interaction between the fibers and the sand. This finding is consistent with previous studies on sandy soil reinforced with polypropylene fibers, as reported by Benziane et al. (2019) and Berkane et al. (2023).

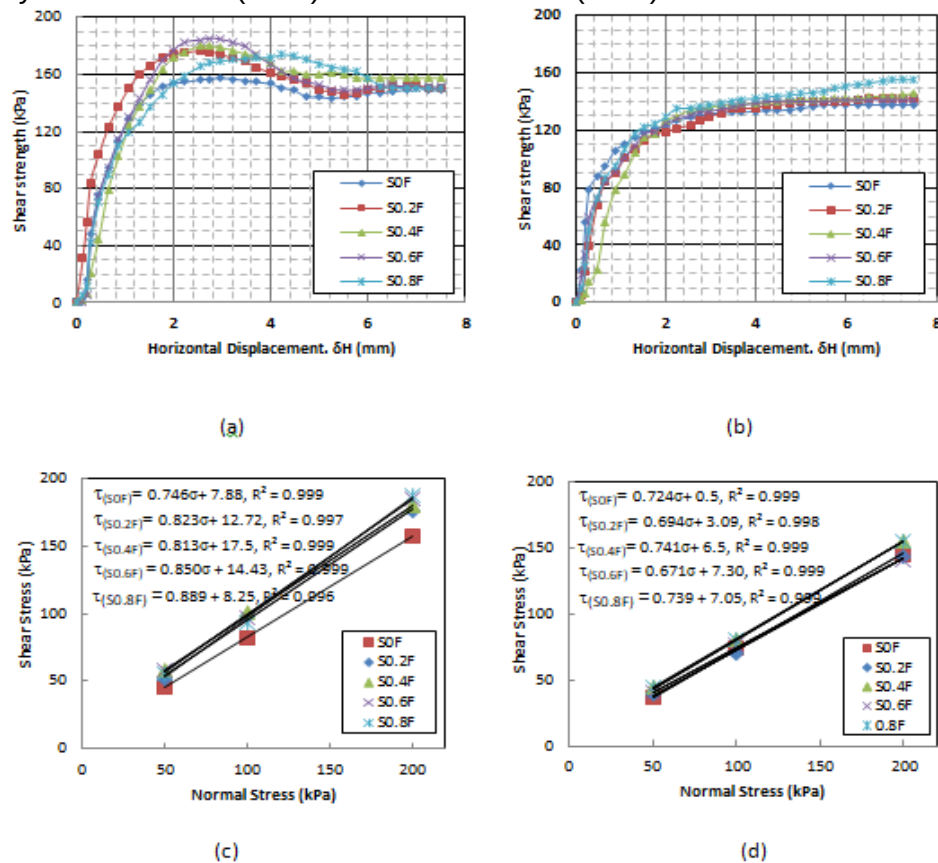


Figure 8 –Effect of fiber content on shear strength, normal stress of 200kPa and average density $Dr=49\%$: (a) variation of shear strength of dry sand versus horizontal displacement δH (mm), (b) variation of the shear strength versus horizontal displacement δH (mm) with a water content $W= 4\%$, (c) intrinsic curves of dry sand, (d) intrinsic curves of wet sand with ($w=4\%$)

Effect of fiber content on cohesion and friction angle

- *Loose samples*

For the loose samples, the shear strength envelopes corresponding to each level of normally applied stress are presented in Figures 6c, 6d, 9a, and 9b. In the case of a dry sand-fiber mixture, the cohesion and the friction angle increase proportionally with fiber content. However, a slight decrease in the angle of internal friction and an increase in cohesion are observed at 0.6% fiber content, a decrease in cohesion at 0.8% fiber content, and an increase in the angle of internal friction. In general, the amount of incorporated recycled fibers directly affects the reinforced soil's cohesion and internal friction angle. The enhanced cohesion results from a binding effect in which the fibers carry tensile loads and create bridging forces. Concurrently, the increase in internal friction angle is attributed to the interfacial shear resistance and the physical restraint that the fibers impose on particle rearrangement during shearing. This finding was also reported by Alhassani (2021) and Manuel et al. (2021).

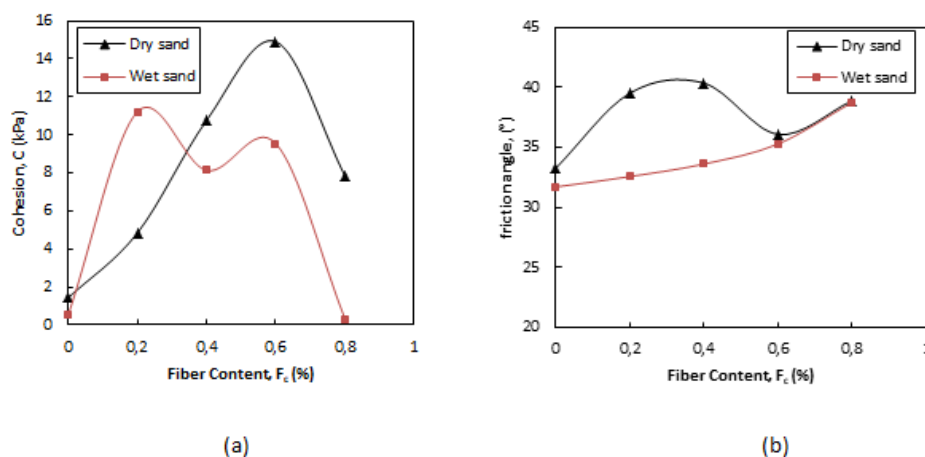


Figure 9 – Effect of fiber content of dry and wet loose sand as function of (a) cohesion, (b) friction angle

- *Medium density samples*

In the case of medium density samples, as shown in Figures 10a and 10b, for dry sand, an increase in cohesion and the angle of internal friction is observed up to a fiber content of 0.4%. From this value, the cohesion decreases, and the angle of internal friction increases to 41.36°. This increase in the angle of internal friction is due to the

development of the fibers network and their mobilization with the sand particles. Figures 10a and 10b show a slight increase in cohesion in wet sand due to the improvement in soil shear strength induced by the fibers in the soil, with the same behaviour observed by Benziane et al. (2019). Furthermore, a distinct variation in the internal friction angle (ϕ) was observed. Consistent with the findings of Isazadeh-Khiav et al. (2022), the internal friction angle exhibited an increasing trend as the fiber content increased. Water content and density affected cohesion and internal friction angle.

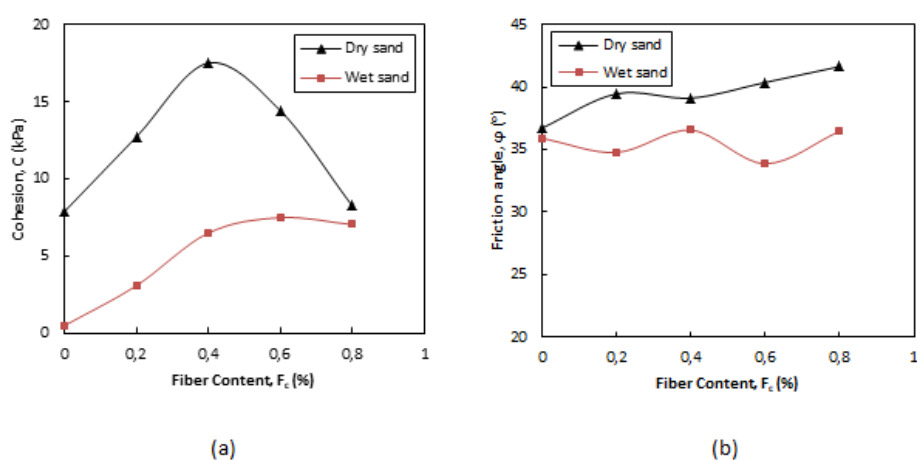


Figure 10 – Effect of fiber content on cohesion and the frictional angle of reinforced dry and wet medium density sand specimens: (a) cohesion, (b) frictional angle

Effect of fibers on contracting-dilatancy

Based on the vertical displacement-horizontal displacement curves, Figure 11a indicates an increase in volume variation for the sandy soil during shearing (dilatancy). Compared to soils without fiber, soils with fiber showed a slightly higher variation. Figure 11b displays a tendency for volume variation to decrease (contracting) for wet sand in the case of unreinforced sand. Additionally, an increase in fiber content increases the volume. The inclusion of strips altered the behavior of the soil at the maximum applied stress levels. Volumetric variation indicates that the soil exhibited a brittle rupture (with dilation), and the material began to display ductile behavior. Similar findings were reported by Eldesouky et al. (2015).

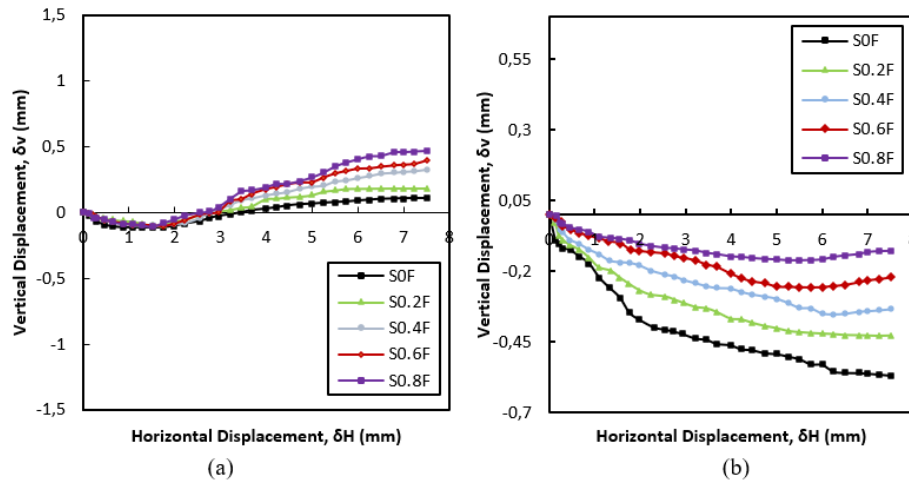


Figure 11 – Vertical displacement versus horizontal displacement curves for loose sand specimens sheared at 200 kPa, (a) dry sand, (b) wet sand

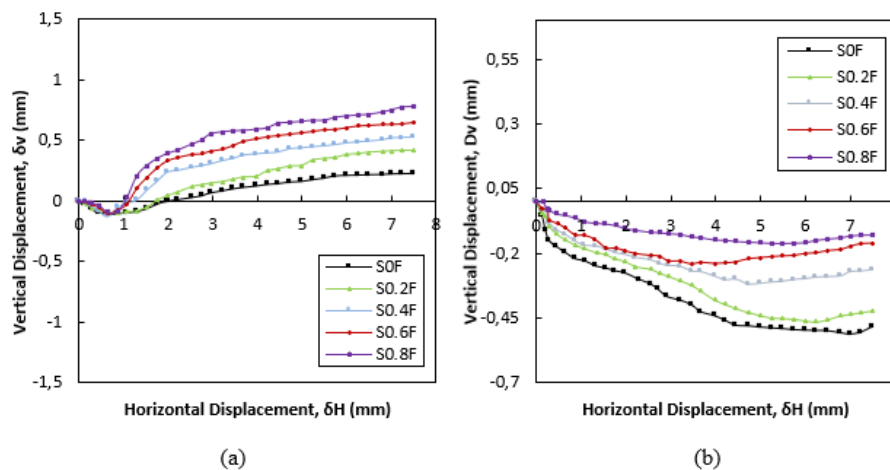


Figure 12 – Vertical displacement versus horizontal displacement curves for medium sand specimens sheared at 200 kPa, (a) dry sand, (b) wet sand.

Figure 12a illustrates the case of dry medium-density sand, where the volume increased with increased fiber content (dilatancy). Figure 12b shows that a greater density of the wet sand increases the contractiveness of the samples, which results in the effect of the relative density and fiber content on the development of the vertical displacement. Similar results indicate the same behavior (Falorca & Pinto, 2011; Aouali et al., 2019; Benziane et al., 2019; Berkane et al., 2023).

Conclusion

A laboratory investigation was carried out to study the effect of the inclusion of recycling fibers on the shear behavior of Zemmouri sand from the Boumerdes region, northern Algeria. Based on the results obtained through this investigation, the following conclusions can be reached:

- Reinforcing sandy soil with discrete recycling fibers can reduce the impact of solid plastic waste on the environment, and ensure sustainability.
- The incorporation of recycled fiber reinforcement reduces soil dilatancy in samples prepared at loose density, while adding fibers increases the dilation tendency in dense samples. This phenomenon can be attributed to the characteristics of the fiber-sand matrix, which exhibits a strong dependence on both relative density and the contribution of fiber reinforcement. Randomly distributed fibers offer strength isotropy and limit the potential planes of weakness that can develop parallel to oriented reinforcement.
- The test results show that the mechanical properties of fiber-reinforced soil are significantly influenced by the presence of recycled fibers, leading to an increase in maximum cohesion and friction angle values at all densities studied.
- The most effective amount of recycling fiber content to achieve the maximum shear strength of Zemmouri sand is 0.4% and 0.6% for a relative density of 25% and 49%, respectively, in dry conditions.

Nomenclature

PP	Polypropylene
R-PP	Recycled Polypropylene fiber
DST	Direct shear test
F_c (%)	Fiber content
W_f (g)	Weight of fiber
W_s (g)	Weight of dry sand
D_r (%)	Relative Density
τ (kPa)	Shear strength
σ_n (kPa)	Normal stress
δ_h (mm)	Horizontal displacement
δ_v (mm)	Vertical displacement
ϕ (°)	Friction angle
C (kPa)	Cohesion

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Ponašanje peščanog tla ojačanog vlaknima od plastičnog otpada pri smicanju

Benathmane Baghdadir^a, **autor za prepisku**, Younes Abed^a, Zine El Abidine Laidani^b

^a NEIGE Laboratory, Civil Engineering Department, Blida 1 University, Blida, People's Democratic Republic of Algeria,

^b Geomaterials and Civil Engineering Laboratory, Civil Engineering Department, Blida 1 University, Blida, People's Democratic Republic of Algeria

OBLAST: građevinarstvo, materijali

KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Zagađenje plastikom predstavlja značajan globalni problem koji zahteva hitno delovanje. Savremene inicijative su usmerene na tehnička rešenja za upotrebu nerazgradive plastike u izgradnji objekata i kolovoza.

Metode: Ovaj rad predstavlja seriju ispitivanja direktnog smicanja u cilju isticanja prednosti upotrebe recikliranih vlakana, posebno u pogledu čvrstoće na smicanje tla. Analiziran je pesak male i srednje gustine ojačan različitim sadržajem vlakana od 0,2, 0,4, 0,6 i 0,8%.

Rezultati: Rezultati pokazuju da su uzorci pripremljeni suvim taloženjem ispoljili značajno veću čvrstoću na smicanje u poređenju sa uzorcima pripremljenim mokrim postupkom. Takođe, povećanje čvrstoće na smicanje je usko povezano sa količinom dodatih vlakana.

Zaključak: Upotreba plastičnog otpada za ojačanje nudi dva rešenja za aktuelne probleme životne sredine: poboljšava ojačanje tla i doprinosi smanjenju uticaja otpada.

Ključne reči: ispitivanje smicanja, peščano tlo, plastični otpad, kohezija, ugao trenja, održivost.

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