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FEASIBILITY OF STRENGTHENING SANDY SOILS USING INDUSTRY WASTE AS GEO-FIBER

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Abstract

Re-using waste generated from daily domestic usage to improve weak soils such as dune sand gives a profitable solution to both environment and the construction sector. In this paper, weak sandy soil was modified with two types of fibers derived from daily domestic use. Plastic bottle waste fiber and tainted polypropylene sediment filter fiber were embedded in the sandy soil with a rate of (0.5%,1%,1.5%, and 2%) by weight of dry soil. Toward this, the direct shear test was conducted to confirm the optimum fiber content and evaluate other parameters such as shear strength, normalized ultimate shear strength, angle of internal friction, and adhesion. The results showed that the 1.5% fiber content showed higher values of angle of internal friction and the normalized ultimate shear strength for both types of fibers. The reinforcement with plastic bottle waste fiber and tainted polypropylene sediment filter fiber enhanced the shear strength parameters and normalized ultimate shear strength. Significant improvement was noticed in the adhesion value with the addition of 2% of tainted polypropylene sediment filter fiber. finally, the effect of fiber addition on the Mohr-coulomb failure envelope was discussed.

Keywords:

Plastic bottle waste;
Tainted polypropylene filters;
Geo-Fibres;
Dune sand;
Shear strength.

1 Introduction

Any material that exceeds the balance of their production or does not readily degrade naturally leads to environmental threats. The innovation of new technologies led to extensive use of plastic in different industry sectors [1]. On the other hand, engineers and researchers have a vision to adopt a sustainable strategy to reuse waste materials in the construction sector [2]. In this context, plastic waste has been reused in the applications of concrete [3], bricks [4], paving blocks, pavements, eco-friendly houses [5], and soil strengthening applications [6].

In geotechnical applications, the addition of cementitious materials like cement, lime, fly ash, and steel slag, as well as the incorporation of discrete constituents like fibers, are frequently used to enhance the mechanical qualities of locally accessible soils [7–10]. These modification methods have been extensively used in a variety of geotechnical engineering applications, including road construction and railway embankments, slope stabilization, and enhancing soft ground [11–14].

Fiber is typically split into two categories: the first is a plant fiber, such as wheat straw, coir, bagasse, sisal, and jute, among others, because of their availability and affordability [15–17]. Other types of fibers are synthetic, including nylon, polyvinyl alcohol, and polypropylene. They have superior durability, corrosion resistance, and tensile strength [18–20]. By causing friction at the interface between the fibers and the soil particles and by having a spatially constrained effect, the fibers may improve the mechanical properties of the soil [21,22]. The excess fibers negatively impacted the strength and deformation resistance of soil, although the addition of less fiber could not have a significant influence on friction [23,24].

The use of short, randomly placed fibers to reinforce soils has been studied for several decades. In contrast to systematically reinforced soil, the shear strength of randomly reinforced soils is assessed by measuring the change in shear strength parameters caused by the addition of the fibers. Typical shear strength tests, such as the direct shear and triaxial tests, are used to measure the shear strength parameters [25]. Meddah studied the potential of reusing old tire fiber to reinforce sandy soil in dense and loose states [26]. Mehdi studied the effect of random inclusion of polypropylene fibers up to 0.75% into sandy soil [27]. According to the researchers, including fibers increases the soil's shear strength

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[28–31]. However, some parameters, such as the reinforced sand's cohesion, are still disputed. Some researchers neglected the cohesion in reinforced sand despite the fact that there are slight increases in the value beyond zero [26, 32]. Other researchers reported that the inclusion of fiber within the structure of the reinforced sand provided ductility, which led to an increase in cohesion values [6].

This work aims to explore the potential of reinforcing dune sand by randomly distributing plastic bottle waste fiber and polypropylene sediment filter fiber. The fibers were incorporated in the sand with rates of (0.5, 1, 1.5, and 2%) of dry weight of sand. A series of direct shear box tests are carried out to study the effect of fiber content and fiber type on the shear strength properties of dune sand. Furthermore, a new explanation for the phenomenon of the cohesion apparent in the reinforced sandy soil was also discussed.

2 Materials and methods

2.1 Soil

The soil used in this work is poorly graded dune sand. It was collected from Maysan city in Iraq and located at the geographical coordinates of 31°50'06.4" N and 46°26'17.5" E with an elevation of 8 meters above sea level. Fig. 1 shows the location and the stack of sand. Table. 1, Fig. 2, and Fig. 3 illustrate some of the geotechnical properties of sand.



Fig. 1: Geomorphological map of Iraq and sampling site of Maysan city.

Table 1: Geotechnical property of the utilized dune sand.

Parameter	Standard	Value /Description
Specific gravity G_s [g.cm^{-3}]	ASTM D854	2.54
C_u	ASTM D422	0.83
C_c	ASTM D422	1.05
USCS	ASTM D2487	SP
$\gamma_{d(max)}$ [kN.m^{-3}]	ASTM D698	13.15
w_{opt} [%]	ASTM D698	13.3%

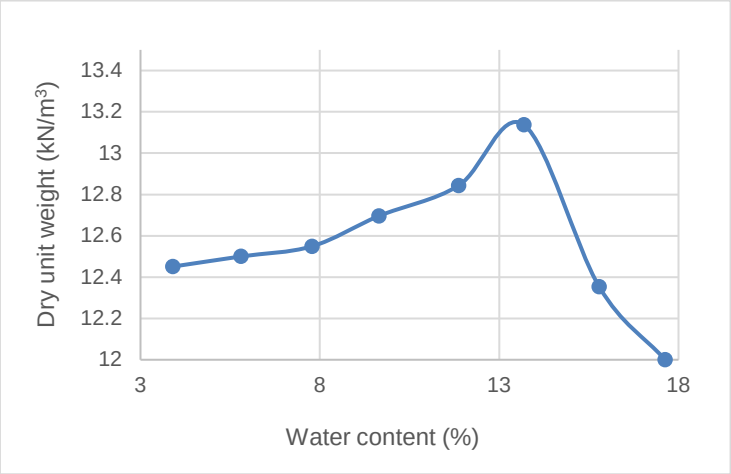


Fig. 2: Compaction curve of sand.

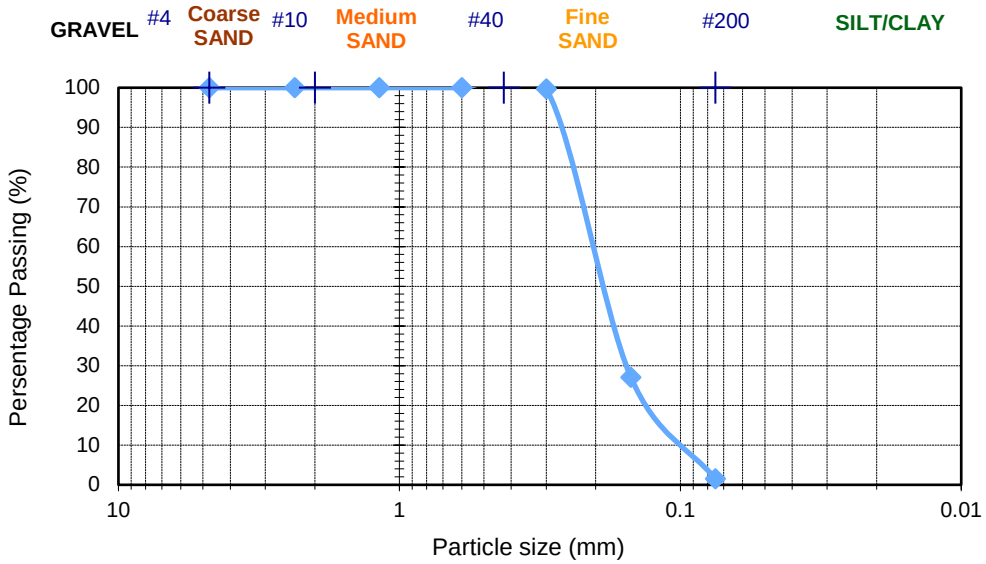


Fig. 3: Particle size distribution curve of sand.

2.2 Fiber

Fibers used in this study were collected from daily domestic usage and mainly derived from two sources. The first source is polyethylene terephthalate (PET), which is used in the application of goods packaging, thermal insulation, and plastic bottle production. The PET was collected from a local recycling plant where plastic bottle waste is chopped into particles with lengths between 0.7 cm and 1.2 cm, as shown in Fig. 4 (c). The polyethylene terephthalate fiber will be symbolized as (PBWF), which alludes to plastic bottle waste fiber. The second source is polypropylene (PP), which is used in the application of various plastic parts, textiles, and sediment filters. The PP is derived from tainted (used) polypropylene sediment filters (PPF). Fig. 4 (a) shows the PPF in a clean and tainted state. The polypropylene sediment filters were chopped into particles between 0.8 and 1 cm using a paper shredder machine, as shown in Fig. 4 (b). The PPF will be symbolized as (TPPF) which alludes to tainted polypropylene filters, as seen in Fig. 4. (b).



Fig.4: Fiber morphology (a) tainted and clean polypropylene filters (b) TPPF (c) PBW.

2.3 Sample preparation and mixing procedure

Previous studies adopted various techniques for preparing fiber-reinforced sand samples in the laboratory. The variables undertaken were moisture level during tamping, compaction rate, and sequence of mixing. The moisture level is introduced mainly by dry and moist tamping techniques. For instance, the dry tamping technique was adopted by Meddah to simulate the dune sand deposited in the arid zones [26], while Wei Shao et al. adopted moist tamping to ensure good compaction and simulate dune sand compacted in the field [6]. Sand rarely existed in dry conditions, especially under foundations. Based on what's mentioned above, moist tamping was adopted in this study to prevent fiber segregation and simulate actual field conditions. Dune sand was pre-wetted by the optimum water content of 13.3%, and then fiber was added and manually mixed to ensure well distribution of fiber. Fiber added by (0.5%, 1%, 1.5%, and 2%) of the dry weight of sand. Lose and dense states were introduced by previous studies [26]. Notwithstanding that, the in-situ applications of sand as a road base or under the foundations exist only in dense states. In this study, the mixture was placed on the standard direct shear apparatus in two layers, and the desired compaction energy was controlled by 20 blows of a wooden tamper to simulate a dense state.

3 Results and discussion

3.1 Shear stress

The direct shear test is applied using a shear box apparatus to examine the mechanical characteristics of dune sand and the introduction of randomly dispersed PBWF and TPPF. It is well-recognized that soil fiber content significantly impacts how well fiber inclusion works [27,31–33]. Therefore, the fiber content is gradually raised from 0.5% to 2% with a rate of 0.5% of the dry weight of sand to quantify this impact. Both reinforced and unreinforced sand samples are exposed to three normal stresses (100, 200, and 400 kPa) since sandy soil shear strength behavior depends on the applied confining pressure. Tables 2 and 3 summarize the fiber content, type of fiber, normal stress, shear strength values, displacements, and adhesion values at peaks and residual states.

Fig. 5, 6, and 7 depict the relationships between the shear stress and the horizontal displacements for reinforced dune sand with PWB fiber, while Fig. 8, 9, and 10 depict these connections for reinforced dune sand with TPPF fiber. The findings demonstrate that the fiber content and the normal stress intensity applied during shearing impact the stress-displacement responses of the reinforced dune sand.

Table 2: Peak strength characteristics.

Fiber content (%)	Normal stress (kPa)	PBW-fiber		Adhesion (kPa)	TPPF-fiber		Adhesion (kPa)
		Peak strength (kPa)	Displacement (mm)		Peak strength (kPa)	Displacement (mm)	
0	100	76.252	3.952	2.303	76.252	3.952	2.303
	200	143.145	3.205		143.145	3.205	
	400	291.044	5.137		291.044	5.137	
0.5	100	87.423	3.419	9.232	85.3	3.29	17.8
	200	163.450	5.044		174	5.01	
	400	319.832	6.145		309	5.14	
1	100	87.410	5.059	9.841	90.09	2.05	18.09
	200	165.250	5.387		170	2.5	
	400	320.388	5.793		314	3.15	
1.5	100	95.564	2.804	11.33	99.25	3.05	25.81
	200	187.504	4.12		199.125	4.21	
	400	355.955	3.787		346	3.7	
2	100	84.149	4.211	13.75	92.5	3.65	36.37
	200	163.026	6.991		208.9	3.74	
	400	303.808	5.481		321.15	2.6	

Table 3: Residual strength characteristics.

Fiber content (%)	Normal stress (kPa)	PBW-fiber		Adhesion (kPa)	TPPF-fiber		Adhesion (kPa)
		Residual strength (kPa)	Displacement (mm)		Residual strength (kPa)	Displacement (mm)	
0	100	74.853	4.568	4.894	74.853	4.568	4.894
	200	141.201	5.012		141.201	5.012	
	400	281.12	5.349		281.12	5.349	
0.5	100	78.476	4.583	3.124	83.1	4.8	13.10
	200	158.202	5.701		164.25	5.9	
	400	308.907	6.953		304.25	5.45	
1	100	81.527	6.445	3.393	84.357	3.8	15.17
	200	159.202	6.346		164.85	4.15	
	400	315.471	6.595		302.75	4.15	
1.5	100	82.161	6.308	8.787	95.78	3.9	20.155
	200	183.287	6.071		187.75	5.25	
	400	330.036	6.301		339.5	4.28	
2	100	82.325	6.333	20.456	89.45	4.25	31.41
	200	162.576	6.991		197.48	6	
	400	286.314	7.331		313.56	4.5	

As can be observed from the data, under shearing conditions, the behavior curve patterns of both types of reinforced dune sand are typical of granular soils. Accordingly, for reinforced sand, deformations grow toward peaks at relatively moderate displacements, followed by declines in shear stresses toward residual strengths (post-failure strengths) at high deformations. Contrarily, it is evident that the shear strength grew in tandem with the normal loads that were applied during shearing.

It is evident that as the content of fibers increased, the rates of the development of shear stresses decreased, indicating that the presence of fibers slowed the deformation process. In addition, when the amount of fibers increases, displacements that reflect ultimate strengths are reduced. As a result, adding fibers to granular soils as stabilizers aids in increasing the sand's ductility, making it ideal for geotechnical applications such as retaining walls and slope stability. Furthermore, the results

demonstrated that the insertion of fibers had little impact on the small initial strains. The results of this study are consistent with those of previous studies [26, 33]. They have reported that incorporating polypropylene and rubber fibers in the sand does not affect initial stiffness. At high displacements, as shown in Fig. 5-10, the ultimate and residual shear strength of sand has been increased by incorporating fibers, which means that the reinforced sand exhibits greater strength. However, it should be noted that when the vertical pressure rises, the influence of fibers at high displacements diminishes.

The figures also show that the improvement was similar for both types of fibers, with a slight advantage for the TPPF-treated samples. This behavior can be explained by the fact that the surface of TPPF is rougher than that of PBWF; therefore, the friction is higher between the fibers and the sand.

The fact that stresses transfer from the dune sand matrix to the fibers, putting them in tension and increasing the tensile strength of reinforced sand, may help to explain the improvement of the local behavior of reinforced sand based on the interaction between the sand grains and fibers during shear stages. Therefore, this interaction mechanism will work more effectively if the friction is higher. Additionally, the presence of fibers in the sand limits relative displacements between the sand grains, creating additional contact forces and improving the overall performance of reinforced structures of dune sand.

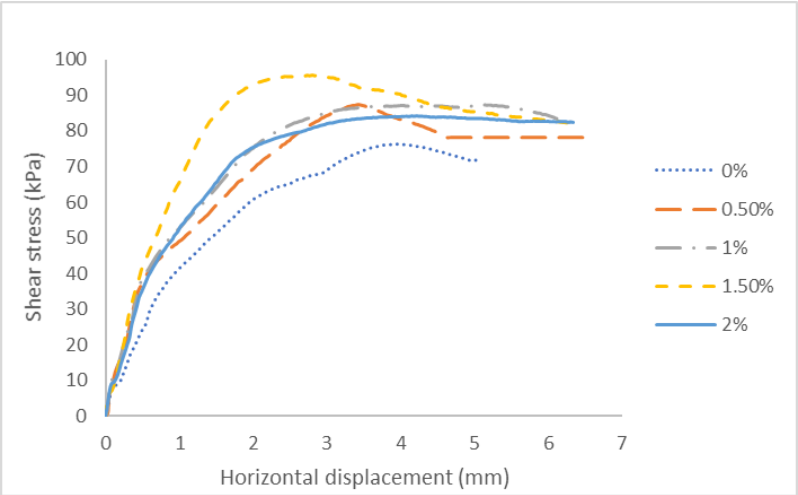


Fig. 5: Effect of PBW fibers on shear stress (σ_n = 100 kPa).

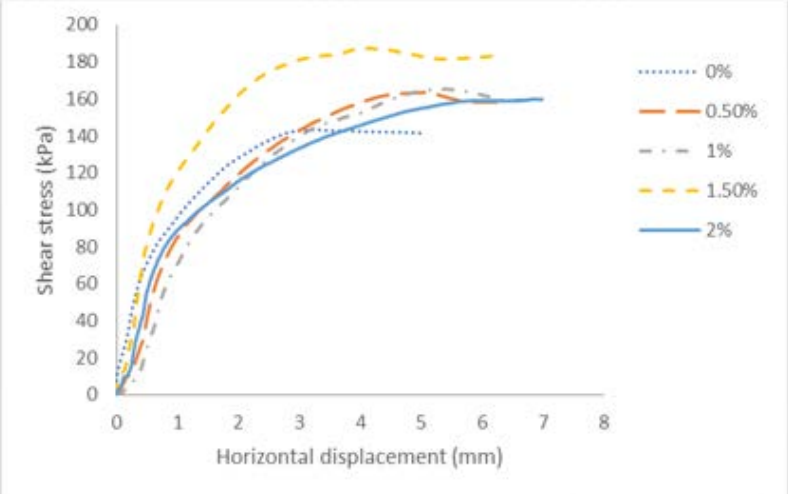


Fig. 6: Effect of PBWF on shear stress (σ_n= 200 kPa).

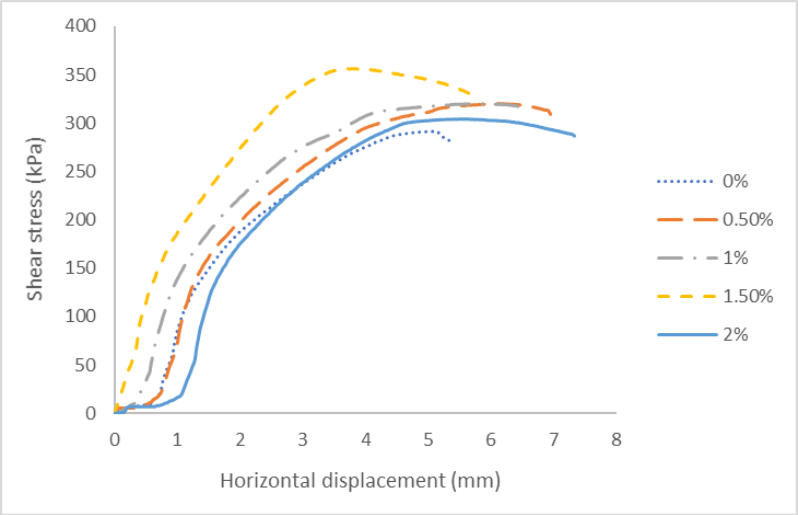


Fig. 7: Effect of PBWF on shear stress (σ_n = 400 kPa).

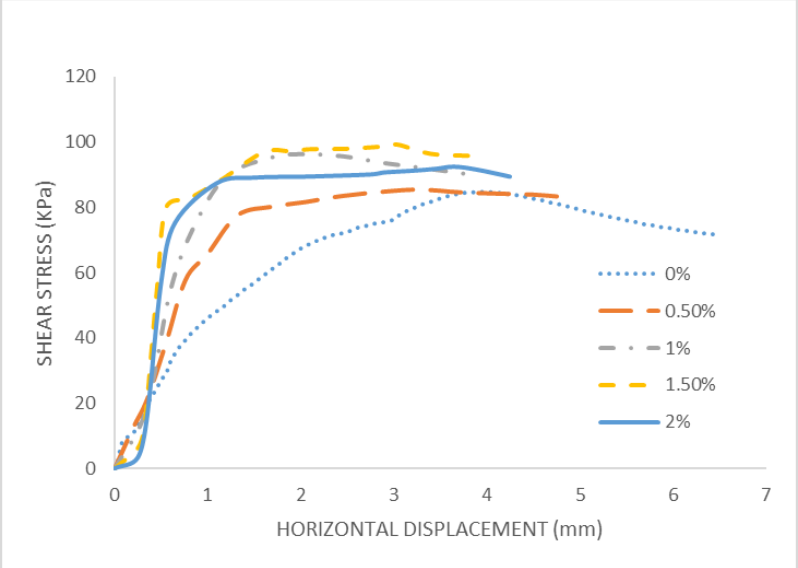


Fig. 8: Effect of TPPF on shear stress (σ_n = 100 kPa).

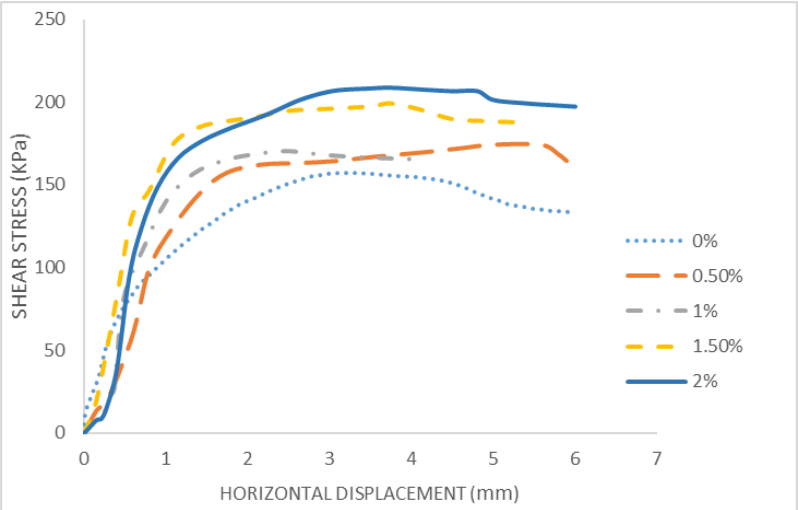


Fig. 9: Effect of TPPF on shear stress (σ_n = 200 kPa).

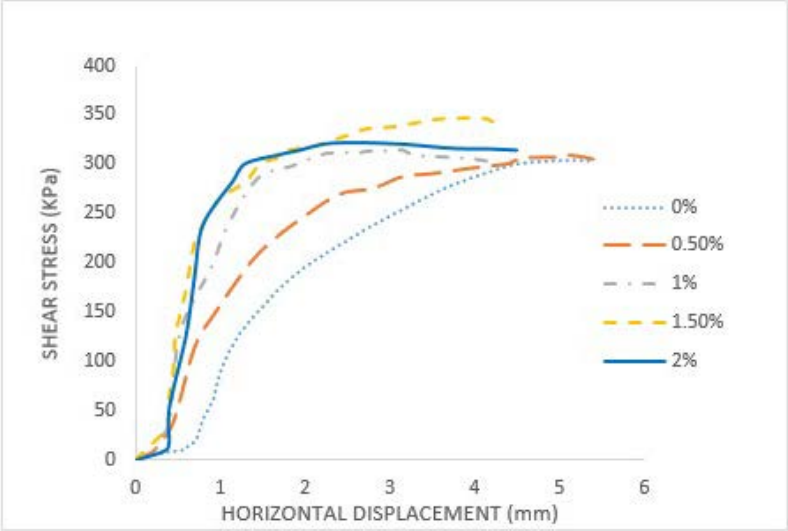


Fig. 10: Effect of TPPF on shear stress (σ_n = 400 kPa).

3.2 Normalized ultimate shear strength

The impact of adding fibers to dune sand on the normalized ultimate shear strength is seen in Fig. 11 and 12. The normalized ultimate shear strength parameter refers to the ultimate shear strength (τ_{ult}) divided by the normal stress (σ_n) that is applied on the dune sand during the process of shearing, i.e., τ_{ult} / σ_n [24].

Fig. 11 and 12 illustrate that increasing the fiber content improves the normalized ultimate shear strength. Meanwhile, for the samples of PBWF, the improvement rate ranged from 4.38% up to 30.99%, and for the samples of TPPF, the percentage of improvement ranged between 6.17 and 45.94. The general behavior tended to improve normalized ultimate shear strength by increasing the fiber content until it reached a fiber percentage of 1.5%. The improvement at this value is as great as possible. Then, this improvement begins to decrease by adding more fiber. Fig. 11 and 12 also show that compared to other normal stresses (200 and 400 kPa), the impact of the fibers is more noticeable for the vertical pressure of 100 kPa. This is in line with the findings of previous research [6, 26]. According to the authors, fiber reinforcement is more useful for soils with low confining pressure. Additionally, fiber-reinforcing techniques are advised for use to enhance the mechanical properties of slope stability and shallow foundations[34]. These results are in line with earlier research on polypropylene and rubber fiber-reinforced sand [25, 26]. According to their studies, adding 1 - 2% of fibers to sand can increase the normalized peak strength by roughly 25–30%. Generally, using TPPF and PBWF significantly impact the normalized peak strength.

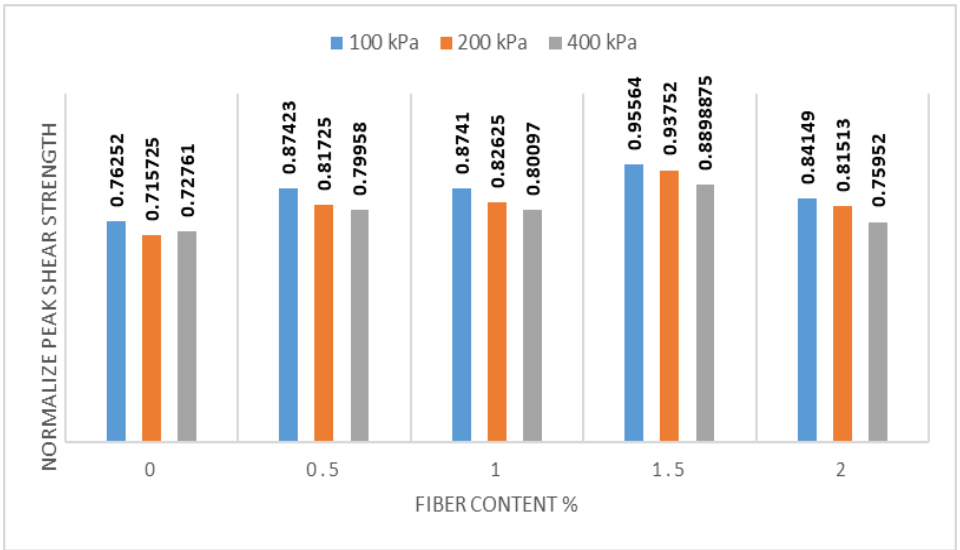


Fig. 11: Normalized ultimate shear strength versus PBWF content.

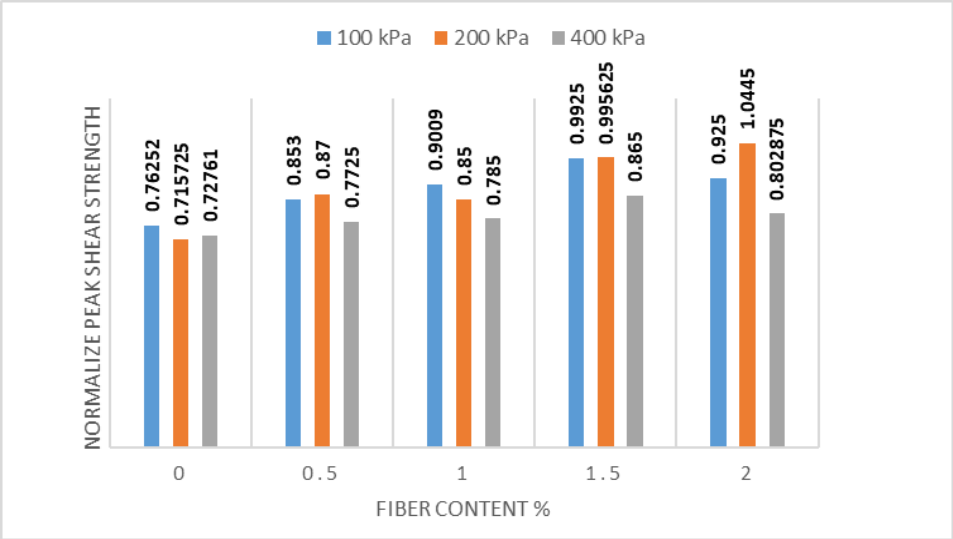


Fig. 12: Normalized ultimate shear strength versus TPPF content.

3.3 Internal friction angle

Due to the low cohesion, dune sand strength often relies on friction angle. Fig. 13 depicts the change in frictional angle with increasing TPPF and PBWF content at peak and residual states. As can be shown, adding fibers to dune sand at a ratio of 0.5 to 1.5% considerably improves this parameter. Adding more fibers, however, has the opposite effect. These results met the previous research results [13, 26, 33].

Moreover, Fig. 13 shows that the improvement in the angle of internal friction when adding TPPF was more significant than the improvement by adding PBWF. This behavior can be explained by the fact that the strength of sand depends on friction, and this friction is greater between sand and TPPF than with PBWF due to the softness of the plastic fibers. These results were similar in the peak or residual state, where the improvement at 1.5% fiber content was 4.7 and 2.47 for TPPF and PBWF, respectively, for the peak state, and the increase in the angle of friction was 3.9 and 3.96 for TPPF and PBWF, respectively for the residue state.

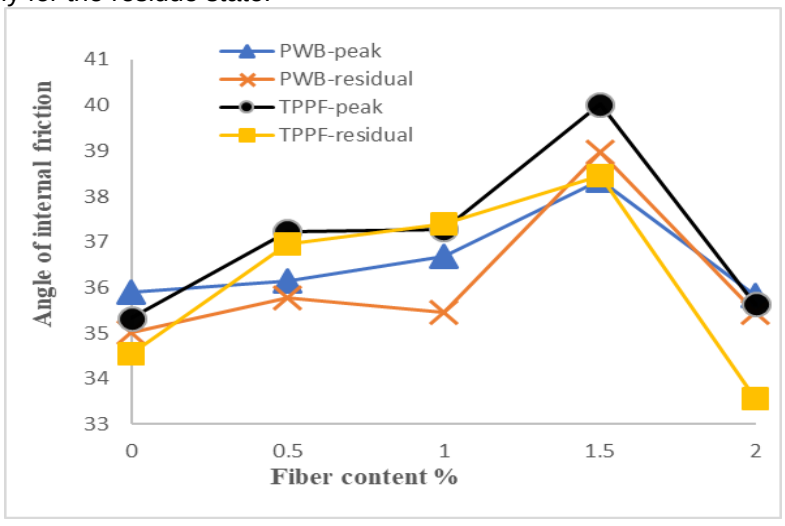


Fig. 13: Angle of internal friction versus fibers content.

3.4 Adhesion or cohesion?

Previous studies on the topic of the cohesiveness of sandy soils reinforced with fibers revealed two different perspectives. Based on the Mohr-Coulomb failure criteria of sand, the first perspective denies the existence of coherence even after fiber inclusion [26]. In comparison, the second perspective maintains that the inclusion of fiber in the sand may develop cohesiveness [13, 33, 35–37]. In general, it is anticipated that the two strength parameters, angle of friction and cohesion, will exhibit opposing tendencies. For instance, the cohesion of soils often diminishes as the angle of friction increases.

However, adding fibers results in an increase in each of these metrics. According to their explanation, the soil's ductility is increased by stretching its fibers, which increases cohesion.
This study presents a new explanation for the phenomenon of cohesion apparent in the fiber-reinforced sand. This interpretation is based on the distinction between the two terms cohesion and adhesion. Cohesion is between the soil particles themselves due to the presence of electrostatic forces or cementation of the skeleton by very fine particles, while adhesion is between the particles of two different materials. In the case of fiber-reinforced sand, the adhesion is between the fine sand and the fibers as a result of the internal strength or resistance to shear forces exhibited by the composite material composed of sand particles and reinforcing fibers.

According to the obtained results, the effect of different fiber reinforcement contents on shear strength parameters (adhesion) at peak and residual state are summarized in Tables 2 and 3 and Fig. 14. The figure shows that an increase in fiber content leads to an increase in adhesion regardless of the fiber type and stresses at peak and residual state. In general, the improvement in the samples with TPPF results was greater than in the samples with PBWF. This can be explained by the fact that the adhesion between the sand and the polyproline fibers was higher than the adhesion with the plastic fibers.

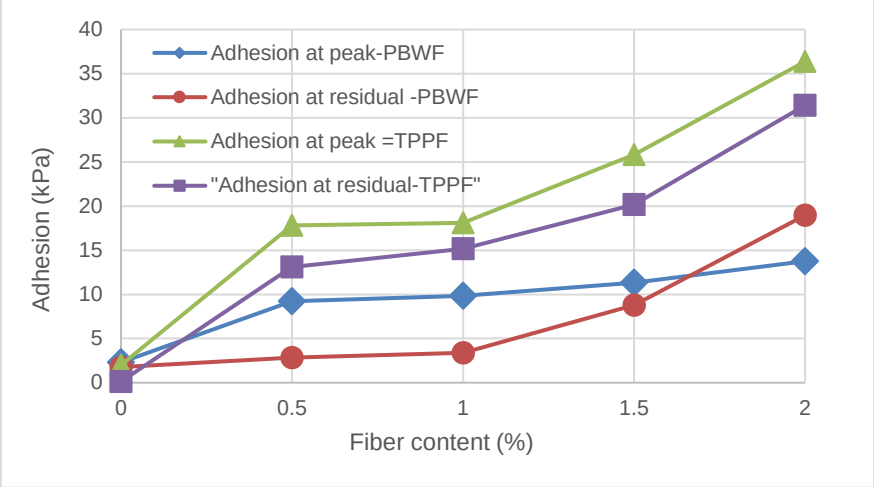


Fig. 14: Adhesion versus fibers content.

Mohr-Coulomb failure criteria represented by the failure envelope of the reinforced and unreinforced sand were presented in Fig. 15. and Fig. 16. The results of peak and residual strength with the inclusion of 2% of TPPF were adopted to describe the development of adhesion values. The results showed two linear failure envelopes parallel to each other for both reinforced and unreinforced sand. According to the liner equations shown, a vertical displacement at peak and residual states was noticed. This displacement illustrates the development of adhesion value due to the stretching of fiber to the yield limit and the frictional resistance between the surface of the fiber and sand particles [38].

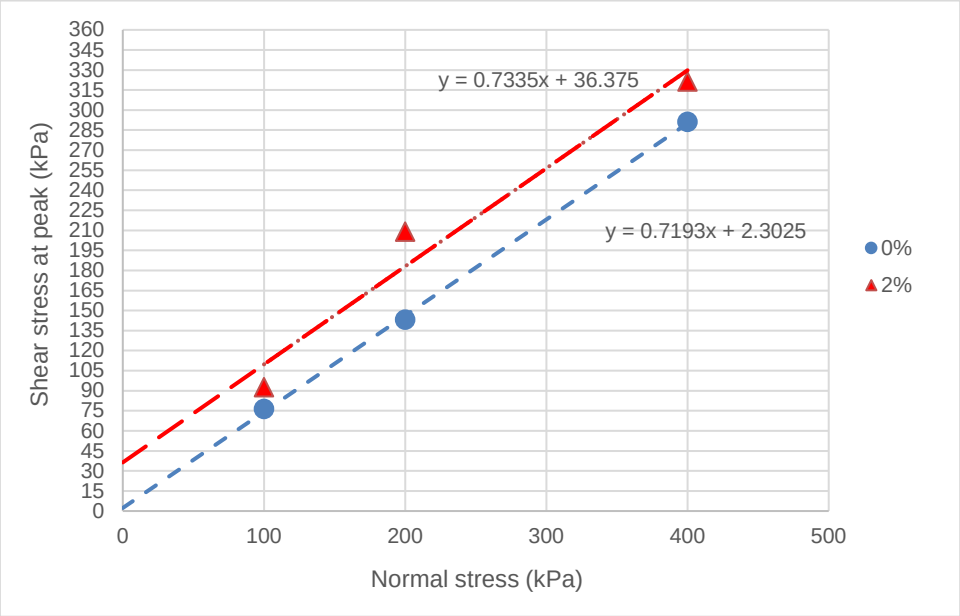


Fig. 15: The effect of TPPF-sand mixture on failure envelope at peak strength.

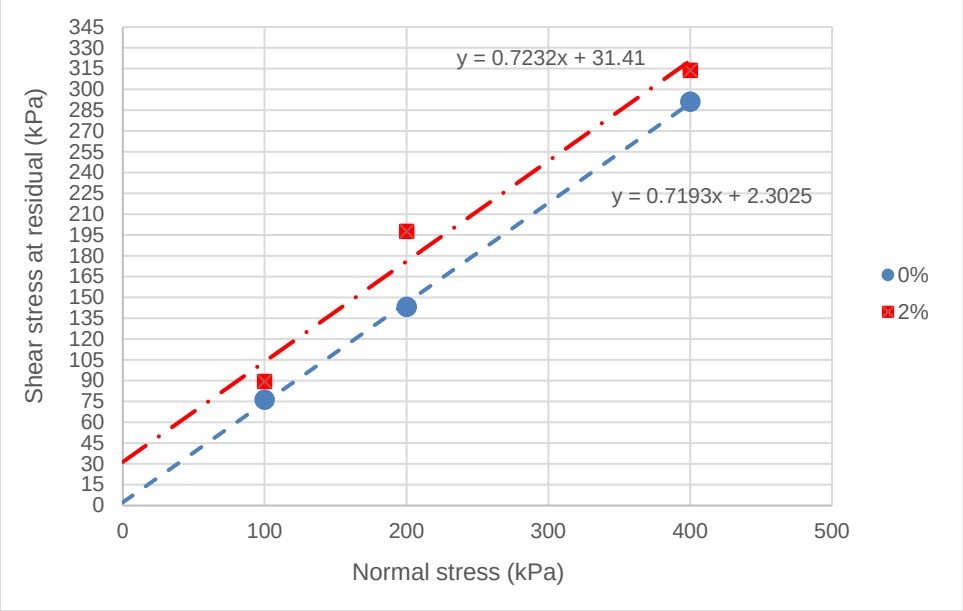


Fig. 16: The effect of TPPF-sand mixture on failure envelope at residual strength.

4 Conclusions

In this work, the results of experimental research are done to determine whether it is feasible to reinforce dune sand using PBWF and TPPF waste. Dune sand is blended with varying quantities of PBWF and TPPF that are randomly distributed. Direct shear tests are performed on moist, fiber-reinforced, and unreinforced sand samples that have been prepared under various normal loads. The following points are a summary of the study's main conclusions:

1) The fiber content and the normal stress intensity applied during shearing impact the stress-displacement responses for reinforced dune sand. For reinforced sand, deformations grow toward peaks at relatively moderate displacements, followed by declines in shear stresses toward residual strengths.

2) When the fibers' content increased, the shear stress development rates decreased. In addition, when the amount of fibers increases, displacements that reflect ultimate strengths are reduced. As a result, adding fibers to granular soils as stabilizers aids in increasing the sand's ductility.

3) The study demonstrated that the insertion of fibers had little impact on the small initial strains.

4) The study shows that the shear stress improvement was similar for TPPF and PBWF, with a slight advantage for the TPPF-treated samples.

5) Increasing the fiber content improves the normalized ultimate shear strength until reaching a fiber percentage of 1.5%. The improvement at this value is as significant as possible. Then, the improvement begins to decrease by adding more fiber. The study also shows that the impact of the fibers is more noticeable for the vertical pressure of 100 kPa.

6) Adding fibers to dune sand at a 0.5 to 1.5% ratio considerably improves the internal friction angle. However, adding more fibers has the opposite effect. Also, the improvement in the angle of internal friction when adding TPPF was more significant than the improvement by adding PBWF.

7) The study shows that the increase in fiber content leads to an increase in adhesion regardless of the soil type or stress condition. Overall, the improvement of adhesion of the samples treated with TPPF was more significant than that treated with PBWF.

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