World Academy of Science, Engineering and Technology
International Journal of Geotechnical and Geological Engineering
Vol:16, No:12, 2022

Improving the Compaction Properties and Shear Resistance of Sand Reinforced with COVID-19 Waste Mask Fibers

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Abstract**—**Due to the COVID-19 pandemic, disposable plastic-based face-masks were excessively used worldwide. Therefore, the production and consumption rates of these masks were significantly brought up, which led to severe environmental problems. The main purpose of this research is to test the possibility of reinforcing soil deposits with mask fibers to reuse pandemic-generated waste materials. When testing the compaction properties, the sand was reinforced with a fiber content that increased from 0% to 0.5%, with successive small increments of 0.1%. The optimum content of 0.1% remarkably increased the maximum dry density of the soil and dropped its optimum moisture content. Added to that, it was noticed that 15 mm and rectangular chips were, respectively, the optimum fiber length and shape to maximize the improvement of the sand compaction properties. Regarding the shear strength, fiber contents of 0.1%, 0.25%, and 0.5% were adopted. The direct shear tests have shown that the highest enhancement was observed for the optimum fiber content of 0.25%. Similar to compaction tests, 15 mm and rectangular chips were respectively the optimum fiber length and shape to extremely enhance the shear resistance of the tested sand.

Keywords**—**COVID-19, mask fibers, compaction properties, soil reinforcement, shear resistance.

I. Introduction

NOWADAYS, many ground improvement techniques have been adopted in engineering applications. Reinforcing soil composites with randomly distributed fibers seem to be an appealing method [6], [9], [11], [17], [21], [26], [27], [33].

Using randomly distributed fibers as a reinforcement technique is probably older than written history [15]. Adding natural fibers to reinforce construction materials originated in ancient times [1], [3], [17], [23], [30], [36] when civilizations in Mesopotamia added straw to prepare reinforced sun-dried soil bricks. The main purpose of this mixture was to enhance the soil integrity by improving its properties and reducing the growth of potential cracks [6], [15].

Reinforcing soils with natural and synthetic fibers is a viable technique to enhance soil properties, stability, and bearing capacity [20], [36]. The most interesting conclusions common to all the research done in this field are an increase in unconfined compressive and ultimate shear strengths of soils reinforced with fibers. In addition to that, reinforced samples had a ductile behavior with higher energy absorption rates. This is due to an increase in the measured strain at failure as well as an important reduction in the post-peak loss in strength at high strains [21], [29]. Furthermore, fiber-saturated composites generally have better compaction properties if the adopted fiber content is adequately selected [5], [6]. Added to that, reinforcing soils with fibers has recently been adopted as a good way to recycle and reuse shredded and fibrous synthetic waste materials in different engineering applications [29], [32]. For example, using waste polymer textile bags to improve weak soil properties is a revolutionary environmentally friendly method to treat these bags that are generally available at no cost [12].

Due to the global health crisis created by the COVID-19 pandemic, it was mandatory to wear face-masks in public places, in almost all countries around the world [28]. In fact, using face-masks is considered to be an effective way to prevent the spread of the virus [28], [37]. Therefore, the production and consumption rates of disposable face-masks produced using polymeric materials such as polypropylene were significantly brought up [14]. The excessive use of disposable masks has led to severe environmental problems. The reason being that, used plastic-based face-masks are thrown everywhere [14], [28], [37]. Hence, it is urgently required to deal with pandemic-generated waste materials as few studies have been conducted in this field until now [28], [37].

Excessively used face-masks have a great potential to be employed as a soil reinforcement material. This new perspective could be a good way to recycle these waste masks [37]. As a direct result to that, this paper presents the results of the experiment that has been conducted to study the effect of mask fibers on the compaction properties and shear resistance of a poorly graded sandy soil. Several parameters have been taken into consideration such as the fiber content, length, and shape.

II. Materials and Methods

A. Materials

1) Ras El-Matn Sand

The tested sand samples were obtained from Ras El-Matn which is a Lebanese village located in the Mount Lebanon Governorate. 1.74% of the soil particles are finer than the No. 200 sieve. Moreover, it does not contain gravel. The sand grain-size distribution is shown in Fig. 1. Different characteristics of

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the tested Ras El-Matn sand are summarized in Table I.

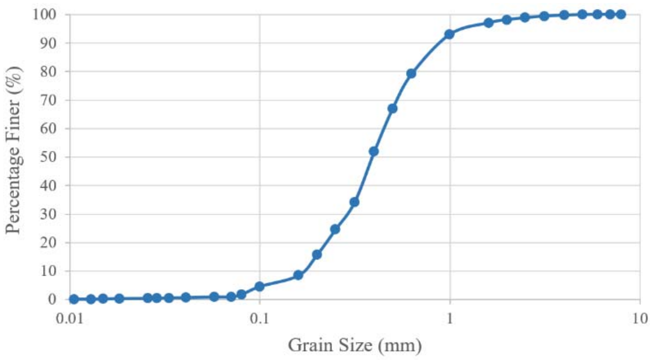


Fig. 1 Grain-size distribution of Ras El-Matn sand

TABLE I
PROPERTIES OF RAS EL-MATN SAND

Soil property	Numerical value
Gravel content (%)	0.00
Sand content (%)	98.26
Fines content (%)	1.74
D_{60} (mm)	0.4511
D_{30} (mm)	0.2854
D_{10} (mm)	0.1679
Coefficient of uniformity Cu	2.6867
Coefficient of curvature Cc	1.0754

According to the Unified Soil Classification System (USCS) [38], the tested soil is a poorly graded sand SP. The direct shear test has shown that Ras El-Matn sand is cohesionless with an internal friction angle of 35.75°. The standard Proctor compaction curve of the sand is shown in Fig. 2. The maximum dry unit weight and the optimum moisture content of the sand are 18.698 kN/m^3 and 10.271%, respectively.

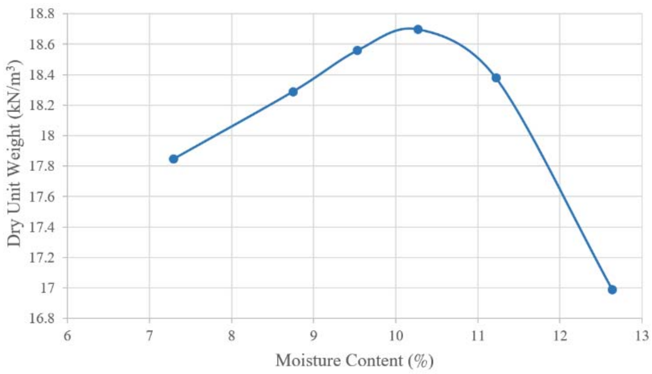


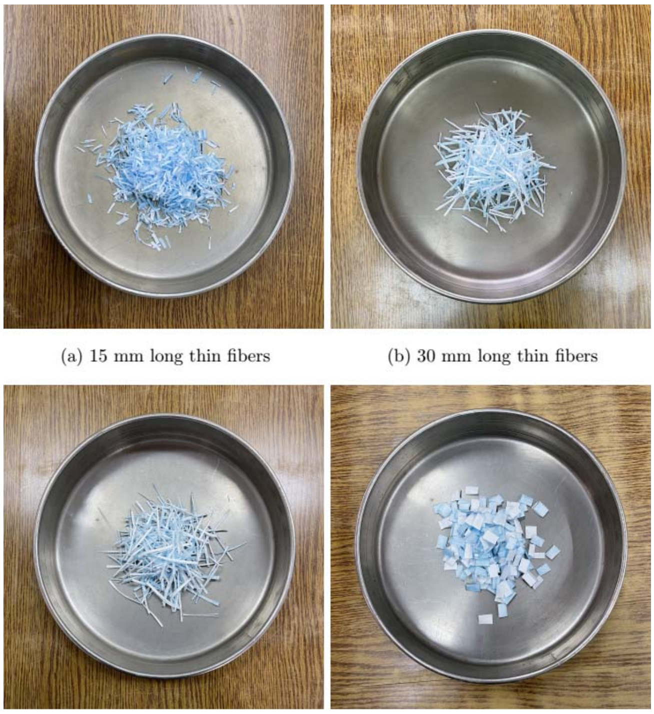
Fig. 2 Compaction curve of Ras El-Matn sand

2) Shredded Masks

Already used face-masks were not adopted in the current laboratory testing program due to health and safety measures. Consequently, clean disposable face-masks were used after being shredded to the required sizes and shapes. Moreover, it should be noted that the ear-loops and metal strips were removed [28].

The adopted face-masks in the current experiment are composed of three successive layers. The top and bottom layers are made of non-woven fabric while the used material in the middle layer is a melt-blown non-woven polypropylene fabric [14], [28]. Fibrous materials are excessively available within face-masks as they are considered to be the main components for filtration [2]. As a direct result to that, fibers obtained from disposable face-masks could be an efficient mean to reinforce soil deposits and enhance their properties.

Face-masks were manually cut to obtain the required fibers. Two unlike fiber shapes were tested. Namely, the effect of adding conventional thin fibers and rectangular mask chips was investigated. Regarding the thin fibers, three different lengths of 15 mm, 30 mm, and 45 mm were separately targeted during the cutting process. Moreover, the rectangular chips had a length of 15 mm and a width of 10 mm. Hence, their targeted aspect ratio was 1.5. The prepared fibers are shown in Fig. 3.



(a) 15 mm long thin fibers (b) 30 mm long thin fibers (c) 45 mm long thin fibers (d) Rectangular mask chips

Fig. 3 Different adopted face-mask fibers

B. Methods

1) Laboratory Testing Program

To properly choose the tested fiber contents, it is suggested to use small increments that are less than 0.2%. When the variation of the compaction properties is investigated, the fiber percentage should be continuously increased until a reduction in the maximum dry density of the prepared composite is observed [5]. The compaction properties of unreinforced and reinforced samples were obtained from standard Proctor compaction tests which were conducted according to ASTM D698.

To test the fiber content effect on the compaction properties of Ras El-Matn sand, the percentage of 15 mm long thin fibers was brought up from 0% to 0.5%, with successive small increments of 0.1%. All the adopted fiber contents in this study were lower than 0.5% since fibers start to form lumps by sticking together at higher percentages [10].

Direct shear tests were also conducted on Ras El-Matn sand. This soil was reinforced with 15 mm long conventional fibers at different contents of 0.1%, 0.25%, and 0.5%, respectively. These tests were conducted in accordance with ASTM D3080 at a constant displacement rate of 1 mm/min.

The fiber length and shape are also important parameters that had to be studied. At a constant fiber content of 0.1%, the compaction properties and the shear resistance of Ras El-Matn sand were established when this soil was separately reinforced with 30 mm long fibers, 45 mm long fibers, and rectangular chips.

All the above-mentioned tests were repeated twice to validate the obtained values. It is important to mention that no significant variation in the results was noted.

2) Sample Preparation

The weight of the fibrous material used for each fiber content is calculated based on the air-dried soil weight [4]-[6], [8], [13], [18], [20], [22], [33], [35]-[37].

To produce a fairly uniform mixture, the required quantity of fibers was first mixed by hand with the dry soil. The predefined fiber content was added in small successive increments. Then, the required weight of water for each moisture content was gradually added and the manual mixing process continued to reach a uniform distribution of fibers within the soil matrix [1], [5], [6], [11], [21], [31], [33]-[35]. The moist sand reinforced with 15 mm long thin fibers at a fiber content of 0.2% is presented in Fig. 4. This sample was prepared for the standard Proctor compaction test.

Fig. 4 Sand mixed with a 15 mm fiber content of 0.2%

It was decided to first mix fibers with dry soil to avoid the fiber clumping which is usually observed when fibers are immediately added to wet soil samples [11], [21]. When this mixing method is adopted, fibers become coated by a layer of dry fine soil particles. Subsequently, fiber clumping and segregation can be prevented when water is added later on [21].

Regarding the direct shear tests, the same mixing method was adopted. However, the samples were kept dry and no water was added to the prepared mixtures.

III. Results and Discussion

A. Compaction Properties

1) Fiber Content Effect

The standard Proctor compaction curves of Ras El-Matn sand reinforced with different percentages of 15 mm long fibers are plotted in Fig. 5. In addition to that, the values of the maximum dry density and the optimum moisture content for each fiber content are summarized in Table II.

TABLE II
Compaction Properties of Sand Reinforced with Different 15 mm Fiber Contents

Fiber content (%)	0.0	0.1	0.2	0.3	0.4	0.5
$\mathbf{g}_{d,max}$ (kN/m^3)	18.698	19.249	18.750	18.557	18.155	17.811
$\mathbf{w}_{optimum}$ (%)	10.271	9.375	10.114	10.294	10.359	10.636

When shredded masks were added at a percentage of 0.1%, the reinforcement clearly enhanced the sand compaction properties. For instance, the maximum dry unit weight increased from 18.698 kN/m^3 to 19.249 kN/m^3 and the optimum moisture content dropped from 10.271% to 9.375%. Beyond this fiber content, the maximum dry density started to drop with an increase in the optimum moisture content. Therefore, 0.1% is the optimum content when reinforcing Ras El-Matn sand with 15 mm long mask fibers. The compacted sand sample reinforced with the optimum fiber content is shown in Fig. 6.

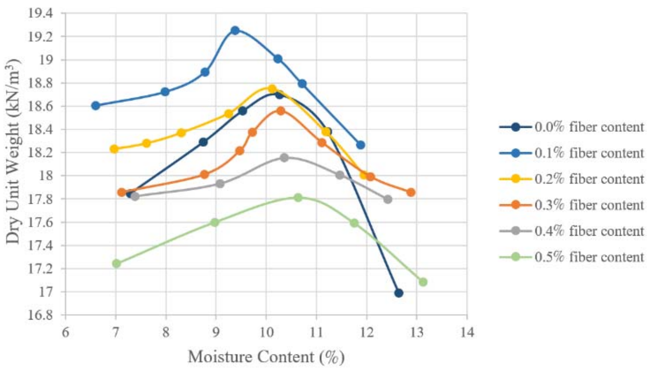


Fig. 5 Compaction curves of sand reinforced with different 15 mm fiber contents

At the optimum content of 0.1%, shredded masks can fill the voids available within the soil matrix. Therefore, more of the air fraction of the voids is eradicated. Sand particles are effectively rearranged and become closer to each other, which reduces the space that can be filled with water. As a direct result to that, the soil densification is enhanced at a lower optimum moisture content.

For a fiber content of 0.2% that exceeds the optimum percentage, the improvement extent became marginal in comparison with the compaction characteristics of pure sand. In fact, [7] estimated that extra fibers replace soil particles instead of only filling the voids. Hence, the sand grains cannot be close to each other. Due to that, more space is left for water. When the fiber content reached higher values of 0.3%, 0.4%, and 0.5%, a significant drop of the maximum dry density and a continuous increase in the optimum moisture content were observed.

Fig. 6 Compacted sand at the optimum fiber content

As already mentioned above, the compaction properties of Ras El-Matn sand are not enhanced beyond a fiber content of 0.1%. Therefore, [37] and [28] who already tested the effect of shredded masks on the compaction characteristics of granular soils did not observe any enhancement as they directly tested fiber percentages higher than 0.5% and 1%, respectively.

2) Fiber Length Effect

At a constant content of 0.1%, Ras El-Matn sand was reinforced with thin mask fibers having different targeted lengths of 15 mm, 30 mm, and 45 mm. Moreover, rectangular mask chips were added to this sand at the same fiber percentage. The obtained compaction curves are presented in Fig. 7. The numerical values of the sand compaction properties for each fiber length are summarized in Table III.

TABLE III
COMPACTION PROPERTIES OF SAND REINFORCED WITH DIFFERENT FIBER LENGTHS AT A FIBER CONTENT OF 0.1%

Fiber length (mm)	15	30	45
$g_{d,max}$ (kN/m^3)	19.249	19.046	18.655
$w_{optimum}$ (%)	9.375	9.926	10.262

For the shortest fibers, the highest maximum dry unit weight and the lowest optimum moisture content were observed, with respective values of 19.249 kN/m^3 and 9.375%.

For higher fiber lengths of 30 mm and 45 mm, the maximum dry unit weight dropped and the optimum moisture content increased. Nevertheless, the improvement in the compaction properties for Ras El-Matn sand persisted when 30 mm fibers were used. For instance, unreinforced sand had a maximum dry unit weight of 18.698 kN/m^3 and an optimum moisture content of 10.271%. For 30 mm long fibers, these parameters were enhanced to reach respective values of 19.046 kN/m^3 and 9.926%. The highest fiber length of 45 mm had no significant effect on the soil compaction properties. Neither an enhancement nor a reduction was observed. In fact, the compaction characteristics of unreinforced and reinforced samples became somehow equal to each other.

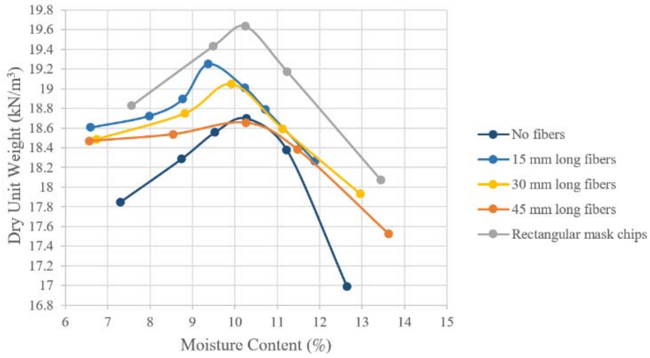


Fig. 7 Compaction curves of sand reinforced with fibers having unlike lengths and shapes at a fiber content of 0.1%

References [24], [25] and [34] affirmed that the use of longer fibers led to lower maximum dry densities with higher optimum moisture contents. Long fibers easily twist and tangle together. More lumps can be formed within the compacted soil. Hence, an increase in the void ratio generally appears. Due to that, the maximum dry unit weight of the prepared composite will be negatively affected.

3) Fiber Shape Effect

Fig. 7 clearly shows that a mask chip content of 0.1% gave the highest maximum dry unit weight among all the other conducted compaction tests. In fact, the maximum dry unit weight reached a numerical value of 19.637 kN/m^3 which is even greater than 19.249 kN/m^3 obtained when a 0.1% content of 15 mm long thin fibers was adopted. Hence, rectangular mask chips have the optimum shape to maximize the maximum dry unit weight of Ras El-Matn sand. On the other hand, the moisture content of sand reinforced with rectangular chips was almost equal to that of unreinforced soil. For instance, an insignificant reduction from 10.271% to 10.243% was obtained.

Rectangular mask chips have a large width of 10 mm in comparison with conventional fibers. Hence, the expanded surface area helps these chips to absorb a significant amount of water that directly percolates into them. The soil can be effectively densified without observing a reduction in the optimum moisture content as excessive water is easily eradicated to mask chips. Added to that, more space is left for sand grains when the mask chips absorb a certain part of the water available within the mixture. Therefore, the particle rearrangement is intensified as they easily get closer to each other. Since more soil is available within the compaction mold, the dry density of the reinforced composite is enhanced.

Only [5] and [6] studied the fiber shape effect on the soil compaction characteristics. They found that fibrillated polypropylene fibers were remarkably more effective than monofilament ones. Similar to large rectangular mask chips, fibrillated fibers, which are a group of monofilament fibers connected together, can effectively eradicate more water into the spaces available within their structure. Due to that, a better compaction is obtained without having a reduction in the optimum moisture content.

B. Shear Resistance

1) Fiber Content Effect

15 mm long fibers were added to Ras El-Matn sand to investigate the fiber content effect on the soil shear strength. Three different percentages of 0.1%, 0.25%, and 0.5% were tested. All the reinforced samples remained cohesionless. However, the different values of the internal friction angle are presented in Table IV. The sand friction angle variation with fiber content is plotted in Fig. 8.

TABLE IV
SAND INTERNAL FRICTION ANGLE FOR DIFFERENT 15 MM FIBER CONTENTS

Fiber content (%)	0.0	0.1	0.25	0.5
Friction angle (°)	35.75	41.99	43.08	43.23

References [16], [29], [31], [33], and many others confirmed that fiber addition can tremendously limit the soil brittle behavior. As a direct result to that, fiber-reinforced samples generally have an enhanced ductility. This tendency was clearly observed when adding different fiber contents to Ras El-Matn sand. All the samples reinforced with 15 mm long fibers did not reach their peak strength at a strain level of 25%. Hence, this strain amplitude defined the failure point of these samples as they became very deformed.

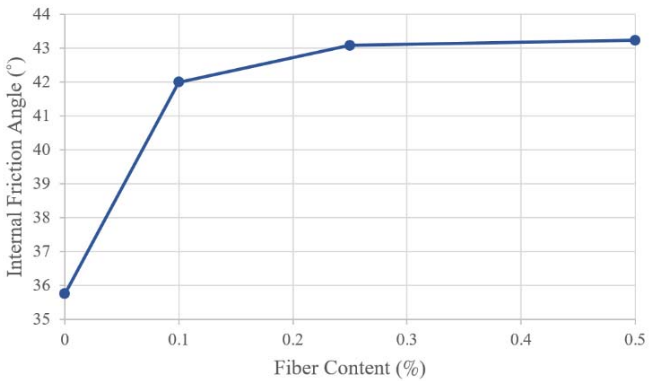


Fig. 8 Friction angle variation with 15 mm fiber content

At a fiber content of 0.1%, the highest improvement rate was observed because the sand friction angle soared from 35.75° to 41.99°, with an enhancement of 6.24°. In fact, the soil densification is at its best for a fiber content of 0.1%. Moreover, [4] and [25] confirmed that the soil-fiber interaction effectively mobilizes the fibers tensile strength. Therefore, the shear resistance remarkably increased as the two above-mentioned reasons coexisted.

When the fiber content increased to reach 0.25%, the increase in the friction angle gently continued to reach 43.08°. The reduction of the enhancement rate can be justified by the fact that the soil dry density was not significantly improved for a fiber content of 0.2%. Additionally, it became lower than that of unreinforced sand for a percentage of 0.3%.

The highest fiber content of 0.5% had an insignificant contribution to the shear strength enhancement. Even if more fibers were available at the failure plane, the mixture became looser. At this stage, the effectiveness of extra fibers would only recover the loss due to lower soil density.

Based on direct shear results, the optimum fiber content is 0.25%. Reference [19] confirmed the existence of an optimum fiber content to maximize the soil shear strength. Reference [25] also realized that no significant improvement in the shear resistance is observed beyond the optimum fiber content.

2) Fiber Length Effect

At a constant content of 0.1%, fibers having three different respective lengths of 15 mm, 30 mm, and 45 mm were separately added to reinforce Ras El-Matn sand. Moreover, rectangular mask chips were also mixed with Ras El-Matn sand at the same fiber content. The effect of fiber length and shape on the soil shear stress-strain curves is shown in Fig. 9. The plotted curves correspond for a vertical stress of 100 kPa.

The different curves in Fig. 9 show that the introduction of mask fibers did not influence the initial stiffness of Ras El-Matn sand at very small strains which are lower than 1%. References [15], [16], [33], and [36] observed similar outputs when reinforcing different soils with fibers. Small strains are not sufficient to mobilize the fibers tensile strength.

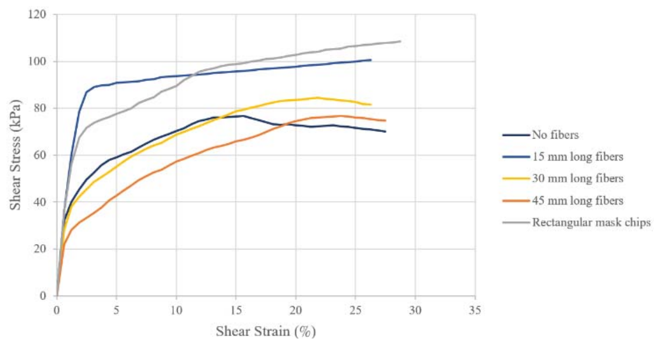


Fig. 9 Stress-strain curves of sand reinforced with unlike fiber lengths and shapes at a fiber content of 0.1% for a vertical stress of 100 kPa

The values of the sand friction angle for different fiber lengths are summarized in Table V.

TABLE V
SAND INTERNAL FRICTION ANGLE FOR UNLIKE FIBER LENGTHS AT A FIBER CONTENT OF 0.1%

Fiber length (mm)	15	30	45
Friction angle (°)	41.99	37.60	34.80

Theoretically, longer fibers can provide more surface interaction with soil particles. Hence, they would be more beneficial. Nevertheless, [25] noted that they are not uniformly distributed within soil samples as they often stick together. Subsequently, the existence of an optimum fiber length was brought to light.

During this experiment, additional fiber length negatively affected the sand shear resistance as its friction angle quasilinearly dropped from 41.99° to reach 34.80° for a fiber length of 45 mm. Therefore, the optimum fiber length for Ras El-Matn sand is 15 mm.

The twisted and tangled long fibers are an important cause that dropped the shear resistance of Ras-El Matn sand. Moreover, 30 mm and 45 mm long fibers are considered excessively long when mixed within soil samples having a height of 40 mm. During the sample preparation, these fibers had a tendency to be horizontally rearranged. As an important part of them became quasi-horizontal and parallel to the shear plane, their contribution to the soil shear resistance immediately reduced.

3) Fiber Shape Effect

Based on Fig. 9, it was clearly observed that rectangular mask chips were the best reinforcement type which led to the highest value of the shear strength. Furthermore, the measured value of the friction angle was 43.83° which is even greater than the values obtained when using 15 mm long fiber contents of 0.25% and 0.5%.

Reference [4] similarly reported that meshes had a better contribution to increase the friction angle of sandy soils when compared to conventional long fibers. In fact, meshes can create a netting effect within the soil matrix. Hence, the interlocking between sand grains and fibers is directly enhanced, which constrains the displacement of soil particles during the direct shear test.

The above-mentioned netting effect could be the same reason that tremendously enhanced the shear strength when using rectangular mask chips in comparison with other conventional thin fibers. The shape of these chips helped them to be barely pulled out. As a direct result to that, the greatest improvement was observed. The sheared sample reinforced with rectangular mask chips is shown in Fig. 10.

Fig. 10 Sheared sample reinforced with mask chips

IV. Conclusions and Perspectives

Due to the excessive use of disposable masks during the COVID-19 pandemic, it was urgently required to deal with pandemic-generated waste materials. In this research, face-masks were cut into small fibers to reinforce a sandy soil. Various parameters have been investigated and the main conclusions can be summarized as follows:

- The compaction properties of sand are enhanced at the optimum fiber content. Nevertheless, the maximum dry density drops and the optimum moisture content increases beyond the optimum fiber percentage;
- The shear strength of sand is enhanced by adding shredded masks at the optimum content as the tensile strength of fibers is mobilized. For higher percentages, no additional enhancement is observed as extra fibers only recover the loss caused by looser composites;
- The optimum fiber contents that maximize the sand compaction properties and shear resistance are different. The fiber content has to be chosen depending on the desired geotechnical application;
- Shorter fibers are more effective to enhance both the compaction and shear properties of sand, which brings to light the existence of an optimum fiber length;
- Both direct shear and standard Proctor compaction tests showed that rectangular mask chips are the best reinforcement type;
- The initial stiffness of fiber-reinforced sand remains invariant for strain amplitudes lower than 1%. At this level, the fiber tensile strength is not effectively mobilized;
- The ductile behavior of fiber-reinforced sand is clearly improved. Due to mask fiber addition, some soil samples failed at higher strains while others did not reach their peak strength even at a strain level of 25%.

The results of this research clearly show that adding shredded masks to soil deposits is an interesting technique to enhance their properties. In addition to that, it is an effective way to reuse pandemic-generated face-masks. This waste material also presents economic benefits when compared to traditional soil improvement methods. Nevertheless, there are various parameters that should be optimized to extremely benefit from the fiber inclusion.

Additional investigations are still required to test the effectiveness of shredded face-masks on the rest of soil characteristics. Furthermore, field experiments should be conducted to clearly evaluate if the obtained results at the laboratory are also observed on construction sites.

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