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Research article

Improving the compaction properties and shear resistance of a sand reinforced with COVID-19 waste mask fibers

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HIGHLIGHTS

- COVID-19 waste face-masks can be recycled and reused as synthetic fibers for soil reinforcement.
- The addition of mask fibers enhances both the compaction properties and shear resistance of Ras El-Matn sand.
- The fiber content, length, and shape have to be optimized to maximize the benefit brought by the fiber reinforcement.

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ABSTRACT

Due to the COVID-19 pandemic, disposable face-masks were excessively used around the world, which led to severe environmental problems. The main purpose of this research is to test the possibility of reinforcing a sandy soil 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%. An optimum content of 0.1% remarkably increased the maximum dry density of the soil and dropped its optimum moisture content. Add 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 an optimum fiber content of 0.25%. Similarly 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.

1. Introduction

Nowadays, the design and construction of many civil engineering projects require incorporating weak soils with very low bearing capacity and shear resistance (Mirzababaei et al., 2018). Therefore, it is extremely necessary to use various ground improvement techniques of which reinforcing soil deposits with discrete randomly distributed fibers is an attractive method that has recently become a focus of interest (Tang et al., 2007; Amir-Faryar and Aggour, 2012; Hejazi et al., 2012; Mirzababaei et al., 2013; Baruah, 2015; Bozyigit et al., 2017; Qadir, 2017; Qadir et al., 2017).

Randomly distributed fiber-reinforced soils can be defined as a ground improvement method where tensile resistant short fibers are randomly mixed within compacted soil deposits (Bordoloi et al., 2017). Thus, soil composites can absorb tensile loads and resist higher shear stresses (Salim et al., 2018). For instance, plant roots which effectively stabilize natural slopes are considered to be a natural way of reinforcing soils with randomly oriented fibers to prevent shear failures (Hejazi et al., 2012; Qadir, 2017; Qadir et al., 2017).

Using randomly distributed fibers as a reinforcement technique is probably older than written history (Freitag, 1986). Adding natural fibers to reinforce construction materials originated in ancient times (Akbulut et al., 2007; Al-Adili et al., 2012; Hejazi et al., 2012; Zaimoglu and Yetimoglu, 2012; Noorzad and Amini, 2014; Salim et al., 2018) 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 (Freitag, 1986; Amir-Faryar and Aggour, 2012).

There are many advantages that currently make the discrete randomly distributed fibers a very appealing technique to reinforce

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problematic soils. In fact, these fibers limit all the potential planes of weakness that generally develop when traditional oriented reinforcement is applied. Moreover, they can be easily added and mixed within soils (Tang et al., 2007; Amir-Faryar and Aggour, 2012; Zaimoglu and Yetimoglu, 2012; Patel and Singh, 2017). These fibers are randomly oriented within the soil matrix to create a uniform distribution (Amir-Faryar and Aggour, 2012), which enhances the homogeneity of the composite (Patel and Singh, 2017). Availability, economical benefits, and invariant performance in all-weather conditions are also noticeable gains of fiber inclusion (Hejazi et al., 2012). Finally, this technique can be applied in limited spaces or in sites with geometric constrains where traditional reinforcement cannot be adopted (Patel and Singh, 2017).

Because of the advantages mentioned above, reinforcing soils with natural and synthetic fibers is considered to be a viable technique to enhance soil properties, stability, and bearing capacity (Maher and Ho, 1994; Zaimoglu and Yetimoglu, 2012). 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 fiber inclusions. In addition to that, reinforced samples had a ductile behavior with higher energy absorption rates. This is due to a noticeable increase in the measured strain at failure as well as an important reduction in the post-peak loss in strength at high strains (Sadek et al., 2010; Mirzababaei et al., 2013). Furthermore, fiber-saturated composites generally have better compaction properties if the adopted fiber content is adequately selected (Amir-Faryar, 2012; Amir-Faryar and Aggour, 2012). Nevertheless, Cabalar and Karabash (2015) observed an immediate drop in the maximum dry density of a well graded gravel reinforced with tire buffings at percentages higher than 5%.

In fact, bond strength and interfacial friction appear to be the dominant mechanisms that affect the improvement extent of fiber reinforcement. Subsequently, the interfacial interactions between soil particles and fibers play the key role in the mechanical response of fiber-reinforced soils (Al-Refeai, 1991; Tang et al., 2007). The main function of the soil-fiber interaction is to transfer stresses from the soil to the tensile resistant elements, which mobilizes their tensile strength. Thus, the deformation of reinforced soils is delayed and their strength is remarkably enhanced (Al-Refeai, 1991). When a given parameter can significantly modify the above-mentioned interactions, the strength of the tested sample will be directly affected.

The studies have shown that the improvement extent of fiber-reinforced soils really depends on the adopted fiber content. For instance, the engineering properties of the reinforced mixtures change with various fiber contents (Amir-Faryar and Aggour, 2012, 2014). Furthermore, the effectiveness of fiber inclusion is considerably dependent on the tested soil (Patel and Singh, 2017). Hence, it is clear that the increase in strength and stiffness of reinforced soils is a function of fiber characteristics, soil properties, and test conditions (Hejazi et al., 2012; Mirzababaei et al., 2013).

Due to the enhanced behavior of reinforced soils, using discrete randomly distributed fibers can be adopted in several geotechnical engineering applications. This method is feasible in foundation, pavement, and retaining walls design. Railway embankments and slope stabilization are additional areas where fiber-reinforced soil deposits can be employed (Hejazi et al., 2012). Moreover, synthetic fibers can improve the soil dynamic properties to avoid damages caused by earthquakes (Hejazi et al., 2012; Amir-Faryar and Aggour, 2016). In fact, they are considered to be an encouraging solution to prevent the liquefaction of very loose sands (Noorzad and Amini, 2014). They are also able to change the site's natural period to avoid its similarity to the building fundamental period (Amir-Faryar and Aggour, 2016).

Fibers can also enhance the soil geotechnical properties when combined with other chemical additives such as cement (Tang et al., 2007; Chen et al., 2015). In fact, cementation effectively develops links between soil particles, which increases the soil stiffness, resistance, and strength (Karabash and Cabalar, 2015). Furthermore, several studies found that the unconfined compressive strength of cemented clay samples rocketed with an increase in fiber content. However, a limited increment or even a slight decrease in strength was induced when the fiber percentage exceeded its optimal value. Undoubtedly, the enhancement in material ductility which reduces the brittle behavior of cemented soils was considered to be one of the main advantages of fiber reinforcement (Tang et al., 2007; Chen et al., 2015).

Add 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 (Sadek et al., 2010; Taha et al., 2020). 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 (Chen et al., 2015).

Adding nylon fibers obtained from waste fishing wire linearly increased the ultimate shear strength of sand as the fiber content was brought up. This enhancement was immediately translated into an improvement in the sand friction angle (Sadek et al., 2010). Similarly, shredded carpets led to a significant enhancement in the unconfined compressive strength and energy absorption rate of reinforced clay samples. Since carpet waste fibers behave like conventional fibers, they can interlock with soil particles, intersect failure zones, and prevent the development of tension cracks due to their tensile strength. Hence, the soil behavior was tremendously improved (Mirzababaei et al., 2013).

Waste tires can also be recycled for several civil and geotechnical engineering applications (Edincliler et al., 2012). Adding tire crumbs to a poorly graded sand delayed the pore water pressure generation during triaxial testing (Karabash and Cabalar, 2015). Furthermore, tires are a source of fiber-shaped buffings which tremendously enhanced the shear strength of reinforced sands when these fibers were added at their optimum content (Edincliler et al., 2012). Cement stabilization can enhance the tire reinforcement contribution to shear resistance, energy absorption capacity, and secant Young's modulus (Karabash and Cabalar, 2015). The CBR value is an additional parameter that is improved when combining tire buffings with cement. Mixing these fibers with chemical additives could be an alternative method to reduce the construction costs by improving the CBR value of sub-base materials in flexible pavement design (Cabalar and Karabash, 2015).

Cement is not the only chemical binder that has been tested to stabilize fiber-reinforced soils. For instance, Mirzababaei et al. (2018) combined polypropylene fibers with poly vinyl alcohol (PVA) to increase the strength of soft high plasticity clays. The results indicated that the proposed combination significantly improved the unconfined compressive strength and ductility of the reinforced samples. Moreover, the fiber-reinforced and stabilized clay lasted longer under water during soaking tests, which reflected an improvement in the stability and durability of these samples.

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 (Saberian et al., 2021). In fact, using face-masks is considered to be an effective way to prevent the spread of the virus (Saberian et al., 2021; Zhang et al., 2022). Therefore, the production and consumption rates of disposable face-masks produced using polymeric materials such as polypropylene were significantly brought up (Fadare and Okoffo, 2020). The excessive use of disposable masks has led to severe environmental problems. The reason being that, used plastic-based face-masks are thrown everywhere (Fadare and Okoffo, 2020; Saberian et al., 2021; Zhang et al., 2022). Hence, it is urgently required to deal with pandemic-generated waste materials as few studies have been conducted in this field until now (Saberian et al., 2021; Zhang et al., 2022).

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 (Zhang et al., 2022). Nevertheless, more investigations remain required to study their effectiveness in practical engineering applications.

2. Significance of the research

The COVID-19 pandemic has not only created severe health and economic crisis all over the world but it has also led to dangerous environmental problems. In fact, disposable face-masks constitute an unprecedented source of plastic pollution. Since few studies have investigated solutions to recycle and reuse pandemic-generated waste materials, this experiment proposes an innovative way to reinforce a sandy soil with mask fibers. Add to the mask fiber content effect on the enhancement brought by fiber inclusion, other parameters such as the mask fiber length and shape were studied for the first time. The obtained results clearly show that reinforcing sands with mask fibers is an effective technique if the different parameters are adequately optimized.

3. Materials and methods

3.1. Materials

3.1.1. 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. This soil is a light brown non-plastic fine to medium mountain sand. Its grains are clearly angular as shown in Figure 1. In fact, the sand was collected from a construction site located in a mountainous region. Hence, the grains have not been transported by wind or water flows.

The sand grain-size distribution is shown in Figure 2. The sand has a fines content of around 1.74%. Moreover, it does not contain gravel. Different characteristics of the tested Ras El-Matn sand are summarized in Table 1.

According to the Unified Soil Classification System (USCS), 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 Figure 3. The maximum dry unit weight and the optimum moisture content of the sand are 18.698 kN/m^3 and 10.271%, respectively.

3.1.2. 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 (Saberian et al., 2021). 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 (Fadare and Okoffo, 2020; Saberian et al., 2021). Fibrous materials are excessively available within face-masks as they are considered to be the main components for filtration (Akduman and Kumbasar, 2018). 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.

The shortest 15 mm long fibers are presented in Figure 4. In fact, many authors such as Amir-Faryar (2012), Amir-Faryar and Aggour (2012), Noorzad and Amini (2014), Bozyigit et al. (2017), Li and Senetakis (2017), Qadir et al. (2017), Wang et al. (2018), Taha et al. (2020),

Figure 1. Ras El-Matn sand sample.

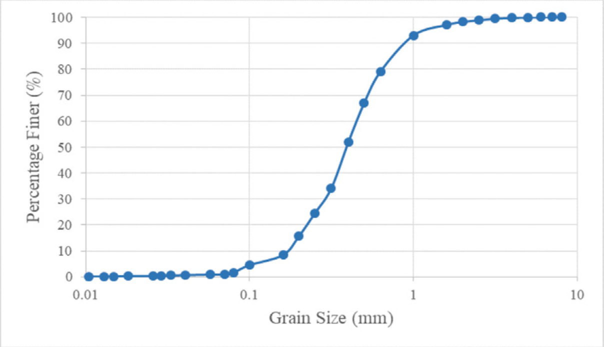

Figure 2. Grain-size distribution of Ras El-Matn sand.

Table 1. 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_{50} (mm)	0.3903
D_{30} (mm)	0.2854
D_{10} (mm)	0.1679
Coefficient of uniformity C_u	2.6867
Coefficient of curvature C_c	1.0754

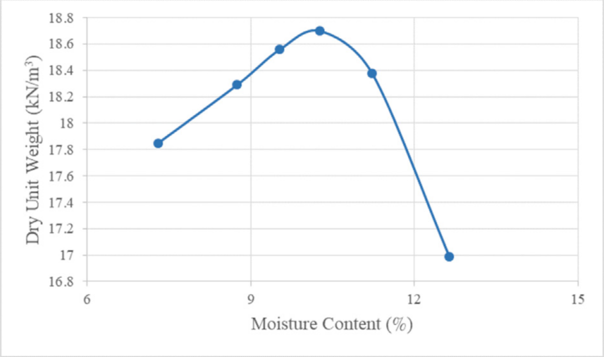

Figure 3. Compaction curve of Ras El-Matn sand.

Figure 4. 15 mm long thin fibers.

and many others have used natural and synthetic fibers having a length of 12 mm. Hence, we targeted a very similar length of 15 mm for the practicality of the manual cutting process. Regarding the values of 30 mm and 45 mm, they were picked since they are the successive multiples of 15 mm, as Noorzad and Amini (2014) and Bozyigit et al. (2017) did in their experiments.

Similarly to Saberian et al. (2021) and Zhang et al. (2022), the rectangular shape was selected. The prepared chips had a length of 15 mm and a width of 10 mm. Hence, their targeted aspect ratio was 1.5. The rectangular mask chips are shown in Figure 5.

3.2. Methods

3.2.1. 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 (Amir-Faryar, 2012). The compaction properties of unreinforced and reinforced samples were obtained from standard Proctor compaction tests which were conducted according to ASTM D698.

Figure 5. Rectangular mask chips.

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 (Behbahani et al., 2016).

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. For each test, an average soil weight of 700 g was required to fill the shear box. Therefore, the relative density of the prepared composites was around 1.75 g/cm^3.

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.

3.2.2. Sample preparation

The weight of the fibrous material used for each fiber content is calculated based on the air-dried soil weight (Al-Refeai, 1991; Maher and Ho, 1994; Tang et al., 2007; Mollamahmutoglu and Yilmaz, 2009; Amir-Faryar, 2012; Amir-Faryar and Aggour, 2012; Zaimoglu and Yetimoglu, 2012; Li and Senetakis, 2017; Wang et al., 2018; Develioglu and Pulat, 2021; Zhang et al., 2022).

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 (Akbulut et al., 2007; Tang et al., 2007; Amir-Faryar, 2012; Amir-Faryar and Aggour, 2012; Mirzababaei et al., 2013; Bozyigit et al., 2017; Tran et al., 2018; Wang et al., 2018; Sujatha et al., 2021). The moist sand reinforced with 15 mm long thin fibers at a fiber content of 0.2% is presented in Figure 6. This sample was prepared for the standard Proctor compaction test.

It was decided to first mix fibers with the dry soil to avoid the fiber clumping which is usually observed when fibers are immediately added to wet soil samples (Mirzababaei et al., 2013; Bozyigit et al., 2017). 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 (Mirzababaei et al., 2013).

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.

4. Results and discussion

4.1. Compaction properties

4.1.1. 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 Figure 7. In addition to that, the values of the maximum dry density and the optimum moisture content for each fiber content are summarized in Table 2. When shredded masks were added at a percentage of 0.1%, the

Figure 6. Sand mixed with a 15 mm fiber content of 0.2%.

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 Figure 8.

Many investigations have led to similar small optimum percentages when reinforcing soil composites with different fiber types. In fact, Mollamahmutoglu and Yilmaz (2009), Amir-Faryar (2012), and Amir-Faryar and Aggour (2012) found that the soil compaction properties were extremely enhanced for fiber contents of 0.1%, 0.2%, and 0.2%, respectively. Notwithstanding, Tran et al. (2018) assumed that a corn silk fiber content of 1.5% was required to maximize the maximum dry density of a low plasticity silt. This dissimilarity can be justified by the fact that sand and silt are totally different soil types. Add to that, shredded face-masks do not have the same characteristics of corn silk fibers.

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, Amir-Faryar and Aggour (2014) 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.

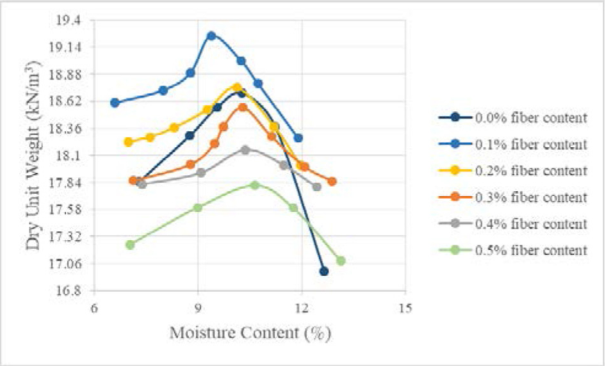

Figure 7. Compaction curves of sand reinforced with different 15 mm fiber contents.

Table 2. 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
$\gamma_{d,max}$ (kN/m^3)	18.698	19.249	18.750	18.557	18.155	17.811
$\omega_{optimum}$ (%)	10.271	9.375	10.114	10.294	10.359	10.636

Figure 8. 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, directly using large fiber increments that exceed the optimum percentage could be the main reason that led to an immediate drop of the maximum dry density in several experimental studies. For instance, when testing fiber contents higher than 0.25% (Mohammad et al., 2017; Sujatha et al., 2021), 0.3% (Wang et al., 2018; Brahmachary et al., 2019), or 0.5% (Baruah, 2015; Qadir, 2017; Qadir et al., 2017), an immediate drop of the maximum dry density was observed. Moreover, the optimum moisture content of the fiber-reinforced composites increased. Hence, no improvement in the compaction properties was reported.

Zhang et al. (2022) and Saberian et al. (2021) already tested the effect of shredded masks on the compaction characteristics of granular soils. However, they did not observe any enhancement as they directly tested fiber percentages higher than 0.5% and 1%, respectively.

4.1.2. 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 Figure 9. The numerical values of the sand compaction properties for each fiber length are summarized in Table 3.

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 of 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%.

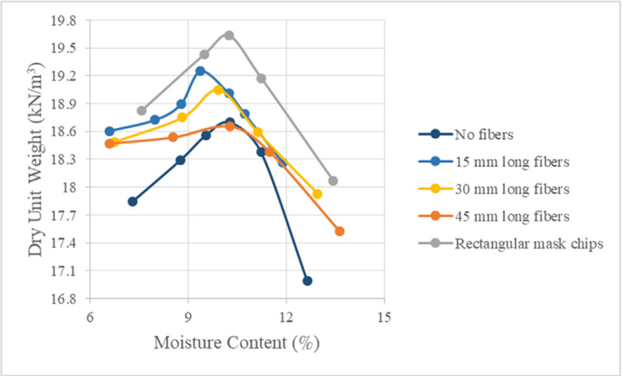

Figure 9. Compaction curves of sand reinforced with fibers having unlike lengths and shapes at a fiber content of 0.1%.

Table 3. Compaction properties of sand reinforced with different fiber lengths at a fiber content of 0.1%.

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

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.

Patel and Singh (2017, 2019) and Tran et al. (2018) 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.

Maher and Ho (1994) also tested the length effect on the compaction properties of kaolinite clay. Neither the maximum dry density nor the optimum moisture content was affected when varying the fiber length between 6.4 mm and 25.4 mm. This dissimilarity can be justified by the fact that kaolinite clay and Ras El-Matn sand are totally different soils. In fact, fibers are generally trapped within cohesive chunks while they are uniformly distributed within sandy soils.

4.1.3. Fiber shape effect

Figure 9 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.

Add 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 particles' 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 Amir-Faryar (2012) and Amir-Faryar and Aggour (2012) studied the fiber shape effect on the soil compaction characteristics. They found that fibrillated polypropylene fibers were remarkably more effective than monofilament ones. Similarly 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.

4.2. Shear resistance

4.2.1. 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 4. The sand friction angle variation with fiber content is plotted in Figure 10.

Heineck et al. (2005), Tang et al. (2007), Sadek et al. (2010), Sujatha et al. (2021), 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.

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, Al-Refeai (1991) and Patel and Singh (2019) 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.

Table 4. 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

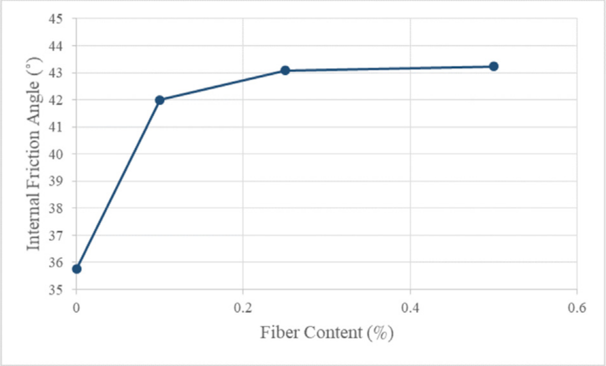

Figure 10. Friction angle variation with 15 mm fiber content.

Based on direct shear results, the optimum fiber content is 0.25%. Maher (1988) confirmed the existence of an optimum fiber content to maximize the soil shear strength. Patel and Singh (2019) also realized that no significant improvement in the shear resistance is observed beyond the optimum fiber content.

Tang et al. (2007) reinforced soils with polypropylene fibers. They observed an enhanced shear resistance with an increase in fiber content from 0% to 0.25%. However, no optimum percentage was noted as additional higher fiber contents were not investigated.

In addition to that, Sadek et al. (2010) assumed that the grain-size distribution affects the value of the optimum content. For instance, fine sands generally have small optimum fiber contents lower than 0.5% while coarse sands have their optimum fiber percentages around 1%. As the D_{60} of Ras El-Matn sand is 0.4511 mm, this soil is very rich in fine sand particles. Therefore, the small optimum fiber content of 0.25% is in accordance with the results of Sadek et al. (2010).

4.2.2. 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 Figure 11. The plotted curves correspond for a vertical stress of 100 kPa.

The different curves in Figure 11 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%. Freitag (1986), Heineck et al. (2005), Tang et al. (2007), and Zaimoglu and Yetimoglu (2012) observed similar outputs when reinforcing different soils with fibers. Small strains are not sufficient to mobilize the fibers tensile strength.

The values of the sand friction angle for different fiber lengths are summarized in Table 5.

Theoretically, longer fibers can provide more surface interaction with soil particles. Hence, they would be more beneficial. Nevertheless, Patel and Singh (2019) noted that long fibers 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 quasi-linearly 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.

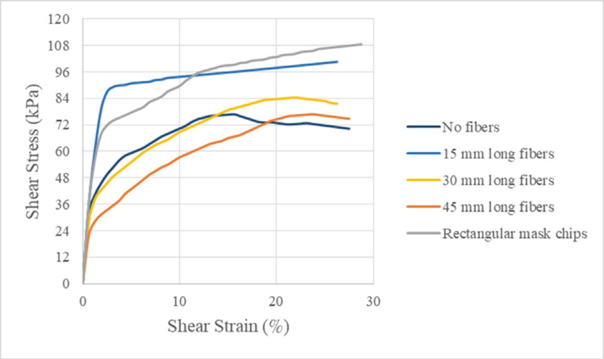

Figure 11. Stress-strain curves of sand reinforced with unlike fiber lengths and shapes at a fiber content of 0.1% for a vertical stress of 100 kPa.

Table 5. Sand 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

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 was immediately reduced.

Tran et al. (2018) found that fibers having respective lengths of 10 mm and 30 mm had a better contribution to the soil shear resistance when compared to 50 mm long fibers. Similarly, Akbulut et al. (2007) affirmed that the soil strength is maximized at an optimum fiber length that depends on the fiber type.

4.2.3. Fiber shape effect

Based on Figure 11, 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%.

Al-Refeai (1991) 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 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 Figure 12.

4.3. Practical applications

The methodology proposed in the presented study led to significant results. In fact, the fiber-reinforced sand composite can be used in road, pavement, and railway embankment design as it has enhanced compaction properties when the fiber characteristics are adequately optimized. In addition to that, this new construction material can be employed as an engineering fill in construction sites or behind retaining walls. Although the experiment has clearly reached its aims, there still are many limitations before using this material. For instance, more investigations and studies remain required. Moreover, the COVID-19 pandemic obliged us to use clean masks. Therefore, the effectiveness of disinfected already used face-masks should be evaluated.

Figure 12. Sheared sample reinforced with mask chips.

5. Conclusions

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 of 0.1%. The maximum dry unit weight increases from 18.698 kN/m^3 to 19.249 kN/m^3 while the optimum moisture content drops from 10.271% to 9.375%. 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 of 0.25% as the tensile strength of fibers is mobilized. For a higher percentage of 0.5%, 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 0.1% and 0.25%, respectively. Since these two percentages are different, the fiber content has to be chosen depending on the desired geotechnical application;
- Shorter fibers with a length of 15 mm are more effective to enhance both the compaction and shear properties of sand, which brings to light the existence of an optimum fiber length. When the fiber length is brought up from 15 mm to 45 mm, the maximum dry unit weight drops from 19.249 kN/m^3 to 18.655 kN/m^3 and the friction angle sinks from 41.99° to 34.80°;
- Both direct shear and standard Proctor compaction tests showed that rectangular mask chips are the best reinforcement type. For instance, the maximum dry unit weight and the friction angle have their maximum values of 19.637 kN/m^3 and 43.83° when this shape is adopted. These two values are the highest among all the conducted tests;
- The initial stiffness of fiber-reinforced sand remains invariant for strain amplitudes lower than 1%. At this level, the fibers 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 economical benefits when compared to traditional soil improvement methods. Nevertheless, there are various parameters that should be optimized to extremely benefit from the fiber inclusion.

It should be noted that all the observations made during this experiment are specific for Ras El-Matn sand, the type of mask fibers that have been used, and the conducted tests only.

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.

Declarations

Author contribution statement

Samah SAID, Muhsin Elie RAHHAL: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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