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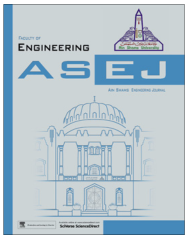

CIVIL ENGINEERING

# Fiber-reinforced sand strength and dilation characteristics

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Direct shear test

**Abstract** Randomly distributed fiber reinforcement is used to provide an isotropic increase in the sand shear strength. The previous studies were not consistent regarding the fibers effect on the volumetric change behavior of fiber-reinforced sand. In this paper, direct shear tests are conducted on 108 specimens to investigate the effects of the fibers content, relative density, normal stress and moisture content on the shear strength and volumetric change behaviors of fiber-reinforced sand. The study investigates also the possibility of using dry fiber-reinforced sand as an alternative to heavily compacted unreinforced moist sand. The results indicate that the fibers inclusion increases the shear strength and dilation of sand. Moisture suppresses the fibers effect on the peak and post-peak shear strengths, and dilation. Dry loose fiber-reinforced sand achieves the same shear strength of heavily compacted unreinforced moist sand, yet at more than double the horizontal displacement.

## 1. Introduction

Soil reinforcement is an efficient mechanical technique for soil stabilization. Soil reinforcement can be achieved either by the inclusion of continuous strips or sheets within the soil mass (systematically reinforced soil) or by the inclusion of short discrete randomly distributed fibers. Systematic reinforcement improves the strength in certain directions. However, continuous planes of weakness develop at the soil–reinforcement interface. Randomly distributed reinforcement, on the other side, provides an isotropic behavior and limits the development of weak planes.

Reinforcing the soil with short randomly distributed fibers has been a point of investigation in the past decades. Unlike systematically reinforced soil, the shear strength of randomly reinforced soil is evaluated by estimating the change in the shear strength parameters due to the fibers inclusion. The shear strength parameters are usually measured using conventional shear strength tests such as the direct shear and triaxial tests. Ranjan et al., Al-Refeai and Al-Suhaibani, Zornberg, Consoli et al., Ibraim and Fourmont, and Diambra et al. [1–6] observed that the fibers inclusion increases the soil shear strength.

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The previous studies did not reveal a consistent trend with respect to the effect of randomly distributed fibers on the volumetric change behavior of fiber-reinforced sand. Consoli et al. [4], and Michalowski and Zaho [7] demonstrated that the inclusion of fibers inhibited the dilation of sand in triaxial tests. Based on plate load tests results, Consoli et al. [8] deduced also that the fibers suppress the sand dilation. Consoli et al. [9] reported that fiber-reinforced sand having a relative density of 50% exhibited minor changes in the dilation angle during shearing unlike unreinforced sand at the same stress level. However, Ibraim and Fourmont [5], and Diambra et al. [6] reported that fiber-reinforced sand exhibited higher dilation tendency than unreinforced sand.

The effect of moisture on the shear strength and volumetric change behaviors was not investigated with the required level of detail in the literature. Lovisa et al. [10] were among few researchers who investigated the effect of the moisture content (range of 0.0–3.0%) on the behavior of fiber-reinforced sand, based on direct shear tests results. Lovisa et al. [10] found that the moist reinforced specimens had a lower peak friction angle than the dry reinforced specimens at the medium dense and very dense states.

Despite the numerous studies conducted to investigate the behavior of fiber-reinforced sand, the behavior is not completely understood due to the discrepancies in the results and the limited number of investigated parameters in some studies, as shown above. This paper aims at conducting a comprehensive experimental study on the shear strength and volumetric change behaviors of dry and moist unreinforced and fiber-reinforced sand using the direct shear apparatus. The effects of the normal stress, relative density, moisture content and fibers content are investigated. The traditional 60 mm-wide direct shear apparatus was employed by many investigators [10–12]. The direct shear box used in this study has plan dimensions of 100 mm × 100 mm, which helps to minimize the size effect of the fibers on the results.

This study investigates four main aspects of the fiber-reinforced sand behavior: the peak shear strength, the post-peak shear strength, the volumetric change during shearing and the effect of moisture content change on the dry side on the shear strength and volumetric change behaviors. The fiber-reinforced sand behavior is compared with the corresponding unreinforced sand behavior.

Many earthworks applications require compacting unreinforced sand to 95% of the maximum dry density in the modified Proctor test at the optimum moisture content. In Egypt, many quarries provide poorly graded sand, which needs a heavy compaction effort and a large amount of water to achieve an acceptable relative density. In addition, water sources are very limited in remote areas. Hence, earthworks could be a costly package of the project. The conducted study in this paper aims also at assessing the possibility of mixing dry sand with fibers at a moderate compaction effort instead of heavily compacting moist unreinforced sand in earthworks applications.

## 2. Experimental testing program

### 2.1. Tested materials

The tested sand is poorly graded siliceous sand, according to the Unified Soil Classification System (USCS). The sand specific gravity equals 2.64, and the maximum and minimum voids ratios equal 0.72 and 0.48, respectively. Fig. 1 shows the grain size distribution, and Fig. 2 shows the compaction curve based on the modified Proctor test results. The maximum dry density equals 17.5 kN/m$^3$, and the optimum moisture content equals 12.8%. The fiber-reinforced sand specimens are prepared by mixing the sand with 6.0 mm-long polypropylene fibers (RHEOFIBRE-BASF). Table 1 shows the fibers properties.

### 2.2. Parametric study

Laboratory specimens are prepared with relative density ($D_r$) values of 25%, 60% and 90% in order to investigate the behaviors of loose, medium dense and very dense sands, respectively. The specimens are sheared at three normal stresses ($\sigma_n$) of 50, 100 and 200 kPa, and four moisture contents ($W_c$) of 0.0%, 4.0%, 6.0% and 10.0%. The moisture contents are chosen on the dry side of the optimum moisture content. The fibers content ($\mu$) is defined as the ratio between the fibers weight ($W_f$) and the solid particles weight ($W_s$), as shown in Eq. (1).

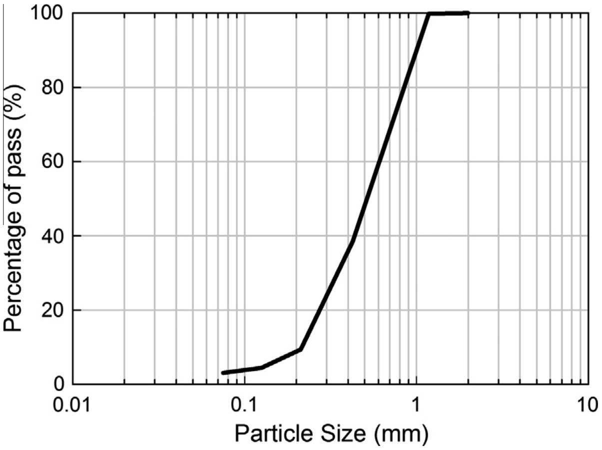

**Figure 1** Grain size distribution of tested sand.

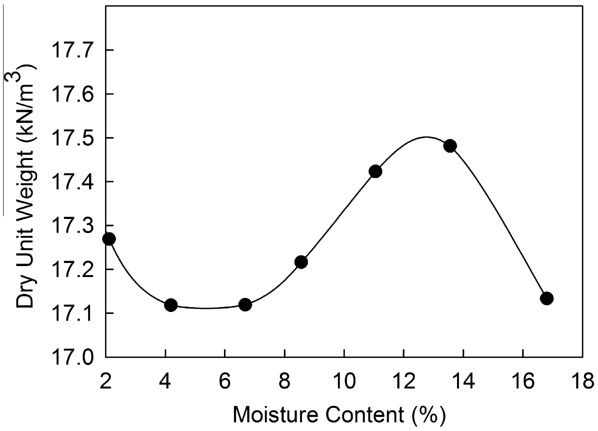

**Figure 2** Modified proctor test results.

$$\mu = W_f/W_s \tag{1}$$

Three fibers contents are utilized: 0.0%, 0.5% and 1.0%. One hundred and eight specimens are tested in the direct shear apparatus. The relative density of fiber-reinforced sand is defined according to one of the following three principles:

- Principle 1: The fibers are part of the solids [7].
- Principle 2: The relative density of the reinforced specimen equals the relative density of an unreinforced specimen having the same dry density [12–14].
- Principle 3: The fibers are part of the voids [5].

In Principle 1, the fibers volume ($V_f$) is part of the solid particles volume ($V_{s(r)}$). Eq. (2) defines the voids ratio ($e$), and Eq. (3) defines the dry unit weight ($\gamma_d$) of fiber-reinforced sand.

$$e = \frac{V_v}{V_{s(r)}} = \frac{V_v}{V_{sand} + V_f} \tag{2}$$

$$\gamma_d = \frac{W_s + W_f}{V_{sand} + V_f + V_v} = \frac{W_s(1+\mu)}{V_{sand} + V_f + V_v} \tag{3}$$

where $V_v$ is the voids volume.

Knowing the fibers content ($\mu$), the specific gravity of the sand and the fibers, ($G_s$) and ($G_f$) respectively, the dry unit weight ($\gamma_d$) and the unit weight of water ($\gamma_w$), the voids ratio is calculated from Eq. (4).

$$e = \frac{G_s G_f \gamma_w}{G_f + G_s \mu} \cdot \frac{1+\mu}{\gamma_d} - 1 \tag{4}$$

In Principle 2, the relative density of the reinforced specimen equals the relative density of an unreinforced specimen having the same dry density. Mathematically stated,

$$\frac{W_{sand(r)} + W_f}{V_{sand(r)} + V_f + V_{a(r)} + V_{w(r)}} = \frac{W_{sand(ur)}}{V_{sand(ur)} + V_{a(ur)} + V_{w(ur)}} \tag{5}$$

where the subscript ($r$) denotes reinforced sand, the subscript ($ur$) denotes unreinforced sand, $V_a$ is the volume of air, and $V_w$ is the volume of water.

In Principle 3, the fibers are part of the voids such as water and air. Hence, the relative density of the reinforced specimen equals that of the unreinforced specimen with the same voids ratio. In a mathematical form,

$$D_{r(r)} = \frac{e_{\max} - e_r}{e_{\max} - e_{\min}} \tag{6}$$

$$e_r = \frac{V_f + V_w + V_a}{V_{sand}} \tag{7}$$

where $D_{r(r)}$ is the relative density of fiber-reinforced sand, $e_r$ is the voids ratio of fiber-reinforced sand, $e_{max}$ is the maximum voids ratio, and $e_{min}$ is the minimum voids ratio.

In the first and second principles, the solid volume consists of fibers and solid particles. The standard tests for determining the maximum and minimum voids ratios of sand are based on a solid volume composed of solid particles only. The third principle enables determining the maximum and minimum voids ratios with the same standard procedures followed for unreinforced sand, since the solid part is composed of sand particles only. The reinforced sand will have the same maximum and minimum voids ratios of the unreinforced sand. The fibers-as-void principle is followed in this study.

### 2.3. Specimen preparation

The direct shear apparatus is employed to determine the shear strength of the tested specimens. The shear box has dimensions of 100 × 100 × 30 mm. Based on the targeted relative density, the natural voids ratio is calculated. Knowing the total volume to be occupied and the specific gravity of the sand, the required amount of sand is weighed with an accuracy of 0.1 g. According to the desired fibers content and moisture content, fibers and water are added with the required weights. Fibers and water are manually mixed with sand. The mixture is poured from a scoop on one layer. This enables the fibers to be randomly-oriented and avoids horizontal orientation of the fibers at the interface of successive layers. The specimen is compacted with a square-ended steel tamper with dead weights surrounding its hand. The dead weights fall freely on the specimen until the used amount of sand fills the inner volume of the direct shear box. The applied energy depends on the tamper weight, the height of fall and the number of drops.

Fig. 3 shows the relationship between the targeted relative density and the required relative energy. The relative energy is defined as the ratio of the energy required to prepare the desired specimen to the energy required to prepare a dry very dense ($D_r$ = 90%) unreinforced specimen. The required energy increases as the targeted relative density increases for all fibers contents and moisture contents. Fig. 3a shows that, for all relative densities, the dry unreinforced specimens require less energy than the moist specimens. The specimens with moisture contents of 4.0% and 6.0% require more energy than the 10.0%-moist specimens. These results are consistent with the compaction curve shown in Fig. 2.

The inclusion of fibers increases the energy required for compaction, as shown in Fig. 3b and c. The dry very dense ($D_r$ = 90%) sand specimen needs higher energy when the fibers content is increased from 0.5% to 1.0%. However, this increase is not observed for the dry medium dense ($D_r$ = 60%) and loose ($D_r$ = 25%) specimens. The 1.0%-reinforced dry specimens require higher energy than the corresponding moist ones, as shown in Fig. 3c. The dry 0.5%-reinforced specimens require four times the energy needed to prepare the dry unreinforced specimens, while the moist 0.5%-reinforced specimens require about twice the energy needed for the corresponding unreinforced ones.

### 2.4. Testing procedure

The box is placed in an automated direct shear apparatus and sheared at a displacement rate of 0.6 mm/min. The direct shear test is adopted despite its limitations due to its simplicity and wide usage in the engineering practice. The relatively larger

**Table 1** Properties of the fibers used in the study.

| Property | Value |
|---|---|
| Specific gravity | 0.91 |
| Diameter of fiber | 0.05 mm |
| Fiber tensile strength | 350 MPa |
| Fiber elastic modulus | 1000 MPa |
| Melting temperature | 165 °C |

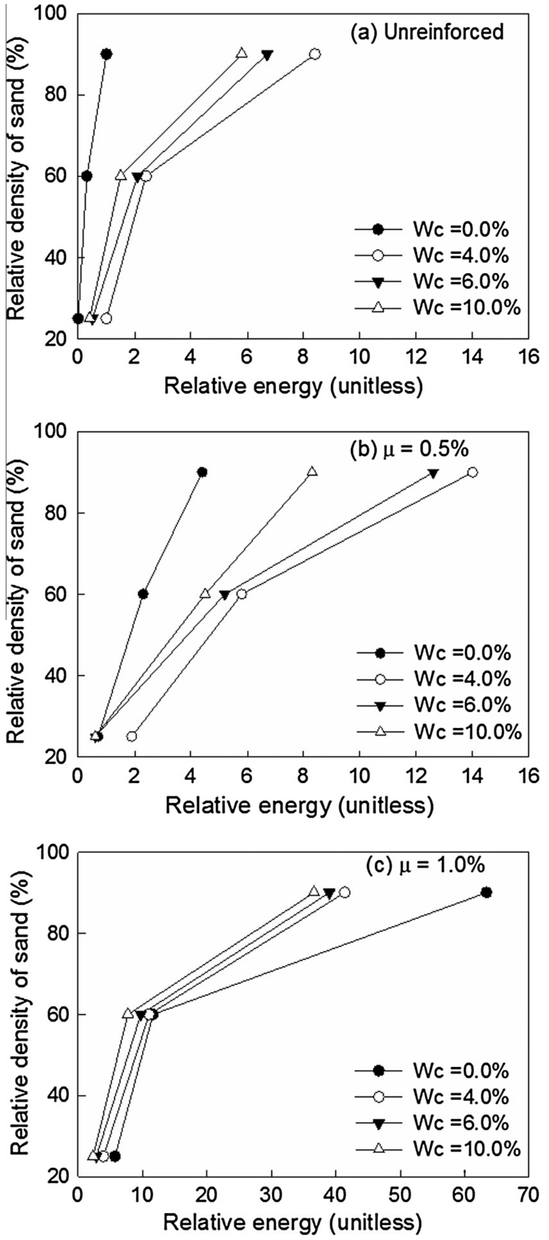

**Figure 3** Relative energy required to prepare unreinforced and reinforced specimens with a certain relative density and various moisture contents. (a) Unreinforced, (b) $\mu = 0.5\%$, and (c) $\mu = 1.0\%$.

dimensions of the direct shear box (100 mm) serve to minimize the size effects of the fibers on the results. The shearing force, horizontal displacement and vertical displacement are measured using electronic transducers and recorded every 18 s. All specimens are sheared until a horizontal displacement of 10 mm is reached. However, some specimens exhibit a bilinear shear stress–horizontal displacement relationship; i.e., they do not exhibit a well-defined peak strength value. The failure stress of these specimens is defined as the stress corresponding to a horizontal displacement of 15 mm. For each test, the shear stress–horizontal displacement and the vertical displacement–horizontal displacement relationships are plotted. It is not possible to measure the thickness of the shear zone, and, hence, the shear strain cannot be quantified. The testing procedure was explained in more detail by Eldesouky [15] and Eldesouky et al. [16].

## 3. Tests results

### 3.1. Shear stress–horizontal displacement behavior

Fig. 4a shows the shear stress–horizontal displacement curves for the dry loose specimens ($D_r = 25\%$). The unreinforced loose sand exhibits a typical loose sand behavior without any post-peak strength drop. However, the fibers inclusion causes the shear strength to decrease after reaching a peak value, a behavior that is typical to medium to very dense sands. The inclusion of fibers increases the peak strength ($\tau_{max}$) and the post-peak strength ($\tau_{pp}$). The comparison of Fig. 4a–c shows that the peak shear strengths of loose reinforced sand ($D_r = 25\%$) correspond to relatively higher horizontal displacements than the medium dense ($D_r = 60\%$) and very dense ($D_r = 90\%$) specimens. The dry loose ($D_r = 25\%$) and medium dense ($D_r = 60\%$) reinforced specimens experience a gradual decrease from peak to post-peak strength, while the dry very dense ($D_r = 90\%$) reinforced specimens experience a sharper drop from peak to post-peak strength.

Fig. 5a shows the shear stress–horizontal displacement curves for the 10.0%-moist loose sand ($D_r = 25\%$). Unlike the dry reinforced loose specimens, the 10.0%-moist reinforced loose specimens exhibit a typical loose sand behavior with no observed peak value. Fig. 5b and c shows that the medium dense ($D_r = 60\%$) and very dense ($D_r = 90\%$) unreinforced and reinforced moist specimens achieve a well-defined peak strength followed by a strength decrease to a post-peak value. Compared to dry specimens, the fibers inclusion into moist specimens has a small effect on the shear stress–horizontal displacement behavior, especially for loose and medium dense specimens at low normal stresses.

The fibers inclusion does not affect the initial tangent stiffness of the dry and the 10.0%-moist specimens. This observation is consistent with the conclusions of Ranjan et al. [1], Consoli et al. [4], and Michalowski and Cermak [17].

Fig. 6 shows the shear stress–horizontal displacement relationship for the dry and moist medium dense ($D_r = 60\%$) specimens sheared under a normal stress of 50 kPa. The relationship is shown for the unreinforced (Fig. 6a) and 1.0%-reinforced (Fig. 6b) specimens. The unreinforced moist specimens have slightly higher stiffness than the unreinforced dry specimens. The peak shear strengths of the dry and moist unreinforced sand specimens are approximately equal. Fig. 6b shows that the peak shear strength of the moist 1.0%-reinforced medium dense specimens is lower than the peak shear strength of the dry 1.0%-reinforced specimen. However, the peak shear strength of the 1.0%-reinforced specimens is not affected by increasing the moisture content from 4.0% to 10.0%.

### 3.2. Peak and post-peak strengths

Fig. 7a illustrates the effects of the fibers content and relative density on the normalized peak shear strength of dry specimens. The normalized peak shear strength is defined as the ratio of the peak shear strength to the applied normal stress,

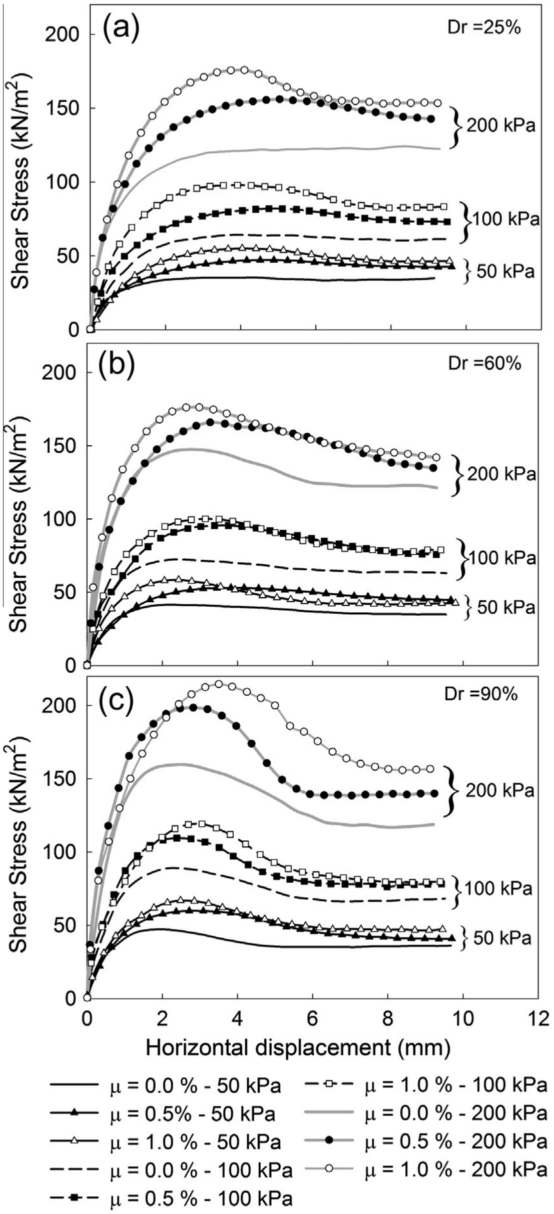

**Figure 4** Shear stress–horizontal displacement relationships for dry unreinforced and reinforced specimens sheared at different normal stresses. (a) $D_r = 25\%$, (b) $D_r = 60\%$, and (c) $D_r = 90\%$.

i.e., $\tau_{max}/\sigma_n$. Fig. 7a shows that the increase of the fibers content from 0.0% to 1.0% improves the normalized peak shear strength of dry sand by up to 50%, while increasing the relative density from 25% to 90% improves the normalized peak shear strength of dry unreinforced sand by about 28% only. Fig. 7b–d presents the effects of the fibers content and relative density on the normalized peak shear strength of specimens with moisture contents of 4.0%, 6.0% and 10.0%, respectively. The presence of moisture reduces the positive impact of fibers on the normalized peak shear strength. At all the tested moisture levels, the increase of the relative density from 25% to 90% has a greater impact on the normalized peak shear strength than the fibers content increases from 0.0% to 1.0%. In general, the moist reinforced specimens have lower normalized peak shear strengths than the corresponding dry reinforced specimens. In addition, there is no significant change in the normalized peak shear strength of the unreinforced and reinforced specimens when the moisture content changes from 4.0% to 10.0%.

Fig. 8a illustrates the effects of the fibers inclusion and relative density on the normalized post-peak shear strengths ($\tau_{pp}/\sigma_n$) of the dry specimens. Fig. 8a shows that increasing the fibers content from 0.0% to 1.0% improves the normalized post-peak shear strength of dry sand by about 25–30%. The moist specimens experience a minor post-peak shear strength improvement when the fibers content is increased from 0.0% to 1.0%, and the yield surface tends to be flat, as shown in Fig. 8b–d.

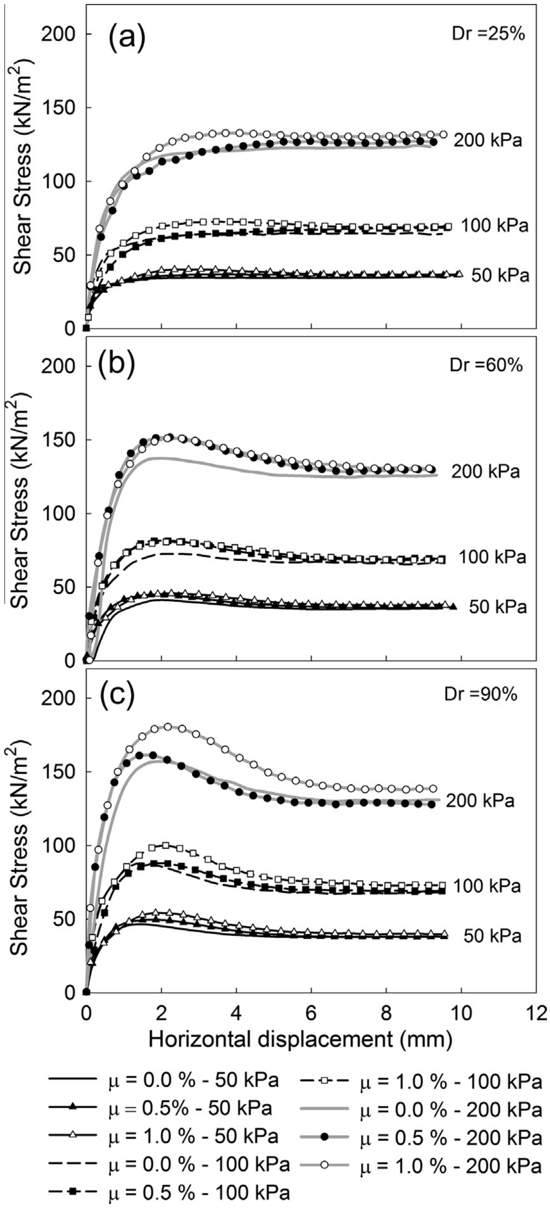

**Figure 5** Shear stress–horizontal displacement relationships for moist ($W_c = 10\%$) unreinforced and reinforced specimens sheared at different normal stresses. (a) $D_r = 25\%$, (b) $D_r = 60\%$, and (c) $D_r = 90\%$.

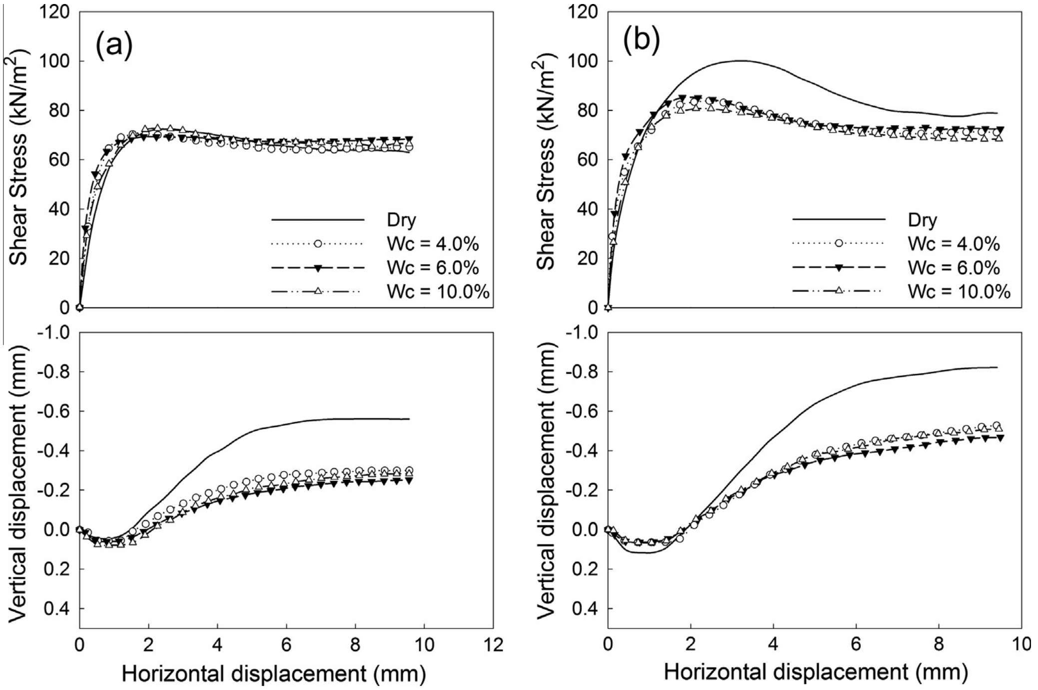

**Figure 6** Shear stress–horizontal displacement and vertical displacement–horizontal displacement relationships for medium dense ($D_r$ = 60%) specimens sheared at 50 kPa for various moisture contents. (a) Unreinforced specimens and (b) $\mu$ = 1.0%.

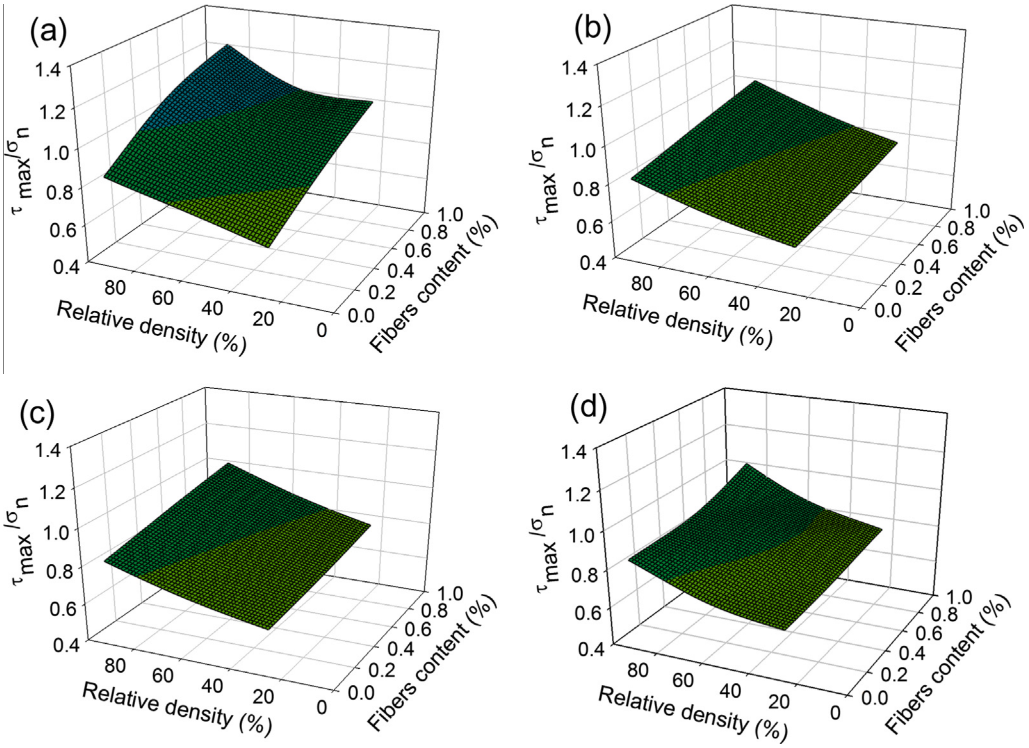

**Figure 7** Normalized peak shear strength versus fibers content and relative density. (a) Dry specimens, (b) $W_c$ = 4.0%, (c) $W_c$ = 6.0%, and (d) $W_c$ = 10.0%.

### 3.3. Volumetric change and dilation

Fig. 6 illustrates the variation of the vertical displacement with the horizontal displacement for the dry and moist, unreinforced and 1.0%-reinforced specimens. The figure shows that the 1.0%-reinforced specimens and the corresponding unreinforced specimens experience almost the same volumetric decrease at the same horizontal displacement during initial

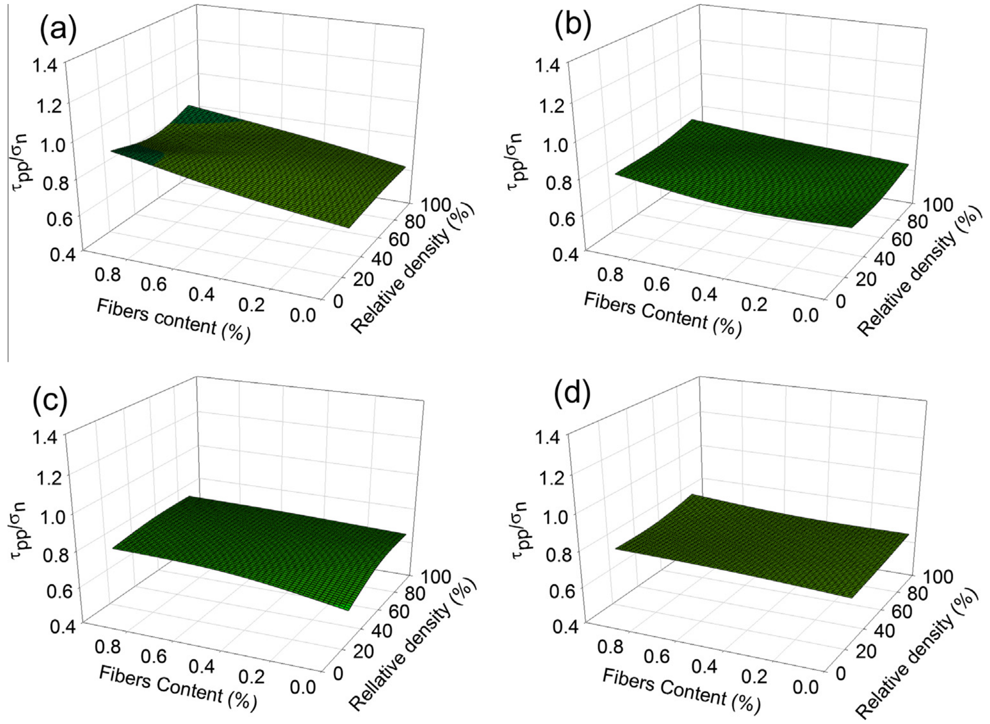

**Figure 8** Normalized post-peak shear strength versus fibers content and relative density. (a) Dry specimens, (b) $W_c$ = 4.0%, (c) $W_c$ = 6.0%, and (d) $W_c$ = 10.0%.

loading stages. At higher horizontal displacements, however, the fiber-reinforced specimens experience higher volumetric increase, i.e., dilation. Similar results were obtained by Falorca and Pinto [11]. The unreinforced specimens reach a constant volume at the test end (at horizontal displacement of 10 mm), while the fiber-reinforced specimens continue to experience a volumetric increase. This observation was also reported by Ibraim and Fourmont [5].

Fig. 6 shows also that the volumetric change of either the unreinforced or the 1.0%-reinforced specimens is very slightly affected when the moisture content is changed from 4.0% to 10.0%. At the maximum horizontal displacement of 10 mm, the vertical displacement of the 6.0%-moist 1.0%-reinforced specimen equals 58% of the vertical displacement of the dry 1.0%-reinforced specimen. The vertical displacements of the 4.0% and 10.0%-moist 1.0%-reinforced specimens equal 63% of the vertical displacement of the dry 1.0%-reinforced specimen.

The dilation angle ($\psi$), defined as the change in the vertical displacement ($\Delta\delta_v$) divided by the change in the horizontal displacement ($\Delta\delta_h$), increases with continued shearing until the maximum dilation angle ($\psi_{max}$) is reached, and then the dilation angle decreases. The maximum dilation corresponds to the peak shear stress, as shown in Fig. 6.

Fig. 9 illustrates the effects of the relative density and fibers content on the maximum dilation angle of the dry and the 10.0%-moist specimens subjected to a normal stress of 50 kPa. The maximum dilation angle of the dry specimens increases by about 10.0° when the fibers content is increased from 0.0% to 1.0%. The same effect is encountered when the relative density is increased from 25% to 90%. The moist specimens have lower maximum dilation angle values than the corresponding dry ones.

Fig. 10 shows a plot of the stress ratio ($\tau/\sigma_n$) against the dilation angle for the dry and 6.0%-moist unreinforced and fiber-reinforced specimens. At the initial test stages, both the dry and moist reinforced specimens experience high contraction rates, i.e., negative dilation angles. The contraction rates increase with increasing the fibers content and moisture content. As the specimen approaches failure, the fiber-reinforced specimens have higher dilation angles than the unreinforced ones. The fibers possibly transfer the shear strains from the shearing plane to other zones inside the soil mass, and, hence, the size of the shear zone is increased, which leads to higher dilation angles. Although these results are specific to the tested sand and fibers, other studies reported a similar behavior; Falorca and Pinto [11] deduced that the fibers mobilize the stress to more soil particles. Shewbridge and Sitar [18] reported also that the shear zone width is strongly dependent on the area of the fibers that intersect the shearing plane.

## 4. Discussion

The conducted study on unreinforced and fiber-reinforced sand enables exploring the shear strength and volumetric change behaviors of fiber-reinforced sand in an elaborate way. The controversies in the literature are highlighted. Moreover, conducting tests on the corresponding unreinforced specimens yields useful implications in earthworks applications that are highlighted in this section.

The fibers inclusion increases the compaction energy required to bring the specimen to a certain relative density. Falorca et al. [19] reported larger recovery of fiber-reinforced sand than unreinforced sand when subjected to repeated

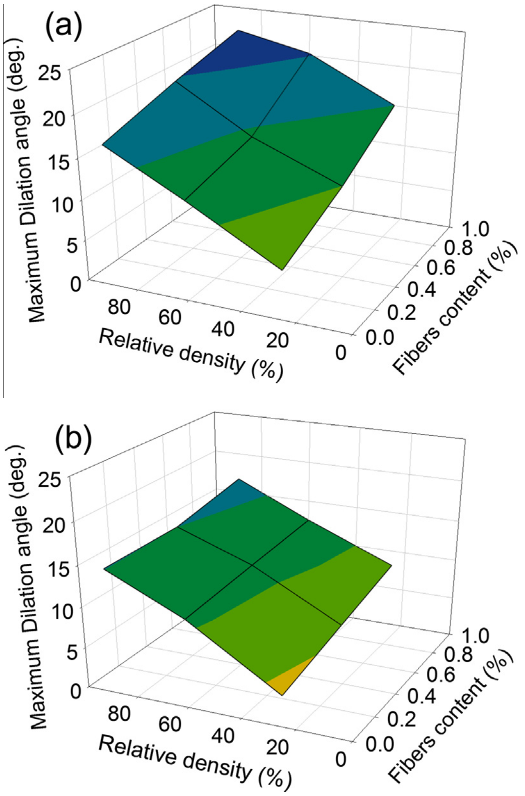

**Figure 9** Effect of relative density and fibers content on the maximum dilation angle of sandy soil specimens sheared at a normal stress of 50 kPa. (a) Dry and (b) $W_c = 10.0\%$.

loading–unloading cycles in the plate load test. The larger recovery indicates that only a fraction of the applied energy is effective in the compaction process. Hence, the compaction energy required for the specimen fabrication is increased. The fibers length is another factor affecting the required compaction energy. The fibers length can hinder reaching the required compaction energy to the soil grains.

The fibers inclusion increases the peak and post-peak shear strengths of sand, although it does not affect the initial tangent stiffness. The unreinforced and fiber-reinforced stress–displacement curves deviate from each other at a threshold displacement of 0.15–1.50 mm. Dry fiber-reinforced sand is characterized by a strain-softening behavior, even in loose conditions. There is a threshold value of the fibers content of 0.5% above which the post-peak to peak shear strength ratio remains almost unchanged.

The peak shear strength of the dry loose 0.5%-reinforced sand equals the peak shear strength of the unreinforced very dense sand prepared at a moisture content of 10.0%, which is close to the optimum value. This observation is valid for all the normal stresses applied in the study. However, the peak shear strength of the dry loose 0.5%-reinforced sand is achieved at a horizontal displacement of about 4.0 mm, while the peak shear strength of the moist very dense unreinforced sand is achieved at a horizontal displacement of 1.6–1.8 mm, approximately. Therefore, mixing polypropylene fibers with dry sand in the loose state could be a good alternative to compacting unreinforced sand using water from the shear strength perspective. These results could have useful implications in earthworks applications in remote areas where the water sources are limited. However, due to the relatively higher displacement required to mobilize its peak shear strength, the deformation characteristics of loose fiber-reinforced sand should be investigated. The use of dry loose fiber-reinforced sand may be limited to applications where serviceability is not a design concern, like sloped backfills. In addition, the financial implications of both techniques should be considered.

The peak shear strength of unreinforced sand is not significantly affected when moisture is introduced to the dry specimens, or when the moisture content is changed on the dry side of optimum from 4.0% to 10.0%. On the other side, introducing moisture to reinforced specimens causes the peak shear strength to decrease by about 17%. However, the peak shear strength of reinforced sand remains unchanged when the moisture content increases from 4.0% to 10.0%.

Introducing fibers by a content of 1.0% increases the maximum dilation angle by the same value as increasing the relative density from 25% to 90%. However, the introduction of moisture causes the specimens to be less dilative. Increasing the moisture content on the dry side does not affect the volumetric increase. Therefore, moisture inhibits the effects of the fibers content and relative density on the volumetric increase, i.e., dilation.

The unreinforced dry and moist sand specimens reach a constant volume at a horizontal displacement of 10 mm. Therefore, the post-peak strength of the unreinforced specimen

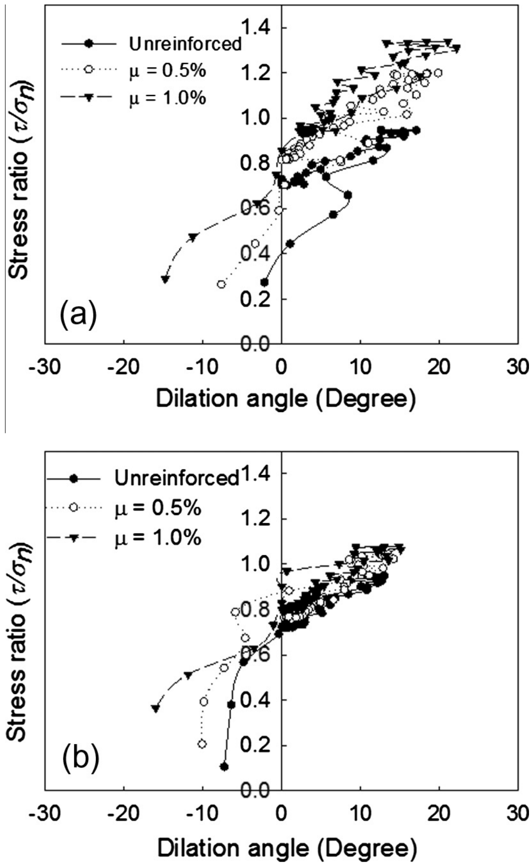

**Figure 10** Stress ratio against dilation angle for very dense ($D_r = 90\%$) specimen of various fibers contents sheared under a normal stress of 50 kPa. (a) Dry and (b) $W_c = 6.0\%$.

can be considered a critical state or steady state strength [20], and the Steady State Line (SSL) can be plotted for the dry unreinforced sand, as shown in Fig. 11. The voids ratio at the steady state is calculated by knowing the initial volume and the vertical displacement at the steady state condition.

The reinforced specimens, on the other side, show increased volume change at the end of the test; i.e., their post-peak shear strengths are not the steady state or critical state strengths. As an approximation, the SSL's of the dry fiber-reinforced sand specimens are constructed by calculating the average post-peak shear strength of the loose, medium dense and very dense specimens at each normal stress, as shown in Fig. 12.

Plotting the SSL enables interpreting the results in terms of the state parameter [21]. The state parameter is the difference between the voids ratio in the initial state, i.e., before shearing, and the voids ratio at the steady state strength. Contractive sands have positive values of the state parameter, and dilative sands have negative values. According to Been and Jefferies [21], interpreting the results in terms of the state parameter is better than relying on the relative density only. The state parameter combines the effects of voids ratio and stress level on the sand behavior in a single parameter, while the relative density does not account for the influence of stress level on the sand behavior. In this study, the effects of the relative density and normal stress on the normalized peak and post-peak shear strengths are investigated, as shown in Figs. 7 and 8.

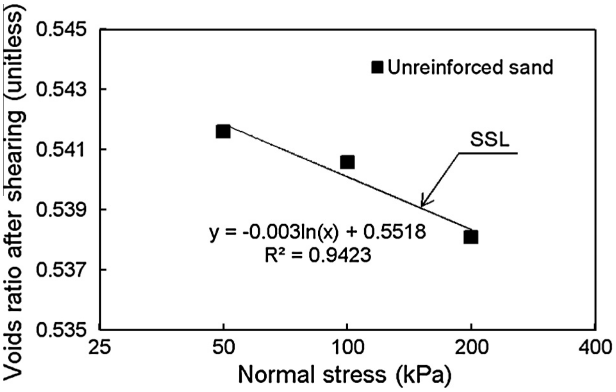

**Figure 11** Steady State Line (SSL) of the dry unreinforced sand.

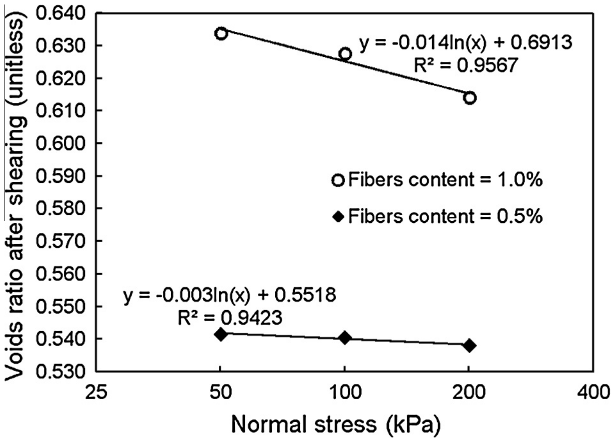

**Figure 12** Steady State Line (SSL) of the dry 0.5%- and 1.0%-reinforced sand.

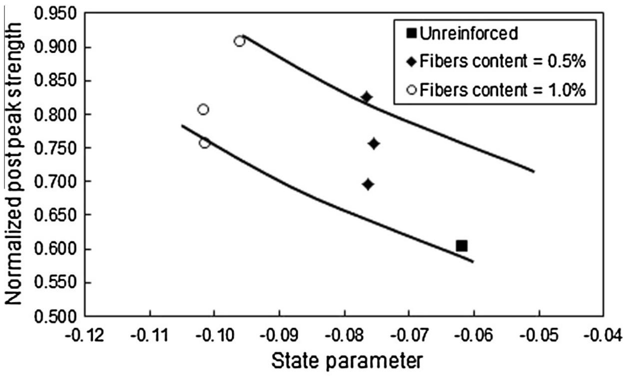

**Figure 13** Normalized post-peak shear strength versus the state parameter for the dry unreinforced, 0.5%-reinforced and 1.0%-reinforced sand.

Hence, the influence of the stress is taken into consideration together with the effect of the relative density.

Been and Jefferies [21] plotted the drained angle of shearing resistance versus the state parameter for different types of sands with different fines content, and established that the drained angle of shearing resistance generally decreases as the state parameter increases. Despite the large number of points used in Been and Jefferies [21] correlation, the scatter was about 4°. Fig. 13 shows the normalized post-peak shear strength versus the state parameter for the unreinforced, 0.5%-reinforced and 1.0%-reinforced dry sand. The figure indicates a general inverse proportion between the two quantities. The scatter corresponds to 6°, approximately. The relatively higher scatter is attributed to the few data points used to establish the correlation and the approximation in determining the value of the post-peak shear strength, which is not exactly equal to the steady state strength of fiber-reinforced sand.

## 5. Conclusions

Direct shear tests are conducted on 108 unreinforced and fiber-reinforced, dry and moist sand specimens prepared at different relative densities and normal stresses. The main conclusions of the study are summarized in the following points:

- The fibers inclusion improves the peak and post-peak shear strengths of sand by up to 50% and 30%, respectively. On the other side, the fibers inclusion increases the sand dilation.
- The introduction of moisture reduces the fibers effect on the peak and post-peak shear strengths. The peak shear strengths of the moist specimens are affected by the relative density increase more than they are affected by the fibers inclusion. The post-peak shear strength drop is reduced by the introduction of moisture to fiber-reinforced sand.
- Changing the moisture content on the dry side does not have any noticeable impact on the peak shear strength, the post-peak shear strength and dilation of unreinforced and fiber-reinforced sand.
- Dry loose 0.5%-reinforced sand achieves the same peak shear strength of moist very dense unreinforced sand, yet at more than double the horizontal displacement.

Therefore, the use of dry loose fiber-reinforced sand instead of moist heavily compacted unreinforced sand may be limited to applications where serviceability is not a design concern, like sloped backfills. The deformation characteristics of fiber-reinforced sand need further investigation. In addition, the collapsibility potential of the dry loose fiber-reinforced sand due to rainfall inundation should be investigated.

- The state parameter concept can be used to account for the influence of stress on the fiber-reinforced sand behavior, provided the specimens are sheared until a constant volume is reached.

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