Engineering properties of plastic waste reinforced sand

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Scientia Iranica
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Abstract: A series of triaxial compression tests were performed to evaluate the benefits of plastic wastes and investigate the engineering properties of sand reinforced with these materials. In this research, the effects of plastic waste contents (0, 0.25, 0.5, 0.75, and 1% by dry weight of sand), types of plastic wastes -polyethylene terephthalate (PET) and polypropylene (PP) fibers- and confining pressures (50, 100 and 200 kPa) on the behavior of Babolsar sand were investigated. The values of deformation modulus (up to 84%), peak (up to 7 times of the unreinforced sand) and steady state shear strength increased with reinforcement. Also, axial strain at failure for fiber-reinforced sand increased up to 1.5 times of unreinforced one (from 3.36% to 8.53% for 1% PP usage at 50 kPa confining pressure). Therefore, it can be generally stated that the use of plastic wastes in the sand leads to low cost soil reinforcement and also lessens the disposal problem of these kinds of wastes.

Keywords: Sand reinforcement, Shear strength, Plastic waste, Fiber-shaped plastic, Triaxial compression test.

1. Introduction

Nowadays lack of accessibility to lands with fair bearing capacity for construction is an important problem, so this problem force engineers to use local lands. In such cases, soil improvement techniques such as soil reinforcement and soil stabilization behaved satisfactorily in many conditions. Soil reinforcement has been performed with different methods and materials such as various types of geosynthetics and fibers.

There are at least two advantages in using randomly distributed fiber as reinforcement. First, the discrete fibers are simply added and mixed randomly with soil, in much the same way as cement, lime, or other additives. Second, randomly distributed fibers limit potential planes of weakness that can develop parallel to oriented reinforcement [1-4].

Nowadays, the tendency to use alternative materials which can fulfill design specification is promoted because of environmental and economic problems. One possible way to reuse these wastes is to convert them into materials for soil reinforcement and construction applications like highway base material and backfill of retaining walls. The soil which is reinforced by waste
plastic strip can be used in embankment/road construction which leads to significant reduction in
cost as well as safe disposal of these waste materials in an environmental friendly manner [5-9].
So, many researchers have focused on finding suitable ways for reusing waste materials. Plastic
wastes are usually materials with high strength and less reaction with acids and alkalis. These
types of wastes are not biodegradable, so they remain unchanged for years and cause
environmental pollution [6-7].

Using plastic wastes such as tire shreds to improve the mechanical properties of soil dates
back to the 1990. Many researchers studied on the engineering properties of plastic waste
reinforced soils [2, 4, 6-18]. The idea of incorporating other plastic wastes in soil was first
proposed by Benson and Khire [19]. They used translucent HDPE milk jugs which were cut into
strips as reinforcing material. Direct shear tests were conducted on samples, and results showed
that adding these wastes into the soil increased friction angle and shear strength of sand. Consoli
et al. [20] conducted an experimental study on uncemented and artificially cemented soil
reinforced with polyethylene fibers derived from plastic wastes. The results demonstrated that
plastic wastes improved the stress-strain response of both uncemented and cemented sand. Kim
et al. [21] investigated the behavior of reinforced and unreinforced lightweight soils. The
unconfined compression tests as well as those of one-dimensional compression tests showed that
the strength of reinforced lightweight soil generally increased after adding waste fishing net (0%,
0.25%, 0.5%, 0.75% and 1% of the dry soil weight), however the level of increase in
compressive strength was not directly proportional to the percentage of waste fishing net. The
results of the tests indicated that the maximum increase in compressive strength was obtained for
soil mixed with 0.25% waste fishing net. Babu et al. [22] conducted experiments on sand
samples reinforced with waste PET pieces (0.5%, 0.75% and 1% of dry soil weight) obtained
from waste water bottles. They observed that inclusion of these plastics in the soil improved the shear strength, tensile strength and internal friction angle of the soil. Muntohar et al. [23] carried out an experimental study on silty soil stabilized with lime and rice husk ash and reinforced with waste plastic fibers. The results showed that this method was an effective way to improve the engineering properties of the silty soil with regard to compressive strength, tensile strength, and shear strength, which enhanced the stability of the soil; also, the optimum amount of fiber in the soil/lime/rice husk ash/fiber mixtures was ranged from 0.4–0.8% of the dry soil weight. Abbaspour et al. [7] performed a series of static and cyclic laboratory tests to contribute to manage and prevent the burial of a part of hazardous wastes produced during the recycling process of worn tires. Their results showed that the fiber inclusion enhances all geotechnical properties of the soil under static state. Also, they concluded that under dynamic state, the fibers can increase the energy absorption and dissipation properties of the soil, as well as the resilient modulus and damping ratio with an optimum fiber content of 1–2%.

Therefore, based on previous researches, the main advantages of using short fibers over planar reinforcement can be summarized as follows:

1. Improving soil physical properties.
2. Provide more uniformity.
3. Provide considerable flexibility.
4. Provide high levels of stiffness to weight ratio.
5. Increase in toughness. This means more energy absorption ability. So, this property makes it suitable for subgrades of airport pavements, blast resistant structures and etc.

In this paper an experimental study of the utilization of two kinds of fiber-shaped plastic wastes (PET and PP) for sand reinforcement and their effects on shear strength, ductility and
stiffness of the sand are described. Also, the effects of plastic waste fiber content, confining pressure and length of PET fibers on sand behavior is examined.

2. Materials

2.1. Sand

The sand used in this research was obtained from shores of Caspian Sea (Babolsar- Iran). The grain size distribution curve of the soil, which was obtained based on ASTM D-422 [24], is shown in Figure 1. Babolsar sand is uniform and clean with subrounded to subgranular particles and classified as SP according to the unified soil classification system, ASTM D-2487 [25]. The mean particle diameter ($D_{50}$) of the sand was 0.2 mm. The specific gravity of sand particles was determined a value of 2.75 based on ASTM D-854 [26]. Minimum and maximum dry unit weights of the sand were obtained according to ASTM D-4254 [27] and ASTM D-4253 [28] equal to 14.8 and 17.4 kN/m$^3$ respectively.

2.2. Reinforcing materials

The reinforcing materials used in this study were two kinds of plastic wastes, polyethylene terephthalate (PET) and polypropylene (PP). The PET waste was recycled from plastic water bottles. These plastic water bottles were accumulated and then melted to transform into fiber-shaped material. The fibers were cut into 5, 10 and 15 mm pieces to be used as reinforcing elements in sand (Figure 2). The waste PP fibers have been taken from a factory which produced polypropylene bags and then cut into 15 mm length pieces (Figure 3). The characteristics of used fibers are shown in Table 1.

3. Sample preparation and testing procedure

To prepare samples mixed with PET fibers, an appropriate amount of the sand as well as plastic waste was weighed. To ensure uniform distribution of PET fibers in the mixture, at first
the specified dry soil was mixed with 5% water content and then the specified weight of plastic waste (by dry weight of the soil) was mixed with soil until obtaining a uniform mixture (It is suggested to add an amount of water to the sand to achieve a better mixture of sand and fiber until it does not cause them to float [29]. In this research, to determine the required amount of water for preparation of samples, different water contents including 5, 10, and 15% were considered and the homogeneity of samples was evaluated. Based on the results, 5% water content was determined as the optimum moisture content to prepare the uniform sand-fiber mixtures). Since the tests were conducted on dry specimens; so, the mixtures were put into an oven at 65°C for 48 hours prior to the tests, to get dry. Because it was observed that the PET fibers begin to deform when the heat was over 65°C, so this temperature was used for the purpose.

To prepare mixtures with PP fibers, the specified amount of sand and PP fibers were mixed in dry condition.

After preparing the sand and plastic waste mixture, specimens were statically compacted in four layers in a cylindrical mold - 38 mm diameter and 76 mm height – (similar to the mold that used by Yadav and Tiwari [18] for the maximum length of 15 mm fiber) to a relative density of 70% based on the procedure proposed by Baldi et al. [30]. Both kinds of plastic wastes were mixed with sand at different percentages (0, 0.25, 0.5, 0.75 and 1% by dry soil weight).

The prepared samples were tested in dry condition in a conventional triaxial apparatus. There has been a lot of research on dry samples of granular soils in the past [31-33]. In this research, the specimen's volume change was recorded and measured to monitor this property during the shear, and also for using in area correction. A twin-burette volume change was applied to measure the volume change of specimens on the cell pressure line. A total of 51 triaxial
compression tests were performed on the unreinforced and reinforced specimens at a strain rate of 0.35% per minute. The tests were performed on the samples with three values of confining pressures (50, 100 and 200 kPa). Deviator load was applied till the specimens fail or attain the axial strain of 15%. Corrections including membrane force [34], membrane penetration [35] and cross-sectional area were taken into account and applied. The investigated variables are illustrated in Table 2.

4. Results and discussion

In this section, the results of performed triaxial compression tests on specimens of unreinforced and reinforced sand with two types of plastic wastes are presented based on peak strength, ductility, failure strain, volumetric strain and secant modulus of deformation.

4.1. Effect on peak strength

As it can be seen in Figure 4, the peak strength increased with reinforcement of the sand. This increment became more considerable with an increase in percentage and length of plastic wastes. For example, the peak strength of the unreinforced sand under a confining pressure of 50 kPa was increased from 230.5 to 288.8 kPa due to the reinforcement by 0.25% PET with 5 mm length. This value was increased to 961.3 kPa (more than 4 times of the unreinforced one) for a sample reinforced by 1% PET with 15 mm length. Also, for PP waste fiber-reinforced sand at 1% usage, the peak strength was reached to 1614 kPa (about 7 times of the unreinforced one) at the same confining pressure. A similar trend was observed in previous works [4, 12-13, 20]. As the plastic waste reinforced sand was subjected to deformation, friction which is appeared between soil and plastic wastes led to development of tensile stress in the plastic wastes, also increase in confinement of the sample, and consequently increase in the shear strength of the samples. As it can be seen in Figure 5, at all PET contents and all confining pressures, the peak
shear stress of sand improved with an increase in the length of waste PET fibers from 5 mm to 10 mm but after this value, the improvement of shear stress was negligible. This may be due to the fact that longer fibers have longer embedment length; therefore, they endure greater tension during shear. Actually, the value of increase in peak shear stress for the sand reinforced with 15 mm length PET fibers is almost the same as that for the sand reinforced with 10 mm length fibers with a negligible difference. Previous research has also indicated a similar trend between the shear strength improvement of fiber-reinforced soil and the length of the fiber [4]. This phenomenon can be attributed to the following reasons:

- The decrease of the number of fibers which participate in the failure zone – when the percentage of the fiber is constant, the number of fibers decreases with the increase in fiber length.
- As the fiber length was increased, it got more difficult to make a uniform mixture with the sand because the long fibers piled up together resulting in slippage; so, less improvement was achieved when the percentage of the fiber was constant in the soil and waste plastic fibers length was increased.

Nevertheless, the stress ratio (ratio of peak deviatoric stress of reinforced specimen to the corresponding value of unreinforced one) decreased with the increase of confining pressure as shown in Figure 6. Consider, for instance, in the sample reinforced by 1% PET with 15 mm length, the stress ratio for 50 kPa confining pressure is 3.98, while for 200 kPa confining pressure is about 1.57. A similar trend was observed in previous researches [4, 32, 36-37]. Improvement of shear strength in dilating soils, with the inclusion of fibers is related to the level of interaction between fibers and soil particles as well as the amount of dilation during the shear stage that mobilizes the tensile strength of fibers. Dilatancy is the result of shear zone expansion
during the mobilization of the reinforcing elements. Increase in the confining pressure limits the rearrangement of the soil structure resulting in less dilation and this restricts the amount of fiber stretch during the shear [4, 32, 36]. Hence, the efficiency of fiber reinforcement to increase the shear strength of the dilating soil is obviously influenced by an increase in the confining pressure. It is evident that the stress ratio of fiber-reinforced sand was reduced from the value of 4 at the confining pressure of 50 kPa to the 1.5 times of unreinforced sand at the confining pressure of 200 kPa and it can be concluded that the efficiency of fibers in increase of the shear strength of medium dense sand reduces at high confining pressures regardless of the fiber content. So, to reach the maximum efficiency, it is appropriate to use these fibers as reinforcement for the soils with low to medium overburden stress range, such as base layer in road construction.

The results obtained from the conducted tests indicated that, for all different waste contents and confining pressures, sand reinforced with PP plastic wastes had a higher peak deviatoric stress compared to the sand reinforced with waste PET fibers. For example the tests conducted under a confining pressure of 50 kPa, indicated that the peak shear stress for sand reinforced with 15 mm length PET fiber (Figure 4-c) is 4.17 times more than unreinforced sand and for sand reinforced with waste PP fibers (Figure 4-d), it was 7 times more than that of the unreinforced one; these values were achieved for specimens with 1% plastic waste. This may be due to the tensile strength of wastes; as the tensile strength of PP fibers was more than the PET fibers, so the PP fibers were crushed during the shearing (Figure 7) but the PET fibers torn in the failure zone.

4.2. Effect on ductility
Based on Figure 4 and Table 3, it can be seen that the post-peak loss of shear stress is decreased for reinforced specimens. Actually, steady state stress of reinforced samples was increased with an increase in plastic waste content and length. The reason for this can be explained by the fact that when the samples are loaded, the fibers act like a bridge and prevent the occurrence of early and large deformations in the soil. As a result, the soil shows significant strength against larger strains and less strength drop. So, the brittleness index, which indicates the fragility and ductility of the reinforced soil, that was calculated based on Bishop's [38] definition (equation 1) and depicted in Table 4, decreased with the inclusion of waste fibers in the soil.

\[ I_B = \frac{q_p - q_s}{q_p} \]  

(1)

Where \( I_B \) is brittleness index, \( q_p \) is peak shear stress and \( q_s \) is steady state shear stress.

According to the Table 4, the brittleness index of the reinforced specimens decreased with an increase in the waste fiber length and percentage. However, the amount of this reduction was very small for the reinforced sand with 5 mm length PET fibers (about 11% for 1% usage). But, the greatest decrease in the brittleness index was observed for the waste PP-reinforced sand (about 75% for 1% usage). Actually, sand reinforced by the waste PP fibers has more ductile behavior than the sand reinforced by the waste PET fibers. The reason for this is explained previous and is related to the tensile strength of wastes. Generally, it can be argued that the ductility of the Babolsar sand improved by reinforcing with plastic wastes. Increase of soil ductility lead to improvement of seismic stability of geotechnical projects such as airport runways and rail embankments [39].

4.3. Effect on failure strain
As demonstrated in the Figures 8-9, sand reinforced with plastic waste had a greater axial strain at failure in comparison to the unreinforced sand and the strain at failure increased with an increase in fiber-shaped waste content and length. As an example, for the sample reinforced with 1% PP at 50 kPa confining pressure, the axial strain at failure increased up to 1.5 times of unreinforced one (from 3.36 to 8.53%). Actually, at all confining pressures, axial strain at failure increased with an increase in plastic waste percentage. As stated earlier, this can be attributed to the appeared friction between the soil and plastic waste fibers (when the load applied to the specimen) which led to development of tensile stress in the plastic wastes. In addition, this tensile stress cause confining pressure in the sample, which result in increase of axial strain at failure in reinforced samples [22]. Due to the greater tensile strength of PP waste fiber (as mentioned earlier), the amount of increase in the axial strain at failure for the PP-fiber reinforced sand is higher than the PET-fiber reinforced one.

4.4. Effect on volumetric strain

The changes of volumetric strain against axial strain for unreinforced and reinforced sand with plastic waste (PET) were presented in Figure 10. A closer look at this figure shows that:

1- As anticipated during the primary part, both unreinforced and reinforced samples exhibited small contraction in their volumes. With the advance of shear stress, the trend is reverted and the samples showed an increase in their volumes. However, the increase in confining pressure restricted the volumetric dilation of them.

2- The dilation of specimens is decreased by the plastic wastes (PET) inclusion. Many researchers [40-41] reported that the dilation occurs principally in the center of samples. Dilation and lateral deformation of the top and bottom of the specimen is restrained by the cap and the base. Also, it is believed that plastic fibers reduce lateral deformation. As
stated previously, inclusion of fiber in the sand due to the appeared friction between soil and plastic waste increase the confinement of the sample, which leads to decrease of the lateral deformation. Therefore, it is obvious that plastic waste fibers efficiently reduce the dilation of the specimens. A similar behavior was reported in previous researches [37, 40-41]. This phenomenon may be attributed to the decrease of maximum dry unit weight of the sand due to the inclusion of fiber in the specimen and also to the small size of fiber holes compared to the D₅₀ of the sand. This outcome becomes more obvious when the PET content and length increases.

4.5. Effect on secant modulus of deformation

The secant deformation modulus (E₅₀), which was shown in Figure 11, increased with the increase in waste content for two types of wastes (PET and PP) and for all lengths. The value of this increment is highest for the sample reinforced by 1% PET with 5 mm length. So that, E₅₀ increased from 18.6 MPa for the unreinforced sample to 34.2 MPa (about 84% increment) for the mentioned sample at 50 kPa confining pressure. As mentioned earlier, by increasing plastic waste length, the peak strength and axial strain at failure increases. Now, it can be stated that for reinforced sample with shorter fiber lengths, axial strain has a more limited increase than peak strength. As a result, the value of E₅₀ has increased further in this case. Also, the figure shows the amount of increase of E₅₀ has decreased with increasing PET length, however for reinforced samples with 10 and 15 mm lengths of PET is almost the same (similar to the results obtained for peak strength of these two samples). Moreover, due to the better strength feature of PP than PET, the sample reinforced by PP with 15 mm length has a higher E₅₀ than the sample reinforced by PET with 15 mm length.
The results of this study generally showed that the use of PET and PP waste fibers in soil reinforcement improves soil behavior. The achieved improvement of reinforcement with PP waste fiber is more than PET one, but both of them significantly improved the soil properties. Depending on the expected conditions and the type of available plastic waste in the area, each of them can be used. By use of them, both the environmental effects of existence of waste are reduced (as stated by Hejazi et al. [3], the main reason of using plastic wastes in geotechnical engineering is the environmental purposes) and the behavior of the soil is improved according to the results of this research.

5. Conclusions

In this research an idea to reuse the plastic wastes in geotechnical engineering applications is presented. A series of triaxial compression tests were conducted on the reinforced sand with these materials. The content of these fiber-shaped plastic wastes varied from 0 to 1%. The effects of four factors on the behavior of plastic waste reinforced sand were investigated: plastic waste type, plastic waste length, plastic waste content and confining pressure. The experimental results showed that:

1) Shear strength of sand increased with the inclusion of both kinds of plastic wastes. As the plastic waste reinforced sand was subjected to deformation, friction which is appeared between soil and plastic wastes led to development of tensile stress in the plastic wastes, also increase in confinement of the sample, and consequently increase in the shear strength of the samples.

2) The amount of increase in peak stress increased with an increase in PET fiber length from 5 to 10 mm, and due to the fact that longer fibers have longer embedment length, after this value the improvement of peak stress was negligible.
(3) The peak shear strength for the PP fiber reinforced sand (for 1% fiber addition, about 7 times of the unreinforced sand) was greater than the PET fiber reinforced sand (for 1% fiber addition and 15 mm length, about 4.17 times of unreinforced sand) due to the more tensile strength of this kind of fiber.

(4) The stress ratio (ratio of peak deviatoric stress of reinforced specimen to the corresponding value of unreinforced one) decreased from 3.98 to about 1.57 (for the sample reinforced by 1% PET with 15 mm length) with the increase of confining pressure from 50 to 200 kPa. Increase in the confining pressure limits the rearrangement of the soil structure resulting in less dilation and this restricts the amount of fiber stretch during the shear.

(5) The inclusion of fiber-shaped plastic wastes in the sand, made its behavior more ductile, and reduced its brittleness index (up to 75%). In the reinforced sample, the fibers act like a bridge and prevent the occurrence of early and large deformations in the soil. As a result, the soil shows significant strength against larger strains and less strength drop.

(6) Due to the fiber inclusion in the sand, strain of the fiber reinforced sand at failure increased up to 1.5 times of unreinforced one (from 3.36 to 8.53% for 1% PP usage at 50 kPa confining pressure) because of the appeared friction between the soil and plastic waste fibers.

(7) The dilation of the plastic waste reinforced sand decreased with an increase in plastic waste content and length, up to about 30%. This phenomenon may be attributed to the decrease of maximum dry unit weight of the sand due to the inclusion of fiber in the specimen.

(8) The secant deformation modulus ($E_{50}$), increased with the increase in fiber (waste) content. The maximum increment is observed for the sample reinforced by 1% PET with 5 mm length (about 84%).
Conflict of interest

The authors confirm that there are no known conflicts of interest associated with this publication.

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References


Table Captions:

Table 1. Characteristics of used fibers
Table 2. Variable factors in the testing program
Table 3. Strength properties of reinforced and unreinforced sand
Table 4. Britteness index for reinforced sand with plastic waste at confining pressure of 100 kPa
Figure Captions:

Figure 1. Grain size distribution curve for Babolsar sand.
Figure 2. Recycled PET fibers.
Figure 3. Waste PP fibers.
Figure 4. Stress-Strain curves at 50 kPa confining pressure: a) for different PET fiber contents with a length of 5 mm, b) different PET fiber contents with a length of 10 mm, c) different PET fiber contents with a length of 15 mm and d) different PP fiber contents with a length of 15 mm.
Figure 5. Effect of PET fiber length on peak deviatoric stress: a) for 100 kPa confining pressure and different PET contents, b) for 1% PET and different confining pressures.
Figure 6. Stress ratio versus confining pressure for sand reinforced by 1% PET and different length.
Figure 7. Waste PP fibers in the failure zone.
Figure 8. Effect of PET: a) fiber content on strain at failure for 50 kPa confining pressure, b) fiber length on strain at failure for 100 kPa confining pressure.
Figure 9. Effect of PP fiber content on strain at failure for different confining pressures.
Figure 10. Volumetric change curves for PET fibers with different lengths and 50 kPa confining pressure: a) fiber content of 0.25%, b) fiber content of 0.5%, c) fiber content of 0.75% and d) fiber content of 1%.
Figure 11. Deformation modulus of reinforced sand by varying contents of plastic wastes at 50 kPa confining pressure.
## Tables:

**Table 1.** Characteristics of used fibers

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Diameter (mm)</th>
<th>Specific gravity (g/cm$^3$)</th>
<th>Elastic modulus (GPa)</th>
<th>UTS* (MPa)</th>
</tr>
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<tbody>
<tr>
<td>PET$^\times$</td>
<td>5,10,15</td>
<td>-</td>
<td>0.4-0.8</td>
<td>0.92</td>
<td>0.65</td>
<td>200</td>
</tr>
<tr>
<td>PP$^\bullet$</td>
<td>15</td>
<td>2-2.5</td>
<td>-</td>
<td>0.92</td>
<td>3.2</td>
<td>300</td>
</tr>
</tbody>
</table>

* Ultimate tensile strength  
$^\times$ Polyethylene terephthalate  
$^\bullet$ Polypropylene
Table 2. Variable factors in the testing program

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
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<tr>
<td>Confining pressure</td>
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<tr>
<td>Plastic waste content</td>
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<tr>
<td>Waste PET length</td>
<td>5, 10, and 15 mm</td>
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<tr>
<td>Waste PP length</td>
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**Table 3.** Strength properties of reinforced and unreinforced sand

<table>
<thead>
<tr>
<th>Material</th>
<th>Confining pressure (kPa)</th>
<th>Peak stress at failure (kPa)</th>
<th>Steady state stress (kPa)</th>
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<tr>
<td>Sand</td>
<td>50</td>
<td>230.5</td>
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<tr>
<td></td>
<td>100</td>
<td>563</td>
<td>343</td>
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<tr>
<td></td>
<td>200</td>
<td>1063.2</td>
<td>747.6</td>
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<tr>
<td>Sand + 1% waste PET (5mm)</td>
<td>50</td>
<td>500.2</td>
<td>282.2</td>
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<tr>
<td></td>
<td>100</td>
<td>943.5</td>
<td>602.7</td>
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<tr>
<td></td>
<td>200</td>
<td>1546.1</td>
<td>1132.2</td>
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<tr>
<td>Sand + 1% waste PET (10mm)</td>
<td>50</td>
<td>917.3</td>
<td>563.7</td>
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<td></td>
<td>100</td>
<td>1242.2</td>
<td>880.3</td>
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<td></td>
<td>200</td>
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<td>1437.3</td>
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<td>Sand + 1% waste PET (15mm)</td>
<td>50</td>
<td>961.3</td>
<td>730</td>
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<td></td>
<td>100</td>
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<td>Sand + 1% waste PP</td>
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Table 4. Britleness index for reinforced sand with plastic waste at confining pressure of 100 kPa

<table>
<thead>
<tr>
<th>Material</th>
<th>Plastic waste content</th>
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<tr>
<td></td>
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<tr>
<td>Sand + waste PET (5mm)</td>
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<tr>
<td>Sand + waste PET (10mm)</td>
<td>0.64</td>
</tr>
<tr>
<td>Sand + waste PET (15mm)</td>
<td>0.64</td>
</tr>
<tr>
<td>Sand + waste PP</td>
<td>0.64</td>
</tr>
</tbody>
</table>
Figures:

Figure 1. Grain size distribution curve for Babolsar sand.
Figure 2. Recycled PET fibers.
Figure 3. Waste PP fibers.
Figure 4. Stress-Strain curves at 50 kPa confining pressure: a) for different PET fiber contents with a length of 5 mm, b) different PET fiber contents with a length of 10 mm, c) different PET fiber contents with a length of 15 mm and d) different PP fiber contents with a length of 15 mm.
Figure 5. Effect of PET fiber length on peak deviatoric stress: a) for 100 kPa confining pressure and different PET contents, b) for 1% PET and different confining pressures.
Figure 6. Stress ratio versus confining pressure for sand reinforced by 1% PET and different length.
Figure 7. Waste PP fibers in the failure zone.
Figure 8. Effect of PET: a) fiber content on strain at failure for 50 kPa confining pressure, b) fiber length on strain at failure for 100 kPa confining pressure.
Figure 9. Effect of PP fiber content on strain at failure for different confining pressures.
Figure 10. Volumetric change curves for PET fibers with different lengths and 50 kPa confining pressure: a) fiber content of 0.25%, b) fiber content of 0.5%, c) fiber content of 0.75% and d) fiber content of 1%.
Figure 11. Deformation modulus of reinforced sand by varying contents of plastic wastes at 50 kPa confining pressure.