Unconfined compressive strength of PET waste-mixed residual soils

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Abstract. Plastic wastes, particularly polyethylene terephthalate (PET) generated from used bottled water constitute a worldwide environmental issue. Reusing the PET waste for geotechnical applications not only reduces environmental burdens of handling the waste, but also improves inherent engineering properties of soil. This paper investigated factors affecting shear strength improvement of PET-mixed residual soil. Four variables were considered: (i) plastic content; (ii) plastic slenderness ratio; (iii) plastic size; and (iv) soil particle size. A series of unconfined compression tests were performed to determine the optimum configurations for promoting the shear strength improvement. The results showed that the optimum slenderness ratio and PET content for shear strength improvement were 1:3 and 1.5%, respectively. Large PET pieces (i.e., 1.0 cm^2) were favorable for fine-grained residual soil, while small PET pieces (i.e., 0.5 cm^2) were favorable for coarse-grained residual soil. Higher shear strength improvement was obtained for PET-mixed coarse-grained residual soil (148%) than fine-grained residual soils (117%). The orientation of plastic pieces in soil and frictional resistance developed between soil particles and PET surface are two important factors affecting the shear strength performance of PET-mixed soil.

Keywords: Polyethylene terephthalate (PET); plastic waste; soil improvement; stress strain behavior; unconfined compressive strength

1. Introduction

Plastics are often used in disposable applications such as food containers, kitchenware, plastic bags, water bottles etc. Most of the plastic bottles used in the current beverage industry are made of polyethylene terephthalate (PET), a polymer formed by combining two monomers, namely modified ethylene glycol and purified terephtalic acid.

Rapid growths in the world's population and beverage consumption have witnessed a drastic increase in accumulation of plastic waste, particularly PET. Every year, bottled water industry produces up to 1.5 million tons of plastic waste (Sivakumar Babu and Chouksey 2011). In highly

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urbanized cities of Southeast Asian countries, plastic contributes to about 10 – 16% of total municipal solid wastes (MSW) (Nguyen Ngoc and Schnitzer 2009). These compositions are comparable to other developed and developing countries worldwide (Troschinetz and Michelcic 2009). The ever increasing amount of plastic waste generated has caused an inevitable environmental issue.

Public awareness of plastic bottle recycling has been raised actively by various environmental campaigns over the past two decades. According to the Environment Protection Agency, United States, about 29% of PET bottles were recycled in 2010. Plastic waste recycling processes can generally be divided into four main categories, namely primary (re-extrusion), secondary (mechanical), tertiary (chemical), and quaternary (energy recovery) (Mastellone 1999, Sharma and Reddy 2004). About three-quarters of reclaimed PET in the United Kingdom and United States are used for manufacturing fibres for carpets, apparels and bottles (Al-Salem *et al*. 2009). Despite of the fact that all PETs are recyclable, the recovery or recycling rate of plastic waste is still at an unsatisfactory level, particularly in developing countries where the availability of technological resources for recycling is limited.

A simpler and more straight forward way of recycling or reusing the plastic wastes is highly desirable. Reusing plastic waste in construction materials has been attempted by numerous researchers. For instances, PET has been used as partial replacements for fine aggregates in concrete (Choi *et al*. 2005, Frigione 2010, Silva *et al*. 2012, Parcheco-Torgal *et al*. 2012). The strengths of PET-mixed concretes were comparable with those normal concrete specimens.

Recent studies showed that shear strength, stress-strain, and compressibility behaviors of soils can be improved by introducing a small portion of plastic pieces into the soil matrix. The idea replicates the fundamental principles of randomly distributed fiber reinforced soil, in which shear stresses in soil mobilize tensile resistance on the high tensile fibers such as tire chips (Yoon *et al*. 2008), polypropylene fiber (Consoli *et al*. 2009), nylon fiber (Ameta *et al*. 2009), coir fiber (Sivakumar Babu and Vasudevan 2008), and geotextile (Tandel *et al*. 2014) etc. In general, the shear strengths of these fiber reinforced soils increase with increases in aspect ratio, fiber content, fiber modulus, and soil fiber surface friction (Hejazi *et al*. 2012). Plastic waste-mixed cement-treated soil attempted by Omine *et al*. (1996) was among the earliest systematic efforts to study the feasibility of reusing plastic waste for soil improvement. The variables considered included cement content (0-300 kg/m³), slenderness of plastic pieces, and plastic content (0-7.5%). The unconfined compressive strength improvements reported were between 20 and 60% depending on the variables considered. Bueno (1997) and Consoli *et al*. (2002) found that plastic waste is capable of improving the stress strain behaviors of both cemented and uncemented soils. Choudhary *et al*. (2010) investigated the shear strength and deformation behaviors of uncemented sand reinforced with high density polyethylene (HDPE) plastic strips. They found that the California Bearing Ratio (CBR) value of plastic strips reinforced sand was approximately 3 times that of the unreinforced specimen. Neopany *et al*. (2012) performed a similar experiment on silty soil. They concluded that the CBR value of reinforced soil was 1.7 times higher than its original state. Sivakumar Babu and Chouksey (2011) investigated the shear strength and compressibility parameter of plastic (PET) mixed soil and sand. By mixing 1% of plastic waste content into the specimens, the improvement in unconfined compressive strength of soil and sand were 73.8% and 93.70%, respectively. The higher improvement in sand can be attributed to higher friction developed between sand particles and plastic waste than that in soil.

Previous studies have proven that plastic waste (PET)-mixed soil is a feasible technique of soil improvement. However, extensive studies need to be taken up before the technique can be readily

applied in practice. This paper investigates factors affecting the shear strength improvement of plastic wastes (PET)-mixed tropical residual soil. The mechanism of plastic reinforcement in tropical residual soil is more complicated than sand because tropical residual soils are normally characterized by large variations in particle sizes attributed to varying degree of weathering. The factors considered in the present study include plastic content, plastic slenderness ratio, plastic size, and soil particle size. A series of unconfined compression tests were carried out to determine the optimum conditions for promoting the shear strength improvement.

2. Materials and methods

2.1 PET

The plastic pieces used in the present study were extracted from typical PET water bottles with a wall thickness of 0.27 ± 0.05 mm. To maintain the consistency of the plastic dimensions and properties, only the upper part of the plastic bottle wall was used (Fig. 1). The water bottles were cut into sheets and subsequently into desired dimensions. Tensile tests were carried out on the PET strips in compliance with BS 527-1 (British Standard 2012). Fig. 2 shows the average stress-strain curve for three samples of PET. The PET has average yield strength of 89 MPa, average ultimate strength of 135 MPa, and average elastic modulus of 2.23 GPa.

2.2 Soil materials

The soil materials used in this study were typical tropical residual soils retrieved from two sites in Universiti Tunku Abdul Rahman, Kuala Lumpur campus, Malaysia. These sites were chosen to represent a coarse-grained and a fine-grained residual soil in order to study the compatibility of
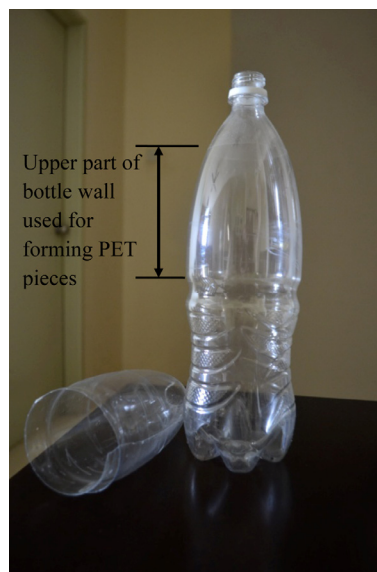

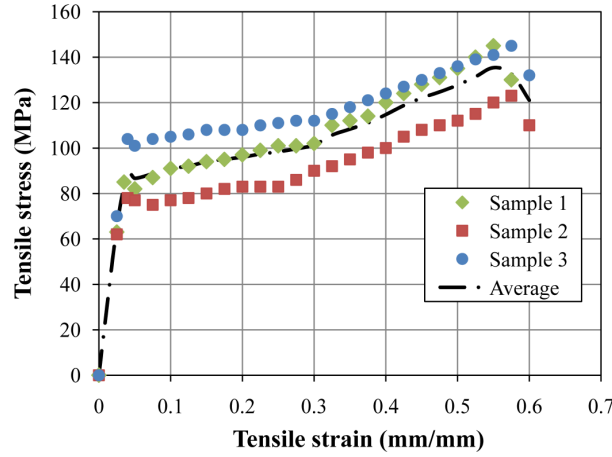Fig. 1 Typical PET water bottle

Fig. 2 Tensile stress -strain curve of PET

Table 1 Soil properties

Properties	Fine-grained soil	Coarse-grained soil
Grain sizes	Gravel - 0%	Gravel - 0%
	Sand - 38%	Sand - 87%
	Silt - 43%	Silt - 11%
	Clay - 19%	Clay - 2%
Liquid limit	40.4%	-
Plastic limit	24.9%	-
Maximum dry density, MDD	1689 kg/m^3	1714 kg/m^3
Optimum moisture content, OMC	16.6%	14.3%
Unconfined compressive strength, q_u	21.2 kPa	33.0 kPa

plastic pieces dimensions with various soil grain sizes. Table 1 tabulates the values of physical indices of the soil specimens. Based on the British Soil Classification System (BSCS), the fine-grained and coarse-grained residual soils were classified as Sandy Silt (MHS), and Well Graded Silty Sand (SWM), respectively.

2.3 Specimen preparations

Desired amounts of plastic waste (PET) pieces were mixed uniformly into air-dried soils at the optimum moisture content (OMC). The soil mixtures were sealed overnight for equilibrium. The soils were then compacted to 90% of maximum dry density (MDD) in three layers into a specimen mould of 50 mm in diameter (> 10% of maximum soil particle size, i.e., 2 mm) and 100 mm in length. This was achieved by setting out standard procedures of compaction for each soil type through trial and error. Finally, the shear strength of the compacted soil specimens were tested by unconfined compression test in accordance to ASTM D2166 (ASTM 2006). The selection of unconfined compression test over other shear strength testing was to enable feasible comparison of

Table 2 Experimental variables

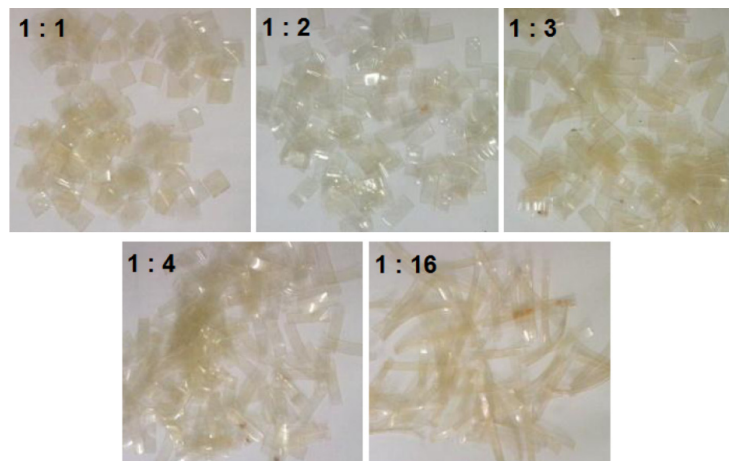| Variables	Values
Plastic content	0%, 0.5%, 1.0%, 1.5%, 2%
Plastic size	0.5 cm^2, 1cm^2
Plastic slenderness ratio	1:1, 1:2, 1:3, 1:4, 1:16
Soil grain size	Coarse grained soil, Fine-grained soil

Fig. 3 PET pieces cut into different slenderness ratios

the present findings with those reported by Sivakumar Babu and Chouksey (2011) whom also studied the strength performance of PET-mixed soils using the same test. It was important to ensure that the moisture content of all the compacted soils were consistent because the moisture content and suction in soil may affect considerably the unconfined compressive strength of soil. For this reason, the final moisture content of the specimen was tested and the specimens with moisture content varied by ± 1% from the average value were discarded.

2.4 Experimental variables

Four variables were considered in this study: (i) plastic content; (ii) plastic slenderness ratio; (iii) plastic size; and (iv) soil particle size, as tabulated in Table 2. These sets of variables have totalled 82 combinations of experiments. It should be noted that the plastic content was calculated as percentage of plastic weight to weight of dry soil. The plastic slenderness ratio is defined as the ratio of width to length. Fig. 3 shows the plastic pieces prepared in different slenderness ratios.
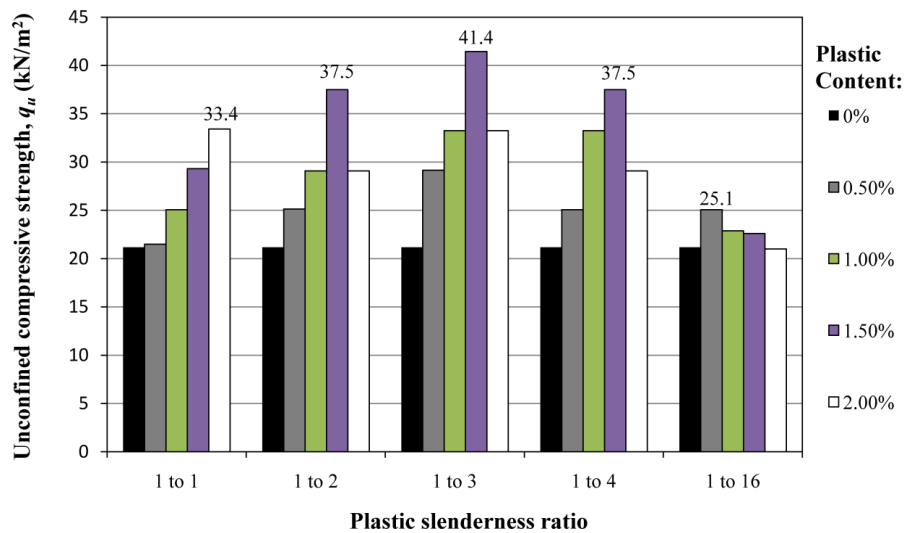
3. Results

Table 3 summarizes the results of unconfined compressive strength for the 82 experiments performed in this study. Comparisons of specific parameters are discussed in detail in the following sections.

Table 3 Summary of unconfined compressive strength results

Soil type	PET size	PET content	Unconfined compressive strength, q_u (kN/m²)				
			Slenderness ratio				
			1:1	1:2	1:3	1:4	1:16
Coarse-grained soil	0.5 cm²	0%			33.0 (0%)		
		0.5%	36.9 (12%)	49.5 (50%)	60.8 (84%)	56.9 (72%)	43.3 (31%)
		1.0%	59.2 (79%)	56.4 (71%)	62.8 (90%)	67.0 (103%)	57.0 (73%)
		1.5%	40.5 (23%)	44.9 (36%)	81.8 (148%)	75.5 (129%)	75.1 (127%)
		2.0%	48.0 (45%)	41.1 (25%)	59.3 (80%)	63.2 (92%)	67.6 (105%)
	1.0 cm²	0.5%	38.8 (18%)	48.7 (48%)	48.5 (47%)	52.9 (60%)	37.6 (14%)
		1.0%	55.6 (68%)	61.4 (86%)	63.1 (91%)	55.4 (68%)	41.6 (26%)
		1.5%	40.5 (23%)	53.2 (61%)	69.3 (110%)	64.3 (95%)	62.4 (89%)
		2.0%	48.1 (46%)	42.4 (29%)	47.4 (44%)	56.3 (71%)	38.8 (18%)
Fine-grained soil	0.5 cm²	0%			21.2 (0%)		
		0.5%	21.5 (1%)	25.1 (19%)	29.2 (38%)	25.1 (18%)	25.1 (18%)
		1.0%	25.1 (18%)	29.1 (37%)	33.2 (57%)	33.2 (57%)	22.9 (8%)
		1.5%	29.3 (38%)	37.5 (77%)	41.4 (95%)	37.5 (77%)	22.6 (7%)
		2.0%	33.4 (58%)	29.1 (37%)	33.2 (57%)	29.1 (37%)	21.3 (0%)
	1.0 cm²	0.5%	25.3 (19%)	25.3 (19%)	33.7 (59%)	25.3 (20%)	25.4 (20%)
		1.0%	26.8 (26%)	33.7 (59%)	41.8 (97%)	29.6 (39%)	29.6 (39%)
		1.5%	29.5 (39%)	37.8 (78%)	46.0 (117%)	33.6 (58%)	21.3 (0%)
		2.0%	21.2 (0%)	33.6 (58%)	29.5 (39%)	25.3 (20%)	16.8 (-21%)

*Note: Percentage in bracket represents improvement of unconfined compressive strength compared to the original soils

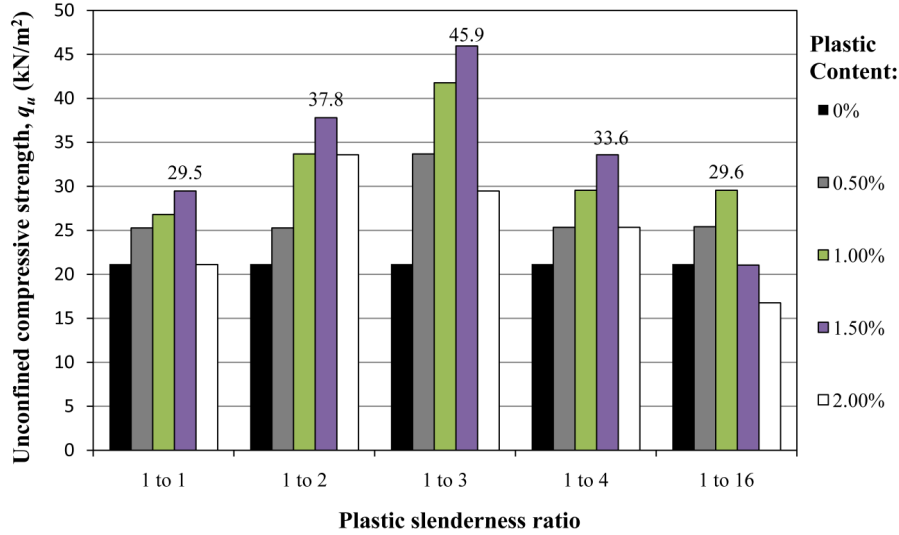Fig. 4 Unconfined compressive strengths of fine-grained soils mixed with 0.5 cm² PET pieces

Fig. 5 Unconfined compressive strengths of fine-grained soils mixed with 1.0 cm^2 PET pieces

3.1 Unconfined compressive strength of PET-mixed fine-grained residual soil

Figs. 4 and 5 show the unconfined compressive strengths of fine-grained soils mixed with 0.5 cm^2 and 1.0 cm^2 PET pieces, respectively. Both the specimens mixed with 0.5 cm^2 and 1.0 cm^2 PET pieces showed that the optimum shear strength improvements were achieved by adding 1.5% of PET content with slenderness ratio of 1:3. The original soil has an unconfined compressive strength of 21.2 kPa. All the PET-mixed soils exhibited improvements in shear strength (0-117%), except for the specimen mixed with 2% of 1.0 cm^2 PET pieces at slenderness ratio of 1:16 in which a decline in shear strength (21%) was observed. This could be attributed to disturbance of soil structures by the high content of slender and large PET pieces. Difficulty in mixing and compacting the soil mixture under such unfavorable PET configurations could be another plausible reason to this observation. The optimum shear strength improvement obtained from the 0.5 cm^2 PET pieces (95%) was comparatively lower than that of 1.0 cm^2 PET pieces (117%).

3.2 Unconfined compressive strength of PET-mixed coarse-grained residual soil

Figs. 6 and 7 show the unconfined compressive strengths for coarse-grained soils mixed with 0.5 cm^2 and 1.0 cm^2 PET pieces, respectively. Similar to the observations of fine-grained soils, the optimum shear strength improvements for coarse-grained soil were also obtained when mixing 1.5% of PET content with slenderness ratio of 1:3 into the soil. The unconfined compressive strength of the original coarse grained soil was 33.0 kPa. Upon mixing with PET pieces, the strengths improved by 12-148% depending on the slenderness ratio, content, and size of the PET pieces used. Opposite to the observations of fine-grained soil, the 0.5 cm^2 PET pieces in coarse-grained soils have consistently outperformed the 1.0 cm^2 counterparts. The optimum shear strength improvements using the 0.5 cm^2 and 1.0 cm^2 PET pieces were 148% and 110%, respectively.
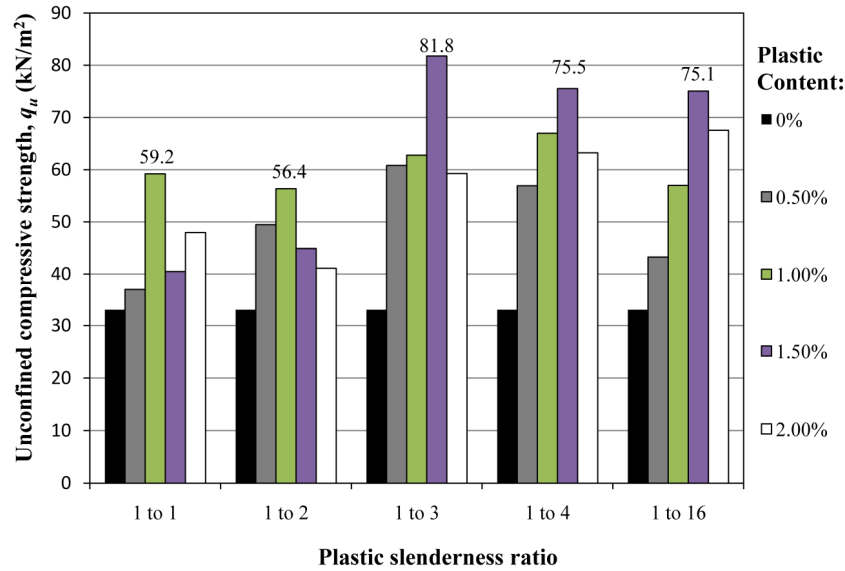
Fig. 6 Unconfined compressive strengths of coarse-grained soils mixed with 0.5 cm^2 PET pieces
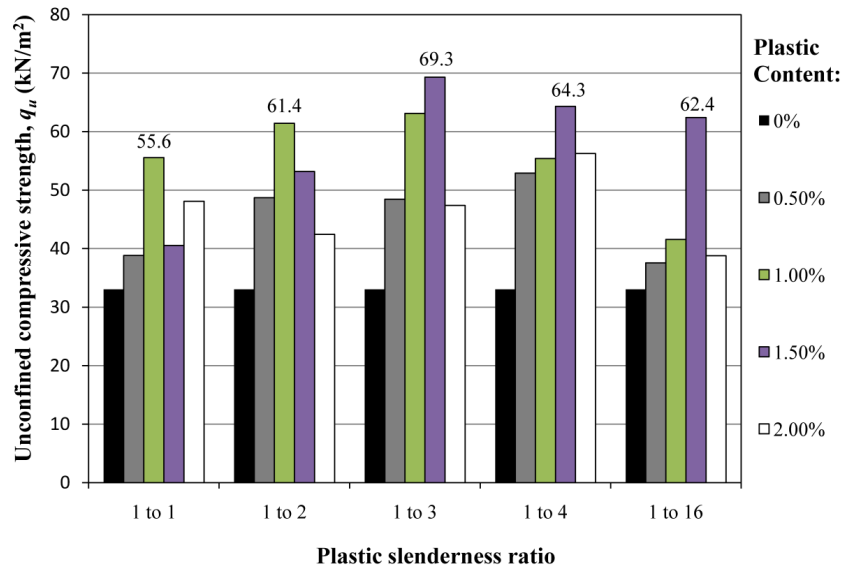

Fig. 7 Unconfined compressive strengths of coarse-grained soils mixed with 1.0 cm^2 PET pieces

3.3 Stress-strain curves of selected specimens

Stress-strain curves of selected specimens are presented to provide insights into the stress deformation behaviors and mechanism of shear strength improvement in PET-mixed soils. Fig. 8 shows the stress-strain curves of the fine-grained soil mixed with various contents of 1:3 and 1.0 cm^2 PET pieces. Apparently, the inclusion of PET pieces has not altered the elastic modulus or

stiffness of the soils as all the curves have almost identical gradients within the linear elastic state. However, the increase in PET content has led to a larger plastic strain. For instances, the original soil deformed about 1% of plastic strain. By mixing 2% of PET pieces, the soil was capable of yielding an approximately 2% of plastic strain before reaching the rupture strength.

  Fig. 9 compares the stress-strain curves for fine-grained soils mixed with PET pieces of various slenderness ratios. The PET content and size were fixed at 1.5% and 1.0 cm^2, respectively. Similarly, the slenderness ratio has negligible effect on the elastic modulus of soil. The plastic

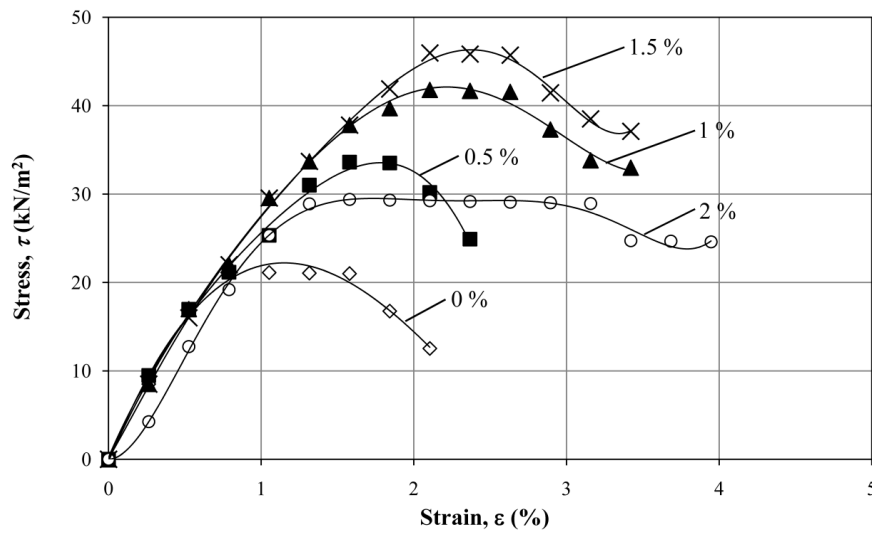
Fig. 8 Stress-strain curves of fine-grained soil mixed with various contents of PET pieces (Slenderness ratio = 1:3, PET size = 1.0 cm^2)
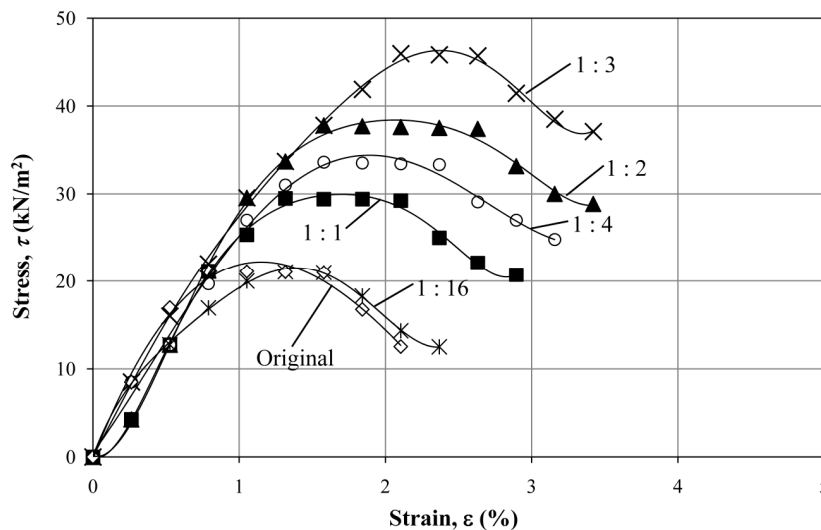

Fig. 9 Stress-strain curves of fine-grained soil mixed with PET pieces of various slenderness ratios (PET content = 1.5%, PET size = 1.0 cm^2)
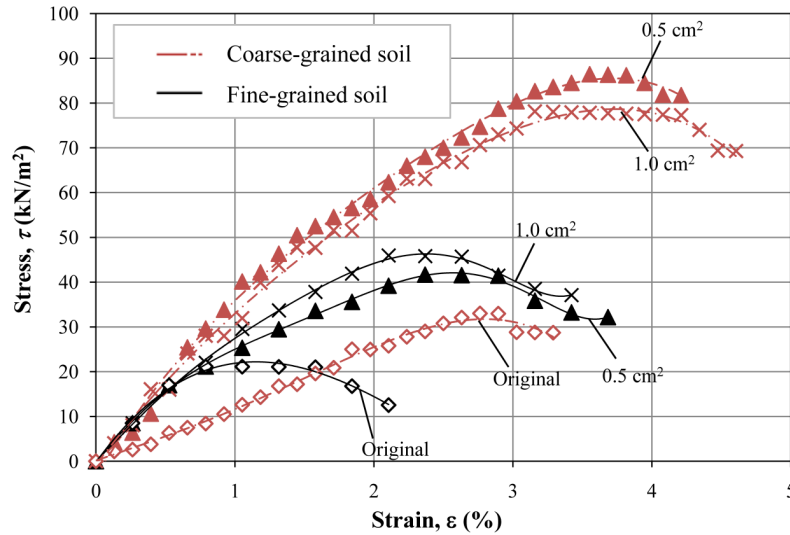
Fig. 10 Stress-strain curves of original soils and soils mixed with optimum PET configurations

strain of soil reduced with increased slenderness of PET. This observation was particularly significant for the PET pieces with the highest slenderness ratio (i.e., 1:16). The soil almost failed instantaneously upon achieving the yield strength. It is suggested that the slender plastic pieces tend to rupture at a high stress and lead to the sudden failure.

Fig. 10 shows the stress-strain curves for coarse-grained and fine-grained soils mixed with the optimum PET configurations. The inclusion of PET pieces into the soils yielded a larger elastic strain, and hence increased the yield strength of soil. The stress-strain curves of both 0.5 cm^2 and 1.0 cm^2 PET pieces mixed in a same type of soil were almost identical to each other. The result implied that the size of plastic pieces has minimal effect on the deformation behavior of soil. By comparing the stress-strain curves of coarse-grained and fine-grained soils, it is obvious that the PET-mixed coarse-grained soil yielded a larger elastic strain and a higher yield strength than that of the fine-grained soil. In addition, PET-mixed coarse-grained soil has a higher elastic modulus than the original soil. This was not observed in the fine-grained soil. The result implied that the soil improvement by PET is more effective in coarse-grained soil than in fine-grained soil.

4. Discussions

Reusing PET waste for geotechnical applications not only reduces environmental burdens of handling the waste, but also significantly improves inherent engineering properties of soil for various construction purposes. Most of the PETs used in current bottled water industry are non-degradable. In additions, they are characterized by high tensile strength, flexible, and high toughness. These characteristics make PET a feasible material for permanent soil reinforcements as it is capable of absorbing tensile stresses and deform plastically without fracturing.

The present experimental results revealed that unconfined compressive strength improvements of PET-mixed soils is a set of functions of PET content, PET slenderness ratio, PET size, and soil grain size. Sivakumar Babu and Chouksey (2011) found that the shear strength of soil increased

with increased PET content. However, their study only focused on 0-1% of PET content. The optimum PET content could not be determined in their study. The present study showed that the findings of Sivakumar Babu and Chouksey (2011) were only valid for PET content up to 1.5%. Increasing the amount of randomly distributed plastic pieces, based on probability principle, would increase the chance for the plastic pieces to be oriented along the direction of principal tensile strain. Higher friction could be developed through greater contact area between soil and plastic pieces, and hence results in a greater shear strength improvement. Beyond 1.5% of PET content (i.e., 2% of PET content), the shear strength showed a decline trend. Ahmed *et al*. (2011) found that excessive PET content may cause slippage when the surfaces of two or more PET pieces were in contact between each other.

The optimum PET slenderness ratio for both coarse and fine-grained soils is 1:3. Short and square PET pieces (i.e., 1:1) are normally weak in pull out resistance. Despite of the fact that slender reinforcing elements are preferred for stress transferring mechanism in reinforced soil matrix, excessively slender PET pieces (1:16), however, are not favorable because the tensile resistance force per unit length of PET pieces tend to decrease with its width. Furthermore, it is difficult to distribute the excessively long and slender PET pieces uniformly into soil matrix. This difficulty was also reported by Al-Refeai (1991) who attempted to reinforce soils with slender glass fibers.

The size of PET pieces could also affect the performance of PET-mixed soil. Contradicting results were observed with regards to the effect of PET size on shear strength improvements for fine and coarse-grained soils. Under a constant PET content, Ahmed *et al*. (2011) found that soils mixed with large PET pieces would yield lower shear strength than that of small PET pieces. This is because more PET pieces are available in the soil matrix when the small PET pieces are used at a fixed gravimetric content. As a result, there are higher chances that PET pieces will intercept the shear plane of soil, and hence improve its shearing resistance. For the PET-mixed fine-grained soil in this study, the large PET pieces have consistently outperformed the small PET pieces. A plausible explanation to this observation is that a large contact area between soil particles and PET pieces may be required for the fine-grained soil to develop sufficient frictional resistance. This is because fine-grained soils are normally characterized by lower internal frictions than coarse-grained soils.

From the results of unconfined compressive strength improvement and stress-strain curves, coarse-grained soils showed a more favorable response to PET reinforcement than fine-grained soils. Again, this can be attributed to the high internal friction of coarse-grained soils. High frictional resistance can be developed between PET surface and coarse soil particles which are normally characterized by rough textures. Similar findings were reported by Sivakumar Babu and Chouksey (2011) who compared the stress strain behaviors of PET-mixed laterite soil and sand. Deb and Konai (2014) also found that the bearing capacity of geotextile reinforced sand decreased with increasing fine contents.

Fig. 11 provides an illustration of the possible mechanism of shear strength improvement by the inclusion of PET pieces into soil matrix. Failure may develop along a potential shearing plane in the original soil when the load applied is in excess of the soil strength (Fig. 11(a)). With the introduction of the randomly distributed PET pieces (Fig. 11(b)), some of the PET pieces are oriented in positions such that they effectively intercept the potential failure plane of soil (PET A). The shearing stresses will be absorbed by the PET pieces in the form of tensile stresses. However, this requires a strong grip at both ends of the PET pieces. Particle grains which cannot develop sufficient frictional resistance with PET pieces may not be able to transmit the shearing stresses to

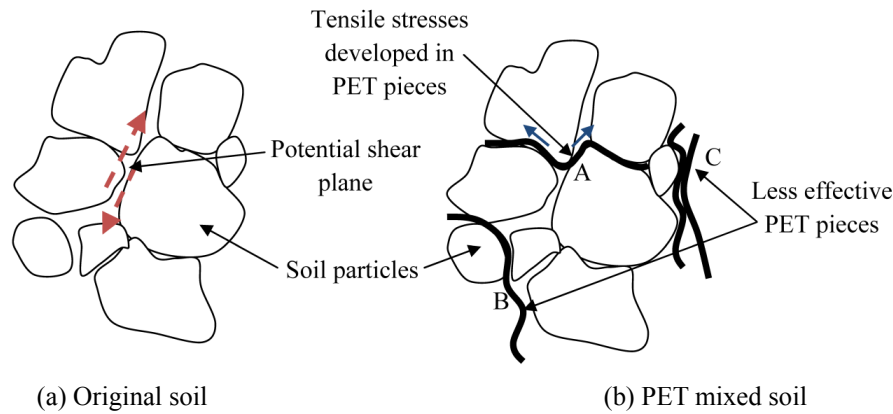(a) Original soil   (b) PET mixed soil

Fig. 11 Mechanism of shear strength improvement in PET-mixed soil

PET pieces effectively (PET B). Some of the PET pieces may be oriented such that they are in contact between each other (PET C). PET pieces with such orientation are not favorable for shear strength improvement as slippage may occur and further weaken the shear strength of soil.

5. Conclusions

A series of unconfined compression tests were carried out to investigate the optimum configuration for promoting unconfined compressive strength improvement in PET-mixed tropical residual soils. The following conclusions can be drawn from the study:

- The optimum slenderness ratio and PET content for unconfined compressive strength improvement are 1:3 and 1.5%, respectively. Large PET pieces (i.e., 1.0 cm^2) are favorable for fine-grained residual soil, while small PET pieces (i.e., 0.5 cm^2) are favorable for coarse-grained residual soil.
- Coarse-grained residual soils show a more favorable response to PET reinforcement than fine-grained residual soils. The optimum unconfined compressive strength improvements for coarse and fine-grained residual soils are 148% and 117%, respectively.
- A high PET content would yield a high plastic strain. In contrast, a high slenderness ratio would reduce the plastic strain and cause the soil to fail instantaneously upon reaching its yield strength.
- The orientation of plastic pieces in soil and frictional resistance developed between soil particles and PET surface are two important factors affecting the shear strength performance of PET-mixed residual soil.

Acknowledgments

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