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Full length article

## Strength properties of soft clay treated with mixture of nano-SiO<sub>2</sub> and recycled polyester fiber



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### ABSTRACT

This paper investigates the effect of recycled polyester fiber, produced from polyethylene (PET) bottles, in combination with nano-SiO<sub>2</sub> as a new stabilizer to improve the mechanical properties of soils. We intend to study the effect of adding nano-SiO<sub>2</sub> and recycled polyester fiber on soil engineering properties, especially the shear strength and unconfined compressive strength (UCS), using clayey soil with low liquid limit. Three different combinations of fiber-soil ratios ranging between 0.1% and 0.5% as well as three different combinations of nano-soil ratios ranging between 0.5% and 1% are used. The shear strength and UCS of treated specimens are obtained from direct shear test and unconfined compression test, respectively. Results of this study show that the addition of recycled polyester fiber and nano-SiO<sub>2</sub> increases the strength of soil specimens. Both the shear strength and UCS are improved by increasing the contents of recycled polyester fiber and nano-SiO<sub>2</sub> in the soil mixture. The increase in the nano-SiO<sub>2</sub> content leads to a reduction in failure strain, but the increase in the content of recycled polyester fiber leads to an increase in failure strain. The increase in the contents of recycled polyester fiber and nano-SiO<sub>2</sub> leads to an increase in elastic modulus of soils. Based on the test results, the addition of recycled polyester fiber improves the mechanical properties of soils stabilized with nano-SiO<sub>2</sub> as well as the recycled polyester fiber has a positive effect on soil behaviors.

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### 1. Introduction

The purpose of soil stabilization is to increase the strength properties and reduce the settlement. The recycled materials in geotechnical engineering have many economic and environmental benefits for the nature. This approach reduces the cost of engineering projects. Thus, several studies have been conducted to investigate the use of recycled materials as a new stabilizer in soil stabilization projects.

For soil stabilization, fiber, cement and different materials were used to increase the strength parameters of soils. The work of Hamidi and Hooresfand (2013) indicated that the addition of polypropylene fiber leads to increases in shear strength parameters and failure stress of cemented soils. Park (2009) studied the influence of polyvinyl alcohol (PVA) fiber on compressive strength of cemented sand, and reported that the 1% fiber makes the axial strain of cemented sand two times larger than that of normal sand.

Mirzababaei et al. (2013) conducted a compaction test on clayey soils containing carpet wastage fiber, and concluded that the addition of fiber decreases the maximum dry unit weight of clay and also increases its optimum moisture, and these two parameters decrease the swelling pressure of clay. Park (2013) carried out a series of tests on the cemented sand reinforced by PVA, and found that the unconfined compressive strength (UCS) of sand with 2% cement and 1% fiber becomes 3.5 times that of non-reinforcement soil. In a study conducted by Mohamed (2013), the addition of 1% dry straw decreases the maximum dry unit weight and shrinkage limit of clay. Estabragh et al. (2013) pointed out that, based on the total and effective stresses, the increase in the content of nylon fiber leads to an increase in shear strength parameters of clay. Zulkifley et al. (2013) believed that the addition of cement and sodium bentonite results in significant reductions in liquid limit, plastic limit and plasticity index of clay.

Several studies have been conducted on the stabilization of soft clay using different materials, such as recycled materials, natural fiber, and chemical materials. However, over the last twenty years, nanotechnology has evolved as an interdisciplinary area, which has attracted great interest. Pham and Nguyen (2014) carried out a series of tests on the clayey soils by adding nano-SiO<sub>2</sub>, and found that the addition of nano-SiO<sub>2</sub> leads to a reduction in the swelling index of clay. In a study conducted by Mohammadi and Niazi (2013), adding nano-clay increases the liquid and plastic limits of

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soil and also increases the shear strength parameters of treated specimens. The research conducted by Noll et al. (1992), Yonekura and Miwa (1993), and Zhang et al. (2004) indicated that the addition of nano-SiO<sub>2</sub> increases the strength and the Atterberg limits of clay and also decreases its permeability. Niroumand et al. (2013) studied the influence of nano-clay on compressive strength of earth bricks as sustainable materials, and found that the nano-clay makes the compressive strength of earth bricks 4.8 times larger than that of normal earth bricks. Taha and Taha (2012) carried out numerous tests on clay behavior by adding nano-particles. They concluded that the addition of nano-Al<sub>2</sub>O<sub>3</sub> to the soil decreases both the values of expansive and shrinkage strains. In a study conducted by Luo et al. (2012), the addition of nano-Al<sub>2</sub>O<sub>3</sub> to the soil reduces the maximum dry unit weight and increases the optimum moisture content, and the addition of different amounts of nano-Al<sub>2</sub>O<sub>3</sub> to treated soil reduces the plasticity index values.

In the studies conducted by above-mentioned investigators, the recycled materials were used alone. In this condition, the recycled materials result in improvement of some engineering properties and deterioration of other properties of soils. Moreover, few previous papers have computed the influence of mixture of recycled polyester fiber and nano-SiO<sub>2</sub> on the strength properties of clay. Hence, the aim of this study is to investigate and evaluate the feasibility of using recycled polyester fiber in combination with nano-SiO<sub>2</sub> as a new stabilizer to improve the mechanical properties of soft clay.

## 2. Materials and methods

### 2.1. Materials used

The expansive soil used was sampled from the Behbahan suburbs in Iran. The soil contains clay and sand. Nano-SiO<sub>2</sub> used was purchased from Nanosany Company in Iran, and recycled polyester fiber used was purchased from Fiberarjan Company in Iran.

According to the unified soil classification system, the soil used is classified as clayey soil with low liquid limit. The liquid and plastic limits of soil are estimated to be 30 and 22, respectively. The grain size distribution curve of soil is illustrated in Fig. 1. From this figure, it can be observed that the soil contains 22% fine sand, 29% silt, and 49% clay. The maximum dry density of soil is 16.4 kN/m<sup>3</sup> and the optimum moisture content of soil is 15%. Recycled polyester fiber, as shown in Fig. 2, was used for reinforcement. Fiber used is made of the bottles waste by chopping them into small length with almost the same minimal diameter of 20 μm. The length of recycled polyester fiber is 20 mm. The physical properties of recycled

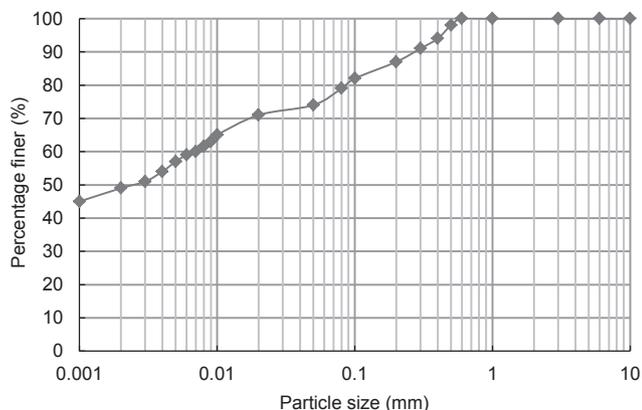


Fig. 1. Grain size distribution curve of soil.

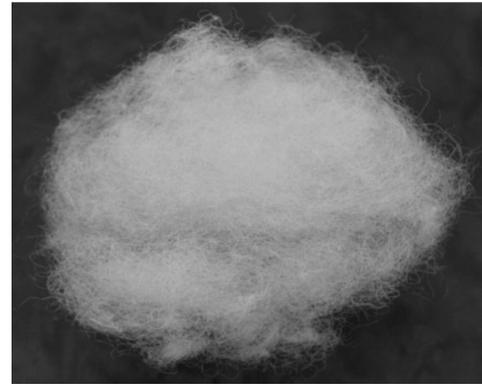


Fig. 2. Picture of recycled polyester fiber.

Table 1

Properties of recycled polyester fiber.

Specific gravity	Moisture content (%)	Tensile strength (MPa)	Color
1.22	0.4	200–400	Colorless

polyester fiber are presented in Table 1. The physical properties and chemical composition of nano-SiO<sub>2</sub> are presented in Tables 2 and 3, respectively.

### 2.2. Test methods

In order to evaluate the effect of nano-SiO<sub>2</sub> and random inclusion of fiber on strength parameters of the specimens, twelve groups of specimens, including one group of natural specimens, one group of specimens reinforced with recycled polyester fiber, one group of specimens stabilized with nano-SiO<sub>2</sub>, and nine groups of specimens treated with fiber-nano-SiO<sub>2</sub>, were used in two tests, i.e. unconfined compression test and direct shear test. To evaluate the shear parameters of mixture, the direct shear tests were carried out in three normal stresses: 100 kPa, 200 kPa, and 300 kPa. To investigate the increase in UCS due to addition of recycled polyester fiber and nano-SiO<sub>2</sub>, a series of unconfined compression tests was conducted on clay treated with recycled polyester fiber and nano-SiO<sub>2</sub> and natural specimens. The laboratory tests were carried out with different contents of recycled polyester fiber (0.1%, 0.3%, and 0.5% of soil dry weight) and different contents of nano-SiO<sub>2</sub> (0.5%, 0.7%, and 1% of soil dry weight).

#### 2.2.1. Sample preparation

In this study, three various contents of nano-SiO<sub>2</sub> (i.e. 0.5%, 0.7%, and 1% of soil dry weight) were selected. In the laboratory, the soil was crashed by a hammer and then screened through sieves. In order to prepare specimens stabilized with nano-SiO<sub>2</sub> and recycled polyester fiber, the soil was divided into five layers and each layer was sprayed with the prescribed amount of nano-SiO<sub>2</sub>. Each layer was mixed alone by horizontally cylindrical mixer for at least 1 h. This procedure is the best method to obtain homogeneous samples (To et al., 2011). Because of the fact that the tests were performed under constant moisture content and due to the absorption of

Table 2

Physical properties of nano-SiO<sub>2</sub>.

Purity (%)	Average particle size (nm)	Specific surface area (m <sup>2</sup> g <sup>-1</sup> )	Bulk density (g cm <sup>-3</sup> )	Real density (g cm <sup>-3</sup> )	Color
99	11–13	600–785	0.1	2.4	White

**Table 3**  
Chemical composition of nano-SiO<sub>2</sub>.

Material	Content (%)
SiO <sub>2</sub>	99.7
Ti	0.012
Ca	0.007
Na	0.005
Fe	0.002

water by nano-SiO<sub>2</sub>, the mixing of soil with >1% nano-SiO<sub>2</sub> content leads to the lack of water in the soil/nano-SiO<sub>2</sub> mixture; consequently, the soil becomes less compressible. Thus, the optimum nano-SiO<sub>2</sub> content was 1%. Then recycled polyester fiber was added to the composite of soil and nano-SiO<sub>2</sub> at various amounts from 0.1% to 0.5%. The composite of soil and nano-SiO<sub>2</sub> was divided into three layers and each layer was mixed with the prescribed amount of recycled polyester fiber. Each layer was mixed alone by hands. It is difficult to mix the soil with >0.5% recycled polyester fiber and the fiber was tangled together to form fiber pockets. Hence, the optimum content of recycled polyester fiber was 0.5%. The composite of soil, nano-SiO<sub>2</sub> and fiber was mixed with the optimum moisture content obtained from standard Proctor compaction test. This nano-composite was mixed in an impermeable metal container in order to reduce water loss, and it was used to evaluate the effect of recycled polyester fiber and nano-SiO<sub>2</sub> on strength properties of the soft clay. When the nano-SiO<sub>2</sub> was used alone, the composite of soil and nano-SiO<sub>2</sub> was provided as described above; in addition, water was added to the composite if needed. When recycled polyester fiber was used alone, the determined amount of recycled polyester fiber was mixed with the soil by hands until all the fiber was mixed thoroughly. Ultimately, the specified amount of water was added.

### 2.2.2. Specimen preparation for direct shear test

The direct shear test is performed under fixed conditions and according to standard ASTM D3080–90. The mixture was filled in a cylindrical mold (101.4 mm in diameter and 116.5 mm in height) in three equal layers and each layer was compacted using a tamping device to attain the target density. In this study, the shear ring with the dimensions 60 mm × 60 mm × 25 mm was used. This ring was pushed into the soil mixture by hydraulic jack. Then the specimens were extruded into the shear box. In order to prepare the consolidated and saturated specimens, the specimens were kept in the shear box bowl filled with water for about 24 h; meanwhile, the normal stresses of 100 kPa, 200 kPa, and 300 kPa were applied. The drainage was allowed from the top and bottom of the shear box. Then the specimen was sheared under undrained condition by applying the shear stress. The rate of horizontal displacement was maintained at 1.25 mm/min. For each combination of mixture, three specimens were prepared and the average of test data was obtained. In total, 144 groups of direct shear tests were conducted by varying contents of recycled polyester fiber and nano-SiO<sub>2</sub>. The effects of nano-material and fiber on the shear parameters of soft clay were recorded up to a total horizontal displacement of 13 mm.

### 2.2.3. Specimen preparation for unconfined compression test

The unconfined compression test was performed under fixed conditions and according to standard ASTM D2166–87. The mixture was filled in a cylindrical mold (101.4 mm in diameter and 116.5 mm in height) in three equal layers and the number of blows required per layer was 25. The stainless steel tube of 38 mm in diameter and 100 mm in height was pushed into the soil mixture by hydraulic jack. Then the specimen was pushed into a stainless metal tube of 38 mm in diameter and 76 mm in height.

Subsequently, the specimen was pushed out from the stainless steel tube without disturbance and used for testing. For each combination of mixture, three samples were prepared and the average value of test data was obtained. The rate of strain was maintained at 1 mm/min. In total, 48 groups of unconfined compression tests were conducted by varying contents of recycled polyester fiber and nano-SiO<sub>2</sub>.

## 3. Test results and discussions

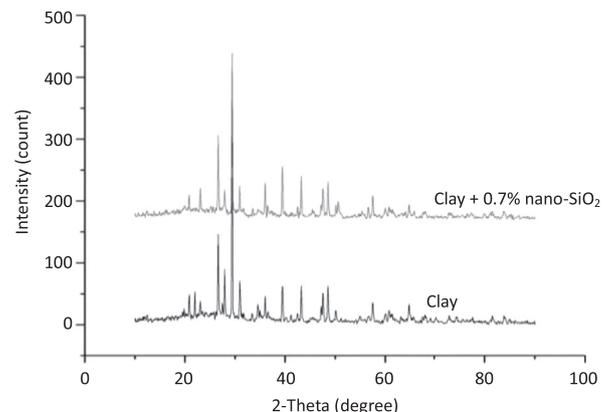
In this study, different tests were carried out on four kinds of specimens, i.e. (1) natural clay specimens, (2) specimens containing recycled polyester fiber, (3) specimens containing nano-SiO<sub>2</sub>, and (4) specimens containing mixture of recycled polyester fiber and nano-SiO<sub>2</sub>. The effects of recycled polyester fiber, nano-SiO<sub>2</sub> and mixture of recycled polyester fiber and nano-SiO<sub>2</sub> on clay behavior, shear strength and elastic modulus were evaluated.

Initially the soil stabilized with nano-SiO<sub>2</sub> was left for curing, then the X-ray diffraction (XRD) test was carried out to check if there is a chemical reaction for nano-material to the soil or not. The curves of natural clay specimen and clay +0.7% nano-SiO<sub>2</sub> specimen obtained from XRD test are shown in Fig. 3. From this figure, one can conclude that the nano-SiO<sub>2</sub> cannot do chemical reaction with soil material by just mixing with water.

### 3.1. Direct shear test

#### 3.1.1. Effect of recycled polyester fiber on shear strength of clay

The relation between shear stress and horizontal displacement of clay reinforced with recycled polyester fiber is illustrated in Fig. 4. It can be seen from Fig. 4 that the shear stress of clay reinforced with recycled polyester fiber occurs at larger displacement in all specimens compared to the natural clay. With inclusion of recycled polyester fiber in the clay, the increase in normal stress  $\sigma_n$  contributes to increase in the peak strength of clay. The main reason could be that by increasing the normal stress, the contact force and interlock between soil particles increase. The increase in the content of recycled polyester fiber leads to an increase in shear strength of the mixture. From Fig. 4, one can conclude that the addition of 0.5% recycled polyester fiber leads to an increase in peak shear stress from 111 kPa to 200 kPa, compared to the natural clay, indicating an increase in shear strength by 80%. Compared to the natural clay, the peak shear stresses increase by 20% and 67%, respectively, when the contents of recycled polyester fiber are 0.1% and 0.3%. However, by further increasing fiber content, as in the case of 0.5%, this increase is only 80%. Hence, addition of recycled



**Fig. 3.** XRD analysis of natural clay and clay stabilized with nano-SiO<sub>2</sub>.

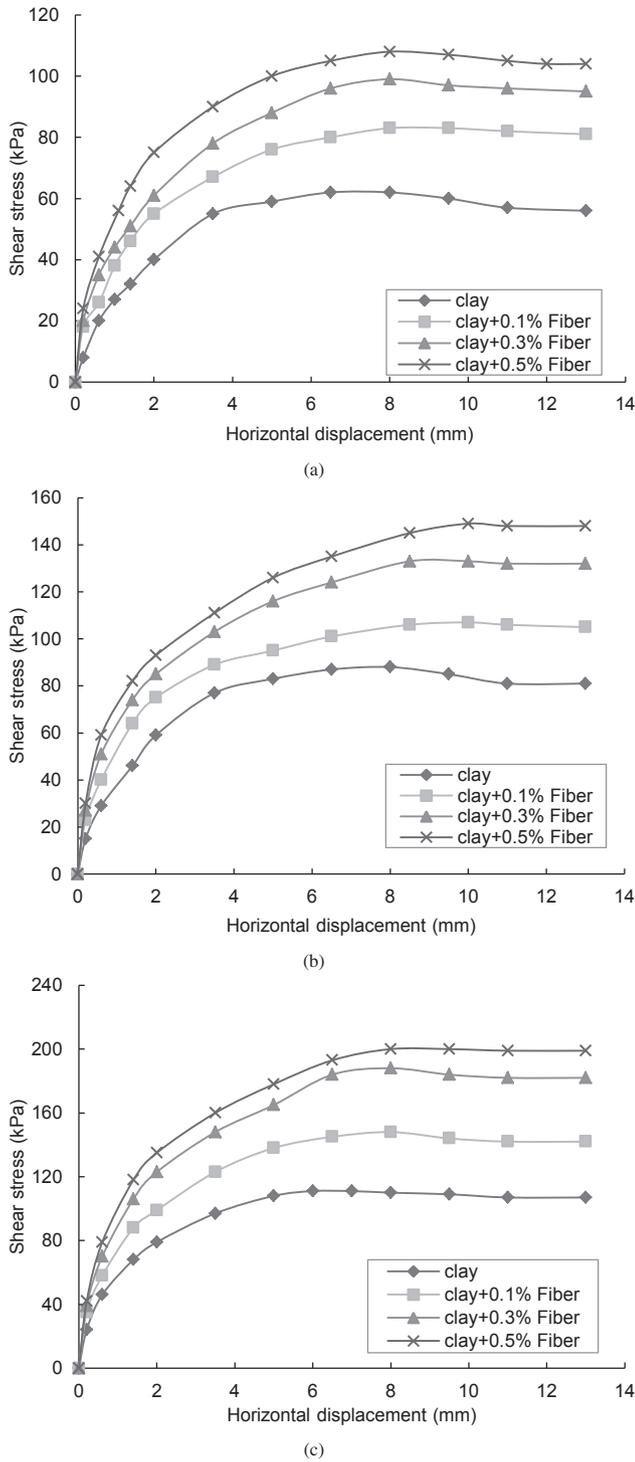


Fig. 4. Stress-displacement curves of clay reinforced by recycled polyester fiber obtained from direct shear test. (a)  $\sigma_n = 100$  kPa, (b)  $\sigma_n = 200$  kPa, and (c)  $\sigma_n = 300$  kPa.

polyester fiber more than 0.3% is not reasonable to increase shear strength. As a result, the optimum content of recycled polyester fiber is found to be 0.3%. The shear strength parameters of specimens are illustrated in Table 4. It is clear from Table 4 that the specimens reinforced with recycled polyester fiber exhibit an increase in the shear strength parameters. When the content of recycled polyester fiber increases from 0.3% to 0.5%, the angle of internal friction and the cohesion increase by 19% and 8%,

Table 4  
Shear parameters of fiber reinforced clay.

Specimens No.	Fiber content (%)	Cohesion, $c$ (kPa)	Angle of internal friction, $\phi$ ( $^\circ$ )
1	0	38	13.5
2	0.1	56	14.6
3	0.3	59	19.3
4	0.5	64	23.3

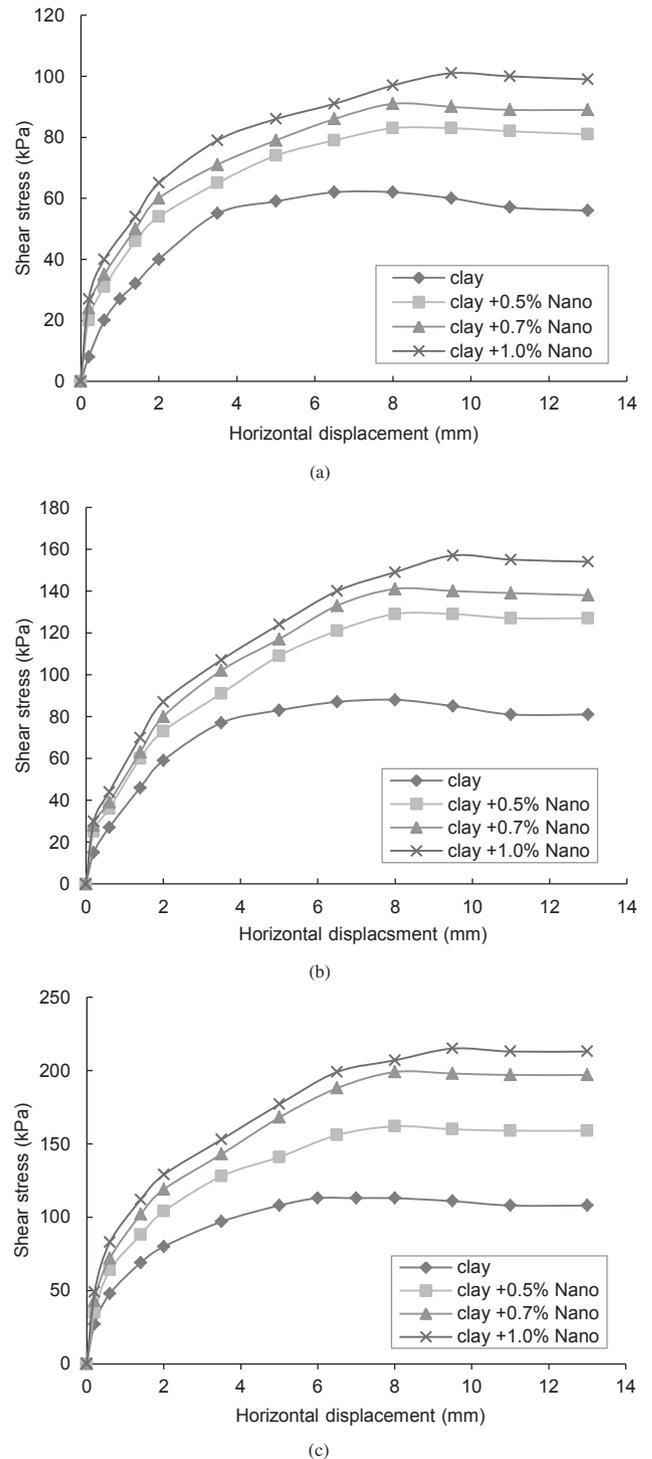


Fig. 5. Stress-displacement curves of clay stabilized with nano-SiO<sub>2</sub> obtained from direct shear test. (a)  $\sigma_n = 100$  kPa, (b)  $\sigma_n = 200$  kPa, and (c)  $\sigma_n = 300$  kPa.

**Table 5**  
Shear strength parameters of clay stabilized with nano-SiO<sub>2</sub>.

Specimens No.	Nano-SiO <sub>2</sub> content (%)	Cohesion, c (kPa)	Angle of internal friction, $\varphi$ (°)
1	0	38	13.5
2	0.5	40.6	21.8
3	0.7	42.3	27.92
4	1	45	29.46

respectively. It means that recycled material performs a significant role in the increase in angle of internal friction. The fiber surface is connected with plenty of clay particles which make the contribution to friction strength between the fiber and clay particles. Consequently, the shear strength parameters of the treated specimens are improved.

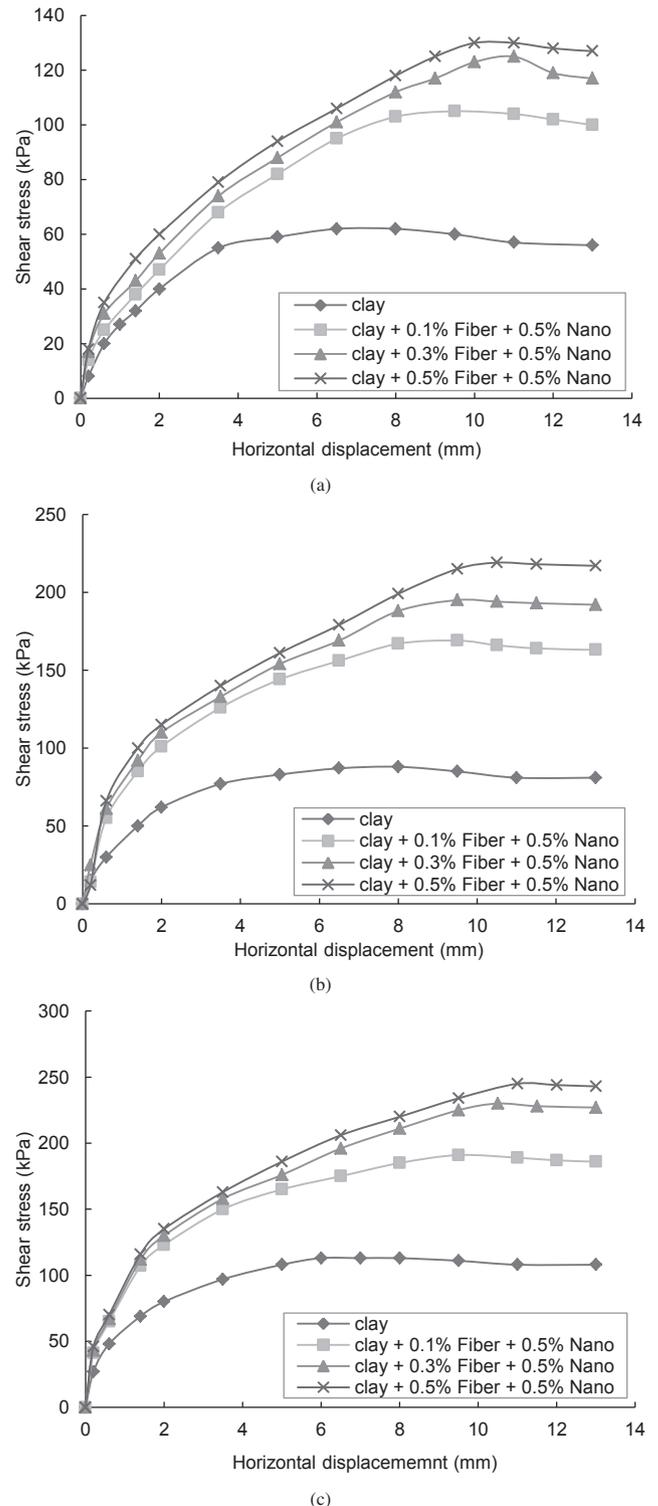
**3.1.2. Shear strength parameters of clay improved by nano-SiO<sub>2</sub>**

The relation between shear stress and horizontal displacement of clay stabilized with nano-SiO<sub>2</sub> is illustrated in Fig. 5. It can be seen from Fig. 5 that the shear stress of specimens stabilized with nano-SiO<sub>2</sub> occurs at larger displacement in all specimens compared to the natural clay. The observation of this figure indicates that the increase in nano-SiO<sub>2</sub> content leads to an increase in shear stress of stabilized clay. With inclusion of nano-SiO<sub>2</sub> to the clay, the increase in normal stress contributes to the increase in shear strength of clay. At the normal stress of 300 kPa, the shear stresses, compared to the natural clay, increase by 42%, 76%, and 90% for 0.5%, 0.7%, and 1% nano-SiO<sub>2</sub> contents, respectively. It can be seen from Fig. 5 that the shear stresses of clay stabilized with 0.7% and 1% nano-SiO<sub>2</sub> are close to each other. Hence, the optimum nano-SiO<sub>2</sub> content is found to be 0.7%. The shear strength parameters are presented in Table 5. It is shown that, with increase in nano-SiO<sub>2</sub> content, the shear strength parameters of clay stabilized with nano-SiO<sub>2</sub> increase. The increase ratios of the angle of internal friction and cohesion are 1.61, 2.1, 2.2 and 1.06, 1.11, 1.18, respectively, for nano-SiO<sub>2</sub> contents of 0.5%, 0.7%, and 1%. The results show that, with increase in nano-SiO<sub>2</sub> content, the increase rate of angle of internal friction is faster than that of cohesion. Therefore, the angle of internal friction of clay stabilized with nano-SiO<sub>2</sub> is more efficient than the cohesion of stabilized soil in increasing the strength of soil.

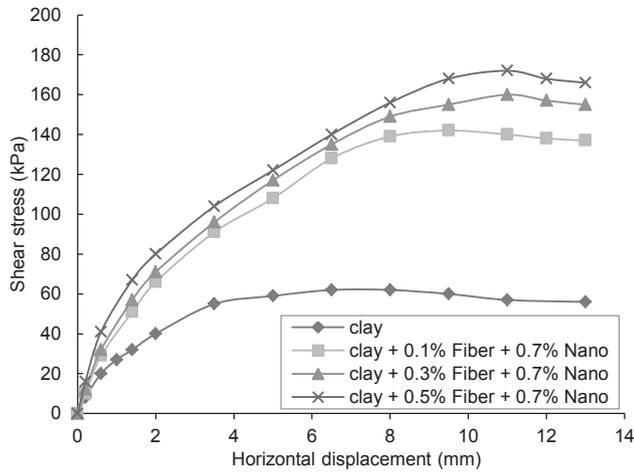
**3.1.3. Shear strength parameters of clay improved by recycled polyester fiber and nano-SiO<sub>2</sub>**

The results of direct shear test on clay improved by recycled polyester fiber and nano-SiO<sub>2</sub> are shown in Figs. 6–8. The observation of these figures indicates that the increase in the contents of recycled polyester fiber and nano-SiO<sub>2</sub> causes the increase in shear stress of clay. The shear stress of specimens treated with nano-SiO<sub>2</sub> and recycled material occurs at larger displacement in all specimens compared to the natural clay. With inclusion of nano-SiO<sub>2</sub> and recycled polyester fiber to the clay, the increase in normal stress contributes to the increase in shear strength of clay. The maximum increase in peak shear stress of treated specimens occurs at 1% nano-SiO<sub>2</sub> content. By adding 1% nano-SiO<sub>2</sub>, the peak shear stresses increase by 163% and 190%, respectively, when the contents of recycled polyester fiber are 0.1% and 0.3%. However, by further increasing the fiber content, as in the case of 0.5% fiber, this increase is 200%, only a little larger than 190%. Because of this, the addition of recycled polyester fiber more than 0.3% is not reasonable to improve the shear strength of clay. The optimum value of the shear strength is observed at 0.3% fiber + 1% nano-SiO<sub>2</sub> content, which is 3 times the shear stress of the natural clay, 1.5 times that of the nano-SiO<sub>2</sub> treated specimens, 1.62 times that of the recycled material treated specimens. The values of cohesion and angle of internal

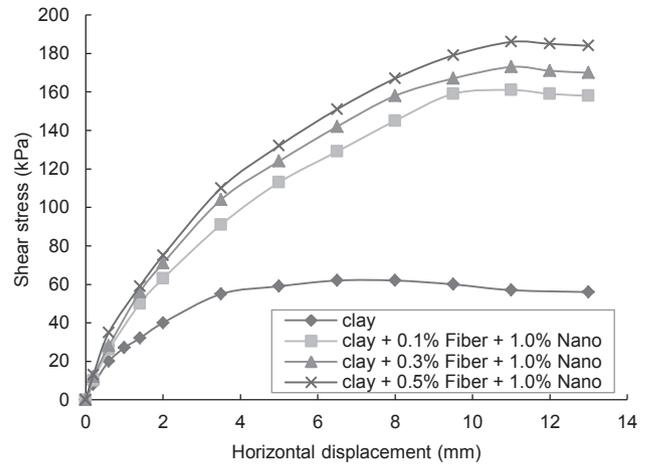
friction of specimens are presented in Tables 6–8. It is clear from Tables 6–8 that the contents of recycled polyester fiber and nano-SiO<sub>2</sub> have a positive effect on the shear strength parameters of treated specimens. By adding 0.5% nano-SiO<sub>2</sub>, the increase ratios of the angle of internal friction and cohesion for treated specimen are 2 and 1.92, respectively, for fiber content of 0.3%. Also by adding



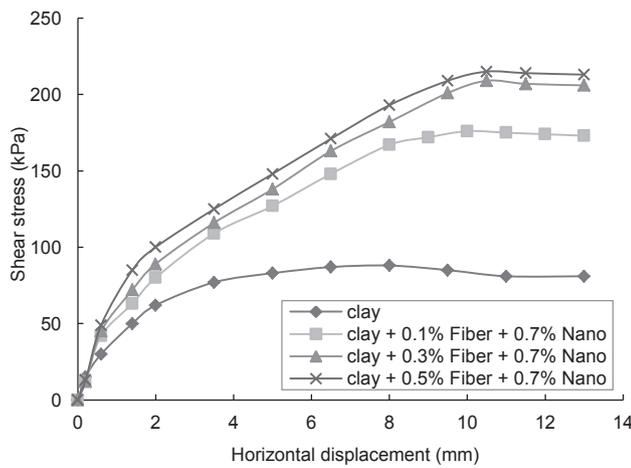
**Fig. 6.** Stress-displacement curves of clay reinforced and stabilized by 0.5% nano-SiO<sub>2</sub>. (a)  $\sigma_n = 100$  kPa, (b)  $\sigma_n = 200$  kPa, and (c)  $\sigma_n = 300$  kPa.



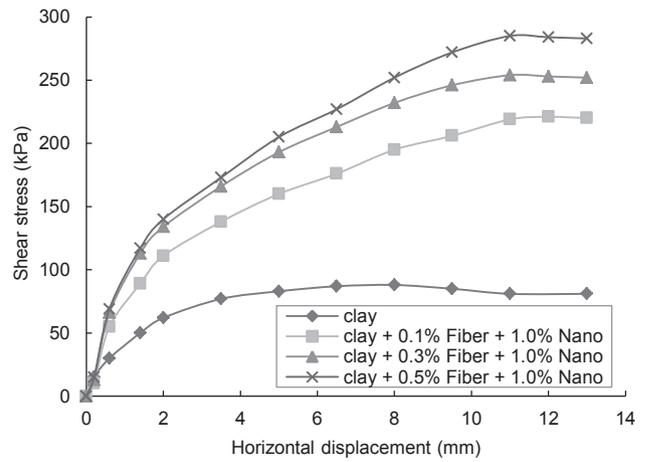
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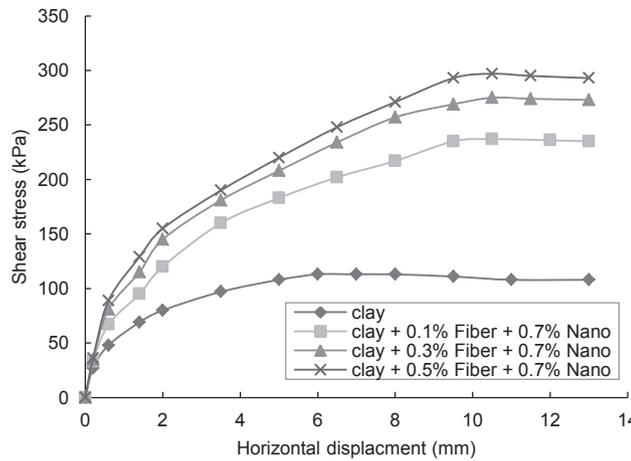
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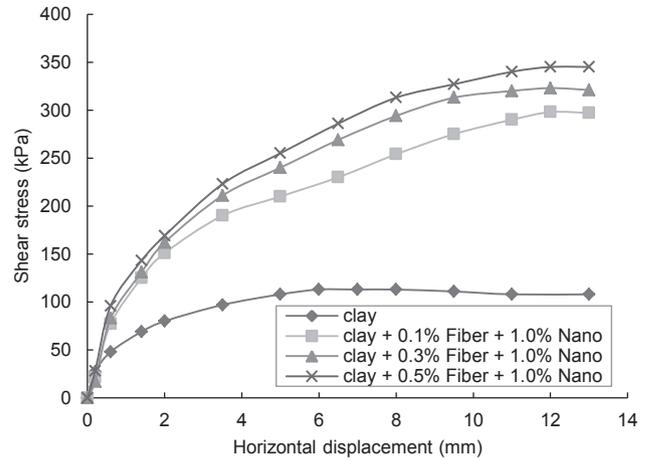
(b)



(b)



(c)



(c)

Fig. 7. Stress-displacement curves of clay reinforced and stabilized by 0.7% nano-SiO<sub>2</sub>. (a)  $\sigma_n = 100$  kPa, (b)  $\sigma_n = 200$  kPa, and (c)  $\sigma_n = 300$  kPa.

Fig. 8. Stress-displacement curves of clay reinforced and stabilized by 1% nano-SiO<sub>2</sub>. (a)  $\sigma_n = 100$  kPa, (b)  $\sigma_n = 200$  kPa, and (c)  $\sigma_n = 300$  kPa.

0.7% and 1% nano-SiO<sub>2</sub>, the increase ratios of the angle of internal friction and cohesion for treated specimen are 2.44, 2.63 and 2.72, 2.81, respectively, for fiber content of 0.3%.

Visual observations indicate that the increase in the content of recycled polyester fiber leads to the increases in unitary coherent mixture; hence, the tensile strength between soil particles is improved. It can be seen from Fig. 9 that in terms of the frictional

Table 6  
Shear strength parameters of fiber-reinforced clay stabilized with 0.5% nano-SiO<sub>2</sub>.

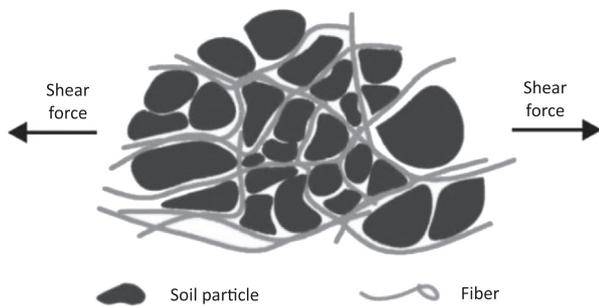
Specimens No.	Fiber content (%)	Cohesion, <i>c</i> (kPa)	Angle of internal friction, $\varphi$ (°)
1	0	38	13.5
2	0.1	65	23.55
3	0.3	73	27
4	0.5	83	30

**Table 7**  
Shear strength parameters of fiber-reinforced clay stabilized with 0.7% nano-SiO<sub>2</sub>.

Specimens No.	Fiber content (%)	Cohesion, <i>c</i> (kPa)	Angle of internal friction, $\phi$ (°)
1	0	38	13.5
2	0.1	90	25.4
3	0.3	100	33
4	0.5	103	32

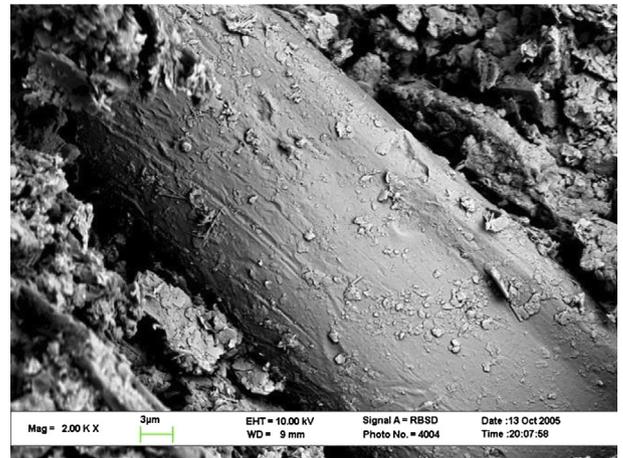
**Table 8**  
Shear strength parameters of fiber-reinforced clay stabilized with 1% nano-SiO<sub>2</sub>.

Specimens No.	Fiber content (%)	Cohesion, <i>c</i> (kPa)	Angle of internal friction, $\phi$ (°)
1	0	38	13.5
2	0.1	93	33.8
3	0.3	107	36.8
4	0.5	113	38.5

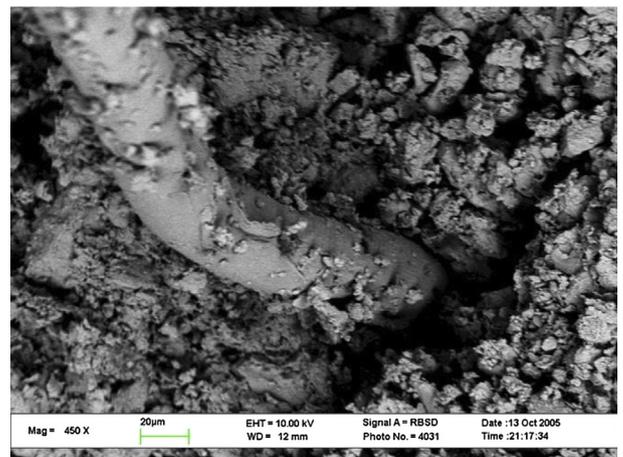


**Fig. 9.** Sketch drawing of interfacial mechanical behavior between soil particles and fiber surface.

strength, the recycled material in the composite is difficult to slip and the composite can withstand tensile stress. High-resolution field emission scanning electron microscopy (FESEM) is achieved using a field emission gun (FEG) in place of the more conventional tungsten hairpin or LaB6 filaments. A resolution of 0.5 nm has been achieved under ideal conditions and 5 nm is regularly achieved at 30 kV with conducting materials. The amount of clay data which can be acquired using back-scatter or conventional secondary electron imaging techniques is limited by the resolution of such instruments. For clay mineral studies, the optimal resolution is 0.5  $\mu\text{m}$  for back-scattered electron microscopy (BSEM) compared with 0.5 nm for FESEM. Good quality photomicrographs can be obtained at a magnification of  $\times 2000$  for BSEM and  $\times 30,000$  for FESEM. The scanning electron microscopy (SEM) images of soil reinforced by fiber (Tang et al., 2010) are shown in Fig. 10. It is clear that the shear stress increases with the increasing nano-SiO<sub>2</sub> content. The mechanism accounting for this increase in strength is not well understood, but probably there are three mechanisms. In the first mechanism, by adding water to clay, nano-SiO<sub>2</sub> produces viscous gel in conjunction with water. Fig. 11 shows that the viscous gel leads to contact between clay particles. The cohesion between clay particles due to viscous gel probably is stronger than that between clay particles due to absorbed water. The viscous gel leads to an increase in frictional strength between clay particles. In the second mechanism, the nano-SiO<sub>2</sub> makes the distance between clay particles smaller and causes a great number of clay particles to contact together. Due to the fact that the contact area between clay particles increases with increasing nano-SiO<sub>2</sub>, the frictional strength improves. Landman et al. (2014) pointed out that nano-



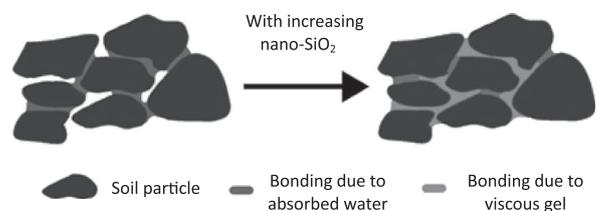
(a)



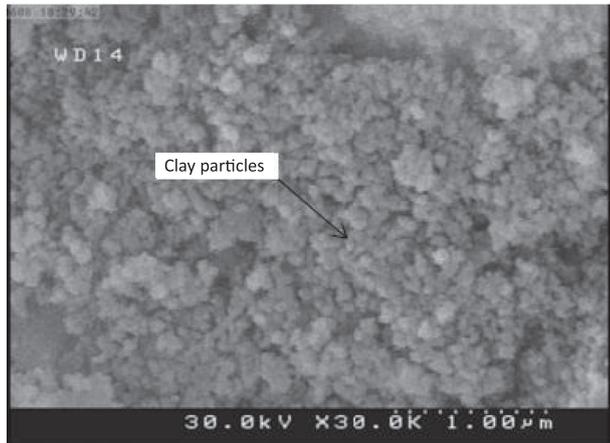
(b)

**Fig. 10.** SEM images of embedded fiber reinforcement in soil matrix (Tang et al., 2010). (a) Magnification of  $\times 2000$ , and (b) Magnification of  $\times 450$ .

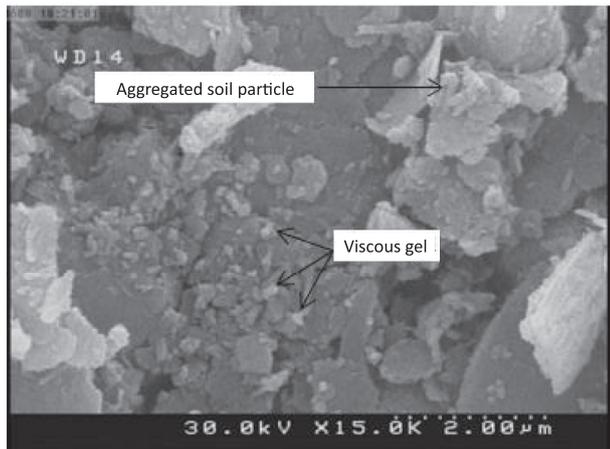
SiO<sub>2</sub> leads to an increase in bond strength. FESEM images of clay stabilized with nano-SiO<sub>2</sub> are presented in Fig. 12. In the third mechanism, the viscous gel adheres to the recycled materials surface and appreciably improves the interfacial bond characteristics and increases the frictional strength between the recycled materials surface and clay particles. This mechanism is shown in Fig. 13. Recycled fiber contributes to the creation of voids. By adding 0.5%–1% nano-SiO<sub>2</sub> to clay, the viscous gel occupies the voids, contributing to the increase in angle of internal friction of the composite. In this regard, the increase in strength of composite is related to the friction created between soil particles, nano-SiO<sub>2</sub>, and recycled materials. This event contributes to the increase in angle of internal friction of composite.



**Fig. 11.** Effect of nano-SiO<sub>2</sub> on bonding between clay particles.



(a)



(b)

Fig. 12. FESEM images of soil specimens: (a) Untreated clay, and (b) Clay stabilized with nano-SiO<sub>2</sub>.

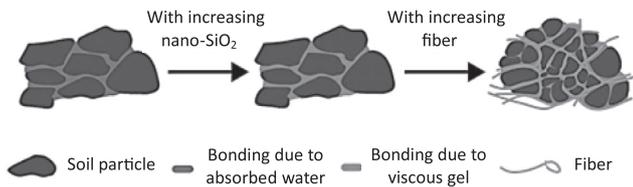


Fig. 13. Sketch drawing of interfacial mechanical behavior of clay reinforced and stabilized with nano-SiO<sub>2</sub>.

3.2. Unconfined compression test

3.2.1. UCS of clay improved by recycled polyester fiber

The results of unconfined compression test of clay reinforced by various contents of recycled materials are presented in Fig. 14. The observation of this figure indicates that the increase in the content of recycled materials contributes to the increase in peak and residual UCSs of reinforced clay. The effect of recycled polyester fiber on the increase in UCS is marginal when the content of recycled polyester is more than 0.3%. It is evident from Fig. 14 that the UCSs due to 0.3% and 0.5% recycled materials are close to each other. As a result, the optimum content of recycled materials is found to be 0.3%. It is clear that the UCS of clay reinforced by recycled materials occurs at higher strain in all specimens compared to the natural clay. From Fig. 14, one can conclude that the addition of 0.3% fiber

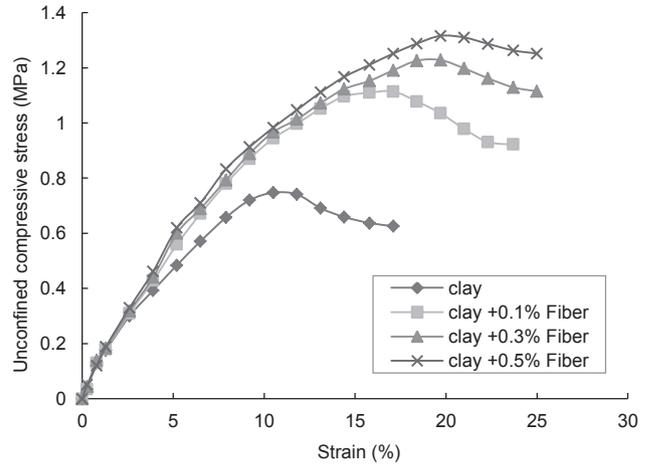


Fig. 14. Stress–strain curves of clay reinforced by recycled polyester fiber obtained from unconfined compression test.

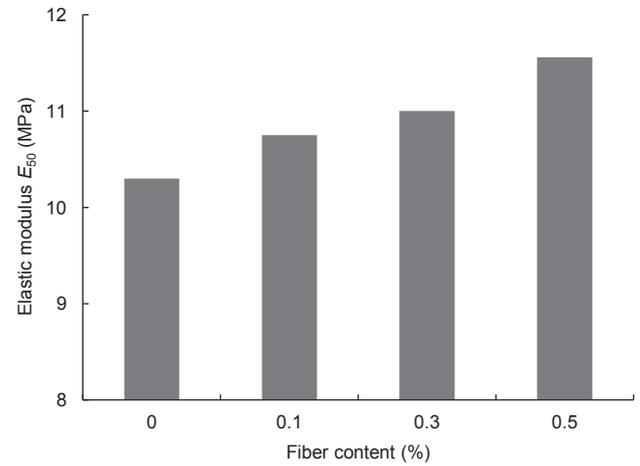


Fig. 15. Elastic modulus ( $E_{50}$ ) of clay reinforced by varying contents of recycled polyester fiber.

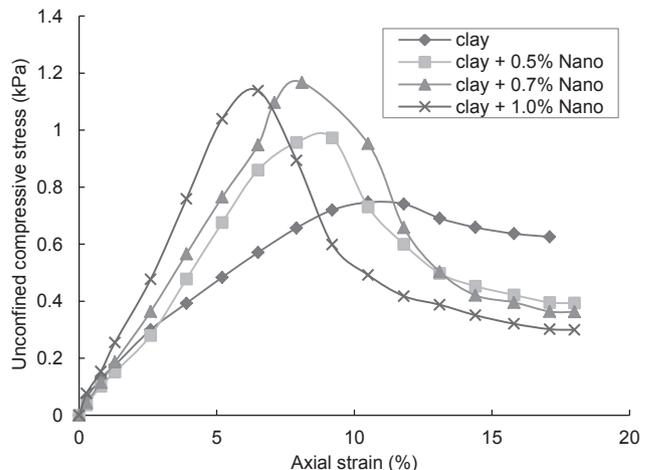


Fig. 16. Stress–strain curves of clay stabilized with nano-SiO<sub>2</sub> obtained from unconfined compression test.

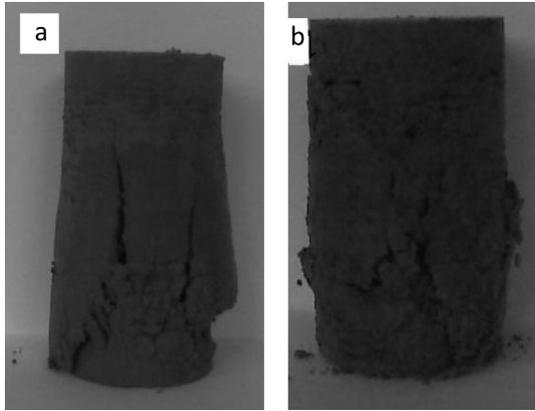


Fig. 17. Effect of nano-SiO<sub>2</sub> on failure characteristics of soil: (a) Clay stabilized with nano-SiO<sub>2</sub>, and (b) Natural clay.

increases the failure deformation from 10.5 mm to 19.7 mm, giving an increase of 88% in the failure deformation. Visual observations indicate that utilization of more than a certain amount of recycled materials results in reduction of the effectiveness of the increase in UCS. This phenomenon may account for the fact that, with increase in recycled fiber content, the fiber coheres to each other and cannot contact with soil particles completely. The elastic modulus ( $E_{50}$ ) was calculated from one half of peak UCS. The elastic modulus ( $E_{50}$ ) of clay reinforced by varying contents of recycled polyester fiber obtained from unconfined compression tests is presented in Fig. 15. It is evident from Fig. 15 that, with the increase in the content of recycled polyester fiber, the increase ratios of elastic modulus ( $E_{50}$ ) are 1.04, 1.11, and 1.12, respectively, for the content of recycled polyester fiber of 0.1%, 0.3%, and 0.5%.

3.2.2. UCS of clay improved by nano-SiO<sub>2</sub>

The results of unconfined compression test of clay stabilized with various nano-SiO<sub>2</sub> contents are presented in Fig. 16. The observation of this figure indicates that, with increase in nano-SiO<sub>2</sub> content, the peak UCS of stabilized clay increases, but the residual UCS of stabilized clay decreases. The UCS increases with the increase in nano-SiO<sub>2</sub> content up to 0.7%, beyond which it decreases. Thus, the optimum nano-SiO<sub>2</sub> content is found to be 0.7%. By adding nano-SiO<sub>2</sub>, the increase ratios of peak UCS are 1.3, 1.56, and 1.5, and the decrease ratios of residual UCS of stabilized

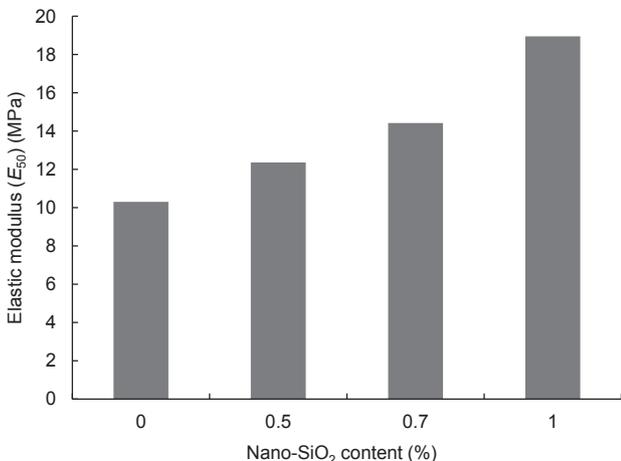
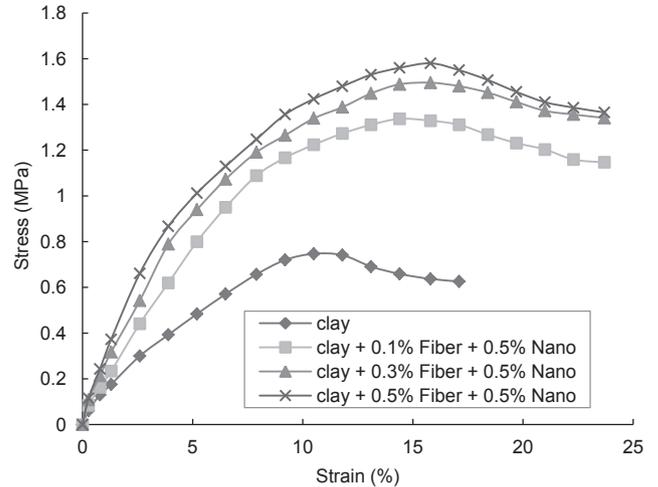
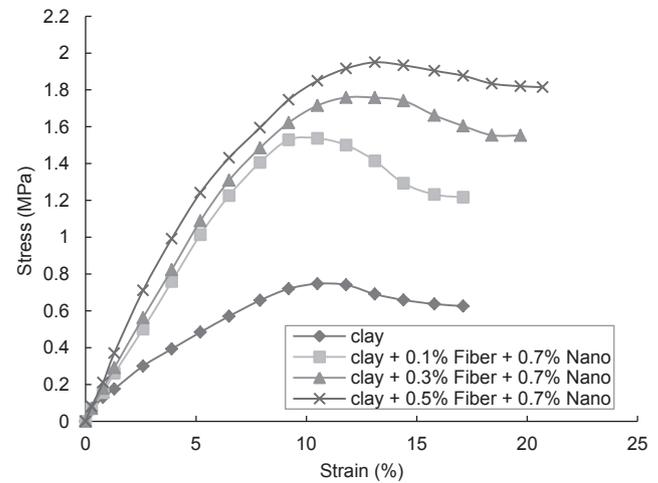


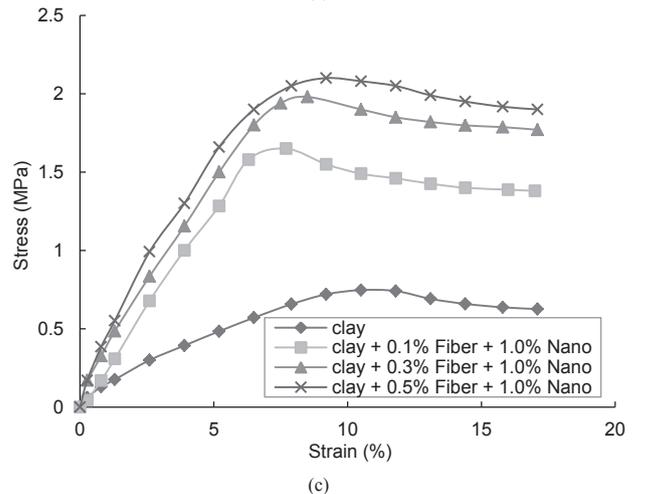
Fig. 18. Elastic modulus ( $E_{50}$ ) of clay stabilized with varying nano-SiO<sub>2</sub> contents.



(a)



(b)



(c)

Fig. 19. Stress–strain curves of clay reinforced and stabilized with (a) 0.5% nano-SiO<sub>2</sub>, (b) 0.7% nano-SiO<sub>2</sub>, and (c) 1% nano-SiO<sub>2</sub>.

clay are 0.63, 0.58, and 0.48, respectively for nano-SiO<sub>2</sub> contents of 0.5%, 0.7%, and 1%. Visual observations indicate that, at constant moisture content, due to the absorption of water by nano-SiO<sub>2</sub>, the clay becomes less compressible which is worsened by increasing the nano-SiO<sub>2</sub> content. This may be the reason for the reduction of

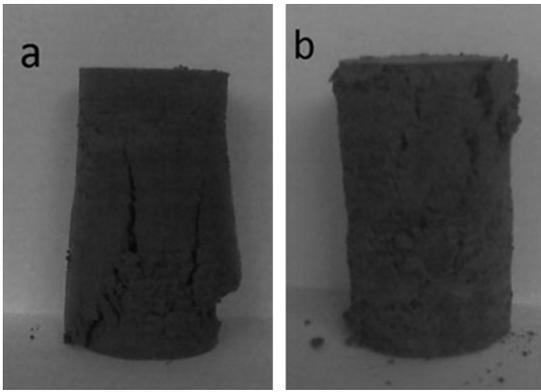


Fig. 20. Specimen deformation pattern for (a) clay stabilized with nano-SiO<sub>2</sub> and (b) fiber-reinforced clay stabilized by nano-SiO<sub>2</sub>.

peak strength of stabilized clay with 1% nano-SiO<sub>2</sub> in comparison with clay stabilized with 0.7% nano-SiO<sub>2</sub>. From this figure, it is clear that the increase in UCS of stabilized clay occurs at lower strain in all specimens compared to the natural clay. It is evident that the decrease ratios of failure strain for soil stabilized by nano-SiO<sub>2</sub> are 0.87, 0.77, and 0.62, respectively, for nano-SiO<sub>2</sub> contents of 0.5%, 0.7%, and 1%. Fig. 17 presents the effect of nano-SiO<sub>2</sub> on the behavior of soil stabilized with different nano-SiO<sub>2</sub> contents. The observation of this figure shows that specimens treated by nano-SiO<sub>2</sub> illustrate very brittle behavior and the tensile cracks due to brittle behavior lead to creation of the failure mechanism. It can be noted that the increase in nano-SiO<sub>2</sub> contents contributes to the creation of tensile cracks in the treated specimens. The elastic modulus ( $E_{50}$ ) of clay stabilized with varying nano-SiO<sub>2</sub> contents obtained from unconfined compression tests is presented in Fig. 18. It can be seen from Fig. 18 that, with the increase in nano-SiO<sub>2</sub> content, the increase ratios of elastic modulus ( $E_{50}$ ) are 1.2, 1.41, and 1.84, respectively, for nano-SiO<sub>2</sub> content of 0.5%, 0.7%, and 1%.

### 3.2.3. UCS of clay improved by recycled polyester fiber and nano-SiO<sub>2</sub>

The UCS values of clay reinforced by nano-SiO<sub>2</sub> and recycled material are shown in Fig. 19. It is clear from Fig. 19 that, by increasing the nano-SiO<sub>2</sub> content, the peak and residual UCSs increase. Hence, the optimum nano-SiO<sub>2</sub> content is found to be 1%. By adding 1% nano-SiO<sub>2</sub>, the peak and residual UCSs increase by from 120% to 165% and 120% to 182%, respectively, when the content of recycled polyester fiber increases from 0.1% to 0.3%. However, by further increasing the recycled polyester fiber, as in the case of 0.5% fiber, the increases are only 181% and 200%, respectively. Hence, the addition of recycled polyester fiber more than 0.3% is not reasonable to increase the UCS of clay, resulting in the optimum content of recycled polyester fiber of 0.3%. The optimum value of the peak UCS is observed at 0.3% fiber +1% nano-SiO<sub>2</sub> content, which is 2.65 times the UCS of natural clay, 1.56 times that of the nano-SiO<sub>2</sub> treated specimens, 1.76 times that of the recycled material treated specimens. The recycled material along with nano-material has a significant effect on the clay behavior. The nano-SiO<sub>2</sub> samples obtained a different failure stress at an axial strain of 6.5%–9% under which the treated specimens declined; but the samples treated by recycled material illustrated ductile behavior. Thus, the addition of the recycled material to the specimens is more efficient than the nano-SiO<sub>2</sub> in improving the clay behavior. Fig. 20 shows the behaviors of treated and untreated specimens. Fig. 20a shows that the specimens treated by nano-SiO<sub>2</sub> illustrate very brittle behavior. The

recycled material impedes the development of cracks, contributing to improvement of the tensile strength of composite. This phenomenon results from friction created by recycled material and clay particles, which is evident in Fig. 20b. The results of the unconfined compression tests show that the recycled material has not extremely influence on the increase in stiffness of treated specimens. On the other hand, the nano-SiO<sub>2</sub> has a positive influence on

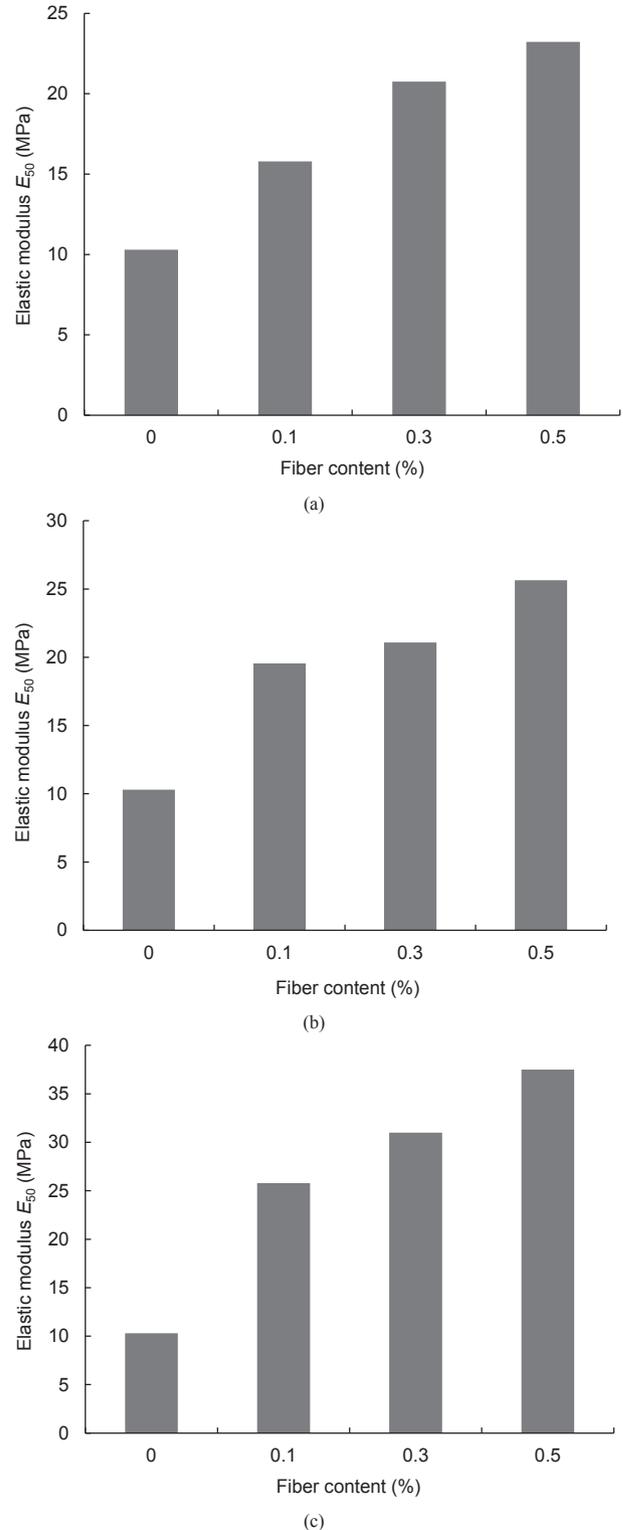


Fig. 21. Elastic modulus ( $E_{50}$ ) of clay reinforced and stabilized with (a) 0.5% nano-SiO<sub>2</sub>, (b) 0.7% nano-SiO<sub>2</sub>, and (c) 1% nano-SiO<sub>2</sub>.

the stiffness of treated specimens. The addition of the nano-SiO<sub>2</sub> to clay causes reduction in failure strain of specimens compared to natural clay and clay reinforced with recycled polyester fiber. It can be noted that an increase in the content of recycled material is associated with a reduction in brittleness of treated specimens. By adding nano-SiO<sub>2</sub>, the failure of specimens is suddenly, but with increase in the content of recycled material, the failure mechanism of treated specimens changes; consequently, with increasing the content of recycled material, the residual UCS of composite increases.

### 3.2.4. Elastic modulus ( $E_{50}$ ) of recycled polyester fiber-reinforced clay improved by nano-SiO<sub>2</sub>

The elastic modulus ( $E_{50}$ ) of treated specimens with varying contents of nano-SiO<sub>2</sub> and recycled polyester fiber obtained from the unconfined compression tests is presented in Fig. 21. It can be seen from Fig. 21 that the maximum value of the elastic modulus occurs at 1% nano-SiO<sub>2</sub> content. By adding 1% nano-SiO<sub>2</sub>, the elastic moduli ( $E_{50}$ ) increase by 150%, 200%, and 264% for 0.5%, 0.7%, and 1% fiber contents, respectively. The maximum value of the elastic modulus is observed at 0.5% fiber +1% nano-SiO<sub>2</sub> content, which is 3.65 times the elastic modulus of the natural clay, 1.97 times that of the nano-SiO<sub>2</sub> treated specimens, and 3.24 times that of the recycled material treated specimens.

## 4. Conclusions

In recent years, research on the application of recycled fiber has become a hot issue due to environmental benefits and cost effectiveness of geofiber. Past studies show that the addition of waste products with chemical agents may improve the strength properties of soft clay. This study investigates the effects of recycled polyester fiber and nano-SiO<sub>2</sub> on the mechanical properties of clay, based on the results obtained from a series of direct shear tests and unconfined compression tests. The following conclusions are drawn:

- (1) For the compacted clay containing nano-SiO<sub>2</sub> and recycled polyester fiber, the shear strength increases with the increase in the contents of nano-SiO<sub>2</sub> and recycled polyester fiber. With 1% nano-SiO<sub>2</sub>, an increase of 190% in shear strength is observed for the mixtures with 0.3% recycled polyester fiber. The shear stress of clay with 0.5% recycled fiber only increases by about 10% in comparison with that of the clay with 0.3% recycled fiber.
- (2) The increase in the contents of nano-SiO<sub>2</sub> and recycled polyester fiber leads to an increase in both angle of internal friction and cohesion. For all the cases, the maximum increase in angle of internal friction of composite is found at the contents of 0.3% fiber +1% nano-SiO<sub>2</sub>. By adding 0.3% recycled polyester fiber +1% nano-SiO<sub>2</sub>, the increase ratios of angle of internal friction and cohesion for treated specimens are 2.72 and 2.81, respectively.
- (3) Both the recycled polyester fiber and nano-SiO<sub>2</sub> have positive influence on the increase in peak and residual UCSs of clay. In all samples, the maximum increase in both peak and residual UCSs is found at the contents of 1% nano-SiO<sub>2</sub> + 0.3% recycled polyester fiber.
- (4) The addition of nano-SiO<sub>2</sub> is more significant than adding recycled polyester fiber in increasing the stiffness of clay. The simultaneous use of recycled polyester fiber and nano-SiO<sub>2</sub> has a significant effect on enhancing the elastic modulus of clay.
- (5) Because of the fact that the nano-SiO<sub>2</sub> covers around the fiber surface, the interlock force between fiber surface and soil

particles increases and bond characteristics improve. Also the use of nano-SiO<sub>2</sub> has a negative effect on the ductility of clay.

- (6) The cracks on the surface are clearly observed. The narrower and shorter cracks are detected on the surface of compacted soil, nano-SiO<sub>2</sub> and fiber mixture. The decrease in cracks can be attributed to the fact that fiber acts as bridges between soil particles and cause matrix reinforcement. As a result, the recycled material provides strength to crack propagation and retains load transfer during tension.

In this paper, it can be noted that the method of clay stabilized with nano-SiO<sub>2</sub> and recycled polyester fiber is a significantly applied method of ground improvement, which increases the shear strength, the UCS, and the elastic modulus of clay. Because of this, it increases the stability of structures, i.e. foundation and roadbed. With the development of the construction technology, this improvement technique can be considered as a practical method for improvement of mechanical behaviors of clay in civil engineering project.

## Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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