Engineering Science and Technology, an International Journal 24 (2021) 1090–1101

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Effect of randomly distributed pet bottle strips on mechanical properties of cement stabilized kaolin clay

Irem Bozyigit [a,*,1], Fatih Bulbul [b], Candas Alp [c], Selim Altun [a]

[a] Department of Civil Engineering, Ege University, Bornova, 35040 Bornova/Izmir, Turkey
[b] Graduate School Of Natural And Applied Sciences, Gazi University, Maltepe, 06570 Maltepe/Ankara, Turkey
[c] Izole Kiremit Industry and Trade Inc., Torbalı, 35875 Torbalı/Izmir, Turkey

ARTICLE INFO

Article history:
Received 11 October 2020
Revised 15 February 2021
Accepted 17 February 2021
Available online 18 March 2021

Keywords:
Cement stabilization
Waste bottle strip
Unconfined compression test

ABSTRACT

In this study, the potential usage of wastewater bottle strips produced from polyethylene terephthalate (PET) as a reinforcing material for strength properties of cement stabilized clay was investigated. For this purpose; unconfined compression strength tests were conducted to determine the parameters affecting the strength properties of cement stabilized-reinforced clay. Four different ratios of cement (0, 3, 6, and 9%) were used for clay stabilization and waste bottle strips obtained by cutting from waste pet bottles were used for reinforcement. Considering that the waste bottle strips behave similar to the fiber material; cement stabilized-reinforced clay samples were prepared with the ratios of 0, 0.5, 1.0, 1.5, and 2.0%, which are generally used as reinforcement ratios for soil. The specimens were stored in the curing room for 1, 7, 28, and 90 days until testing. Test results were evaluated according to cement content, water bottle strip ratio and curing time parameters. The experimental results showed that the optimum water bottle strip ratio for maximum strength gain ranged from 1 to 1.5%. It was also observed that the plastic strips and cement used for soil improvement also changed the strength-deformation behavior of the kaolin clay. Besides, the augmentation in cement inclusion level and curing period increased the strength of kaolin clay.

1. Introduction

Growing industrialization and technological developments have caused an increase in environmental pollution. It is very important to regularly dispose of waste in a non-hazardous manner to restrain environmental pollution and to protect the ecosystem. Today, PET (Polyethylene-terephthalate) manufacturing and PET usage for beverage and water packages are some of the fundamental factors causing environmental pollution. Pet is a light, durable, flexible, and inexpensive material. Therefore; it is a widely used material especially for bottled water and beverages. Furthermore, bottled water purchasing has increased 500% over the last decade and 1.5 million tons of plastic are used to bottle water every year according to the International Bottled Water Association (IBWA) [1]. Although the PET bottle use in Turkey is low when compared to other countries, this amount is increasing day by day. It is known that 1.2 kilograms of crude oil are used for one PET bottle production and the degradation time for PET bottle varies between 100 and 1000 years in nature [2].165,000 tons of PET bottles are produced annually in Turkey, however, only 40,000 tons of PET bottles can be recycled and 125,000 tons of PET bottles are mixed in nature every year [2]. Using these waste materials for soil stabilization is an alternative method to improve the mechanical properties of soil. This method can meet the requirements of soil improvement and reduce the quantity of waste PET bottle.Using strips obtained from waste pet bottles as reinforcement agents with a combination of a binder on weak soils could be an effective improvement method. Soil reinforcement techniques can be categorized according to different perspectives such as application method, reinforcement type, binder type, etc. and summarized in Fig. 1 [3].

Ground reinforcement is applied by using two different methods: the inclusion of fibers randomly in the soil matrix or the placement of geosynthetics such as geocell, geonet, geogrid on the soil in layers. Nowadays, fiber reinforcement is frequently used for soil improvement and investigated extensively, in the literature [4–9]. In these studies, it has been observed that the use of fiber improves the strength properties of the soil. Fiber type, fiber content, fiber length, and also binder type are important parameters in fiber-reinforced soil. Fiber types can be divided into three groups

* Corresponding author.
E-mail address: irem.kalipcilar@ege.edu.tr (I. Bozyigit).
[1] ORCID: 0000-0001-7189-8098

https://doi.org/10.1016/j.jestch.2021.02.012
2215-0986/

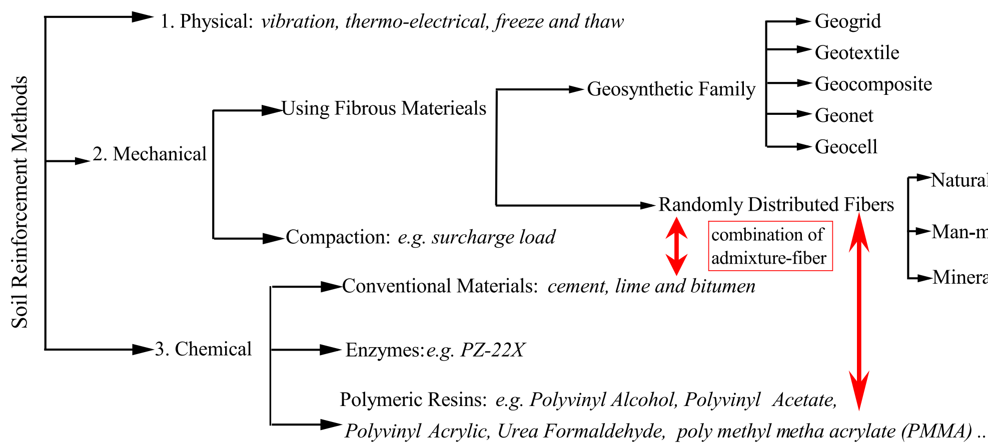

Fig. 1. Different procedures of soil reinforcement [3].

Table 1
Index Properties of Kaolin.

Properties	Values	Standards
Liquid Limit, w_L	52	ASTMD4318
Plastic Limit, w_P	28	ASTMD4318
Plasticity Index, I_P	24	ASTMD4318
Specific Gravity	2.62	ASTMD854
Optimum Water Content (%)	33	ASTMD698
Maximum Dry Unit Weight (kN/m^3)	12.75	ASTMD698
Soil Classification	CH	USCS

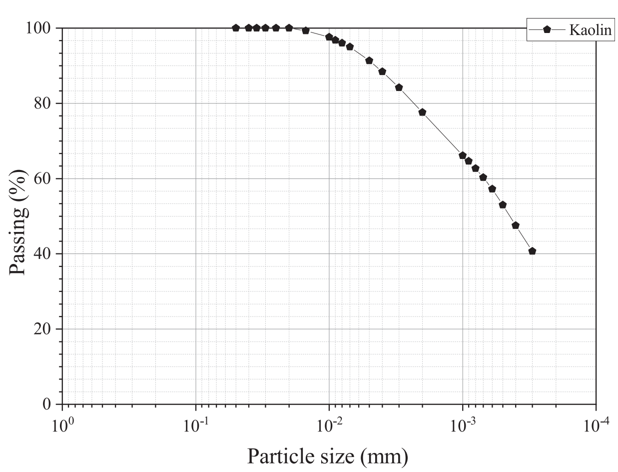

Fig. 2. Grain size distribution of kaolin.

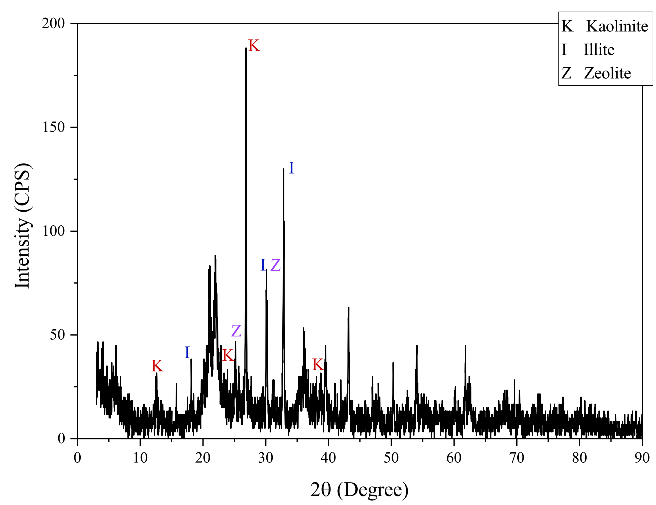

Fig. 3. X-ray diffraction analysis of Kaolin clay.

Table 2
Chemical Properties of Ordinary Portland Cement.

Components	Value
SiO_2	18.27
Al_2O_3	4.12
Fe_2O_3	3.49
CaO	63.32
MgO	2.43
Na_2O	0.36
K_2O	0.92
SO_3	3.04
Loss on ignition	3.9

as man-made (synthetic), natural, and mineral. Cornsilk fiber, banana fiber, coconut fiber, palm fiber, jute, bamboo, wheat straw, rice straw, kenaf, hay, etc. are the most commonly used natural fiber types. Tran et al. [10] performed a study to assess the effect of fibers (with the ratios of 0.5, 1, 1.5, and 2%) on mechanical properties of silt soil. A maximum unconfined compressive strength increase was observed as 38% at 1% fiber content. Sunny and Joy [11] investigated the use of waste banana fiber in geotechnical applications by using unconfined compression strength and California bearing ratio test. Prabakar and Siridihar [12] treated raw soil by using sisal fibers at 0.25, 0.5, 0.75, 1.0% of fiber content. The authors concluded that shear strength increased by increasing fiber content and optimum fiber content was obtained as 0.75%. Beyond this fiber content, shear strength decreased by increasing fiber content. Natural vernacular fibers of Grewia Optivia and Pinus Roxburghii (chir pine) also was used as a reinforcement element by Sharma et al. [13]. Moreover, natural, synthetic, and waste reinforcement elements can be combined with chemical binders. Danso and Manu [14] investigated the influence of coconut fibers and lime on the properties of soil–cement mortar. In their study; 0.2–0.8% of fiber inclusion level, 5% of cement content, and 0–15% of lime content were selected to improve the soil. Maximum strength was obtained at 0.2% of coconut fiber and 5% of lime content. However, preparation and compaction methods have a great

Table 3
Mechanical and Physcial Properties of Ordinary Portland Cement.

Properties	Values
Specific gravity -Density (kg/m^3)	3.18
Specific surface-Blaine (cm^2/g)	3120
İnitial setting time (min)	110
Final setting time (min)	165
Volume expansion (mm)	1
1-day compressive strength (MPa)	21.34
7-day compressive strength (MPa)	32.43
28-day compressive strength (MPa)	42.67
90-day compressive strength (MPa)	44.09

Table 4
Mechanical and Physcial Properties of Plastic Bottle Strips.

Properties	Values
Specific gravity	1.38
Width (average) (mm)	4
Length (average) (mm)	10
Aspect ratio (average)	20
Thickness (mm)	0.05
Tensile strength, (σ_t) (MPa)	64
Modulus of elasticity, (E) (MPa)	2950
Resistance to acid and alkaline	High

effect on the behavior of fiber-reinforced soil. Abou Diab et al. [15] compared different compaction methods which are kneading and impact compaction. As a result of their study; it was indicated that specimens prepared by impact compaction showed better performance utilizing strength tests due to fiber orientation. The use of fiber has many advantages in most circumstances such as cold regions, under dynamic effects, etc. Bozyigit et al. [16] investigated the effect of fiber length and fiber content on dynamic properties of fiber-reinforced clayey sand. According to the authors' study, it was observed that until 1% fiber content dynamic shear modulus was increased however, beyond 1% fiber content a reverse effect occurred. The use of fiber is also advantageous in cold regions and increases the resistance to freezing and thawing [17–20]. Moreover, fibers can be used with varying binder materials such as cement, lime, or polymers. Nguyen et al. [21] proposed a constitutive model to identify the behavior of the fiber-reinforced cement treated clay based on the critical state soil mechanics and the modified cam clay model.

Reinforcement of soil with fibers can be divided into two groups (systematically and randomly) according to the orientation of the fibers. However, randomly distributed fiber-reinforced soils have some advantages. Randomly distributed fibers ensure strength isotropy and limit potential planes of weakness that generally was constituted the cause of systematically reinforced soil [22]. As environmental consciousness increases, the use of waste and natural materials has gained importance for geotechnical engineering. When waste and natural fiber-like materials are mixed with soil, they behave similarly to the fiber in reinforced soils. Most researchers used waste materials such as waste carpet fiber, waste tire rubber, plastic strips, textile waste etc [23,24,10,25–29]. Consoli et al. [30] evaluated the engineering behavior of uniform sand reinforced with PET fiber obtained from recycling waste plastic bottles. Considering the experiments, the peak and ultimate strengths of uncemented and cemented specimens improved due to the inclusion of fiber. Babu and Chouksey [31], selected recycling plastic waste from water bottles as fiber for reinforcement and stated that a significant improvement was observed in the strength properties with waste plastic addition. Furthermore, Peddaiah et al. [24] investigated the behavior of waste plastic bottle strip reinforced silty clay with varying percentages of plastic strips and different aspect ratios. Maximum performance in engineering properties was obtained for 0.4% plastic content. Zhao et al. [32] searched the factors affecting the shear strength of PET reinforced soil. The optimum PET content for maximum unconfined compressive strength was determined as 1.5%.

Although there are many studies on waste plastic until today, in literature the behavior of plastic bottle strip reinforced cemented clay has not been investigated yet to the best of authors' knowledge. Moreover; cement stabilization is a widely used soil improvement technique, it may be beneficial to use a waste material with cement. Waste material usage can reduce the cement amount to achieve desired strength properties and may cause a more economical improvement method. Therefore, it is important to reveal the strength properties of the plastic bottle strip reinforced cemented clay. Materials with low density, high durability, and thermal insulation are preferable for embankments, landfills, etc. Since waste plastic has a low density and durable material, it can be a choice in landfill engineering. This study aims to clarify the influence of the cement content and plastic bottle strip (PBS) insertion on the stress–strain and strength behavior of clay under

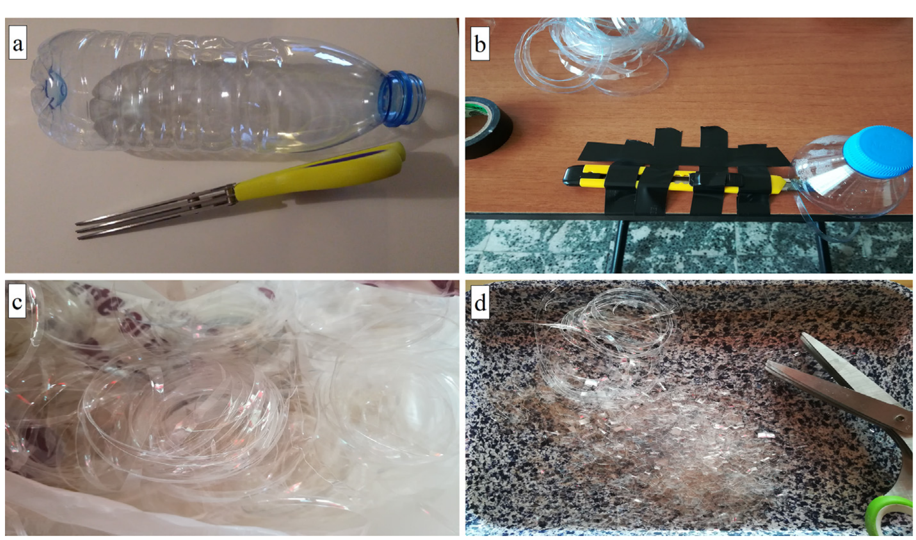

Fig. 4. a. Plastic water bottle and 3 blade scissors b. cutting plastic bottle in a form of rope c. cut plastic ropes d. plastic bottle strips chopped by 3 blade scissors.

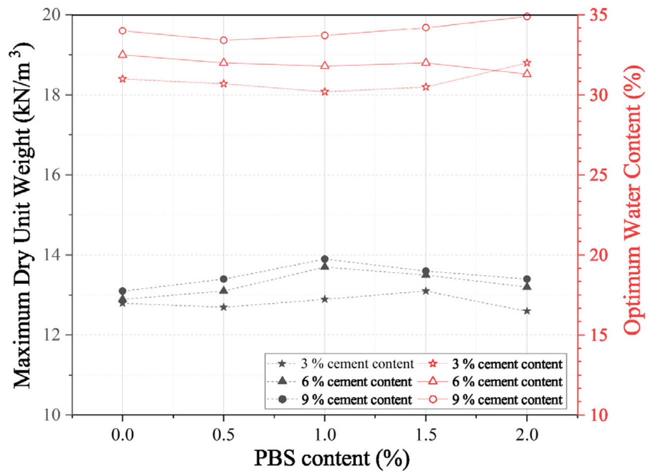

Fig. 5. Maximum dry unit weight and optimum water content of PBS reinforced-cement stabilized kaolin.

undrained loading conditions from the point of ultimate strength, brittleness, energy absorption capacity, and elasticity modulus. Besides, the interactions between PBS-cement and clay are scrutinized with microstructure analysis. For this purpose, several unconfined compression tests were conducted and test results evaluated utilizing cement inclusion level, plastic bottle strip content, and curing period. Also, regression model is constituted for prediction of unconfined compressive strength of PET reinforced cemented clay.

2. Materials and methods

2.1. Materials

A commercial type of kaolin clay was used to investigate the effect of waste plastic bottle strips on the strength properties of cement stabilized clay. Physical and index properties of kaolin are determined in accordance with ASTM standards (Table 1). Kaolin is classified as CH in the unified soil classification system and the grain size distribution of kaolin is given in Fig. 2. The mineralogical composition of kaolin was analysed by X-ray diffraction. The wavelength (λ) of the X-radiation was set to 1.540562. Two-Theta (2θ) range was 3–90° with 0.02° step size. The X-ray diffraction (XRD) pattern of kaolin is shown in Fig. 3. Some of the diffraction peaks of kaolin could be found at 2θ values of 12.55, 23.03, 26.37, 38.55 similar with [33]. Rietveld analysis revealed the presence of 59.4% kaolinite, 37.1% illite, 2.4% zeolite and 1.1% vermiculite in kaolin. Ordinary portland cement (OPC) was chosen for the stabilization of clay. Chemical properties and mechanical-physical properties of OPC are shown in Tables 2 and 3, respectively. The unconfined compressive strength of pure kaolin was determined as 20 kPa.

Similar to use of fiber, plastic water bottle strips were utilized as a reinforcement agent for clay. Plastic bottle strips were obtained from plastic waste water bottles. Plastic bottles are produced from polymers and according to Plastic Industry Trade Association (SPI), the plastics are identified into seven categories (PETE, HDPE, V, LDPE, PP, PS, and others). Water bottles are usually made of PETE (polyethylene terephthalate). The PET is chemically

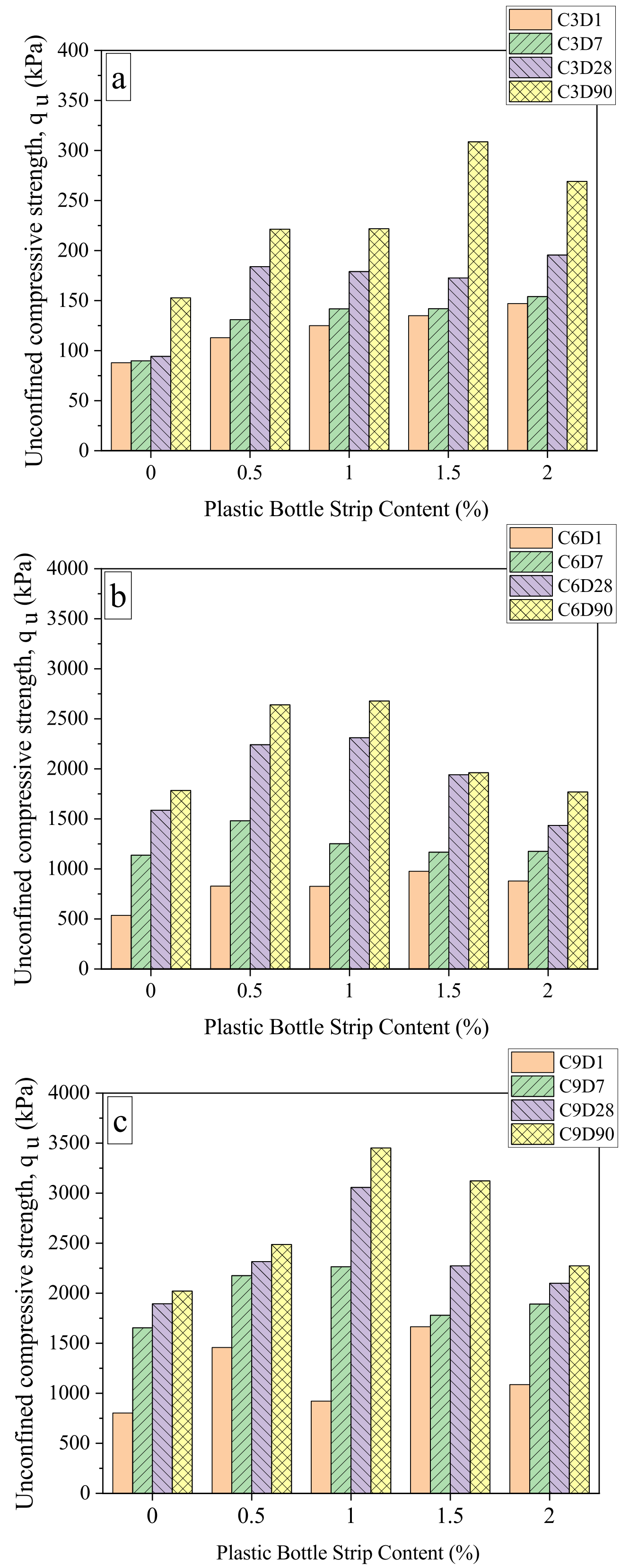

Fig. 6. Variation of unconfined compressive strength of reinforced kaolin stabilized with a) 3% b) 6% c) 9% of cement.

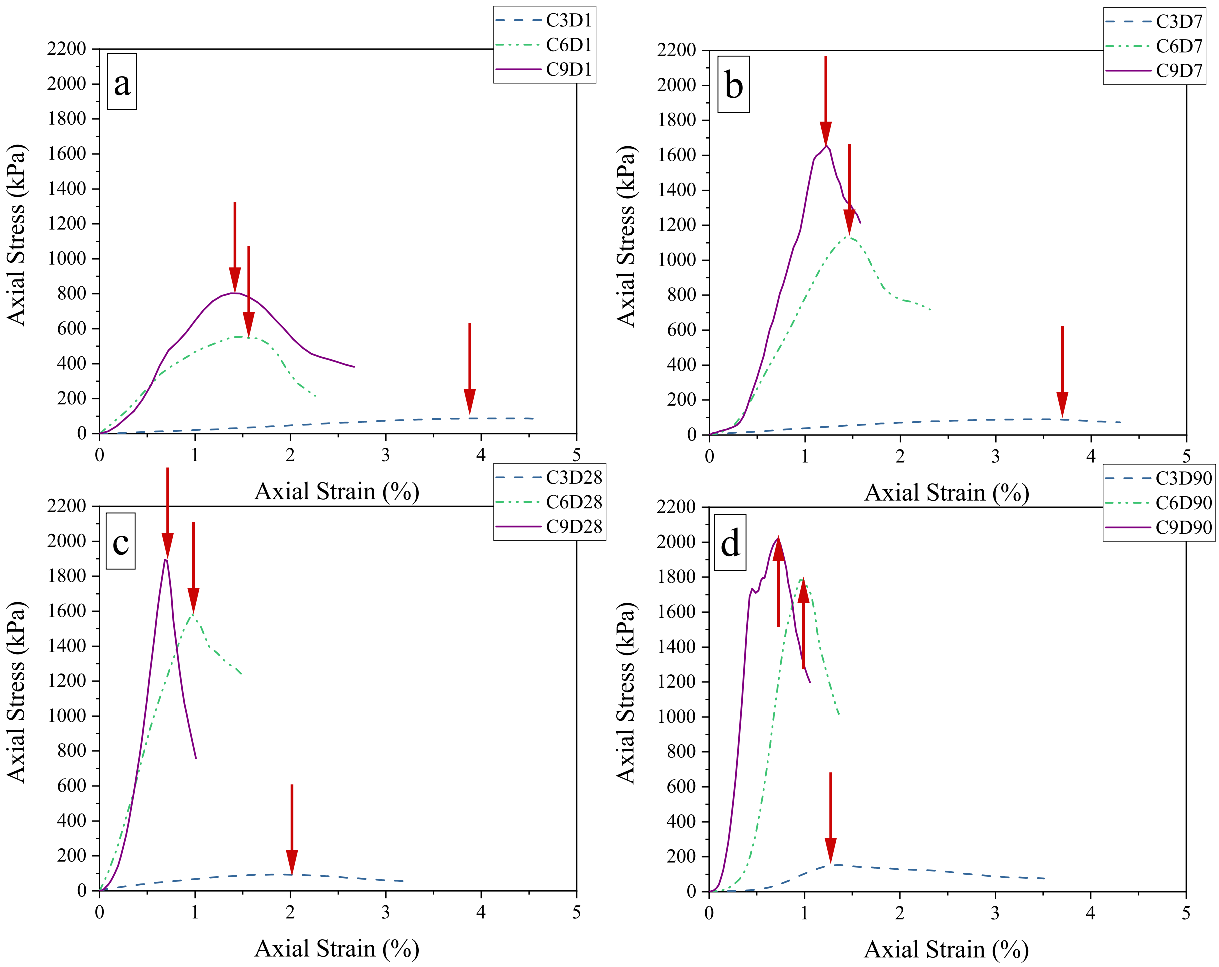

Fig. 7. Stress–strain curves of cement contained specimens with a) 1-day b) 7-day c) 28-day d) 90-day curing period.

expressed as $(C_{10}H_8O_4)_n$ and produced from petroleum, a result of the reactions between ethylene glycol and terephthalate acid. Also, it can be preferable as an additive due to its low coefficient of friction and high flexural modulus. Mechanical and physical properties of plastic bottle strips (PBS) were presented in Table 4.

Before the experimental study; bottles are cleaned and cut in a form of rope with the help of a snap blade knife to prepare the plastic bottle strips. Then, ropes were chopped into pieces randomly using 3 blade shredding scissors. The PBS preparation process is also shown in Fig. 4. The obtained plastic strips have random dimensions due to the cutting method.

2.2. Specimen preparation

An experimental framework was set up to investigate the effect of PBS and cement stabilization on strength. Therefore, the kaolin was stabilized with OPC at four cement inclusion levels (0%, 3%, 6%, 9%). Plastic bottle strip content was selected as 0.5, 1.0, 1.5, and 2%. PBS and cement content were calculated as a percentage by dry weight of kaolin. Firstly, standard proctor tests were conducted to obtain the optimum water content of specimens that contain both PBS and cement. Specimens were prepared regarding the compaction test results. Initially; kaolin, cement, and PBS were mixed in a dry form to ensure homogeneity. Then, the required amount of water equivalent to optimum water content was added and mixed again for 2 min. After the mixing stage, the mixture was placed in cylindrical molds with dimensions of 50x100 mm. In order to provide standard proctor energy, a special hammer (approximately 1/2 scale of standard Proctor hammer) was designed and specimens compacted by using standard proctor energy. It is important to lubricate the inside of the mold before the compaction process to prevent side friction during extraction. Since the initial setting time of cement is 30 min, the specimen preparation stage was completed in less than 30 min to avoid setting. At least three specimens prepared for each case to provide repeatably. All specimens were covered with LLDPE (Linear low-density polyethylene) film to avoid moisture loss and placed in a curing room at 25 °C temperature and 97% relative humidity until the testing day. Also, specimens were named regarding their content before curing. B, C, and D indicate PBS content (%), cement content (%), and curing time (day), respectively. Following numbers indicate the additive content or curing period.

3. Results and discussion

3.1. Effect of cement and PBS contents on compaction properties

Mechanical properties (strength, cohesion, permeability, swelling, etc.) are apparently affected by compaction parameters such as maximum dry unit weight and optimum water content. Maximum dry unit weight and optimum water contents of PBS reinforced- cement stabilized clay specimens were obtained by applying standard effort by 600 kN-m/m^3 according to ASTMD698. The specimens were compacted in a standard mold with dimen-

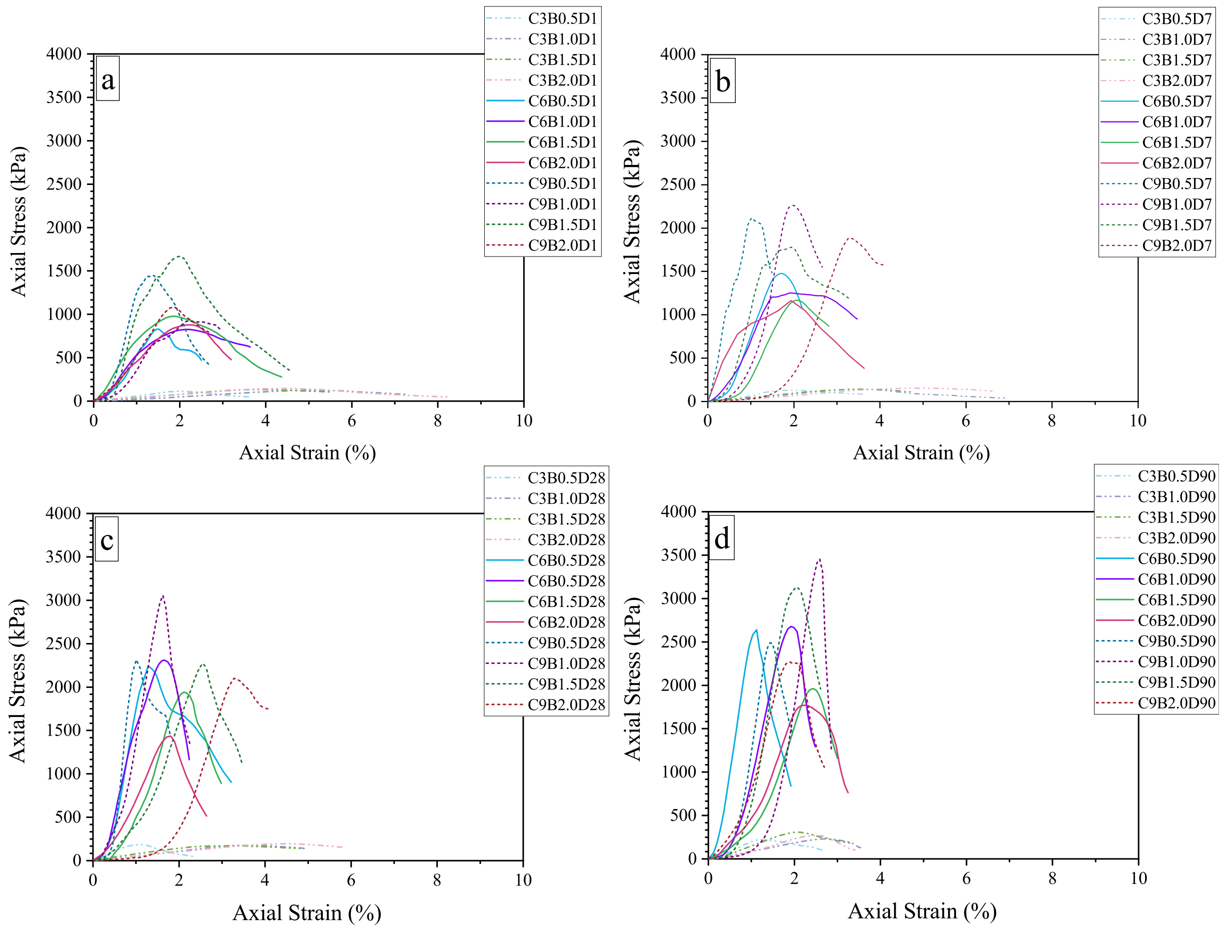

Fig. 8. Stress–strain curves of a a) 1-day b) 7-day c) 28-day d) 90-day cured cement contained specimens with varying amount of PBS.

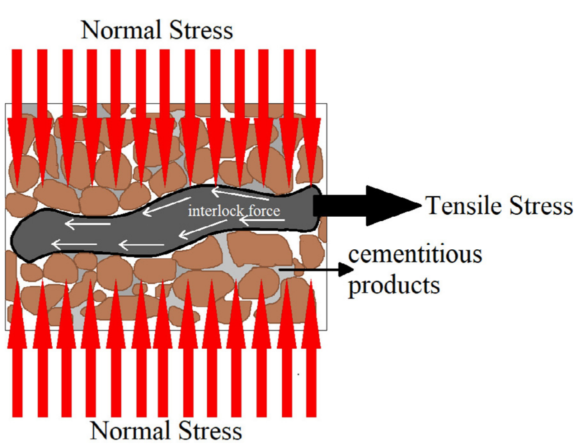

Fig. 9. Schematic diagram of interlock force between soil and fiber (or reinforcement element).

sions of 101.6 mm diameter and 116.4 mm height. The compaction curves of PBS reinforced- cement stabilized clay specimens were presented in Fig. 5. Considering the Fig. 5, PBS and cement content showed an insignificant effect on optimum water content. However, the maximum dry unit weight has generally shown an increasing trend till 1.5% PBS content, beyond this point maximum dry unit weight decreased. This phenomenon may be caused by the reduction of voids in the fiber-cement-soil matrix. Beyond 1.5% fiber content; lumps and air pockets were formed depending on the structure of fiber-soil–cement matrix [12].

3.2. Effect of cement and PBS contents on strength and deformation

The effects of PBS on strength of cement treated clay were evaluated with strain-controlled unconfined compression test device in accordance with ASTM D 2166 standard, at a constant speed of 1.42 mm/min until a maximum 20% of strain was reached or failure occurred. Cement content, curing time, and PBS were designed as variable parameters. Unconfined compressive strength of cement treated kaolin at various plastic bottle strip (PBS) was shown in Fig. 6. A remarkable increase in strength was observed with increasing cement inclusion level, irrespective of PBS content. Although; undrained strength of pure kaolin is determined as 20 kPa, the maximum unconfined compressive strength is obtained as 3452 kPa for a 90-day cured specimen containing 1% of PBS and 9% of cement. Besides, the minimum strength was determined for a 1-day cured specimen having 3% cement inclusion level. In other words, the contribution of cement and PBS is observed as 4 to 173 times increase in unconfined compressive strength values. Lorenzo and Bergado [34] characterized strength properties of cement stabilized clay at high water contents. It was found that the strength of specimens containing 10% cement at 80% water content was increased 23 to 37 times according to pure clay. Moreover, Khalid et al. [35] found this strength increment interval between 4 and 13 for 3–6% cement inclusion level. These results obtained from specimens cured up to 28 days. More duration of curing and higher cement content induced to higher strength increments [36,37].

The main reason for the strength gain mechanism due to cement addition is the reactions between cement and kaolin. As

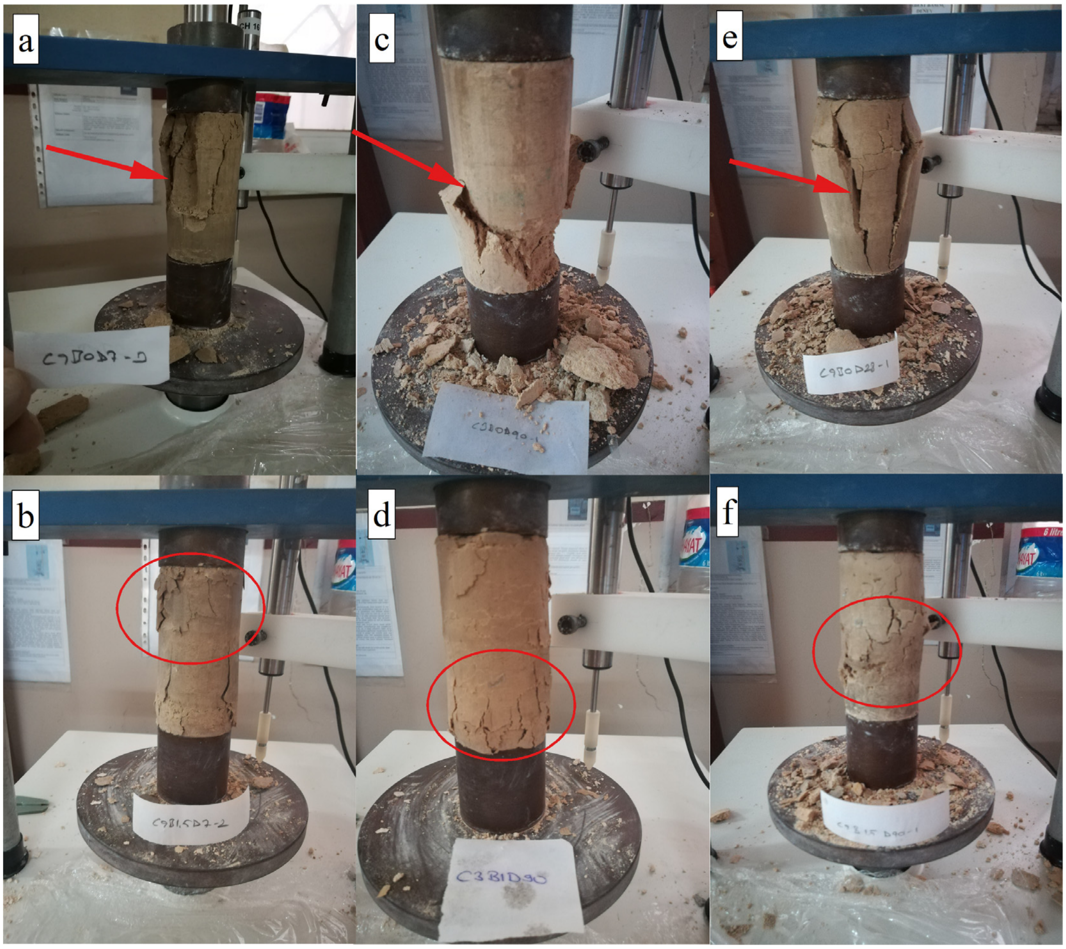

Fig. 10. Image of fracture patterns of specimens a) 9% cement treated (C9B0D7) b)9% cement treated with 1.5% PBS content (C9B1.5D7) c) 3% cement treated (C3B0D90) d) 3% cement treated with 1.0% PBS content (C3B1.0D90) e) 9% cement treated (C9B0D28) f) 9% cement treated with 1.5% PBS content (C9B1.5D90).

the cement and soil are mixed with water, different kinds of cementitious materials have occurred in soil–cement matrix from several reactions [38–40]. These products namely primary and secondary cementitious products formed as a result of hydration and pozzolanic reactions, respectively. Hydration of cement provides strength in early curing days. However, in long term, the strength increment is continued by pozzolanic reactions. Furthermore, kaolin provides usage of Ca^{+2} ions produced by cement during the pozzolanic reaction. Thereby, the presence of kaolin induces cement stabilization more effectively. Therefore, more cementitious materials are produced with increasing cement inclusion level and curing time to improve strength. Although cementitious products cause strength increase, these products are also quite effective in stress–strain behavior.

Fig. 7 shows the stress–strain curves of cement-stabilized clay specimens without PBS. As the cementitious products are increased due to increment of cement inclusion level and curing time, stress–strain relationships show brittle/semi-brittle behavior from ductile/semi-brittle behavior. This means that greater stress values are needed for a specimen to continue deformation and axial strain. After stress reaches the peak value, the strength dropped significantly to a much lower value. It is important to note that specimens including 3% cement content maintain ductile behavior since the cement addition produces an insufficient amount of cementitious products. The axial strain values of 1–7 and 28 days cured specimens vary between 2 and 4%. After 90-day curing time as the amount of cementitious products reaches their maximum value, 3% cement containing specimens tend to show semi-brittle behavior. Eventually, the axial strain reaches approximately 1.5%. All specimens containing 6% cement content tend to show semi-brittle behaviour at the beginning of 1-day curing time in that the required amount of cementitious products formed in specimens and axial strains ranged from 1 to 1.5%. Considering all cement contents, the greatest amount of cementitious products are formed in specimens containing 9% cement. Therefore, semi-brittle behavior is more pronounced in these specimens. As a consequence of cementitious products, an increase in cement content caused a lower axial strain corresponding to peak strength. It should be underlined that both curing period and cement content parameters are effective for cement stabilized clay behavior, however, the cement content parameter has a more dominant influence on clay behavior rather than curing period. Moreover, each additive used for improvement has an effect on the mechanical properties of the soil. PBS also affects the soil deformation behavior as well as cementitious products. Stress–strain curves of cement stabilized- PBS reinforced kaolin are shown in Fig. 8.

PBS that is used as a soil reinforcement caused ductile behavior in contrast to cement content influence. Two mechanisms specify the behavior of reinforced-stabilized clay specimens. The first mechanism is occurred by cementitious products due to the cement content and curing time, led to brittle behavior. The second mechanism is originated from the reinforcement element (plastic bottle strips) and forced clay specimens to show ductile behavior. These two mechanisms can be explained as the cementation process that causes the increase of compressive strength and the soil reinforcement that induces tensile strength increment. Two mech-

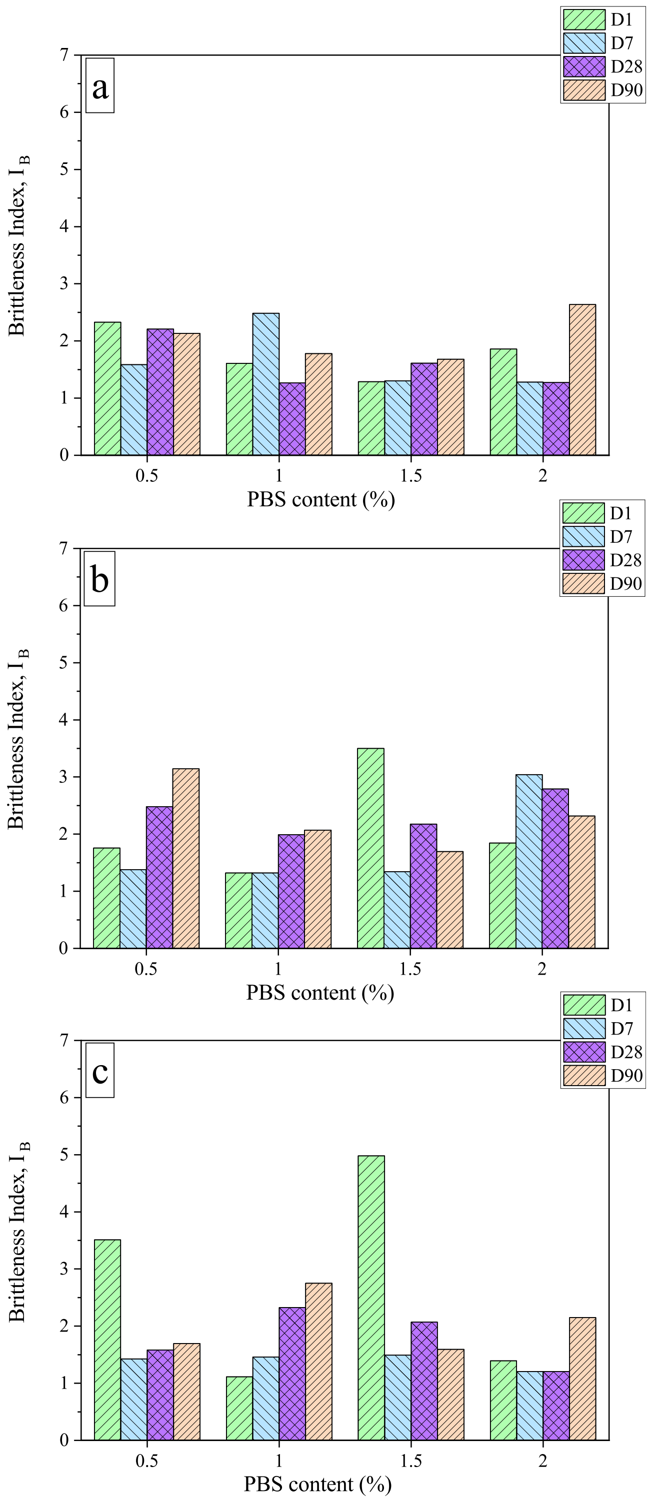

Fig. 11. Brittleness index of a) 3% b) 6% c) 9% of cement treated kaolin for various PBS content.

anisms affect simultaneously, causing an improvement in the mechanical behavior of clay due to additive inclusion level. However, each additive has an optimum content for maximum strength increase. For the specimens with 3% cement content, it is observed that the optimum PBS inclusion level causing maximum strength value is 2% PBS content up to 28 curing days. After 28 days, the optimum value of PBS is decreased to 1.5%. Maximum strength values of specimens contained 6 and 9% cement content are obtained generally from specimens with 1% PBS content. Akbulut et al. [41] investigated the influence of randomly oriented fiber content on strength of clay using scrap tire rubber, polyethylene, and polypropylene fiber. It was specified that unconfined compressive strength values of specimens increased with the addition of tire rubber fiber up to 2% and beyond this value, the strength of specimens tended to decrease. Also, Tafti and Emadi [42] evinced that the optimum fiber content for clayey soils was 1.5%. As it can be seen from Fig. 6; test results are compatible with literature [41,42]. Therefore; it should be noted that PBS showed the same behavior with fiber. Besides, Zhao et al. [32] indicated that beyond 1.5% of waste pet content, the shear strength showed a declining trend. Moreover, the optimum plastic contents are obtained as 1.5% for both fine and coarse grained soils. Zhao et al. [32] indicated that the increase in PBS (or PET) content led up to 2 times larger strain. Reinforcement elements which are PBS in this study, can efficiently restrain potential tensile cracks and reduce further deformations as a consequence, reinforced soil shows more ductile behavior. It can be said that the interlocking mechanism and bridge effect induced this ductile behavior. When the soil was subjected to normal stress, stress was transmitted to soil particles and movement of soil particles started to compress to form a denser structure. This movement of the soil grains caused a deformation on fiber like material that lay in the voids. The rotation and motion of soil particles on the deformation zone (the area that soil particles contacted with deformed fiber) generated interlock and frictional forces. Eventually, tensile stress on fiber was mobilized by particle interlocking and frictional forces. The mechanism of interlocking forces is shown in Fig. 9. Due to the particle interlocking and frictional effects, sliding of clay particles and the fiber-clay-cement matrix were more difficult, soil–cement–fiber matrix becomes more resistant to tensile stress. Also, randomly distributed fibers behave like a structural grid holding the soil matrix as a consequence soil strength and integrity were increased. To examine the bridge effect and increased soil integrity, fracture patterns of PBS free and PBS contained specimens were shown in Fig. 10. In PBS free specimens, apparent fractures and deeper cracks were observed, on the other hand, despite all cracks, PBS containing specimens tended to preserve their structural integrity.

For 3% cement contained specimens, PBS is more effective on clay behavior. However, after 90 days of the curing period, it is observed that axial strain value is decreased considerably and specimens slightly tend to show semi-brittle behavior due to increase in cementitious material. In Fig. 8; stress–strain curves of 6% of cement treated specimens containing varying amounts of PBS content and axial strain values of the stabilized specimens with different PBS content are higher than non-PBS specimens. Also, the stress–strain behavior of 0.5% PBS contained specimens is very close to non-PBS specimens. In this case, the cementation process becomes more dominant to induce semi-brittle behavior. However, specimens show a more ductile behavior beyond 0.5% of PBS content and axial strain values reach higher values. If strength-deformation behavior of specimens containing PBS stabilized with 6% of cement are comparatively analyzed, peak stress values are increased and as the curing time increases, specimens tend to show semi-brittle behavior. If specimens contained 9% cement are considered, it is seen that PBS content is more dominant in stress–strain behavior when compared to cement content. The axial strain values corresponding to peak shear stress are significantly increased with PBS content.

3.3. Energy absorption capacity and brittleness index

The stress–strain behaviour of soils can be also specified by using the brittleness index (I_B) that shows the ductile and brittle behavior of soils [43]. Brittleness index is calculated as:

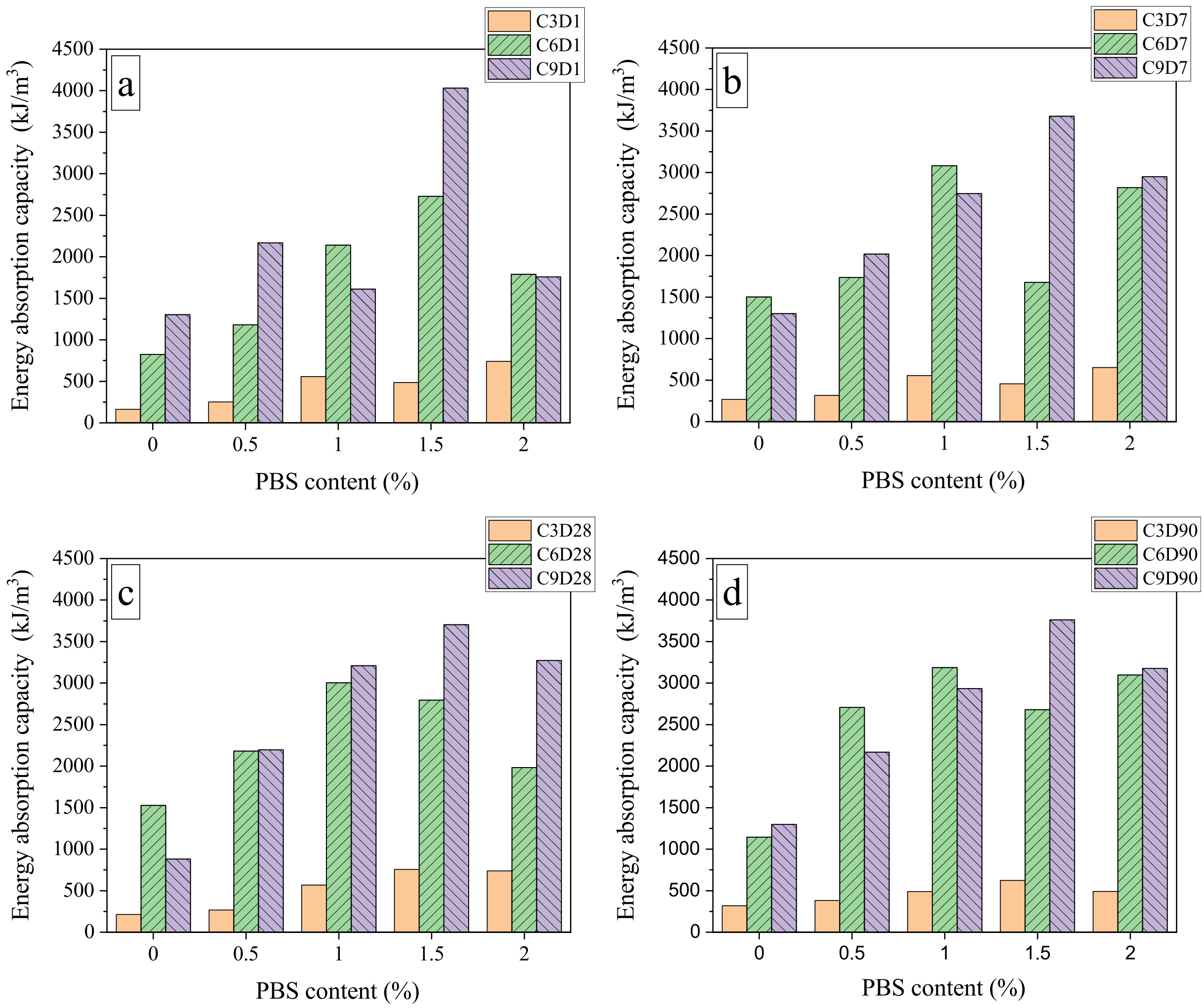

Fig. 12. Energy absorption capacity of a) 1-day b) 7-day c) 28-day d) 90-day cured cement treated kaolin for various PBS content.

Table 5
Quantitative correlations for cemented soil from literature

Materials	Functions	R^2	Sources
Sediments with cement, lime and fly ash	E_{50} = 119.91 UCS	0.8013	[45]
Sediments with cement	E_{50} = 167.3 UCS	0.94	[46]
Lead-polluted soils with cement	E_{50} = 57.2 UCS + 57.2	0.9179	[47]
Kaolin with cement	E_{50} = 89.529 UCS	0.7854	[48]
Kaolin with cement and magnesium sulphate	E_{50} = 91.343 UCS	0.8731	[48]

$$I_B = \frac{q_f}{q_{ult}} - 1 \quad (1)$$

where q_f and q_{ult} are the failure stress and ultimate stress, respectively. As the brittleness index approaches zero value, the specimen shows more ductile behavior. The specimen with the highest brittleness index value shows more brittle behavior than the others. The brittleness index (I_B) of cement and PBS contained specimens is shown in Fig. 11. Fatahi et al. [44] indicated that increasing cement content increased brittleness index also brittleness decreased by increasing fiber content. The average value of (I_B) is 1.77 for 3% cement stabilized kaolin. However, this value increased up to 1.99 for 9% of cement treated kaolin. As cement and PBS additives have an opposite contribution to stress–strain behavior, I_B decreases with increasing cement content. Also, increase in PBS content cause the tendency to ductile behavior. Considering PBS contained specimens, no significant change was observed on I_B. Since toughness indicates energy absorption capacity, it would be more useful to determine the effect of PBS on stress-stain beha-

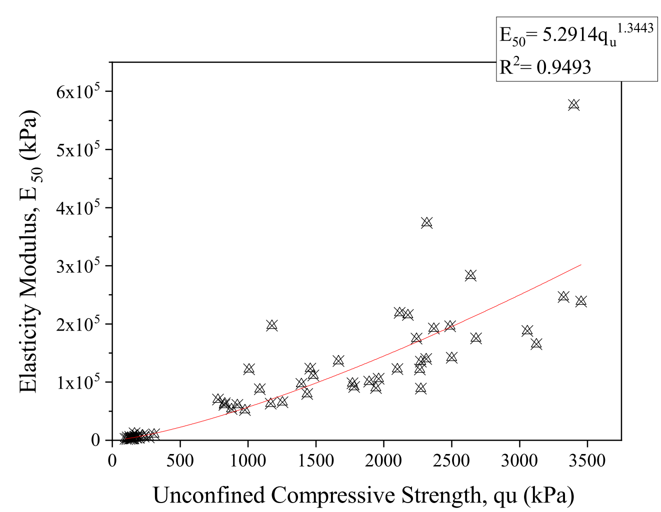

Fig. 13. The relationship between elasticity modulus and unconfined compressive strength of specimens with PBS and cement.

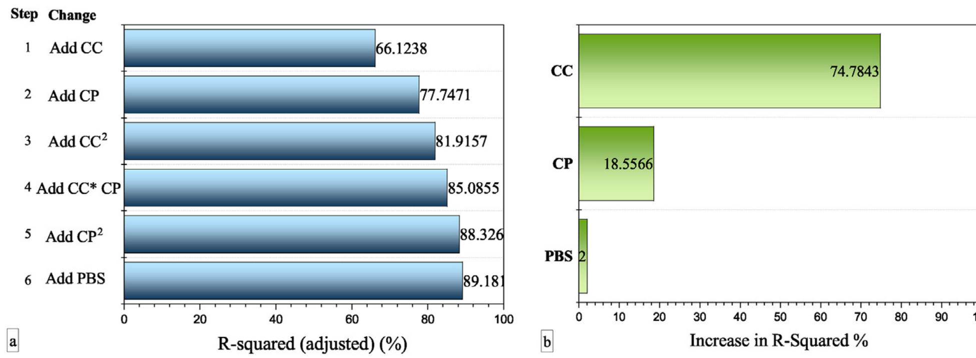

Fig. 14. a. model building sequence b. incremental impact of variables.

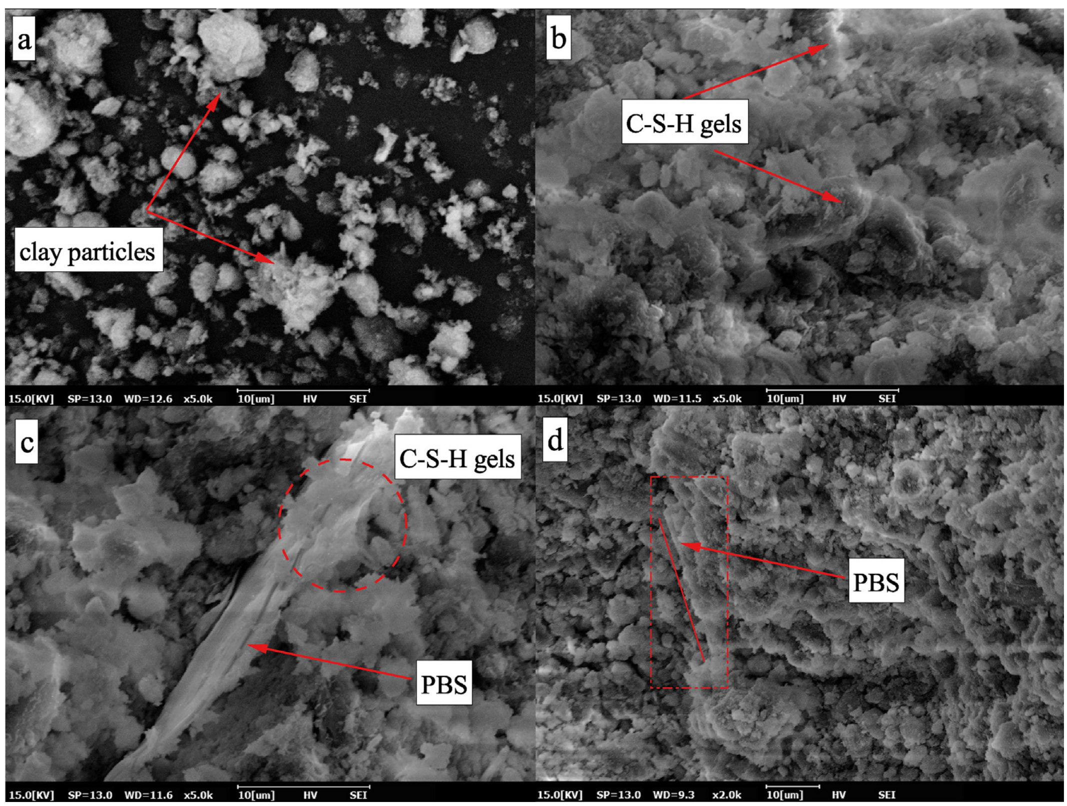

Fig. 15. SEM images of a. kaolin clay b. 9% cement stabilized kaolin c. 9% cement stabilized kaolin with PBS d. 6% cement stabilized kaolin with PBS.

viour. Toughness is an important parameter to evaluate the effect of fibers on soil stabilization. Toughness indicates the energy absorption ability of material until the failure point and can be calculated by integrating the area under the stress–strain curve [10].

The energy absorption capacity of cement stabilized-PBS reinforced kaolin is given in Fig. 12. The energy absorption capacity increased significantly with increasing PBS content. Toughness (energy absorption capacity) of PBS-cement treated specimens multiplied from 1.11 to 4.56 times than non-PBS contained specimens. In each case, the maximum toughness value was determined in 1.5% PBS contained specimens. Considering that more energy is required for the same deformation level, PBS is more effective on specimens containing 1.5% fiber.

Deformation modulus or Secant modulus (E_{50}) is an important parameter in soil deformation behavior and represents the resistance capacity to elastic and plastic deformation. Quantitative correlations for cemented soil from literature are presented in Table 5. The relationship between elasticity modulus (E_{50}) and unconfined compressive strength (q_u) is shown in Fig. 13. An exponential trend line is suitable with obtained data with $E_{50} = 5.2914q_u^{1.3443}$ and the coefficient of determination value (R^2) is determined as 0.9493.

3.4. A simple model for estimation of UCS

A mathematical model is established between the unconfined compressive strength and the three variable parameters as curing time, cement content, PBS content. According to experimental data, it has been seen that unconfined compressive strength values are related to these parameters. In order to obtain a relation with these variables with the greatest coefficient of determination, multiple regression analysis were performed and a mathematical model for unconfined compressive strength is presented in Eq. (2).

$$q_u = 844CC - 175.2PBS + 22.03CP - 48.4CC^2 - 0.2621CP^2 + 2.063CCxCP - 2003 \quad (2)$$

Here; CC, CP PBS indicate cement content, curing period, PBS content, respectively. It should be noted that these models are obtained for cement stabilized and PBS reinforced kaolin clay. Mathematical equation can be used practically to predict the undrained strength of cement-PBS treated clay in structures such as embankment or under-foundation materials. It is also important to obtain degree of the effectiveness of these variables on the strength properties of clayey soil. For this purpose,the impact of variables on the coefficient of determination (R^2) is analyzed to determine the contribution of these variables to the model. The variable that caused the greatest increment in the coefficient of determination would be the most effective parameter. It was obtained that; in order of significance, variables were obtained as cement content, curing time, and PBS content. Stages of model building and the impact of variables were shown in Fig. 14. As expected; since the effect of cement stabilization on soil improvement is greater than fiber and fiber-like elements, cement, and cement related curing time variables has a great significance on the model.

3.5. Scanning electron microscopy (SEM) analysis

After unconfined compressive strength tests, selected specimens were analyzed by scanning electron microscopy. In Fig. 15 the SEM images of pure kaolin and specimens were shown. Since the PBS strips have low density and have a transparent color, it is not easy to recognize PBS in SEM analysis. C-S-H gels formed with cement inclusion increase the contact of the grains with each other by wrapping the clay grains. After PBS addition, PBS was placed in the voids in the soil matrix and also surrounded by C-S-H gels. Analyzing the Fig. 15; PBS was deformed during the unconfined compression test due to the normal stresses, then interlocking and friction forces occurred between clay-cement and PBS. Also, some gap creations were observed at the interface caused by poor adhesion between soil and PBS.

4. Conclusions

In this study, the effects of PBS on the strength properties of cement stabilized kaolin are investigated experimentally. The concluding remarks are listed below:

- At the same PBS content, unconfined compressive strength increases by increasing cement content.
- As the amount of cementitious products formed by cement content increases, lower deformation values are observed at peak strength.
- It is observed that the specimens at the same cement content tend to behave more ductile with increasing PBS content.
- Test results revealed that optimum PBS content for cement stabilized clay range between 1 and 1.5%.
- A mathematical model is proposed to estimate the unconfined compressive strength of cement stabilized kaolin which was reinforced by using PBS.
- Recycling of PET waste in geotechnical applications has two advantages. While improving the geotechnical properties of soils, utilization of this non-degradable waste in soil stabilization also reduces environmental damage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] P. Subramanian, Plastics recycling and waste management in the us, Resources, Conservation and Recycling 28 (3–4) (2000) 253–263.
[2] A.E. Tayyar, S. Üstün, et al., Usage of recycled pet, Pamukkale University Journal of Engineering Sciences 16 (1) (2010) 53–62.
[3] S.M. Hejazi, M. Sheikhzadeh, S.M. Abtahi, A. Zadhoush, A simple review of soil reinforcement by using natural and synthetic fibers, Construction and Building Materials 30 (2012) 100–116.
[4] M.H. Maher, D.H. Gray, Static response of sands reinforced with randomly distributed fibers, Journal of Geotechnical Engineering 116 (11) (1990) 1661–1677.
[5] N.C. Consoli, P.D. Prietto, L.A. Ulbrich, Influence of fiber and cement addition on behavior of sandy soil, Journal of Geotechnical and Geoenvironmental Engineering 124 (12) (1998) 1211–1214.
[6] C.-S. Tang, B. Shi, L.-Z. Zhao, Interfacial shear strength of fiber reinforced soil, Geotextiles and Geomembranes 28 (1) (2010) 54–62.
[7] H. Güllü, H.I. Fedakar, On the prediction of unconfined compressive strength of silty soil stabilized with bottom ash, jute and steel fibers via artificial intelligence, Geomech Eng 12 (3) (2017) 441–464.
[8] N. Tiwari, N. Satyam, An experimental study on the behavior of lime and silica fume treated coir geotextile reinforced expansive soil subgrade, Engineering Science and Technology, an International Journal (2020) 1214–1222.
[9] A. Boz, A. Sezer, T. Özdemir, G.E. Hızal, Ö.A. Dolmacı, Mechanical properties of lime-treated clay reinforced with different types of randomly distributed fibers, Arabian Journal of Geosciences 11 (6) (2018) 122.
[10] K.Q. Tran, T. Satomi, H. Takahashi, Effect of waste cornsilk fiber reinforcement on mechanical properties of soft soils, Transportation Geotechnics 16 (2018) 76–84.
[11] T. Sunny, A. Joy, Study on the effects of marine clay stabilized with banana fibre, International Journal of Scientific Engineering and Research (2016) 96–98.
[12] J. Prabakar, R. Sridhar, Effect of random inclusion of sisal fibre on strength behaviour of soil, Construction and Building Materials 16 (2) (2002) 123–131.
[13] V. Sharma, H.K. Vinayak, B.M. Marwaha, Enhancing compressive strength of soil using natural fibers, Construction and Building Materials 93 (2015) 943–949.
[14] H. Danso, D. Manu, Influence of coconut fibres and lime on the properties of soil-cement mortar, Case Studies in Construction Materials 12 (2020) e00316.
[15] A. Abou Diab, S.S. Najjar, S. Sadek, H. Taha, H. Jaffal, M. Alahmad, Effect of compaction method on the undrained strength of fiber-reinforced clay, Soils and Foundations 58 (2) (2018) 462–480.
[16] I. Bozyigit, N. Tanrınıan, E. Karakan, A. Sezer, D. Erdoğan, S. Altun, Dynamic behavior of a clayey sand reinforced with polypropylene fiber, Acta Physica Polonica A 132 (3) (2017) 674–678.
[17] M.E. Orakoglu, J. Liu, F. Niu, Dynamic behavior of fiber-reinforced soil under freeze-thaw cycles, Soil Dynamics and Earthquake Engineering 101 (2017) 269–284.
[18] E. Kravchenko, J. Liu, W. Niu, S. Zhang, Performance of clay soil reinforced with fibers subjected to freeze-thaw cycles, Cold Regions Science and Technology 153 (2018) 18–24.
[19] A. Saygili, M. Dayan, Freeze-thaw behavior of lime stabilized clay reinforced with silica fume and synthetic fibers, Cold Regions Science and Technology 161 (2019) 107–114.
[20] A. Boz, A. Sezer, Influence of fiber type and content on freeze-thaw resistance of fiber reinforced lime stabilized clay, Cold Regions Science and Technology 151 (2018) 359–366.
[21] L. Nguyen, B. Fatahi, H. Khabbaz, Predicting the behaviour of fibre reinforced cement treated clay, Procedia Engineering (2016).
[22] S. Shukla, N. Sivakugan, B. Das, Fundamental concepts of soil reinforcement-an overview, International Journal of Geotechnical Engineering 3 (3) (2009) 329–342.
[23] J. Nyuin, N. Khalil, C. Petrus, Performance of sand reinforced with white coir fibre, MS&E 429 (1) (2018) 012031.
[24] S. Peddaiah, A. Burman, S. Sreedeep, Experimental study on effect of waste plastic bottle strips in soil improvement, Geotechnical and Geological Engineering 36 (5) (2018) 2907–2920.
[25] M. Bekhiti, H. Trouzine, M. Rabehi, Influence of waste tire rubber fibers on swelling behavior, unconfined compressive strength and ductility of cement stabilized bentonite clay soil, Construction and Building Materials 208 (2019) 304–313.
[26] A.J. Choobbasti, M.A. Samakoosh, S.S. Kutanaei, Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers, Construction and Building Materials 211 (2019) 1094–1104.
[27] J. Yadav, S. Tiwari, The impact of end-of-life tires on the mechanical properties of fine-grained soil: a review, Environment, Development and Sustainability 21 (2) (2019) 485–568.
[28] H. Ramesh, K. Manoj Krishna, H. Mamatha, Compaction and strength behavior of lime-coir fiber treated black cotton soil, Geomechanics and Engineering 2 (1) (2010) 19–28.
[29] W. Yixian, G. Panpan, S. Shengbiao, Y. Haiping, Y. Binxiang, Study on strength influence mechanism of fiber-reinforced expansive soil using jute, Geotechnical and Geological Engineering 34 (4) (2016) 1079–1088.

[30] N.C. Consoli, J.P. Montardo, P.D.M. Prietto, G.S. Pasa, Engineering behavior of a sand reinforced with plastic waste, Journal of Geotechnical and Geoenvironmental Engineering 128 (6) (2002) 462–472.
[31] G.S. Babu, S.K. Chouksey, Stress–strain response of plastic waste mixed soil, Waste Management 31 (3) (2011) 481–488.
[32] J.-J. Zhao, M.-L. Lee, S.-K. Lim, Y. Tanaka, Unconfined compressive strength of pet waste-mixed residual soils, Geomechanics and Engineering 8 (1) (2015) 53–66.
[33] D.L. Bish, Rietveld refinement of the kaolinite structure at 1.5 k, Clays and Clay Minerals 41 (6) (1993) 738–744.
[34] G.A. Lorenzo, D.T. Bergado, Fundamental parameters of cement-admixed clay-new approach, Journal of Geotechnical and Geoenvironmental Engineering 130 (10) (2004) 1042–1050.
[35] U. Khalid, C. Liao, G.-L. Ye, S.K. Yadav, Sustainable improvement of soft marine clay using low cement content: a multi-scale experimental investigation, Construction and Building Materials 191 (2018) 469–480.
[36] S. Chew, A. Kamruzzaman, F. Lee, Physicochemical and engineering behavior of cement treated clays, Journal of Geotechnical and Geoenvironmental Engineering 130 (7) (2004) 696–706.
[37] S. Horpibulsuk, R. Rachan, A. Suddeepong, Assessment of strength development in blended cement admixed bangkok clay, Construction and Building Materials 25 (4) (2011) 1521–1531.
[38] A. Kezdi, Stabilized Earth Roads, Elsevier, 2016.
[39] J. Mitchell, State-of-the-art report, session 12, in: 10th Int. Conf. on Soil Mechanics and Foundation Engineering, 1981, pp. 506–565..
[40] V. Schaefer, J. Mitchell, R. Berg, G. Filz, S. Douglas, Ground improvement, ground reinforcement and ground treatment: developments 1987–1997, in: Ground Improvement in the 21st Century: A Comprehensive Web-Based Information System, 2012, pp. 272–293..
[41] S. Akbulut, S. Arasan, E. Kalkan, Modification of clayey soils using scrap tire rubber and synthetic fibers, Applied Clay Science 38 (1–2) (2007) 23–32.
[42] M.F. Tafti, M.Z. Emadi, Impact of using recycled tire fibers on the mechanical properties of clayey and sandy soils, Electronic Journal of Geotechnical Engineering 21 (2016) 7113–7125.
[43] N.C. Consoli, M.A. Vendruscolo, A. Fonini, F. Dalla Rosa, Fiber reinforcement effects on sand considering a wide cementation range, Geotextiles and Geomembranes 27 (3) (2009) 196–203.
[44] B. Fatahi, H. Khabbaz, B. Fatahi, Mechanical characteristics of soft clay treated with fibre and cement, Geosynthetics International 19 (3) (2012) 252–262.
[45] D. Wang, N.E. Abriak, R. Zentar, Strength and deformation properties of dunkirk marine sediments solidified with cement, lime and fly ash, Engineering Geology 166 (2013) 90–99.
[46] W. Zhu, C.-L. Zhang, Y.-F. Gao, Fundamental mechanical properties of solidified dredged marine sediment, Journal-Zhejiang University Engineering Science 39 (10) (2005) 1561.
[47] L. Chen, S. Liu, Y. Du, F. Jin, Unconfined compressive strength properties of cement solidified/stabilized lead-contaminated soils, Yantu Gongcheng Xuebao/Chinese Journal of Geotechnical Engineering 32 (2010) 1898–1903.
[48] I. Kalipcilar, A. Mardani-Aghabaglou, A. Sezer, S. Altun, G. Inan Sezer, Sustainability of cement-stabilised clay: sulfate resistance, Proceedings of the Institution of Civil Engineers-Engineering Sustainability 171 (5) (2016) 254–274.