Applied Clay Science 80–81 (2013) 117–125

Contents lists available at ScienceDirect

Applied Clay Science

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

Research paper

Preparation of scrap tire rubber fiber–silica fume mixtures for modification of clayey soils

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A R T I C L E I N F O

Article history:
Received 23 August 2011
Received in revised form 21 March 2013
Accepted 20 June 2013
Available online 23 July 2013

Keywords:
Clayey soil
Silica fume
Scrap tire rubber fiber
Modification
Geotechnical property

A B S T R A C T

This experimental work was performed to investigate the influence of silica fume–scrap tire rubber fiber mixture inclusion on the geotechnical properties of clayey soils. The natural and modified clayey soil samples were subjected to the unconfined compression, the shear box, the odometer and the falling-head permeability tests after compaction at optimum moisture content. The results of experimental research indicated that silica fume, fiber and silica fume–fiber mixture modification enhanced both the unconfined compression strength and strength parameters. Although, the fiber modification increased in the hydraulic conductivity, it decreased in the swelling pressure. It was observed also that the silica fume and silica fume–fiber modification decreased both the hydraulic conductivity and swelling pressure. Consequently, it is concluded that the silica fume–fiber mixture materials can be successfully used for the modifications of clayey soils in the geotechnical applications.

1. Introduction

Construction of buildings and other civil engineering structures on weak or soft soil is highly risky because such soil is susceptible to differential settlements due to its poor shear strength and high compressibility. Improvement of certain desired properties like bearing capacity, shear strength parameters and permeability characteristics of soil can be undertaken by a variety of round improvement techniques such as the use of prefabricated vertical drains or soil stabilization (Abuel-Naga et al., 2006; Chu et al., 2006; Tang et al., 2007).

The concept of earth modification is an ancient technique and demonstrated abundantly in nature by animals, birds and the action of tree roots (Prabakar and Sridhar, 2002). Constructions using these techniques are known to have existed in the fifth and fourth millennium BC (Jones, 1985). Randomly distributed fiber-modified soils have recently attracted increasing attention in geotechnical engineering (Yetimoglu and Salbas, 2003). Vidal (1969) firstly developed the concept of soil modification and he demonstrated that the introduction of modification elements in a soil mass increases the shear resistance of the medium. The primary purpose of modifying soil mass is to improve its stability, increase its bearing capacity, and reduce settlements and lateral deformation (Akbulut et al, 2007; Hausmann, 1990; Kalkan, 2012; Prabakar and Sridhar, 2002; Yarbasi et al., 2007).

Several soil modification methods are available for modifying clayey soils. These methods include modification with chemical additives, rewetting, soil replacement, compaction control, moisture control, surcharge loading, and thermal methods (Chen, 1988; Nelson and Miller, 1992; Steinberg, 1998). All these methods may have the disadvantages of being ineffective and expensive. Therefore, new methods are still being researched to increase the strength properties and to reduce the swell behaviors of clayey soils (Puppala and Musenda, 2002). Many investigators have experienced on natural, fabricated, and by-product materials to use them as additive materials for the modification of clayey soils (Aitcin et al., 1984; Akbulut et al., 2004; Akbulut et al., 2007; Asavasipit et al., 2001; Cetin et al., 2006; Kalkan and Akbulut, 2004; Kalkan, 2006; Kayabali, 1997; Prabakar et al., 2004; Sandra and Jeffrey, 1992).

Recently, there have been many experimental researches on the reinforcement of soils with randomly disturbed natural and synthetic fiber materials (Akbulut et al., 2007; Cetin et al., 2006; Charan, 1995; Gray and Ohashi, 1983; Kaniraj and Havanagi, 2001; Maher and Gray, 1990; Nataraj and McManis, 1997; Park and Tan, 2005; Pierce and Blackwell, 2003; Prabakar and Sridhar, 2002; Ranjan et al., 1996; Santoni et al., 2001; Tang et al., 2007, 2010). These previous investigations indicate that strength properties of fiber-reinforced soils consisting of randomly distributed fibers are a function of fiber content and fiber–surface friction along with the soil and fiber strength characteristics. The use of fibers in geotechnical design and application is a major focus of several research studies because fiber materials are cost-competitive with other materials (Gregory and Chill, 1998; Musenda, 1999; Puppala and Musenda, 1998). In addition, these fiber materials can be recycled from plastic and rubber waste materials, so the fiber stabilization of soils method can potentially reduce (Akbulut et al., 2007).

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0169-1317/$ – see front matter
http://dx.doi.org/10.1016/j.clay.2013.06.014

Randomly distributed fibers acting as new modification material have become a focus of intense interest in recent years. In comparison with conventional modification materials, the mixing of discrete fibers with soil mass is simple and quite similar to other admixtures such as cement and lime. One of the primary advantages of randomly distributed fibers is the absence of potential planes of weakness that can develop parallel to oriented modification (Maher and Gray, 1990). Therefore, they have attracted the attention of scientists worldwide, and a number of triaxial tests, unconfined compression tests, California Bearing Ratio tests, direct shear tests on this subject have been conducted (Cai et al., 2006; Consoli et al., 2009; Kaniraj and Havanagi, 2001; Karahan and Atiş, 2011 Latha and Murthy, 2007; Park, 2009; Prabakar and Sridhar, 2002; Ranjan et al.,1996; Santoni et al., 2001; Tang et al., 2007; Yetimoglu and Salbas, 2003; Yetimoglu et al., 2005). Consoli et al. (1998) added the randomly distributed fibers to cemented soil, conducted triaxial compression tests on the mixture, and concluded that the fiber modification increased both the peak and residual strength, and changed the cemented soil's brittle behavior to a more ductile one. The inclusion of fibers significantly changed the failure mechanism by preventing the formation of tension cracks (Consoli et al., 2003). Miller and Rifai (2004) reported that the shrinkage crack reduction and hydraulic conductivity of compacted clay soil increased with an increase in fiber content. All these investigations show that the inclusion of discrete fibers can improve the strength behavior, and significantly enhance the ductility and fracture toughness of soil matrix. It has been proved that discrete fibers can be considered as good earth modification material (Tang et al., 2010).

The main objective of this paper is to investigate the use of waste materials such as silica fume and scrap tire rubber fiber in geotechnical applications and to evaluate the effects of scrap tire rubber fiber and scrap tire rubber fiber–silica fume mixture on the unconfined compressive strength (UCS) and strength parameters such as cohesion and internal friction angle, hydraulic conductivity and swelling pressure of clayey soils. The data of UCS were obtained from the compression tests, strength parameters from the shear box tests, swelling pressure from odometer tests and hydraulic conductivity from the falling-head permeability tests under laboratory conditions.

2. Materials

2.1. Clayey soil

The clayey soil was supplied from the clay deposits of Oltu Oligocene sedimentary basin, Erzurum, Northeast Turkey. It consists of montmorillonite and quartz and calcite non-clay minerals. According to the United Soil Classification System, this soil is inorganic clay of high plasticity (CH) and highly compressible inorganic silt and organic clay (MH) (Kalkan, 2003; Kalkan and Bayraktutan, 2008). The grain-size distribution and XRD pattern of clayey soil are given in Figs. 1 and 2. Its chemical composition and engineering properties are summarized in Tables 1 and 2, respectively.

2.2. Silica fume

Silica fume used in this experimental study has been supplied from Ferro-Chromate Factory in Antalya (Turkey). Silica fume, a very fine solid material generated during silicon metal production, has historically been considered a waste product. It is a by-product of producing silicon metal or ferrosilicon alloys. Although the silica fume is a waste of industrial materials, it has become the most valuable by-product pozzolanic materials due to its very active and high pozzolanic property. One of the most beneficial uses for silica fume is in concrete. Because of its chemical and physical properties, it is a very reactive pozzolan (Atis et al., 2005; Kalkan and Akbulut, 2004). The grain-size distribution of silica fume is shown in Fig. 1. Its chemical composition and index properties are summarized in Tables 1 and 2, respectively.

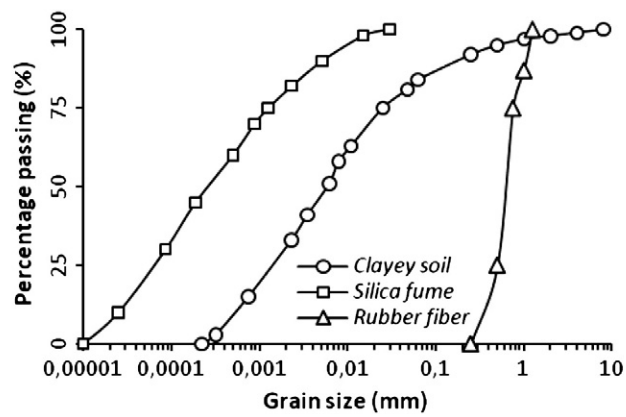

Fig. 1. The grain-size distributions of clayey soil, silica fume and scrap tire rubber fiber.

2.3. Scrap tire rubber fiber

The scrap tire rubber fibers were supplied from local recapping truck tire producers in Erzurum, Northeast Turkey. When the tread on truck tires are down, it is more economical to stave off the old tread and replace it than to purchase brand new tires. The tire is shaved off into 150 mm length and smaller strips using a sharp rotating disc. These strips are then ground into scrap rubber (Akbulut et al., 2007; Pierce and Blackwell, 2003). The scrap tire rubber fibers were sieved to remove finer and coarse fiber particles. They had length ranging from 5 to 10 mm, thickness ranging from 0.25 to 0.50 mm and width ranging from 0.25 to 1.25 mm. The grain-size distribution was determined by using fiber width. The grain-size distribution and engineering properties of scrap tire rubber fiber used in this study are summarized in Fig. 1 and Table 3, respectively.

3. Experimental study

3.1. Preparation of mixtures

The clayey soil used in this study has been dried in an oven at approximately 65 °C and then ground before using the mixtures. First, the required amounts of clayey soils, silica fume and scrap tire rubber fiber have been blended together under dry conditions. The contents of silica fume are 10 and 20% by the total weight of mixtures. In the same way, the contents of scrap tire rubber fiber were chosen as 1, 2, 3 and 4% by total weight of mixtures. As the fibers tended to lump together, considerable care and time were spent to get a homogeneous distribution of the fibers in the mixtures. Then the prepared

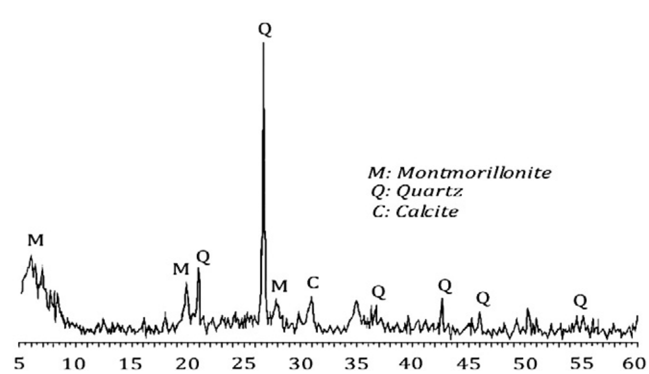

Fig. 2. XRD pattern of clayey soil.

Table 1
Chemical compositions of clayey soil and silica fume used in the study.

Property	Clayey soil	Silica fume
Compound		
SiO_2, %	46.83	85–95
Al_2O_3, %	15.35	1–3
Fe_2O_3, %	6.81	0.5–1
CaO, %	11.02	0.8–1.2
MgO, %	4.56	1–2
Na_2O, %	0.94	–
K_2O, %	1.23	–
TiO_2, %	0.81	–
Loss on ignition (LOI), %	12.45	0.5–1

mixtures have been mixed with the required amount of water according to the optimum moisture content. The weights of the mixtures were determined according to the formulas below;

$$W_{CSF} = W_C + W_{SF} \quad (1)$$

$$W_{CFB} = W_C + W_{RF} \quad (2)$$

$$W_{CSFRF} = W_C + W_{SF} + W_{RF} \quad (3)$$

where W_{CSF}, W_{CRF}, and W_{CSFRF} are the total dry weights of clayey soil–silica fume mixtures, clayey soil–scrap tire rubber fiber mixtures, and clayey soil–silica fume–scrap tire rubber fiber mixtures, respectively and W_C, W_{SF}, and W_{RF} are the weights of clayey soil, silica fume and scrap tire rubber fiber, respectively. The component of the samples used in the experimental studies is summarized in Table 4.

3.2. Preparation of samples

The mixtures of silica fume–clayey soil, scrap tire rubber fiber–clayey soil and silica fume–scrap tire rubber fiber–clayey soil mixtures were blended together in dry conditions. Then natural clayey soil and mixtures were mixed with the required amount of water for optimum water content. All mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. The unconfined compression and shear box tests were carried out on the cylindrical samples compacted at optimum water contents. The compaction processes were performed by Standard Proctor test. After compactions of the clayey soil and the mixtures, cylindrical samplers were pressed into the compacted samples within the mold to obtain samples with appropriate length-to-diameter ratios for unconfined compressive and shear box tests. Then the cylindrical samples taken into the cylindrical samplers were extruded using a hydraulic sample extractor. The samples of unconfined compression tests had 35 mm diameter by 70 mm length. In the tests, at least three samples were tried for each combination of variables. After each sample was extracted from the cylindrical samplers, it was wrapped in plastic to prevent from water loss. The samples with 60 mm diameter and 35 mm length were used for the shear box tests.

Table 2
Engineering properties of clayey soil and silica fume used in this study.

Property	Clayey soil	Silica fume
Density		
Density, (Mg/m^3)	2.63	2–2.5
Grain size		
Sand (2000–75 μm), %	2	–
Silt (2–75 μm), %	66	20
Clay (<2 μm), %	32	80
Atterberg limits		
Liquid limit, %	72	–
Plastic limit, %	35	–
Plasticity index, %	37	–
Specific surface area		
Specific surface area, m^2/g	243.6	20.12
Soil classification		
Unified Soil Classification (USCS)	CH	–
Mineralogy		
Clay minerals		
Montmorillonite	x	–
Non-clay minerals		
Quartz	x	–
Calcite	x	–

Table 3
Engineering properties of scrap tire rubber fiber used in this study.

Property	Scrap tire rubber
Property	
Fiber type	Single fiber
Density, (Mg/m^3)	1.153–1.198
Elastic modulus (MPa)	1–97–22.96
Tensile strength (MPa)	28.1
Extent at failure (%)	44–55
Softening temperature (°C)	175
Component	
Styrene butadiene copolymer (%)	62
Carbon block (%)	31
Extender oil (%)	1.9
Zinc oxide (%)	1.9
Stearic acid (%)	1.2
Sulphur (%)	1.1
Accelerator	0.7

3.3. Testing program

3.3.1. Compaction tests

To determine the optimum water contents of natural and modified clayey soil samples and to prepare the samples for the unconfined compression and shear box tests, Standard Proctor tests were carried out by referring to the ASTM D 698. During the compaction process, a soil at selected water content was placed in three layers into a mold of standard dimensions, with each layer compacted by 25 blows of rammer dropped from a distance of 305 mm, subjecting the soil to total compaction effort. This procedure was repeated for six numbers of water contents to establish a relationship between the dry unit weight and the water content for the clayey soil and the mixtures. The compaction curves were plotted from the data and the values of optimum water content and maximum dry unit weight were determined from the compaction curves. The clayey soil and the mixtures were compacted at the optimum water content to prepare the samples for the unconfined

Table 4
Clayey soil, silica fume and scrap tire rubber fiber ratio of composite samples.

		Materials (%)		
Samples	Clayey soil	Silica fume	Scrap tire rubber fiber	Total
C	100	–	–	100
CSF1	90	10	–	100
CSF2	80	20	–	100
CRF1	99	–	1	100
CRF2	98	–	2	100
CRF3	97	–	3	100
CRF4	96	–	4	100
CSFRF1	89	10	1	100
CSFRF2	88	10	2	100
CSFRF3	87	10	3	100
CSFRF4	86	10	4	100
CSFRF5	79	20	1	100
CSFRF6	78	20	2	100
CSFRF7	77	20	3	100
CSFRF8	76	20	4	100

C: clayey soil, CSF: clayey soil–silica fume mixture, CRF: clayey soil–fiber mixture, CSFRF: clayey soil–silica fume–fiber mixture.

compression, shear box tests, odometer and the falling-head permeability tests.

3.3.2. Unconfined compression tests

The UCS values of clayey soil and modified clayey soil samples were determined from the unconfined compressive tests in accordance with ASTM D 2166. This test is widely used as a quick and economical method of obtaining the approximate compressive strength of the cohesive soils. In this study, three cylindrical samples were prepared and tested for each combination of mixtures. The unconfined compressive tests were performed at a deformation rate of 0.16 mm/min.

3.3.3. Shear box tests

In order to determine the shear strength parameters of clayey soil and modified clayey soil samples, a series of shear box tests was carried out in accordance with ASTM D 3080. For these tests, samples were placed in the standard shear box apparatus with 60 mm in diameter and 35 mm in length. To obtain the shear strength parameters such as cohesion and internal friction angle, the values of shear stress versus the value of normal stress were plotted to construct a best fit straight line through the plotted points. The cohesion values were obtained from the intercept with the ordinate axis and the slops of the internal fraction angles from the slope.

3.3.4. Odometer tests

Swelling pressure values of the natural and modified clayey soil samples were obtained from odometer tests carried out according to ASTM D 2435. The samples were all initially compacted at their optimum moisture content in a Standard Proctor mold and extruded using a cutting ring before the one dimensional consolidation tests. The samples used in the tests were 74 mm in diameter and 20 mm high in standard Odometer apparatus (ASTM D 2435). The swelling pressure of each sample was directly measured from the surcharge, which loads the sample. The sample was confined in the consolidation ring, and water was added to the sample, and it was allowed to swell. As the samples were swelling, the deflection of the dial gage was set up to zero. As a result, the samples showed no further tendency to swell and the maximum surcharge load, P_{ms}, at that point was used for the calculation of the swelling pressure. The swelling pressure can be expressed as;

$$SP = P_{MS}/A \tag{4}$$

where swelling pressure (SP) is in kilopascals, P_{MS} is the maximum surcharge load on the sample in kilonewtons, and A is the area of the sample, in square centimeters.

3.3.5. Falling-head permeability tests

The falling-head permeability tests were conducted in accordance with ASTM D 5084. The samples were placed inside a cylindrical mold with a 102 mm in diameter and 117 mm in length and then allowed to flow through the sample. The test apparatus consists of a mold with lids and a standpipe 10 mm in diameter and 100 mm in length. During the tests, prepared samples in molds were saturated under water pressure for two days, and then permeability values were calculated for 48 h. The permeability values were calculated by the following equation:

$$k = aL/At \ \ln(h_1/h_2) \tag{5}$$

where k is the permeability in centimeters per second, h_1 is the hydraulic head across sample at the beginning of the test ($t = 0$) in centimeters, h_2 is the hydraulic head across sample at the end of the test ($t = t_{test}$) in centimeters, t is elapsed time in second, A is the across area of sample in square centimeters, a is the across area of standpipe in square centimeters and L is the length of sample in centimeters.

3.3.6. Imaging tests

In order to evaluate the interaction between clayey soil and silica fume particles, clayey soil and modified clayey soil samples were subjected to image analysis by using scanning electron microscope (SEM). Images of samples were magnified 5000 times by means of a SEM modeled Jeol 6400 SEM. After blending clayey soil and silica fume under dry conditions and mixing them with the required amount of water for optimum moisture content to obtain reaction between clayey soil and silica fume particles, all samples were allowed to air-dry to their initial water content at 22 °C up to water removing. After curing, all samples were subjected to imaging for microscopic analysis to determine the nature of the pores and the effect of varying the silica fume content on the pore structure.

4. Results and discussions

4.1. Effects of silica fume and tire rubber fiber on the compaction parameters

Standard proctor tests were carried out to determine the effect of silica fume and tire rubber fiber on the compaction parameters such as maximum dry unit weight and optimum water content and results were summarized in Figs. 3 and 4. It was observed that the maximum dry unit weight values decreased and the optimum water content values increased with the addition of silica fume. The decrease in the maximum dry unit weights was attributed to the addition of higher amounts of silica fume, which filled the voids of the silica fume-modified clayey soil samples (Attom and Al-Sharif, 1998; Kalkan and Akbulut, 2002; Kalkan and Akbulut, 2004). In the same way, the increase in the optimum water content was due to the change in the particle size distribution and surface area of the silica fume stabilized clayey soil samples (Pera et al., 1997; Kalkan, 2006, 2011). On the other hand, with the addition of tire rubber fiber both the maximum dry unit weight (Fig. 3) and optimum moisture content (Fig. 4) decreased. These decreases were attributed to the low density and large specific surface area of tire rubber fiber (Prabakar and Sridhar, 2002; Akbulut et al., 2007; Şenol, 2012).

4.2. Effect of silica fume and scrap tire rubber fiber on the UCS

The effect of silica fume, scrap tire rubber fiber and silica fume–scrap tire rubber fiber mixtures on the UCS were illustrated in Figs. 5 and 6. As can be seen in Fig. 5, the silica fume increased the UCS value of clayey soil. As compared with clayey soil, the UCS value of silica fume-modified clayey soil sample containing 20% silica fume increased from 92.8 to 182 kPa, which is 0.97 times more than that of unmodified (Fig. 6). The increase in the UCS is attributed to the internal friction of silica fume particles and chemical reaction between the silica fume and

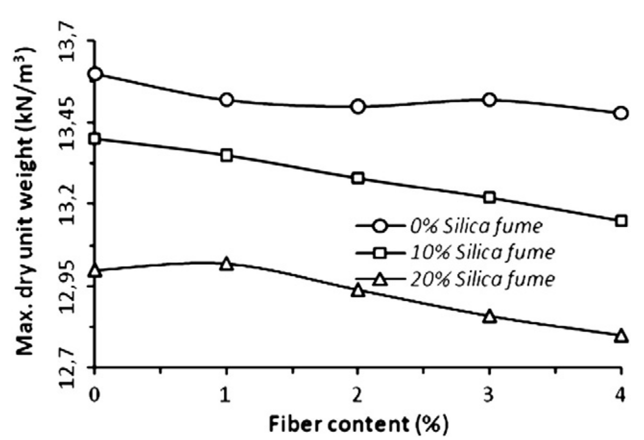

Fig. 3. Effect of the scrap tire rubber fiber on the maximum dry unit weight.

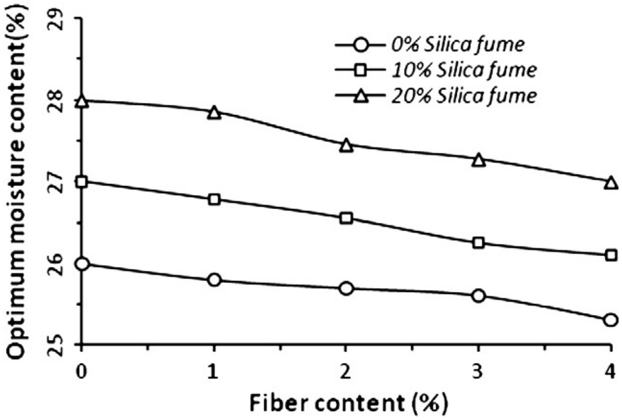

Fig. 4. Effect of the scrap tire rubber fiber on the optimum moisture content.

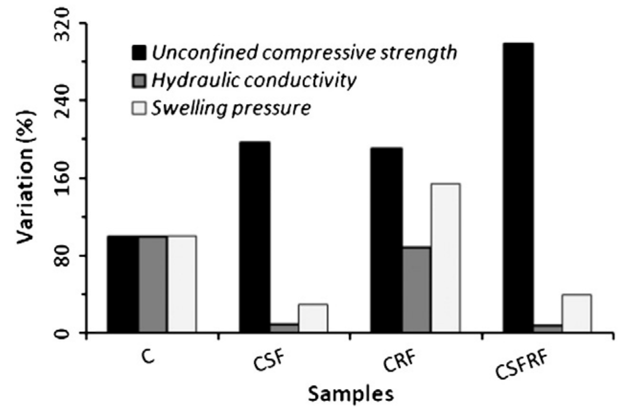

Fig. 6. Variation of UCS, swelling pressure and hydraulic conductivity with the silica fume, fiber and silica fume–fiber mixtures.

clayey coil particles (Gillot, 1968; Kalkan, 2006, 2009a,b; Kalkan and Akbulut, 2004; Ola, 1978). The clayey soil used in this study has significant amounts of calcium containing compounds (Table 1) that can produce Ca^{2+} and OH^{-1} ions. The active silica reacts with calcium and hydroxide forming calcium silicate hydrate gels. This chemical modification likely causes stronger and more brittle forms of material composing the clayey soil–silica fume mixture and decreases their volumetric shrinkage strain (Bell, 1993; Kalkan, 2011; Kalkan and Akbulut, 2004; Sherwood, 1993).

The effects of scrap tire rubber fibers on UCS values of clayey soil and silica fume-modified clayey soil samples are given in Figs. 5 and 6. This figure indicates that the UCS values of fiber-modified clayey soil and silica fume and fiber-modified clayey soil have a tendency to increase first, after a peak value, the UCS values decrease. It was found that the UCS values increased due to the rise of 2% fiber content from 92.8 to 177.1 kPa and from 182.7 to 278.1 kPa for the silica fume and silica fume-modified clayey soil samples, respectively.

To express the variation of the UCS, hydraulic conductivity and swelling pressure values as a percentage, these values were normalized equalizing these values of clayey soil samples to 100. These normalized values were depicted in Fig. 6. It was observed that the percentage of increase in the UCS values was 96.88, 90.78 and 199.67% for the silica fume-modified clayey soils, rubber fiber-modified clayey soil and silica fume and rubber fiber-modified clayey soil, respectively (Fig. 6). According to the test results, the optimum tire rubber fiber content is 2%.

Both the silica fume and rubber fiber contents play an important role in the development of UCS. The results indicate that silica fume–rubber fiber mixtures have more effect on the UCS than that of rubber fiber. The increase in UCS is attributed to the internal friction of silica fume particles and chemical reaction between silica fume and clay materials.

Interaction mechanism of fiber/soil interface is complex. The previous research results show that pullout response is influenced by many factors, e.g. the confinement stress, soil dry density, displacement rate, embedded modification length, modification surface roughness, shape and so on (Bakeer et al., 1998; Beyerlein et al., 2001; Brandstetter et al., 2005; Khedkar and Mandal, 2009; Li et al., 2005; Lopes and Ladeira, 1996; Moraci and Recalcati, 2006; Sieira et al., 2009). The main interaction mechanisms affecting the pullout resistance of extruded rubber fiber particles are the skin friction, between soil and fiber surface, and the bearing resistance that develops against the transversal element (Moraci and Gioffre, 2006). The pullout response of rubber fibers, also pointed out that the friction between soil and fiber, the nature and the confinement of soil are the most important factors affecting pullout response of fiber. After compaction, the fiber is enwrapped by interlocked or inter-bonded soil particles. After the fiber is pulled out, some soil particles are attached on the fiber surface. It indicates that the interfacial soil structure is disturbed even broken during the shear process. Therefore, when shear occurs, the interfacial friction strongly depends on the resistance of soil particle rearrangement and rotation (Fig. 7). The soil particle rotation occurs, when the resistance offered by mineral friction and mechanical interlock between adjacent soil particles is smaller than that between the particles and the manufactured material surface (Dove et al., 2006; Racana et al., 2003; Tang et al., 2010).

During compaction, some angular hard particles in soil may cause plastic deformation of fiber body (Fig. 8), especially at high compaction load. This phenomenon was confirmed by Tang et al. (2007), who investigated the interface morphologies of fiber-modified clayey soil.

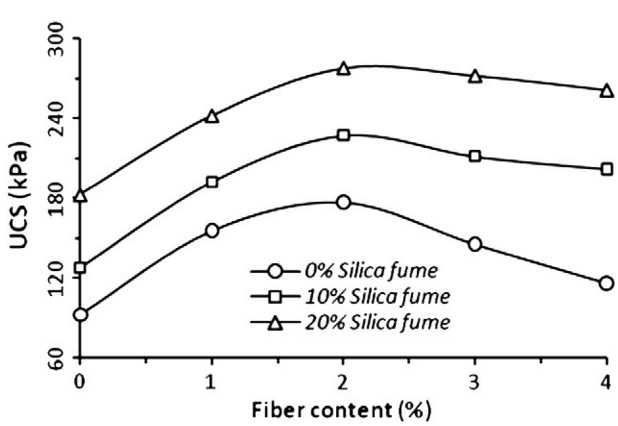

Fig. 5. Effect of the scrap tire rubber fiber on the UCS.

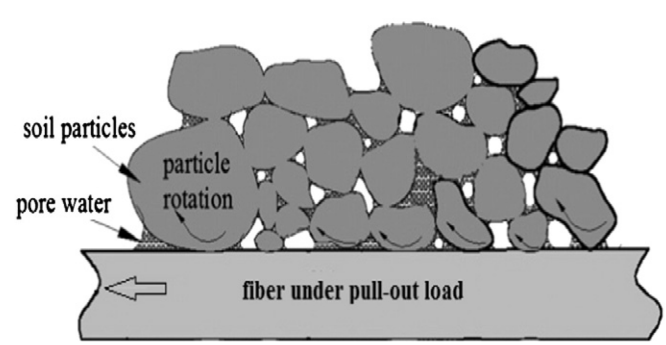

Fig. 7. Sketch drawing of interfacial mechanical interactions between soil particles and fiber (modified from Tang et al., 2010).

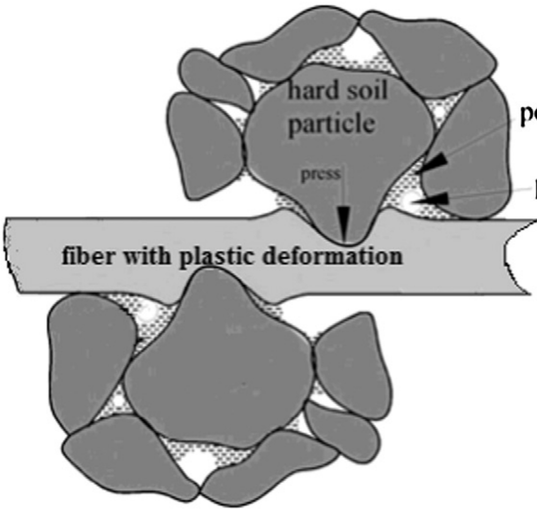

Fig. 8. Sketch drawing of contact condition between hard soil particles and fiber surface under press (modified from Tang et al., 2010).

4.3. Effect of silica fume and scrap tire rubber fiber on the strength parameters

The shear box test results showed that the cohesion and internal friction angle values increased by the addition of silica fume (Figs. 9 and 10). This indicates the addition of silica fume increases shear strength parameters for the same conditions. The maximum cohesion value of silica fume-modified clayey soil samples was observed for 20% silica fume as 192.7 kPa, which is 1.1 times more than that of the unmodified clayey soil samples. Meanwhile, the maximum internal friction angle value observed from modified clayey soil containing 20% silica fume was 28, which is 1.7 times more than that of the unmodified clayey soil samples. In literature, Ola (1978) and Gillot (1968) have reported that soil type, its composition, mineralogy, particle shape, and particle size distribution influence the results of soil modification. The increase in the cohesion and internal friction angle was attributed to the very fine particle size and internal friction of silica fume particles and chemical reaction between silica fume and clayey soil particles (Kalkan, 2009a; Kalkan and Akbulut, 2004).

The relationship between shear strength parameters and scrap tire rubbe fiber was illustrated in Figs. 9 and 10. It is indicated that the percentage rubber fiber and silica fume–fiber mixture content plays an important role in the development of the shear strength parameters cohesion and internal friction angle. The cohesion and internal friction angle of the samples increase with the increasing fiber content up to 2%. It was found that the cohesion values increased due to the rise of 2% fiber content from 176 to 214 kPa and from 176 to 268 kPa for clayey soil and modified clayey soil containing 20% silica fume, respectively. The increase in the cohesion of fiber-modified clayey soil samples might be due to the increase in the confining pressure due to the development of tension in the fiber, and the moisture content in the fiber favors the formation of absorbed water layer on the clay particles, which enables the modified soil to act as a single coherent matrix of soil–fiber mass (Prabakar and Sridhar, 2002). In general, the internal friction angle value of each modified sample increased, and these values ranged from 16 to 32° and from 16 to 48° for clayey soil and modified clayey soil containing 20% silica fume, respectively.

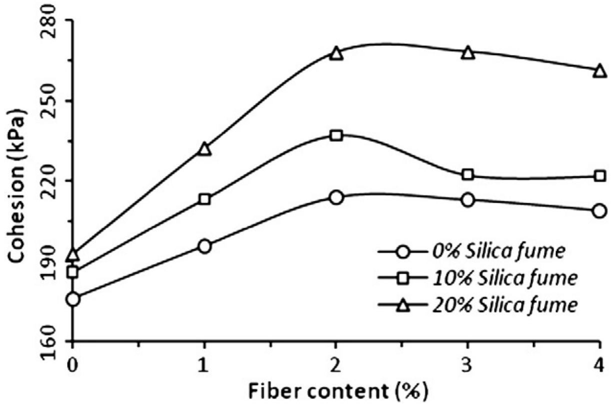

Fig. 9. Effect of the scrap tire rubber fiber on the cohesion.

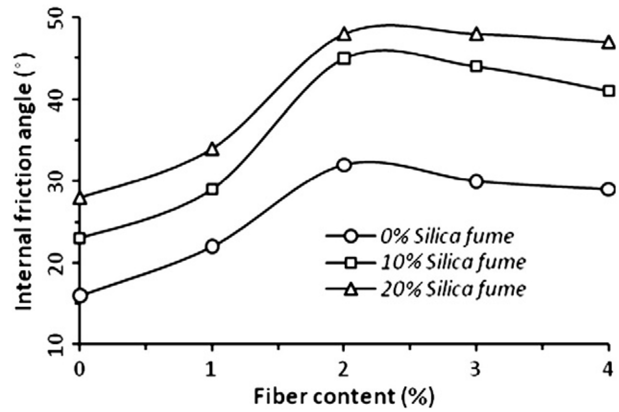

Fig. 10. Effect of the scrap tire rubber fiber on the internal friction angle.

In the literature it is noted by Tang et al. (2010) that after compaction, the fiber is enwrapped by inter-locked or inter-bonded soil particles. After the fiber is pulled out, some soil particles are attached on the fiber surface. It indicates that the interfacial soil structure is disturbed even broken during the shear process. Therefore, when shear occurs, the interfacial friction strongly depends on the resistance of soil particle rearrangement and rotation. Normally, the less likely the soil particles rearrange during shearing or the more inter-locked the soil particles, the higher is the interfacial resistance to shear. The soil particle rotation would occur, when the resistance offered by mineral friction and mechanical interlock between adjacent soil particles is smaller than that between the particles and manufactured material surface (Dove et al., 2006; Frost and Han, 1999; Tang et al., 2010).

4.4. Effect of scrap tire rubber fiber on the failure characteristics

The failure characteristics of clayey soil and modified clayey soil samples with silica fume, fiber and silica fume–fiber mixture are illustrated in Fig. 11. It is observed that the addition of silica fume and fiber has a significant influence on the failure characteristics of modified samples. The high degree of stiffness of the attached hydration crystals also toughened the distributed fibers, which act similarly to plant roots in distributing the stresses in a broader area and inhibiting fissure propagation. Therefore, the combined silica fume and fiber inclusions increase the efficiency of transfer of the load from matrix to fibers. Furthermore, the hydration of the silica fume binds the soil particles together and makes the matrix compact, and causing an increase in normal stress around the fiber body and the effective contact area. As a result, the static friction coefficient between fiber and composite matrix is increased (Tang et al., 2007). It is shown from Fig. 11 that there is a difference in the size of the cracks in the surface of these four samples after compression failure. It is clearly shown that big cracks gradually vanish and small ones appear instead of them while the addition of 2% fiber content. Similar trends have been obtained from some experimental works by adding lime–fiber (Cai et al., 2006), cement–fiber (Tang et al., 2007, 2010).

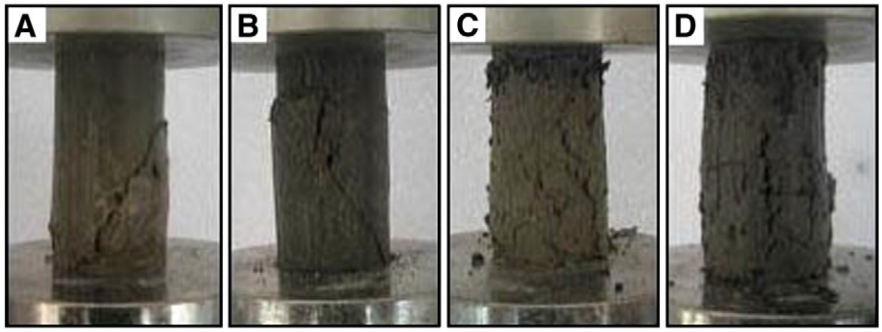

Fig. 11. Effects of silica fume, fiber and silica fume–fiber mixtures on the failure characteristics; (A) natural clayey soil, (B) 20% silica fume–modified clayey soil, (C) 2% fiber-modified clayey soil and (D) 20% silica fume and 2%fiber-modified clayey soil.

4.5. Effect of silica fume and scrap tire rubber fiber on the hydraulic conductivity

Fig. 12 presents the effect of silica fume, fiber and silica fume–fiber mixtures on the hydraulic conductivity of clayey soil. The hydraulic conductivity values steadily decreased with increasing silica fume content and the low values were finally reached in the 20% silica fume-modified clayey soil. The hydraulic conductivity values of silica fume-modified clayey soil samples decreased from 1.86×10^{-7} to 5.53×10^{-8} cm/s. The decrease in the hydraulic conductivity values is due to the decreasing void ratio of the silica fume-modified samples.

As can be seen in Fig. 12, scrap tire rubber fiber increased the hydraulic conductivity of fiber-modified clayey soil samples, but silica fume–fiber mixtures decreased the hydraulic conductivity. As compared with natural clayey soil samples, it was found that the hydraulic conductivity of 2% fiber-modified clayey soil samples increased from 1.86 to 2.86×10^{-7} cm/s. On the contrary, the hydraulic conductivity of 20% silica fume and 2% fiber-modified clayey soil samples decreased from 1.86×10^{-7} to 6.45×10^{-8} cm/s. The increase in hydraulic conductivity was attributed to the rubber fiber particles in the modified samples. The fiber surface caused the water to move easily in the fiber-modified clayey soil samples. The decrease in the hydraulic conductivity values was due to the decreasing void ratio of the modified clayey soil samples containing silica fume (Kalkan, 2009a; Kalkan and Akbulut, 2004).

4.6. Effect of silica fume and scrap tire rubber fiber on the swelling pressure

The effect of silica fume and scrap tire rubber fiber on the swelling pressure was investigated and the results were illustrated in Fig. 13. The swelling pressure steadily decreased with increasing silica fume content. With the addition of 20% silica fume, the swelling pressure decreased from 230 to 17 kPa. The decrease in the swelling pressure is due to the addition of low-plastic materials and the interaction between clay and silica fume particles (Kalkan, 2006). The addition of silica fume increased the pH values. The increase in pH values decreased the relative clay mineral contents (Eades, 1962; Kalkan, 2009b). The modified clayey soil samples with low relative clay mineral contents and low liquid limit displayed low swelling pressure behavior.

The variations of swelling pressure with scrap tire rubber fiber are plotted in Fig. 13. It is observed that silica fume and rubber fiber contents caused the decrease in swelling pressure. The swelling pressure values decreased from 230 to 204 kPa, from 230 to 30 kPa and from 230 to 17 kPa for the 2% fiber-modified clayey soil, 10% silica fume and 2% fiber-modified clayey soil and 20% silica fume and 2% fiber-modified clayey soil samples, respectively. The minimum swelling pressure is recorded as 17 kPa from 20% silica fume and 2% fiber-modified clayey soil sample (Fig. 13). The decrease in swelling pressure could also be attributed to the presence of fibers, which create drainage paths for the dissipation of pore pressures of a loaded soil sample. Another reason could be that the fibers, being tensile elements, restrain the swelling pressures generated during loading by enhancing soil shear strength (Cai et al., 2006; Puppala and Musenda, 1998).

4.7. Image analysis

Fig. 14 shows SEM micrographs of the silica fume-modified clayey soil samples. It is shown from Fig. 14A that large continuous pores among the clayey soil particles provide a large portion of the total void ratio while small connected pores exist among the micro-fine silica fume particles. It is seen from the images that silica fume particles cover the surrounding clayey soil particles and fill the voids of the modified clayey soil samples. In the samples with 10% silica fume content, grain surfaces are partly covered by silica fume particles and

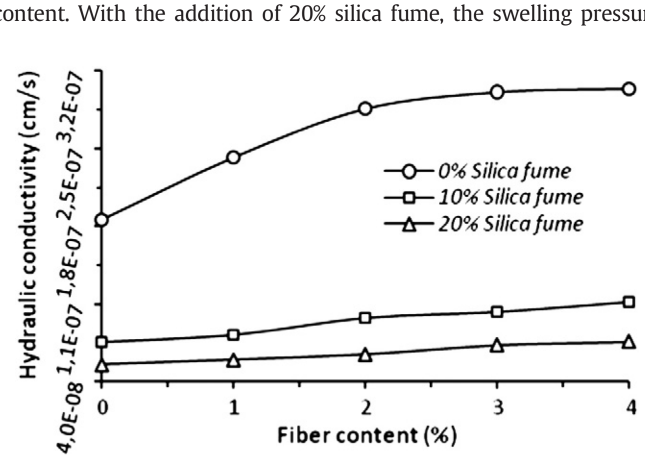

Fig. 12. Effect of the silica fume and fiber on the hydraulic conductivity.

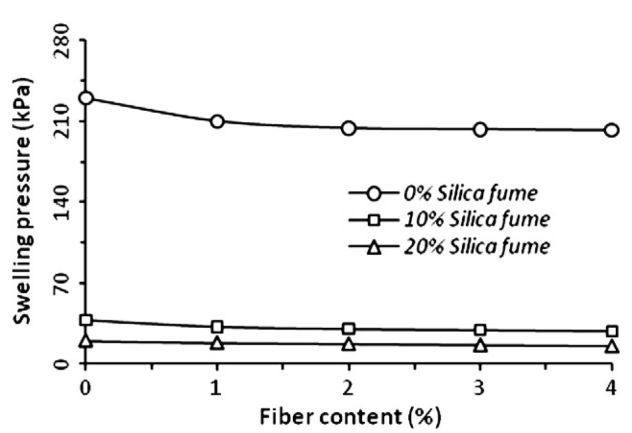

Fig. 13. Effect of the silica fume and scrap tire rubber fiber on the swelling pressure.

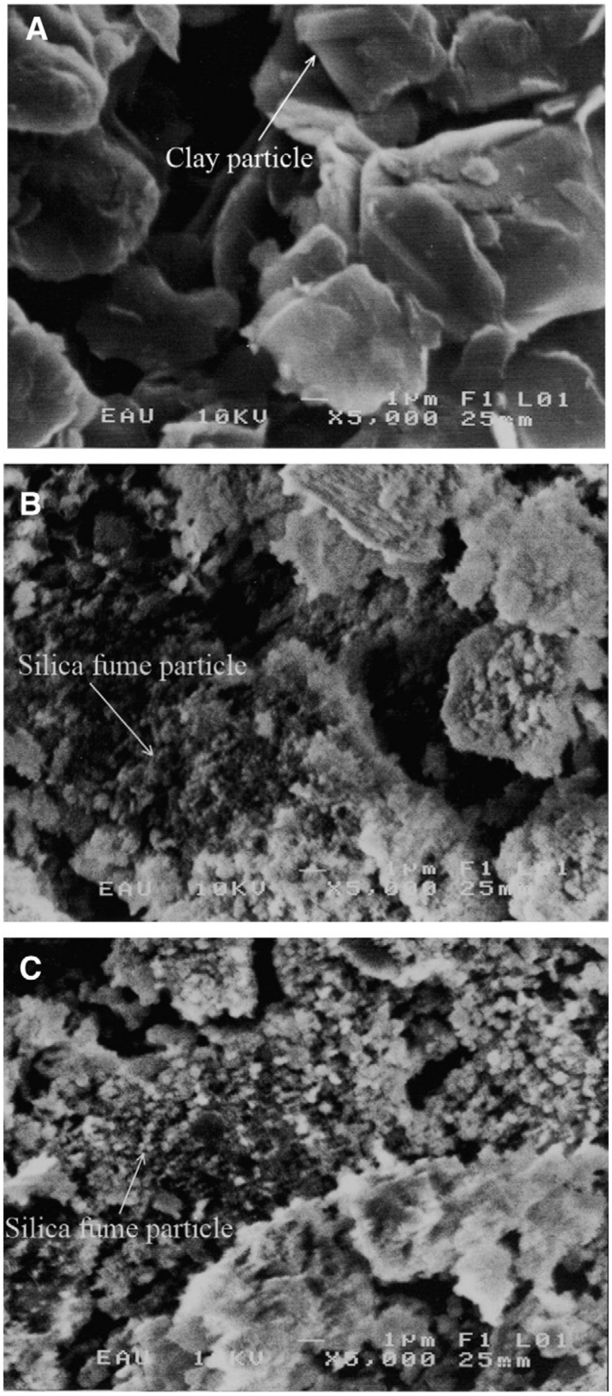

Fig. 14. Images of silica fume-modified clayey soil with (A) 0% silica fume, (B) 10% silica fume and (C) 20% silica fume.

most of the pore spaces still contain air (Fig. 14B). In the samples with 20% silica fume content, grain surfaces are covered by silica fume particles in significant ratios. The silica fume particles settle in the pore spaces among the clayey soil particles, and then the settled silica fume particles react to form hydration products in the surrounding fine-grained soil particles (Fig. 14C). This textural event causes a significant decrease in swelling pressure and swelling potential. A detailed examination of each micrograph reveals that most of the flocculation products are deposited on the surfaces of the soil grains or at the contact points. These micrographs and the experimental results above have also revealed the possibility that a chemical reaction with silica fume and clay particles may occur (Kalkan, 2011; Kalkan and Akbulut, 2004).

5. Conclusion

The following conclusions are derived from this investigation:

- The silica fume, scrap tire rubber fiber and silica fume–scrap tire rubber fiber mixtures increased the UCS. Although the UCS values of all modified clayey soil samples increased with increasing silica fume and fiber content, it was observed that the maximum UCS value was obtained by addition of 20% silica fume–2% fiber mixture.
- The shear box test results indicate the addition of silica fume increases shear strength parameters. The maximum cohesion and internal friction angle values were obtained by addition of 20% silica fume–2% fiber mixture.
- The hydraulic conductivity and swelling pressure decreased with the addition of silica fume–fiber mixture. The maximum improvement for the hydraulic conductivity and swelling pressure has been observed by using 20% silica fume–2% fiber mixture content.
- Observations of SEM showed that the structure of raw clay samples could be changed through silica fume contents in the sample. The structure of a material had a significant influence on its engineering properties such as permeability, strength and stiffness.
- The investigation showed that the silica fume–fiber mixture is a valuable material to modify the properties of clayey soils. In the geotechnical applications, the silica fume–fiber mixture in the applications should be taken into account due to its positive effects on the unconfined compressive strength, hydraulic conductivity and swelling pressure.
- It is conclude that the silica fume–fiber mixture can be used for modification of clayey soils. In addition, this mixture can potentially reduce stabilization costs by utilizing wastes in a cost-effective manner.

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