Effect of waste tire cord reinforcement on unconfined compressive strength of lime stabilized clayey soil under freeze–thaw condition

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a b s t r a c t

Mechanical properties of fine-grained soils, which are subjected to freeze–thaw condition, often change considerably, so when these soils are used as a part of a structure or as an infrastructure, determining a proper solution is necessary. In this paper, stabilization and fiber reinforcement are simultaneously examined as a soil modification method. A series of unconfined compression tests was carried out to investigate the effects of tire cord waste products on mechanical characteristics of a lime stabilized and unstabilized clayey soil sub- jected to freezing and thawing cycles. Several specimens were prepared at three percentages of lime (i.e. 0%, 4%, and 8%) and four percentages of discrete short nylon fiber (i.e. 0%, 0.5%, 1%, and 1.5%) by weight of dry soil. The samples were saturated and exposed to one up to three freeze–thaw cycles before testing. The re- sults indicated that the compressive strength and stress–strain behavior of specimens depend considerably on the amounts of both fiber and lime. For stabilized specimens, the reinforcement effect of fiber was more than unstabilized ones and also, by inclusion of fiber, 4% lime stabilized specimens indicated more strength in comparison to the untreated and 8% lime stabilized specimens. Furthermore, the contribution of fiber in the strength of samples increased as the number of freeze–thaw cycles was increased.

Keywords:
Fiber reinforced soil Lime stabilization Unconfined compression test Freeze–thaw cycle

1. Introduction

Inferior soils are usually an unavoidable problem due to the extension of constructing projects and lack of desirable grounds, so civil engineers employ several techniques to amend them. Soil stabilizing by adding chemical materials is one of the most common methods for treating fine grained soils. Lime has been used to improve some mechanical and plastic properties of fine grained soils since many years ago. Some of the useful effects of lime on engineering parameters of soils are increase in strength, durability, and decrease in plasticity (Akinlabi ola, 1977; Al-Rawas et al., 2005; Bell, 1993; Guney et al., 2007; Sherwood, 1993). However, occurrence of some unfavorable phenomena such as reduction in failure strain, residual strength, and toughness of soil has been reported due to lime application (Abdi and Khayyat-Baharlooyi, 2010; Cai et al., 2006; Clare and Cruchley, 1957).

Soil reinforcing with discrete fibers has been developed as another soil improving method in recent years. Ghavami et al. (1999) explained that inclusion of natural fibers like sisal and coconut fiber provides ductility as well as increase in strength of soil. Similar results about reinforcing soils with natural fibers have been reported by other researchers (Ahmad et al., 2010; Bouhicha et al., 2005; Prabakar and Sridhar, 2002; Zhang et al., 2010). Furthermore, desirable efficiency of synthetic fibers like polypropylene, polyamide, and polyester fibers in improving mechanical properties and failure characteristics of soils has been con- firmed (Diambra et al., 2009; Hataf and Rahimi, 2006; Ibraim and Fourmont, 2006; Kumar et al., 2006; Michalowski and Cermak, 2002; Park and Tan, 2005; Viswanadham et al., 2009; Yetimoglu and Salbas, 2003; Yetimoglu et al., 2005). Some researchers utilized advantages of fiber reinforcing by use of waste or byproduct materials as an economical and eco friendly solution for improving engineering properties of weak soils. Hataf and Rahimi (2006) and Yoon et al. (2006) mixed scrap tire rubber with sand. Cetin et al. (2006) and Akbulut et al. (2007) mixed waste rubber with clayey soil and also, Kim et al. (2009) reinforced light weight soil with waste fishing net. These researchers reported that fiber reinforcing causes increasing in unconfined compressive strength,ductility and toughness of soil samples.

Few studies have been carried out on effects of fiber inclusion on mechanical behavior of stabilized soil, as an idea to employ the positive effects of randomly oriented fiber reinforcing to eliminate brittleness of stabilized materials. Cai et al. (2006) conducted some unconfined compressive, direct shear, swelling, and shrinkage tests on polypropylene fiber reinforced lime stabilized clayey soil. While lime stabilized samples showed a brittle failure pattern, fiber-lime specimens showed strain-softening ductile failure. Also, inclusion of fiber with cement stabilized soil has shown increase in strength as well as rise in ductility and reduction in brittleness of stabilized material (Chauhan et al., 2008; Consoli et al., 2009; Park, 2009; Tang et al., 2007).

Seasonal freeze-thaw cycles are an important problem that specially affects mechanical properties of fine grained soils. In the temperature below 0° Celsius, water in pores turns to ice. This process, which is also known as soil freezing, causes many of lands to be exposed to freeze-thaw condition (Watanabe, 1999). In such regions, pavements are subjected to freezing and frosting heave in the winters, and thaw settlement and weakening in the springs. This cycle imposes enormous loss on cold region countries annually. For example, during 1994 thaw period of spring, 25% of national road network of Sweden tolerated traffic restriction and reconstruction of destructed roads consisted 25% of entire road maintenance budget of that country (Simonsen and Isacsson, 1999). Several researchers described the destructive effects of freeze-thaw cycles on soil engineering properties (Hohmann-Porebska, 2002; Qi et al., 2008; Qin et al., 2010; Sheng et al., 1995; Shoop et al., 2008; Simonsen and Isacsson, 1999; Wang et al., 2007; Zhang et al., 2004).

Different techniques have been proposed to provide more durability for freeze-thaw exposed soils. Shoop et al. (2003) examined some rapid stabilizers for thawing soils. Yarbasi et al. (2007) used waste materials such as silica fume, fly ash, and red mud for modifying granular soils against harmful impacts of freeze-thaw cycles. Results showed that waste additives could improve the compressive strength and CBR values of stabilized soil and also, they can increase durability versus freeze-thaw cycles. They reported that after 60 cycles of freeze-thaw, for unstabilized specimens compressive strength decreased 77.1% while this value was 15.6% for treated soil with waste materials. Also, after the cycles, CBR values of unstabilized specimens decreased from 68% to 56%, but it varied from 250% to 233% for stabilized specimens. Kalkan (2009) added silica fume to fine grained soil used in landfill system and showed that increase in number of freeze-thaw cycles reduced strength and increased permeability of soil, but addition of silica fume to soil as a stabilizer showed favorable results by increasing strength and declining permeability. Some chemical stabilizers have been examined by other researchers to improve durability of soils (Altun et al., 2009; Liu et al., 2010).

A new approach for improving soil characteristics against freeze-thaw condition is reinforcing soil with randomly oriented discrete fibers. Zaimoglu (2010) studied freezing-thawing behavior of reinforced soil by unconfined compressive tests. His experiments disclosed efficacy of fiber reinforcing in increasing of strength and durability of fine grained soils. Some recent studies have confirmed effectiveness of fiber reinforcing against freeze-thaw deterioration in soils (Ghazavi and Roustaie, 2010; Gullu and Hazirbaba, 2010).

In spite of the mentioned studies, synergic effects of stabilization and fiber reinforcement on mechanical properties of soils under freeze-thaw condition have not been investigated yet. Furthermore, previous investigations have not considered the behavior of reinforced soil under condition of absorbing water during thaw period. In the present study, effect of stabilization by lime and reinforcing with waste tire cord on freeze-thaw subjected kaolinite is studied by conducting several unconfined compression tests. The employed fiber is the waste product of tire cord factories and its application as reinforcing elements can solve the problem of disposing as well as supplying an economic material for soil improvement.

2. Materials and experimental procedure

Soil and lime

A homogenous Zonouz kaolinite soil from East Azerbayjan's mines, which is classified as CL according to the Unified Soil Classification System (USCS), was selected for this study. The particle size distribution curve and the engineering properties of the clay are shown in Fig. 1 and Table 1 respectively. Industrial hydrated lime was used for soil stabilization. Table 2 presents some physical properties and chemical compositions of the employed lime.

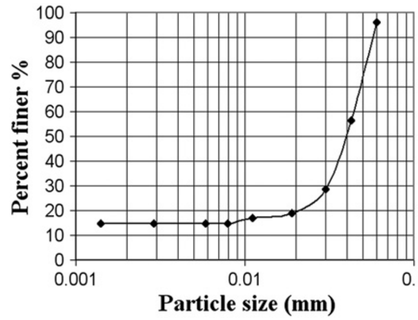


Fig. 1. Grain size distribution of Zonouz clay.

Fiber

The fiber is derived from waste material of tire cord factory products. The main constitutive substance of this fiber is nylon 6-6. High resistance against heat, fatigue, impact, and sunlight, and high resilience are some of the valuable characteristics of this fiber, which is usually used in tire and seat belt of vehicles, fishnet, reinforced hoses, and so on. In tire cord company, quality control unit regularly tests samples of productions based on tensile strength, tensile strain at failure point, H-adhesion test, absorption percentage of resorcinol formaldehyde latex (RFL) which is used for adhesion between the interface of fiber and rubber, and hot air thermal shrinkage. The products which do not satisfy particular standards and also, some fibers which become torn in tire production process are discarded as waste products. Usually 10% of nominal production capacity of tire cord factories is waste material. Fig. 2 shows tire cord with 20 mm length and its properties are given in Table 3.

Sample preparation and test procedures

According to requirements of ASTM D5102, cylindrical specimen with 57 mm diameter and 120 mm height was selected for unconfined compressive test. Based on pre-test results, the lime contents of 0%, 4%, and 8% and fiber contents of 0%, 0.5%, 1%, and 1.5% by weight of dry soil were selected for examining the behavior of fiber in different matrix (i.e. 0% lime for unstabilized soil matrix, 4% for well stabilized soil matrix, and 8% for a matrix soil with extra lime).

For every combination, weight of each material was determined exactly based on the optimum moisture content and maximum dry density which is obtained from the standard Proctor compaction test. Clay and lime were mixed in dry condition properly. Then, water was added gradually and mixture was pushed to pass from sieve No. 10 for pulverizing crumbs. Afterwards, fiber was mixed until a uniform mixture was formed. The uniformity of distribution was checked by eye observation.

For exchanging moisture among particles and forming homogenous blend, the mixtures were kept in plastic bags for 24 h. Weight of each specimen was determined in accordance with given specimen volume and obtained maximum dry density from compaction tests. This weight was divided into four portions and each portion was

Table 1
Properties of Zonouz clay.

Soil properties	Values
Specific gravity	2.69
Liquid limit	41.3%
Plastic limit	25.2%
Plasticity index	16.1%
USCS classification	CL
Optimum moisture	25.15%
Maximum dry density	15.06 kN/m^3
PH	9.69

Table 2
Physical and chemical compositions of lime.

Lime properties	Values
Specific gravity	2.69
Natural moisture	0.4%
LOI	24.2%
PH	12.56
Chemical compositions	
$Ca(OH)_2$	92%
$CaCO_3$	2.3%
SiO_2	0.9%
Al_2O_3	0.3%
Fe_2O_3	0.2%
MgO	0.3%

Table 3
Properties of nylon fiber.

Fiber properties	Values
Fiber type	Yarned
Equivalent diameter	0.54 mm
Length	20 mm
Specific gravity	0.91 gr/cm^3
Failure force	284 N
Failure strain	27.99%
Elastic modulus	1.49 N/mm^2
Water absorption	13.97%

compacted in 30 mm layer in a reinforced PVC mold. The interface of layers was scratched properly to provide effective interlock between layers and to prevent formation of weak planes. The specimens were cured in a plastic bag to avoid evaporation in a place having a temperature about 21 °C for 7 and 28 days. Some specimens were subjected to maximum three freeze–thaw cycles before testing. Freeze–thaw test was performed according to ASTM D 560. Water saturated felt pads were put on the bottom of a carrier and molded samples were laid on it. The assembly was placed in a freezer, which had a constant temperature about −23 °C for 24 h. Then the assembly was taken out from freezer and placed on a water saturated sand container to provide water for samples during a thawing period of 23 h. Thawing process was performed in moist room with a constant temperature about −21 °C. All these stages were regarded as 1 cycle. In whole freeze-thaw process, a 6 N metal disk was placed on the top of the samples. The mold encasing the specimen during freezing and thawing provides confining stress of the half space soil layer and the surcharge metal disk acts like the pavement's weight on subgrade. Ice lensing along with thermally-induced water migration causes frost heave. In addition to freezing temperature and frost susceptible soil, water must be available for formation of frost heave (Bronfenbrener and Bronfenbrener, 2010; Penner, 1961; Sheng et al., 1995). During freeze-thaw process water was kept available to simulate water migration from deep unfrozen zone to the freezing front.

To minimize cracks and weaknesses in specimens, the internal surface of molds was lubricated with a thin layer of oil before preparing the specimens. After different freeze-thaw cycles, a hydraulic extruder was used to remove the specimens from the molds with constant rate vertically from bottom to top to avoid bending and formation of tensile cracks. Then the specimens were immediately tested under strain controlled condition at constant loading rate of 1.0 mm per min, according to requirements of ASTM D 2166. For each combination, three specimenswere examined to assure repeatability of results.

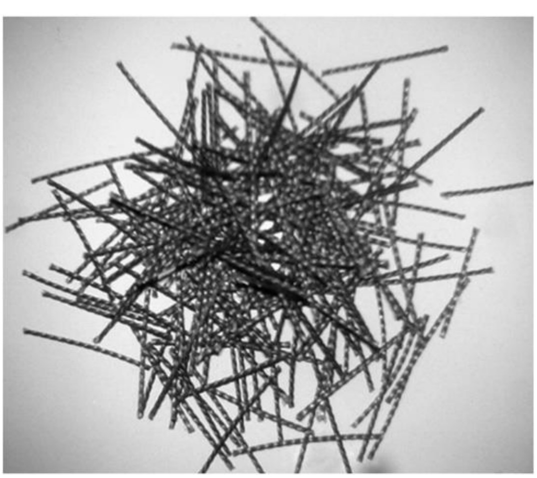


Fig. 2. Tire cord with 20 mm length.

For abbreviating, the sample properties are represented by some symbols and numbers (for instance, the specimen 4 L–0.5 F–3 C–28 has 4% lime and 0.5% fiber and exposed to 3 cycles of freeze-thaw and cured for 28 days).

3. Results and discussion

Compaction

For 12 soil-lime-fiber combinations, standard Proctor compaction test was carried out and the results for four combinations are given in Fig. 3.

It is observed that by increasing lime content, maximum dry density (MDD) decreases and optimum moisture content (OMC) increases. Because of low specific gravity of lime in relation to soil, replacement of soil by lime decreases MDD. Also, when lime is added to soil, instantaneous reaction as cation exchange occurs, and clay particles flocculate together. This process leads to formation of air voids among particles and makes creation of a porous medium with lower MDD. Furthermore, more water is necessary for filling voids, so OMC is increased. This figure also shows that inclusion of fiber leads to reduction of both MDD and OMC because of low specific gravity and lower water absorption of fiber as compared to the soil. These mentioned effects are combined in lime-fiber-soil mixture too, but in the range of selected contents of materials, lime content has more effect on compaction parameters in comparison with fiber content.

Unconfined compression tests

a) Non freeze-thaw subjected specimens

Effect of fiber content on unconfined compressive strength values of unstabilized specimens is presented in Fig. 4.

Inclusion of fiber increases the unconfined compressive strength (UCS) until 1.5%, while further values decrease it. Excessive contents of fiber increases probability of fiber agglomerating which means reduction of effective interfacial contact area between fibers and matrix.

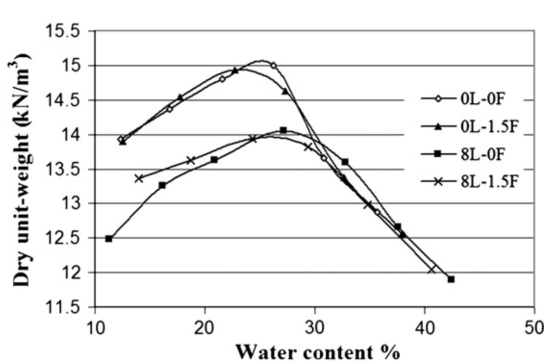


Fig. 3. Dry density versus water content for some mixtures.

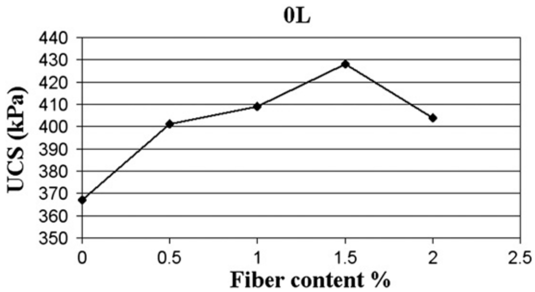


Fig. 4. Unconfined compressive strength (UCS) values for unstabilized specimens versus fiber content.

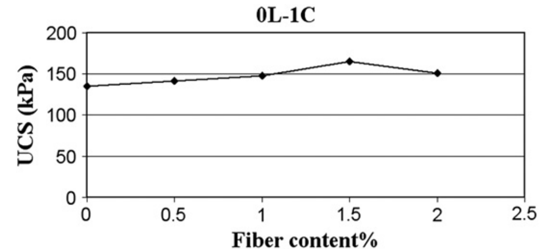


Fig. 6. UCS values of unstabilized specimens versus fiber content after 1 cycle of freeze-thaw.

Thus, interruption of reinforcement mechanism leads to decrease of compression strength. The UCS of untreated soil is 367 kPa and it is increased to 428 kPa by reinforcing with 1.5% fiber content.

Fig. 5 shows the unconfined compressive strength for stabilized and reinforced soil.

Adding fiber content increases the UCS until 1.5% and for same curing time, UCS is affected from both lime and fiber contents. The specimens with 4% lime indicate more strength than those of with 8% lime. It seems that 8% lime stabilized soil has more extra free lime content and whereas free lime is not as cohesive as the replaced soil, it decreases the UCS. The difference in strength of 4% and 8% lime stabilized specimens is clearly observable in Fig. 5(a) for low curing time (7 days) when free lime values are high due to incomplete reaction between soil and lime. Although, increase in curing time somewhat compensates lack of strength in 8% lime stabilized specimens, 4% lime stabilized specimens still show higher strength after 28 days (see Fig. 5(b)). The UCS reaches to 962 kPa after stabilizing with 4% lime and 28 days curing time. The maximum strength belongs to the 4 L–1.5 F–28 with value of 1204 kPa and for 8% lime stabilized specimens, 8 L–1.5 F–28 shows the most strength with value of 1104 kPa.

b) Freeze-thaw subjected specimens

The unconfined compressive strength values versus fiber content for unstabilized specimens after one freeze-thaw cycle are given in Fig. 6.

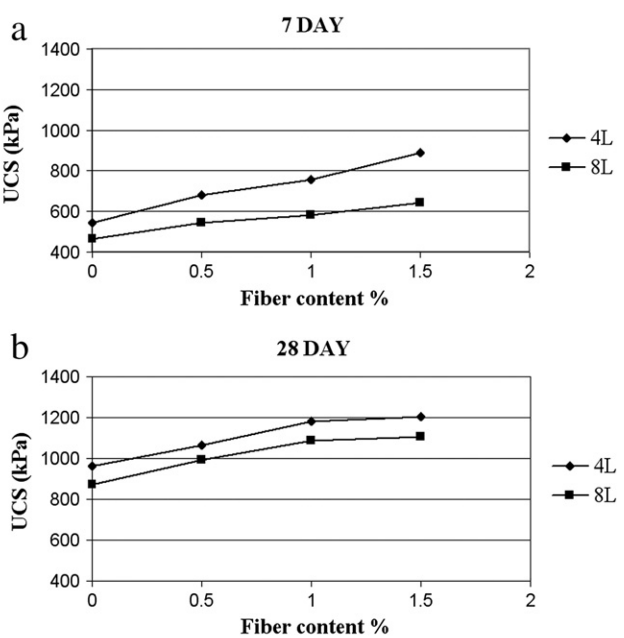


Fig. 5. UCS values of stabilized specimens versus fiber content for: (a) 7 days curing time; (b) 28 days curing time.

After 1 cycle, inclusion of fiber until 1.5% enhances the strength and adding further values decreases it. Unstabilized specimens can bear only 1 cycle of freeze-thaw and after 2 cycles, they will be destroyed completely.

In Fig. 7, unconfined compressive strength is plotted for stabilized specimens after 1 cycle of freeze-thaw.

The specimens exhibit rising UCS until 1.5% of fiber content and all the strength curves related to 4% lime stabilized specimens are above the 8% lime stabilized ones for all ages. Also, fiber is more effective in increasing of UCS for 4% lime stabilized specimens. Before freeze-thaw, the difference between UCS of specimens with 1% and 1.5% fiber content is small (see Fig. 5(b)), but 1 cycle of freeze-thaw makes this difference be increased (Fig. 7(b)). It indicates that the role of high percents of fiber becomes more distinguished after freeze-thaw cycle.

Fig. 8 shows the unconfined compressive strength for different fiber percents after 3 cycles of freeze-thaw for stabilized specimens.

As can be seen from Fig. 8(a), all the specimens with 8% lime and also, the specimen with 4% lime and without fiber cannot tolerate the third cycle of freeze-thaw at the age of 7 days.

According to Fig. 8(b), the difference between UCS of the specimens with 4% and 8% lime at the same fiber content, is increased after 3 cycles. This difference can be ascribed to existence of more free lime in 8% lime stabilized specimens. Because of fine particles and lack of cohesion, free lime is sensitive to freeze-thaw cycles. Destruction of young stabilized specimens with 8% lime may be due to the free lime. Therefore, it can be interpreted that under freeze-thaw condition, excessive lime in soil stabilizing not only has no advantages but it also leads to high level of sensitivity against freezing. However, curing condition such as time,

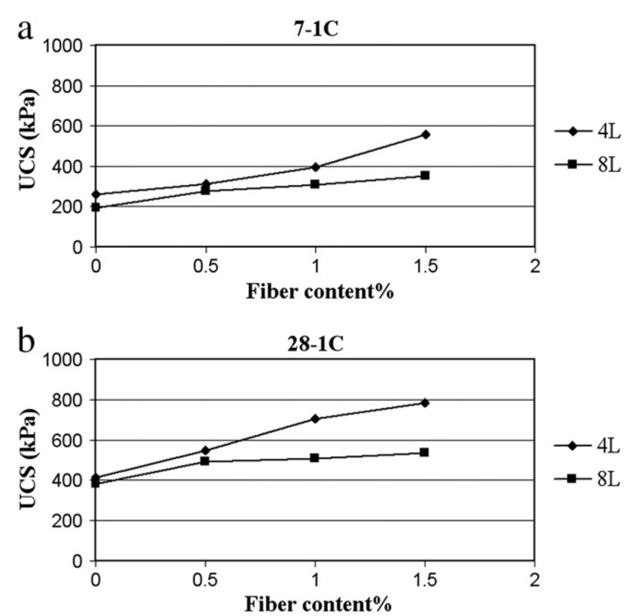


Fig. 7. UCS values of stabilized specimens versus fiber content after 1 cycle of freeze-thaw for: (a) 7 days curing time; (b) 28 days curing time.

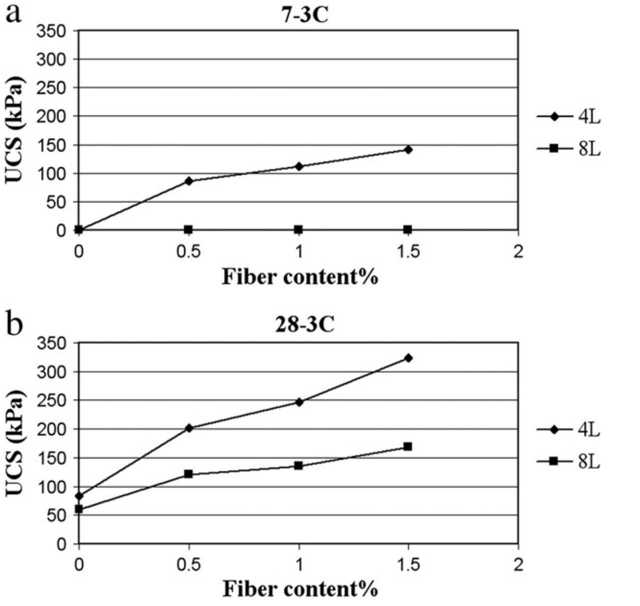


Fig. 8. UCS values of stabilized specimens versus fiber content after 3 cycles of freeze-thaw for: (a) 7 days curing time; (b) 28 days curing time.

temperature, and accessibility to water, has considerable effect on amount of remained free lime after curing time and it must be considered cautiously. Fig. 8(b) also shows that the strength of reinforced specimens has a distinct difference as compared to unreinforced soil.

Fig. 9 shows the unconfined compressive strength of some specimens corresponding to the number of freeze-thaw cycles.

The unconfined compressive strength decreases as the number of cycles increases. Maximum loss of strength occurs after the first cycle, and for subsequent cycles, the strength reduces with fewer rates. The maximum and minimum strength are related to reinforced specimens with 1.5% fiber and unreinforced specimens respectively. The difference between strengths of reinforced and unreinforced specimens increases by increasing the freeze-thaw cycles. After freezing, pore water needs more space, making an internal pressure which tends to separate soil particles. For reinforced specimens, fiber is interlocked with soil particles, so it resist against movement of particles with friction at interfacial contact area. Friction between fiber and matrix converts to tension in fiber. Even some fibers which are squeezed in matrix are applied after expansion and so, the role of fiber increases after freezing. The difference between strengths of unreinforced and reinforced specimens is small for 8% lime stabilized specimens (Fig. 9(b) and (d)) and this reveals that fiber cannot exhibit its positive effect in relation to 4% lime stabilized specimens.

Summary of UCS of specimens after 28 days curing time is presented in Table 4. Durability index (Di) as a criterion of permanence is introduced by dividing the strength of a specimen after a specific cycle of freeze-thaw into its strength before freeze-thaw. Di is varied between zero and one, in which zero shows no durability and one presents the best durability without any loss of strength (Abdi, 2010). According to Table 4, the specimens with 4% lime have higher Di and the specimens without lime have the least Di for a specific cycle. The Di depends on the initial strength before freeze-thaw. The more initial strength is, the more durability after freeze-thaw cycles is. In the main, for a constant content of lime and same cycle, Di is enhanced as the content of fiber increases. Moreover, the reinforcing effect of the fiber increases by increase of cycles. After 1 cycle, Di of 4% lime stabilized specimen increases 51% (from 0.43 to 0.65) when 1.5% fiber is added, while after 3 cycles, Di increases from 0.09 to 0.27 which is 200%. This is also true for specimens with 8% lime content.

The contribution of the fiber reinforcement in increasing UCS of specimens after inclusion of the 1.5% fiber to unreinforced specimen with the same content of lime is also presented in Table 4. For any specific cycle, the strength of 1.5% fiber reinforced specimens relates to the strength of unreinforced specimen with the same content of lime. Increasing of the strength is more for unreinforced specimen with higher strength. Although the role of 1.5% fiber is nearly similar for 4% and 8% lime stabilized specimens, it could be observed that the effect of fiber becomes more pronounced for 4% lime stabilized specimens as the cycles of freeze-thaw increase. While inclusion of 1.5% fiber to 4% lime stabilized specimens increases UCS to 25% before freeze-thaw, it enhances to 286% after 3 cycles. These values are 23% and 186% for 8% lime stabilized specimens. The strength ratio of unreinforced specimens with 4% lime to those with 8% lime increases by cycles (i.e. 962=897 ¼ 1:07, 412=382 ¼ 1:08,

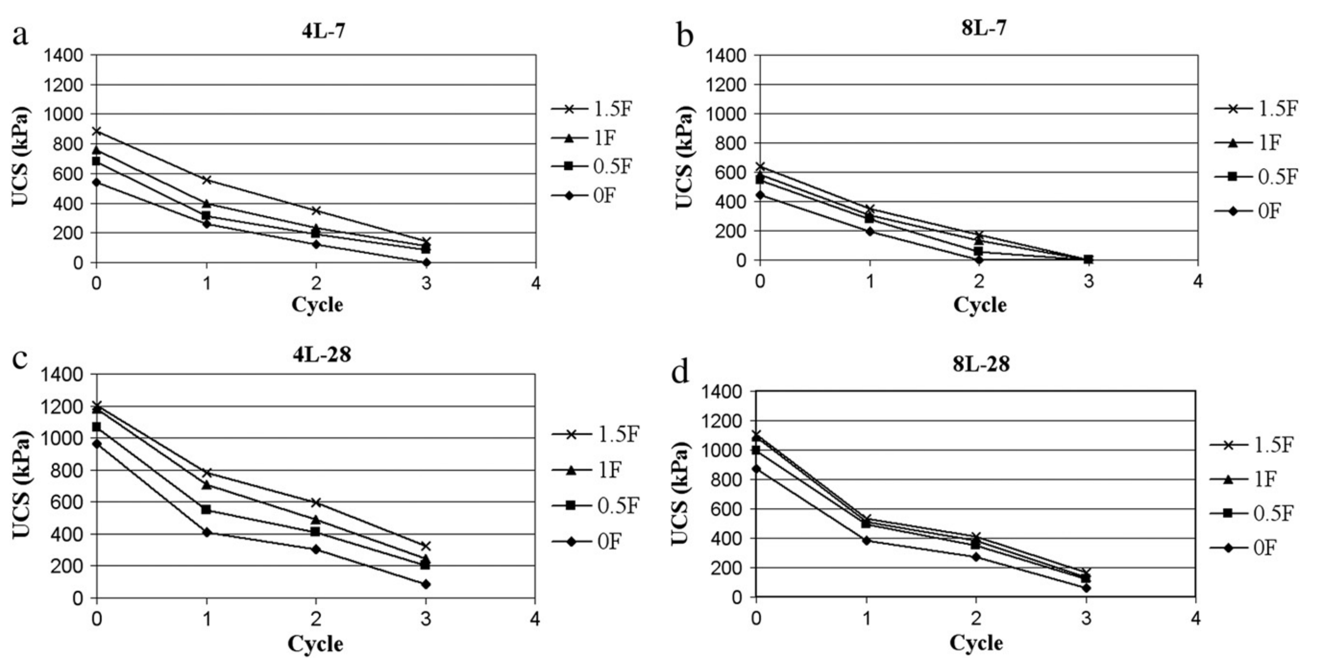


Fig. 9. The UCS versus cycles of freeze-thaw for: (a) 4% lime stabilized specimens with 7 days curing time, (b) 8% lime stabilized specimens with 7 days curing time, (c) 4% lime stabilized specimens with 28 days curing time and (d) 8% lime stabilized specimens with 28 days curing time.

Table 4
Values of UCS, durability index and contribution of 1.5% fiber in increase of strength for 28 days cured specimens.

		Unconfined compressive strength (kPa)				Durability index (Di)			Contribution of 1.5% fiber in increase of strength (%)			
		0 C	1 C	2 C	3 C	1 C	2 C	3 C	0 C	1 C	2 C	3 C
0 L	0 F	367	135	0	0	0.37	0.00	0.00	17	22		
	0.5 F	401	141	0	0	0.35	0.00	0.00				
	1 F	409	148	0	0	0.36	0.00	0.00				
	1.5 F	428	165	0	0	0.39	0.00	0.00				
4 L	0 F	962	412	301	84	0.43	0.31	0.09	25	91	97	286
	0.5 F	1065	548	409	202	0.51	0.38	0.19				
	1 F	1182	706	488	246	0.60	0.41	0.21				
	1.5 F	1204	785	594	324	0.65	0.49	0.27				
8 L	0 F	897	382	271	59	0.43	0.30	0.07	23	40	51	186
	0.5 F	993	492	349	120	0.50	0.35	0.12				
	1 F	1088	509	382	135	0.47	0.35	0.12				
	1.5 F	1104	535	409	169	0.48	0.37	0.15				

$^{301}=_{271}$ ¼1:11, $^{84}=_{59}$ ¼1:42 for cycles zero to three, respectively) indicating the matrix of 4% lime stabilized specimen shows better behavior, presumably due to the better interaction of fiber with better matrix.

For the specimens without lime, the influence of 1.5% fiber increases after freeze-thaw and the effect is lower than those for lime treated specimens. Cai et al. (2006) showed that untreated clayey soil forms big package of soil when water is available, which resulted in formation of large pores. In addition, fiber reinforcing does not change microstructure of soils and big pores remained in the reinforced soils without lime. Freezing of saturated water big pores causes high internal stress which is intolerable for weak bounds of big packets of soil. Under this condition, soil structure is sensitive to freeze-thaw and reinforcement effect of fiber is limited. So the fiber could not play a significant role after 1 cycle and after the second cycle, the specimen collapses entirely.

In the lime treated soil, clay particles show hydrophobic behavior preventing formation of big size pores. On the other hand, some pores are filled with cementitious materials of lime-soil reaction, so pore size is decreased as well as being disconnected. This limits the water migration to freezing front and ice lenses do not grow as much as those of untreated soil. Furthermore, cementitious gel increases inter-particle bonds which cause more strength against swelling of freezing. This denser fabrication of matrix makes better friction and load transferring between fiber and matrix (Cai et al., 2006).

c) Stress-strain behavior

In order to compare stress-strain characteristics, axial stress-strain curves are plotted for five different specimens in Fig. 10.

Comparing the curves of two unstabilized specimens (0 L–0 F and 0 L–1.5 F) indicates failure strain increases by inclusion of fiber slightly. The initial stiffness is not significantly affected by fiber content with the same lime content. This issue has been reported by Tang et al. (2007) and Consoli et al. (2009) for cemented soil and by Zaimoglu (2010) for unstabilized soil. On the contrary, the stiffness is affected by lime content considerably. Moreover, the lime reduces strain at failure, residual strength, and toughness of soil, which means that stabilizing by lime causes brittle behavior. The stabilized specimens (4 L–0 F–28 and 8 L–0 F–28) exhibit high stiffness, but they fail in low strain abruptly. After the failure, the stabilized soil loses strength with high rate, so absorbed energy before complete destruction is small. By inclusion of fiber to stabilized soil, these weaknesses in failure characteristics are improved to some extent. Without changing high stiffness of stabilized soil, fiber reinforcing promotes residual strength as well as toughness significantly and also, increases the failure strain slightly.

For two combinations of unstabilized specimens, stress-strain curves are shown in Fig. 11 before and after one freeze-thaw cycle.

The stress-strain curve of unstabilized material is flattened after 1 cycle of freeze-thaw and fiber cannot improve it considerably. Soil matrix is sensitive to freeze-thaw and loses its strength and stiffness. Under this condition, fiber cannot act properly, so after freeze-thaw, negligible differences are observed between curves of unreinforced and reinforced specimens. Excessive deformation occurs after just 1 cycle of freeze-thaw for unstabilized specimens inasmuch as they exhibit bulging failure.

Fig. 12 shows the strain-strain curves of 4% lime stabilized specimens for different freeze-thaw cycles.

After 1 cycle of freeze-thaw, strength and stiffness are decreased severely for unreinforced specimens with 7 days curing time. This loss of strength is so intensive that after 3 cycles, the specimens collapse entirely (Fig. 12(a)). Comparable curves are available for similar specimens with 1.5% fiber content in Fig. 12(b). It is clear that by reinforcing, specimens exhibit more strength and stiffness. Also, loss of strength occurs gently as they can tolerate the third cycle. For the reinforced specimens, the stress-strain curve is flattened after 3 cycles, while this happens after 2 cycles for the unreinforced specimens.

By comparison of Fig. 12(c) and (d), it is observed that fiber reinforcing makes lower reduction rate of strength and stiffness against freezing and the shape of stress-strain curve does not change after freeze-thaw cycles considerably, while behavior of unreinforced specimens is quite different before and after freeze-thaw. Fig. 12(c) also indicates that after cycles, unreinforced specimens show residual strength, while these specimens before freeze-thaw, do not show post peak strength and collapse suddenly. This change of behavior, which is seen as the increase of flexibility and compressibility, may be because of increase in porosity of soil due to ice lens.

Stress-strain curves for specimens with 4% lime content and 28 days curing time are presented in Fig. 13.

Before freeze-thaw and after 1 cycle, fiber does not affect initial stiffness of stabilized material cycle, while it increases post peak strength and the failure occurs in soft behavior (Fig. 13(a) and (b)). After 2 cycles, it is clearly observed in Fig. 13(c) that stiffness is affected by inclusion of fiber and initial part of stress-strain curve of the reinforced specimens is separated from the unreinforced one. Also, residual strength increases in relation to peak strength. After 3 cycles, unlike the reinforced specimens, the unreinforced specimen loses its strength and its stress-strain curve

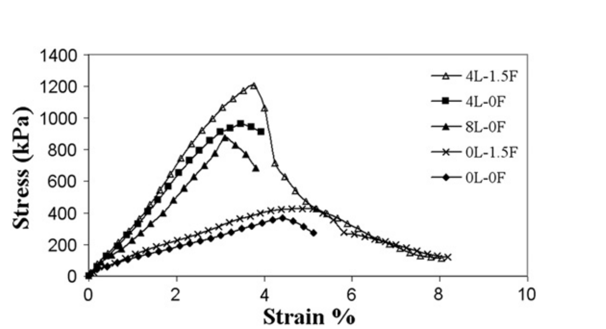


Fig. 10. Stress-strain curves of some specimens before freeze-thaw cycles.

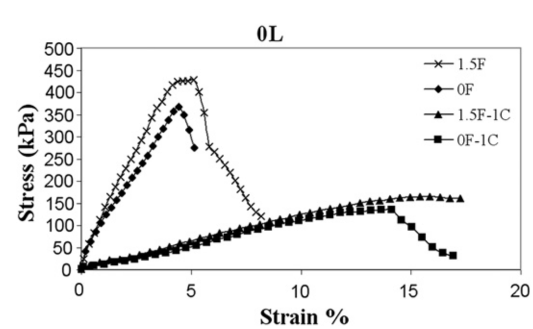


Fig. 11. Stress-strain curves of unstabilized specimens after 1 cycle of freeze-thaw.

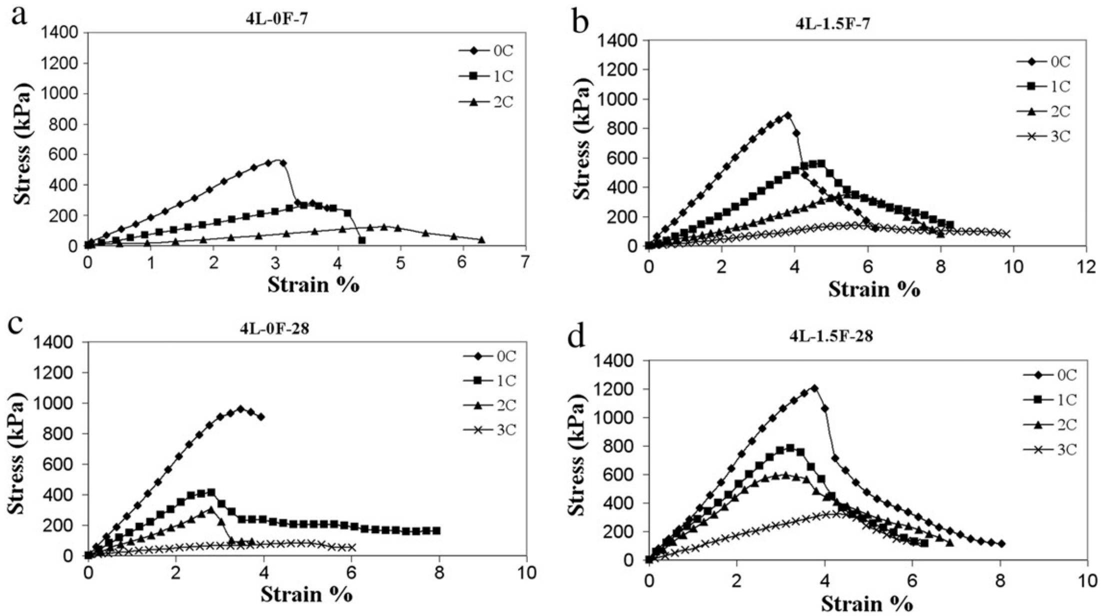


Fig. 12. Stress-strain curves of stabilized specimen with 4% lime for different cycles for: (a) 7 days curing time specimens without fiber, (b) 7 days curing time specimens with 1.5% fiber content, (c) 28 days curing time specimens without fiber and (d) 28 days curing time specimens with 1.5% fiber content.

is flattened. This implies the valuable role of fiber in maintaining stiffness and strength as freeze-thaw cycle numbers increase up to 2 cycles.

d) Not water absorbed specimen

In some previous studies (Ghazavi and Roustaie, 2010; Zaimoglu, 2010), the specimens were subjected to freeze-thaw with the initial water content of prepared samples and water was not available during thaw period. For comparing results of present study with those of previous researches, some specimens were placed in humid environment for thawing term and then unconfined compression test was carried out. Fig. 14 presents the unconfined compressive strength of not water absorbed specimens during thaw period for unstabilized specimens.

For not water absorbed specimens, loss of strength is very low inasmuch as after 3 cycles of freeze-thaw, only 11% of strength decreases for the specimen with 1.5% fiber content. Such a small loss of strength is in accordance with results of the mentioned studies. When water table is near to ground surface, water migrates to freezing front and freezing subjected soil absorbs water from deep layers (Sheng et al., 1995). In this condition, loss of strength is higher. The 1.5% fiber content specimen with absorbing water during thaw period loses 62% of its strength after only 1 cycle of freeze-thaw. And also, it cannot tolerate the next cycle. Thus, in presence of water migration, effectiveness of fiber reinforcement of not water absorbed specimens is overestimated and it may mislead designers.

Effects of absorption of water are clearly obvious on the stress-strain curves of specimens as it is plotted in Fig. 15. In this figure, for comparing behavior of water absorption during thaw period, water absorbed sample's stress-strain curve was exhibited as well as that of not water

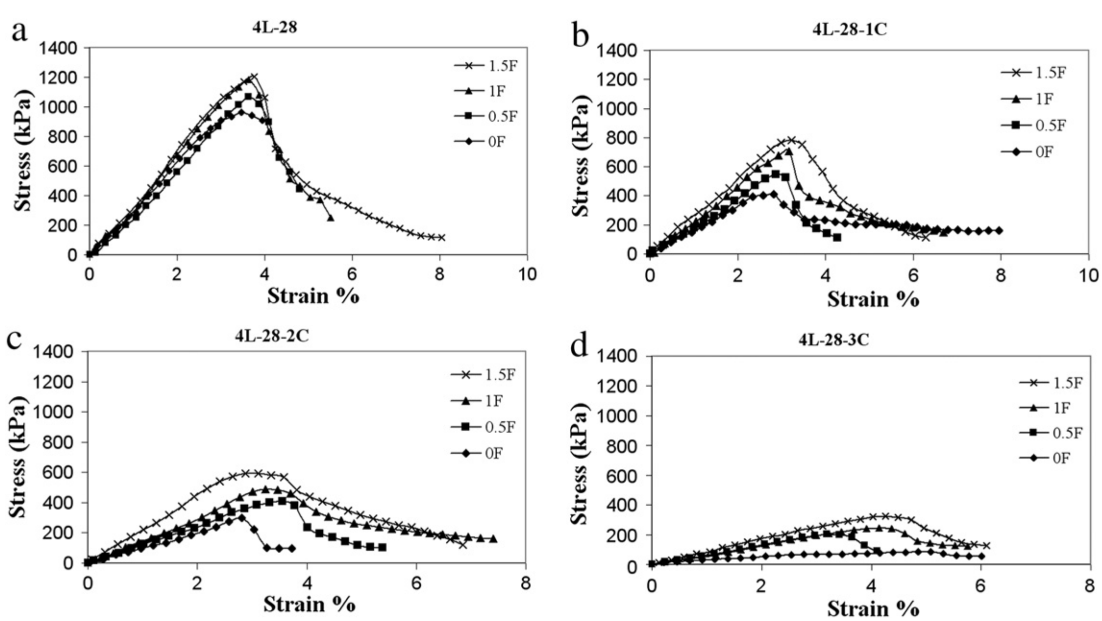


Fig. 13. Stress-strain curves of 4% lime stabilized specimens and reinforced with different fiber contents for: (a) before freeze-thaw, (b) after 1 cycle of freeze-thaw, (c) after 2 cycles of freeze-thaw and (d) after 3 cycles of freeze-thaw.

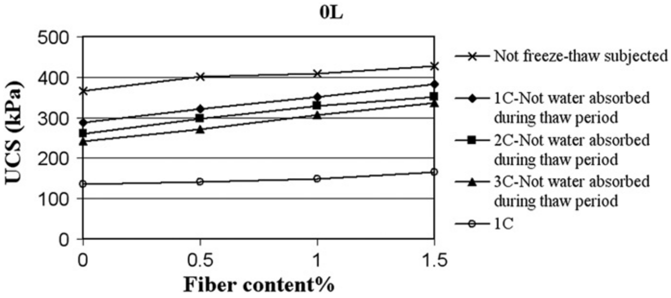


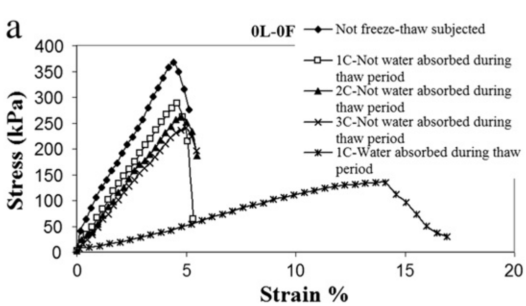
Fig. 14. UCS values of not water absorbed during thaw period specimens.

absorbed and non freeze-thaw subjected specimens. Not water absorbed specimens have high stiffness and low failure strain and residual strength. This is true even after 3 cycles of freeze-thaw. Generally, behavior of not water absorbed specimens is similar to non freeze-thaw subjected specimens. On the contrary, after 1 cycle of freeze-thaw, water absorbed specimens lose their strength and stiffness excessively and failure strain is increased considerably.

4. Conclusions

The effect of tire cord reinforcement of stabilized and unstabilized soil under freeze-thaw condition was investigated by unconfined compression tests and parameters such as compressive strength, stiffness, and failure properties were discussed in the present study. The main results of conducted experiments can be summarized as follows:

1) The contribution of fiber in increasing strength is enhanced as the cycles of freeze-thaw increase. The role of fiber is dependent on the performance of matrix. When frost heave occurs, friction between fiber and matrix resists against expansion. If the matrix like untreated soil is sensitive to freeze-thaw and saturation, the fiber cannot show effective role. In lime treated soil, load transferring mechanism behaves better and fiber has higher contribution in increasing strength. For 4% content of lime because matrix of soil acted better than 8% stabilized soil, fiber exhibited a better role.
2) Durability index is directly related to the initial strength of the specimens before freeze-thaw. The best durability index belongs to specimens with 4% lime content and it increases by inclusion of fiber.



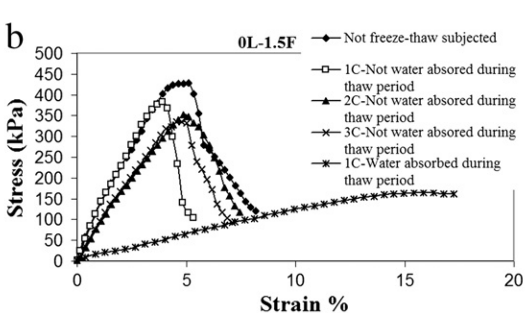


Fig. 15. Stress-strain curves of water absorbed and not water absorbed specimens during thaw period for: (a) unreinforced specimens; (b) specimens with 1.5% fiber content.

3) Extra free lime, which is left in stabilized specimens, brings about more sensitivity to freeze-thaw. Because of incomplete reactions of soil-lime, particularly, for low age specimens that contain more free lime, strength loss after freeze-thaw is higher.
4) Lime severely increases stiffness and reduces failure strain, residual strength, and toughness. Inclusion of fiber somewhat causes flexible behavior and compensates for weaknesses of stabilization. Before freeze-thaw and after 1 cycle, fiber does not considerably affect the initial stiffness of specimens, but after 2 cycles, stiffness increases by fiber reinforcing.
5) For the specimens, which do not absorb water during thaw period, the characteristics such as high stiffness and strength and low failure stress are generally like non freeze-thaw subjected specimens. While loss of strength for 1.5% fiber content soil after 1 cycle of freeze-thaw is 62%, this value for not water absorbed specimen after 3 cycles is only 11%. In cold regions, because of high probability of absorbing water for freeze-thaw subjected soils, fiber reinforcement is not as effective as for not water absorbed specimens and mechanical behavior of not water absorbed specimens is misleading.

It is noteworthy that reported results of present paper were obtained under determinate condition with specific materials, so further studies are required to generalize the findings.

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