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Effect of Freeze-Thaw Cycles on Triaxial Strength Properties of Fiber-Reinforced Clayey Soil

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Abstract

Understanding effect of freezing phenomenon in a fiber-reinforced soil structure is essential to foundation technology, road construction and earthwork application in cold region. This research aims to present the results of experimental investigation relative to the unconsolidated-undrained triaxial compression behavior of fine-grained soil as a function of freeze-thaw cycles and fiber volume fractions. All measurements were carried out for 3 selected glass and basalt fiber fractions (0%, 0.5%, and 1%) and 5 selected freeze-thaw cycles (0, 2, 5, 10, and 15). It has been observed that for the studied soil, strength of unreinforced soil reduced with increasing number of the freeze-thaw cycles while fiber-reinforced soil shows greater effect and the strength reduction amount reduces from 40% to 18%. Moreover, the reduction trend for cohesion of the fiber-reinforced soil decreased, this was seen more prevalent on 1% glass fiber-reinforced soil. The resilient modulus of all specimens reduced with increasing number of the freeze-thaw cycles. The experimental results demonstrated that different fiber fractions and their mixtures could be employed as supplement additive to improve the freeze-thaw performance of cohesive soils for road construction and earthworks.

Keywords: *freeze-thaw cycles, fiber-reinforced soil, failure strength, resilient modulus, cohesive force, friction angle*

1. Introduction

The stress-strain behaviors, failure strength and resilient modulus of reinforced soils subjected to freeze-thaw cycle usually change greatly. Therefore, when the soils are utilized as a part of an engineered infrastructure, determining a fitting technical solution is always essential. The engineering properties of soils change substantially after freeze-thaw cycles because of possible moisture migration and ice formation below 0ºC. So, a requirement for geotechnical engineering in seasonally frozen soil regions, analysis of stability and solution is the accessibility of engineering properties of subgrade soil exposed to periodic freezing-thawing (Ghazavi and Roustaei, 2010; Roustaei *et al*., 2015).

Many studies have been conducted on soil additives and their mixtures to determine durability under freeze-thaw cycles and the effects of their static and dynamic behaviors. Ghazavi and Roustaei (2010) investigated the effects of freeze-thaw cycles on the Unconfined Compressive Strength (UCS) of fiber reinforced cohesive soil. Their results indicated that UCS of the unreinforced clay specimens reduced a 20% to 25% with an increment of freeze-thaw cycles. The UCS of the reinforced soil with 3% polypropylene fibers subjected to freeze-thaw cycles increased by 60% to 160% and frost heave declined by 70%. Zaimoglu (2010) showed that the influence of polypropylene fibers on the strength behavior of a cohesion soil exposed to freezing-thawing cycles. He found that the mass loss in unreinforced soils was about 50% higher than reinforced one, and the UCS of soil samples exposed to freezing-thawing cycles increased with increment fiber content. Singh and Bagra (2013) carried out a number of triaxial compression tests with variables confining pressures on local soil (Itanagar, Arunachal Pradesh, India) without and with jute fiber (0.25%, 0.5%, 0.75% and 1% ratios). The results investigated that with addition of jute fiber, the cohesion, the internal friction angle and the stiffness modulus of the specimens increased. Gullu and Khudir (2014) showed that the influence of freeze-thaw cycles on the UCS of fine-grained soil reinforced with steel fiber, jute fiber, and lime. The results revealed that the UCS of untreated soil increased from 220 kPa to 1330 kPa before freeze-thaw cycle, from 205 kPa to 1300 kPa after 1 freeze-thaw cycle, from 156 kPa to 1100 kPa after 2 freeze-thaw cycles, and from 114 kPa to 900 kPa after 3 freeze-thaw cycles. Wu *et al.* (2014) carried out triaxial shear tests to show the mechanical properties of silty clay reinforced with randomly oriented sisal fibers. The results showed that the silty clay reinforced with a 1.0% and 10 mm long sisal fibers was 20% stronger than unreinforced silty clay. Roustaei *et al*. (2015) determined the influences of freeze-thaw cycles on Unconsolidated-undrained (UU) triaxial compressive strength of polypropylene

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fiber-reinforced soil with different blended ratios. The results showed that strength of unreinforced soil reduced with increasing freeze-thaw cycles. Also, reinforced specimens exhibited better reduction from 43% to 32%. In the same vein, Liu *et al*. (2010) studied on triaxial tests on lime and cement reinforced soils with variable blended ratios exposed to freeze-thaw cycles under dynamic loading. Their results investigated that the reinforced soils after freeze-thaw cycles exhibited better behavior than before reinforcement.

According to previous studies, using of different fibers in soil reinforcement has significant results on static, dynamic and thermal properties of subgrade soil. The glass fiber with the different blended ratios was often used to investigate the engineering properties of soil. However, this fiber was not much studied under freeze-thaw cycles in the literature. Also, the glass fiber has taken place among the most adaptable in construction of civil and highway engineering. In this application, the glass fiber presents effective bulk density, hardness, stability, and flexibility and stiffness. Besides, the basalt fiber was not studied enough in blended soil on the soil engineering properties although these fibers are generally utilized as an alternative to metal reinforcements in building materials, such as steel and aluminum. Moreover, basalt is used in reinforcement technology for stabilization of road and highway to maintain the pavement life by decreasing the effects of cracks caused by excessive traffic loading, age hardening and temperature changes (Singha, 2012). Due to these useful and advantage properties of basalt and glass fibers, both were chosen to investigate triaxial compression behavior of blended soil with these fibers exposed to freeze-thaw cycles.

In seasonally frozen region, soils are subjected to at the least one freezing-thawing cycle in a year. Understanding effect of freezing phenomenon in a fiber reinforced soil structure is essential to foundation technology, road construction and earthwork application in cold region. Also, determining a proper technical solution is always important because soils are generally used as a part of an engineered infrastructure. The aim of present study was to elucidate the influences of freeze-thaw cycles on the stress-strain behavior, cohesion, internal friction angle, resilient modulus, and also failure strength of clayey soils reinforced with randomly distributed glass and basalt fibers by performing unconsolidated-undrained (UU) triaxial test. For this aim, investigations of the physical and engineering behaviors of cohesive soils reinforced with different fibers were performed before and after expose to freeze-thaw cycles.

2. Materials

In this paper, clay soil from the Qinghai-Tibet Plateau in China was used to determine the triaxial compression behavior. The physical parameters such as liquid limit is 30.04% and plasticity index is 12.09%, maximum dry density of 19.3 KN/m^3 and

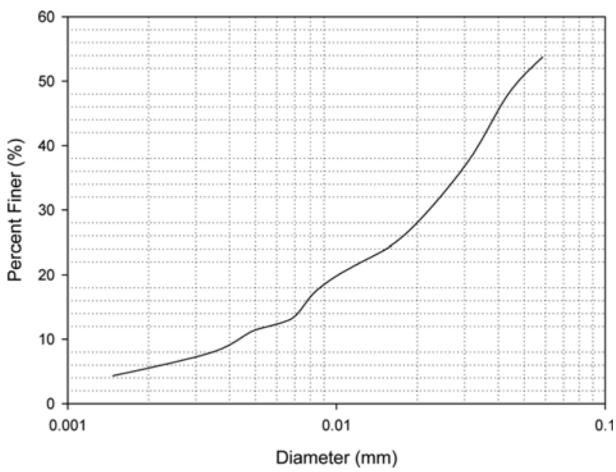


Fig. 1. Particle Size Distribution of the Studied Clayey Soil

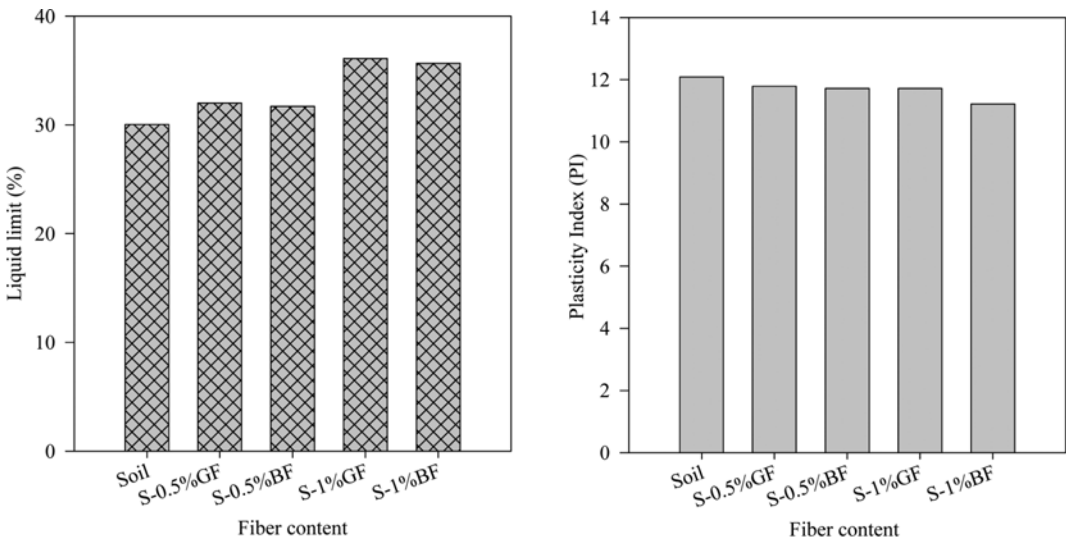


Fig. 2. Variation of Liquid Limit and Plasticity Index with Addition of Glass and Basalt Fibers

optimum water content of 12.9%. Fig. 1 depicts the particle size distribution of clayey soil. The previous researches showed that fiber addition had little or no effect on compaction characteristics (Nataraj and McManis, 1997; Miller and Rifai, 2004; Abdi *et al.*, 2008). For that reason, in the present research, all specimens were prepared using the same dry density and optimum water content. Moreover, 20 liquid limit tests were performed on different contents of glass and basalt fibers. Fig. 2 depicts the liquid limit and the plasticity index of unreinforced and reinforced soil with glass and basalt fibers. The results showed that liquid limit increased with an increase in fiber contents. This was observed more prevalent on glass fiber-reinforced soil. The liquid limit increased about 7% for 0.5% glass fiber-reinforced soil and about 20% for 1% glass fiber-reinforced soil. On the other hand, the liquid limit increased about 5.5% for 0.5% basalt fiber-reinforced soil and about 18% for 1% basalt fiber-reinforced soil. Moreover, the Plasticity Index (PI) decreased with addition of fibers due to increment of plastic limits. These reduction were observed for 0.5% glass fiber-reinforced soil about 2.5%, for 1% glass fiber-reinforced soil about 3.1%, for 0.5% basalt fiber-reinforced soil about 3.1% and for 1% basalt fiber-reinforced soil about 7.2%. All these findings are in good agreement with the results of both Kinjal *et al.* (2012) and Behbahani *et al*. (2016).

The specimens were reinforced with randomly distributed basalt and glass fibers, which were blended at 0%, 0.5%, and 1% ratios and all fibers have the same length and diameter. In this study the basalt and glass fibers were derived from Hebei province in China and their engineering properties are presented in Table 1 (Singha, 2012).

3. Testing Procedure

3.1 Specimen Preparation

All specimens were formed into columns of 39.1 mm in diameter and 80 mm in height. The basalt and glass fiber contents were varied at 0%, 0.5%, and 1% by weight of dry soil. For every mixture, the exact weight of each additive material was determined based on maximum dry density and the optimum moisture content measured by the standard Proctor test. The clayey soil and fibers were blended in dry condition, then water was added slowly and mixture pushed the sieve 4.75 mm for flocculate. The mixtures were put into plastic bags and blocked for 24 hours to provide uniform distribution of water content within the mixtures. The water content was checked again before preparation of the specimens. The mixtures of soil-fiber-water were compacted by three layers. Further, all specimens were prepared at the same initial water contents to investigate their physical (water content and mass loss) properties and static behaviors under a number of freeze-thaw cycles. Figs. 3(a) to d depict the preparation of soil specimens for triaxial testing.

3.2 Freeze-thaw Performance

The soil specimens were exposed to 0, 2, 5, 10, and 15 freeze-thaw cycles before testing. The specimens were put in a digital refrigerator with a constant temperature of about -20°C, for 12 h (Fig. 3(c)). Then, they were removed from the refrigerator and put in a moisture cabinet maintained at room temperature (about 20°C) to provide a thawing period of 12 h. All of these stages were considered as one cycle. Further, the specimens were tested at the room temperature about 20°C. The cycles were held to 15 cycles. The number of freeze-thaw cycles was selected because the most reduction of soil strength could become in the first cycles and a new dynamic stability would occur prevalent on specimens after tenth freeze-thaw cycles. At the end of the needed freeze-thaw cycles, changes of physical properties and static behavior under unconsolidated-undrained conditions of unreinforced and fiber-reinforced soil were determined. Table 2 presents the planning of the freeze-thaw tests for soil specimens before tests.

After fifteenth freeze-thaw cycles, the test specimens were dried at 105±5°C for 12 h. The re-corrected dry mass of the specimen (*RCODM*) was formulated as the following (Zaimoglu,

Table 1. The Engineering Properties of the Studied Basalt and Glass Fibers (Singha, 2012)

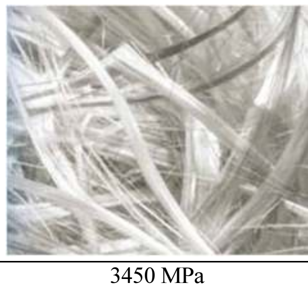
	Basalt Fiber	Glass Fiber
		
Breaking strength	3900 MPa	3450 MPa
Modulus of elasticity	86.2 GPa	74 GPa
Breaking extension	3.1%	4.7%
Fiber diameter	10 μm	10 μm
Linear density	60-4,200 tex	40-4,200 tex
Length	15 mm	15 mm

Fig. 3. Preparation of Soil Specimens for Triaxial Testing: (a) The Specimen Covered Membrane before Tests, (b) The Triaxial Compression Test System, (c) The Freeze-thaw Cabinet, (d) The Specimen after Tests

Table 2. The Planning of the Freeze-thaw Tests for Soil Specimens before Tests

Dimension of test specimen		Tested material**	Number of F-T test*					Temperature		Tested temperature
H*	D*		0	2	5	10	15	Freezing	Thawing	
39.1	80	S	+	+	+	+	+	-20 ºC	20 ºC	Room temperature ~20 ºC
		S-0.5G	+	+	+	+	+			
		S-1G	+	+	+	+	+			
		S-0.5B	+	+	+	+	+			
		S-1B	+	+	+	+	+			

*F-T: freeze-thaw cycles; H: Height (mm); D: Diameter (mm)
**S is soil; S-0.5G is reinforced soil with 0.5% Glass fiber; S-1G is reinforced soil with 1% Glass fiber; S-0.5B is reinforced soil with 0.5% Basalt fiber; S-1B is reinforced soil with 1% Basalt fiber.

2010):

$$RCODM = (DMA/WP) \cdot 100 \quad (1)$$

where *DMA* is the dry mass after drying, and *WP* is water percentage preserved in the specimen plus 100. The mass loss (*ML*) was formulated as:

$$ML(\%) = (RM/RBM) \cdot 100 \quad (2)$$

where *RM* is the real calculated dry mass minus the final corrected dry mass (*OM* = *OBM* - *RCODM*), and *RBM* is the real (i.e., before freezing-thawing cycles) computed dry mass.

In cold regions, soil particles are formed in various shapes and sizes with a thin layer of unfrozen water binding them (Andersland and Ladanyi, 2004). The water, or ice, in the voids affects the permeability, the porosity and the soil density. A decrease in grain size causes a change in specific surface area and a significant decrease in the permeability (Usowicz *et al.*, 2013). In the freezing process, the curve of the water/ice interfaces increase sharply, which results in smaller capillaries. Hence, there is a correlation between the radius of the water/ice interface and the particle size distribution (Brady and Weil, 2002).

A dimensionless parameter, D, for the soil specimens after freeze-thaw cycles has been determined to perform the effect of freezing-thawing cycle on soil specimen's water content as below:

$$D = \frac{\Delta w}{w_0} \tag{3}$$

where Δw is the increasing amount of the water content after N cycles in the thawed phase, w_o is the water content at the beginning in the unfrozen soil.

3.3 Static Test Procedure

The soil specimens subjected to freeze-thaw cycles were tested by UU triaxial compression tests to determine the strength parameters. The strain rate was held constant at 0.7 mm per-min.

Since the freeze-thaw cycles are usually seen in interface of soil which is particularly linked with pavement and is exposed sudden loading resulted from vehicles, the cohesive soil with lesser permeability may not be provided drainage and consolidated. Therefore, applying of the UU test to the specimens is more appropriate for researching the performance of melting soil subjected to fast and duplicated traffic load. To model these at subgrade of soil, three confining pressures of 100, 200, and 300 kPa have been chosen for triaxial tests.

4. Results and Discussion

4.1 Effects of Freeze-thaw Cycles on Mass Loss and Water Content of Unreinforced and Fiber- Reinforced Specimens

To show the influence of the fiber in soil on triaxial compression test, mass losses were computed after 15 freeze-thaw cycles. The change of mass losses with variable fiber ratios was shown in

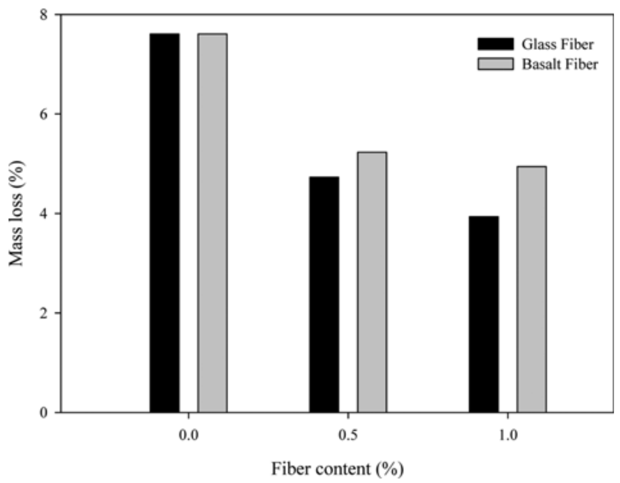


Fig. 4. The Variation of Mass Loss with Fiber Content after 15 Freeze-thaw Cycles

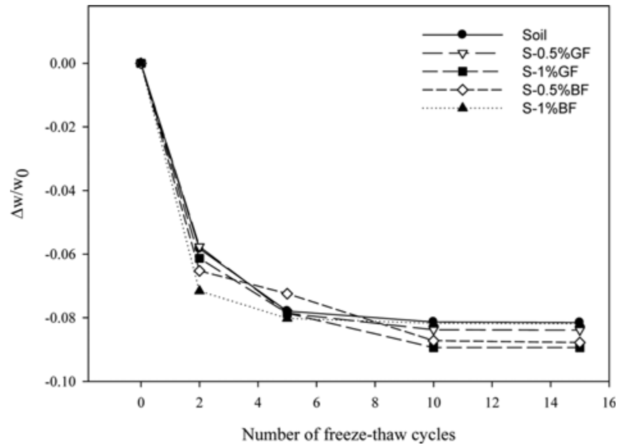


Fig. 5. D Versus the Number of Freeze- Thaw Cycles

Fig. 4. The mass loss of soil subjected to freeze-thaw cycles decreased with the addition of fiber. With the increment of glass fiber content in soil, mass loss reduced after 15 freeze-thaw cycles about 3.8%. The most remarkable effect of mass loss was observed on the specimens reinforced with 1% glass fiber about 4.2%. For the other fiber mixtures, mass losses were determined in range of 5-5.5%. The previous researches showed that it was not important effect on the stability of soil when mass losses were about less than 10% (Chamberlain *et al.*, 1990; Hassini, 1992; Zaimoglu, 2010). Thus, the fiber-reinforced soil shows more resistivity against to the effects of freeze-thaw cycles. Also, this reduction amount was related with the water drainage of glass fiber-reinforced soil.

Also, Fig. 5 shows the relationships between D and the freeze-thaw cycles for unreinforced and reinforced specimens. At the beginning, the water content of the specimens reduced with increasing number of freeze-thaw cycles, then slowly steadied after tenth freezing-thawing cycle. Moreover, it is observed that with the inclusion of basalt and glass fibers, the water content decreases little more than unreinforced soil. Since, woven fibers like basalt and glass fibers layer can drain water in the soil volume. However, this reduction is negligible. Further, glass fiber-reinforced soil has a significant effect of draining capacity in the soil volume compared with basalt fiber-reinforced soils. However, this effect was described in the literature as insignificant.

Due to presented figures, the tenth freeze-thaw cycle is a key cycle. After this cycle, height of the specimens reaches a constant value, thus the specimens obtain a new dynamic stability in their textures. Supplied the moving pore water from middle to the top of soil specimens during freezing period, as onward moving, the moving from the top to the middle side, during thawing period, is called reversed moving. The quantity of moving between onward and reversed moving will also attain a dynamic stability.

4.2 Effects of Freeze-thaw Cycles on Stress- Strain Behavior of Unreinforced and Fiber- Reinforced Specimens

Figures 6 through 10 depict the stress-strain behavior of the specimens exposed to freeze-thaw cycles. The failure strength of

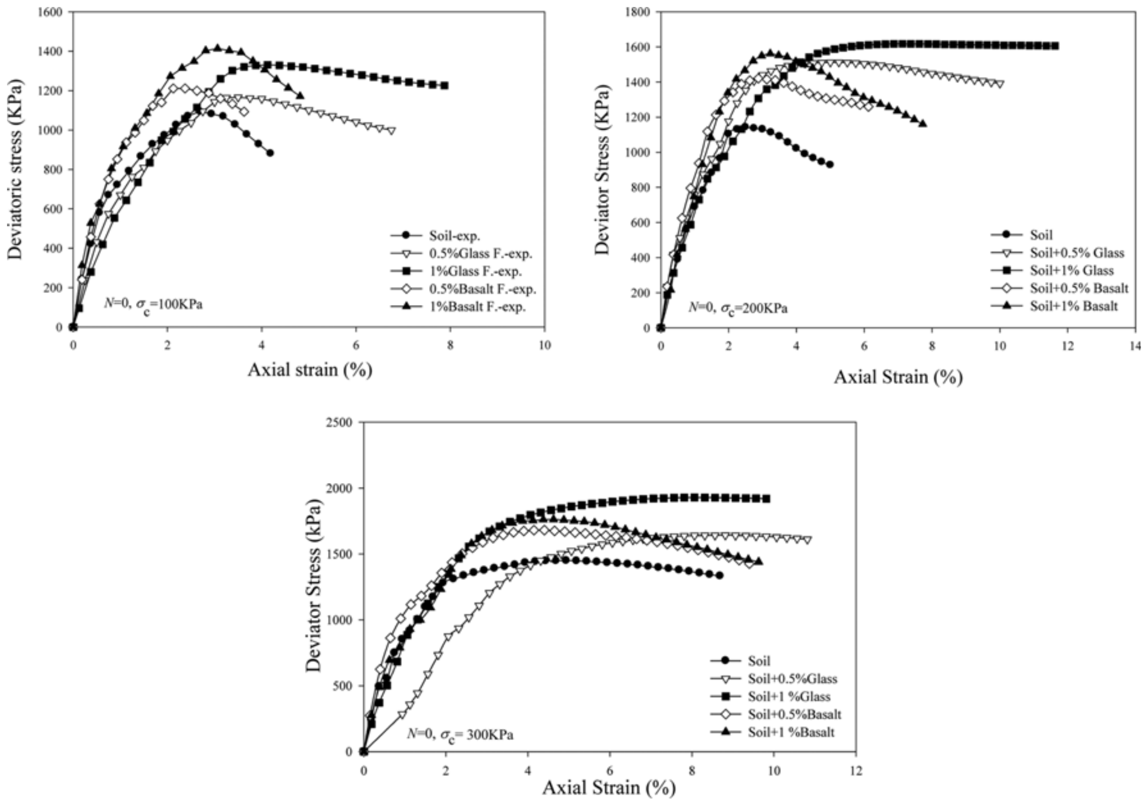


Fig. 6. Stress-strain Relations of Reinforced and Unreinforced Soil Specimens Under Different Confining Pressures before Freeze-thaw Cycles

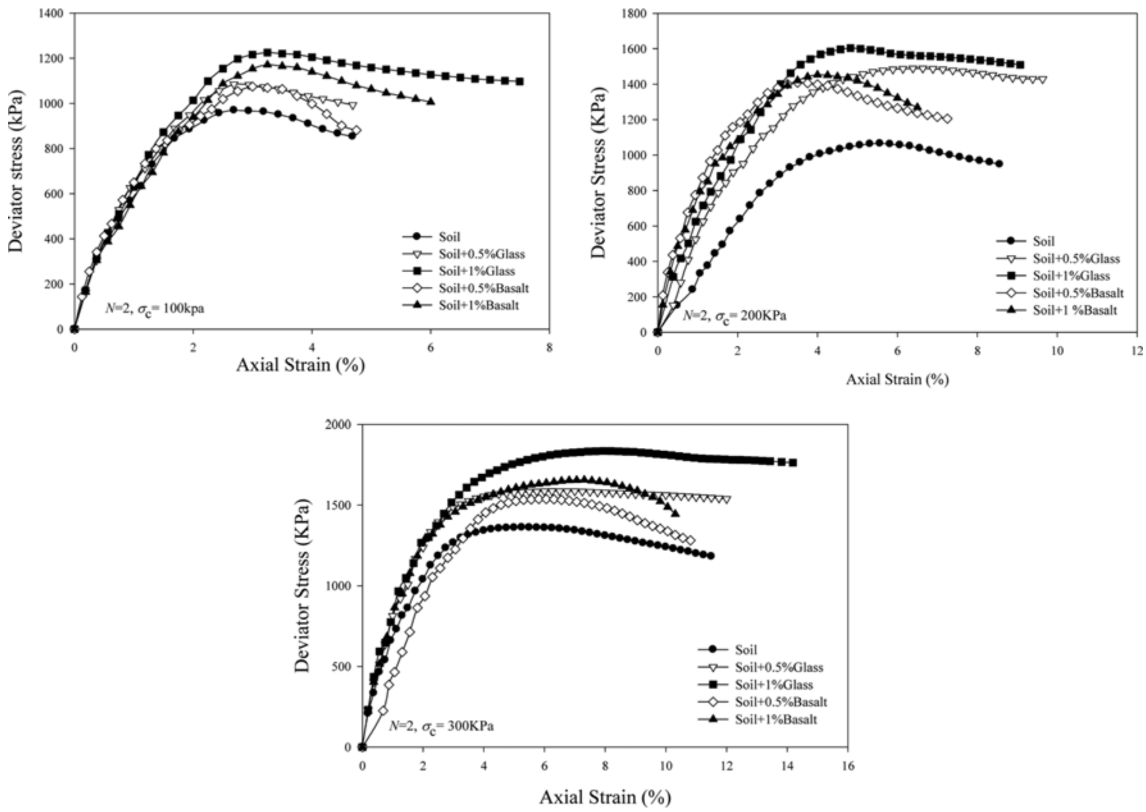


Fig. 7. Stress-strain Relations of Reinforced and Unreinforced Soil Specimens Under Different Confining Pressures after 2 Freeze-thaw Cycles

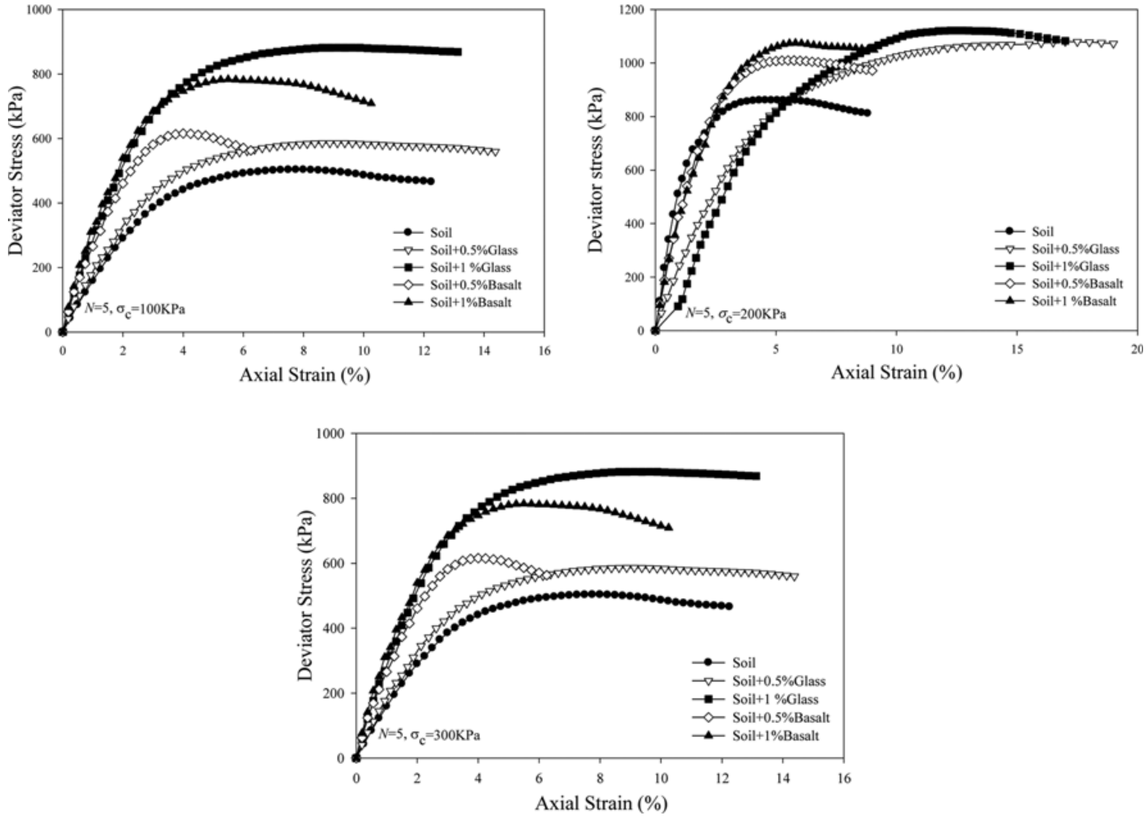


Fig. 8. Stress-strain Relations of Reinforced and Unreinforced Soil Specimens Under Different Confining Pressures after 5 Freeze-thaw Cycles

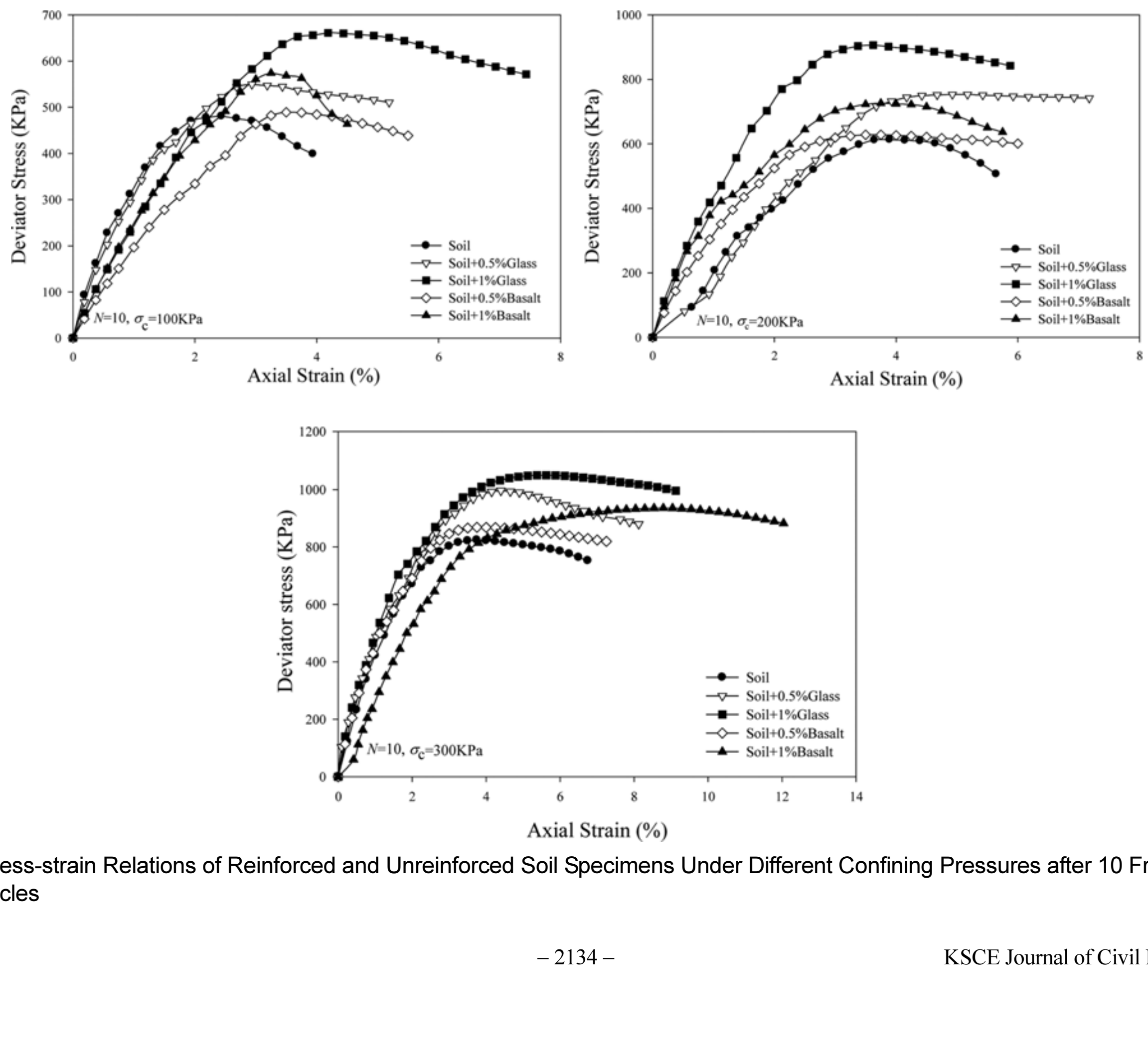


Fig. 9. Stress-strain Relations of Reinforced and Unreinforced Soil Specimens Under Different Confining Pressures after 10 Freeze-thaw Cycles

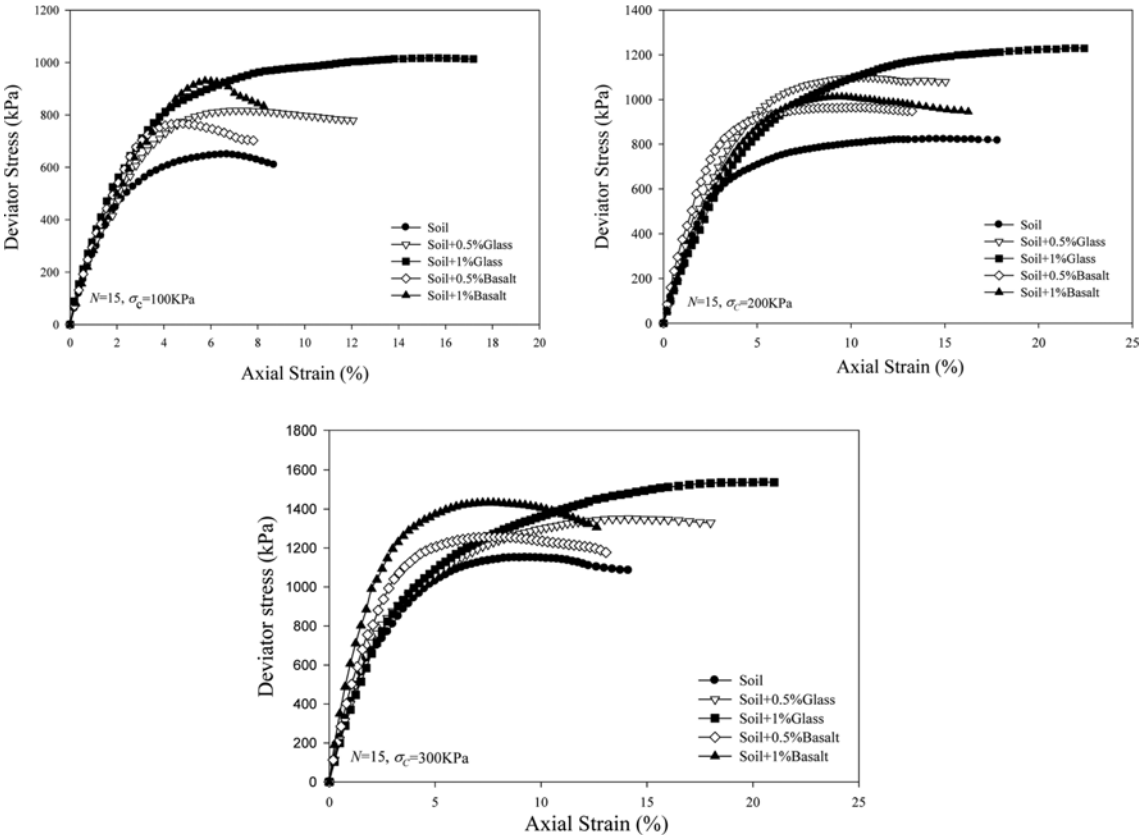


Fig. 10. Stress-strain Relations of Reinforced and Unreinforced Soil Specimens Under Different Confining Pressures after 15 Freeze-thaw Cycles

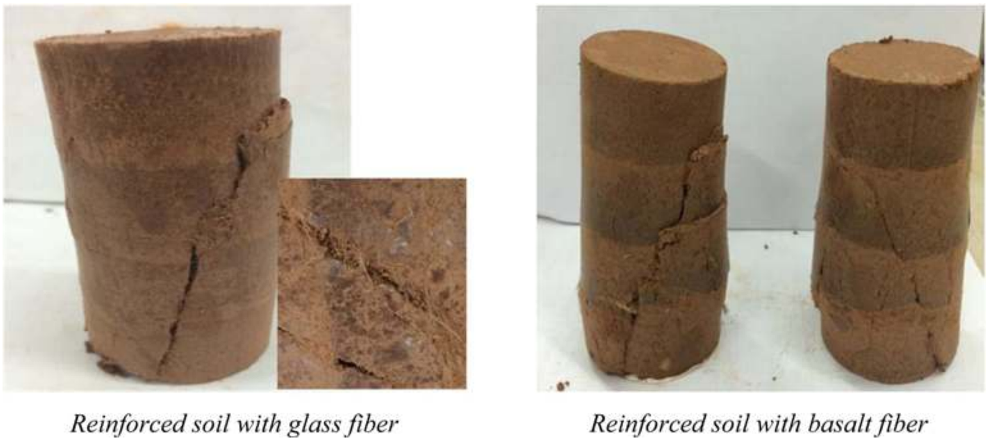


Fig. 11. Fracture Modes of Reinforced Soil with Glass and Basalt Fibers

soil subjected to freeze-thaw cycles increased with an increment in fiber ratio. Moreover, a decrease was observed on the strength of all specimens after freeze-thaw cycles, but fiber-reinforced soils were exhibited minimum reduction on the strength. Also, in clayey soil reinforced with fibers, the stress-strain behavior transitioned from strain-softening to strain-hardening, and this condition was more prevalent in soil reinforced with glass fibers. Moreover, strength of the basalt fiber-reinforced soil was observed little more than glass fiber-reinforced soil before freeze-thaw cycles. As presented in Table 1, the breaking strength and modulus of elasticity of basalt fiber were higher than the glass fiber. Thus, this exhibits more resistance under different confining pressure. However, breaking extension of the basalt fiber was less than the glass fiber and this can be stated as the transition from their strain-softening to strain-hardening is smaller than glass fiber-reinforced soil.

When the soil specimens were exposed to 15 freeze-thaw cycles, the coincidental behavior was seen on ultimate strength of the specimens. This can be stated that under the effect of freeze-thaw processes, internal texture of the specimens had a dynamic balance. In this research, it was determined as tenth freeze-thaw cycle. After this cycle, with this dynamic balance of the specimens were principally exhibited in the form of brittle failure. This was observed in Fig. 9 with 300 kPa of confining pressure.

Figure 11 shows the crack failure modes of soil reinforced with basalt and glass fibers. The additive content significantly influences the fracture mode. The crack fracture mode is the lateral fracture mode, particularly in the soil reinforced with fibers. The crack development increased gradually with increasing the additive content.

4.3 Effects of Freeze-thaw Cycles on Failure Strength

When soil is subjected to freezing period, the pore water in it turns into ice. The ice force causes soil particles to separate from each other, which increases the pore water pressure. However, during thawing, the increased pore water pressure cannot revert to its exact previous state. Thus, freeze-thaw cycles generally decrease the soil strength (Andersland and Ladanyi, 2004). Many studies have clearly shown that the strength of unreinforced soil and reinforced soil decreases with an increment number of freeze-thaw cycle.

In this research, soil failure strength was explained by a ratio that is determined as the strength of unreinforced and fiber-reinforced soil after required number of freeze-thaw cycles divided by that of soil which was not exposed to any freeze-thaw cycles.

Figure 12 shows the failure strength ratio versus the number of freeze-thaw cycles under different confining pressures. According to these figures, an increment of the freeze-thaw cycles caused a decrease in the failure strength ratio of unreinforced and fiber-reinforced soils. Also, the compression strength of the unreinforced specimen reduced by 20% to 40% after 15 freeze-thaw cycles; this decreasing trend was about 17% to 29% for 0.5% glass fiber-reinforced soil, 20% to 23% for 1% glass fiber- reinforced soil, 25% to 36% for 0.5% basalt fiber- reinforced soil, and 18% to 34% for 1% basalt fiber- reinforced soil. However, the failure strength ratio of all specimens increased at all fiber contents and confining pressures after tenth freeze-thaw cycle. This is related to tenth freeze-thaw cycle is a key cycle. After this cycle, the soil specimens height reach a constant value, thus the specimens obtain a new dynamic stability in their textures. The quantity of moving between onward and reversed moving will also attain a dynamic stability. The soil failure was principally described in the form of plastic failure after this key cycle. These findings are in good agreement with the results of Wang *et al.* (2007).

4.4 Effects of Freeze-thaw Cycles on Shear Strength Properties

Figure 13 shows the variation of shear strength parameters of

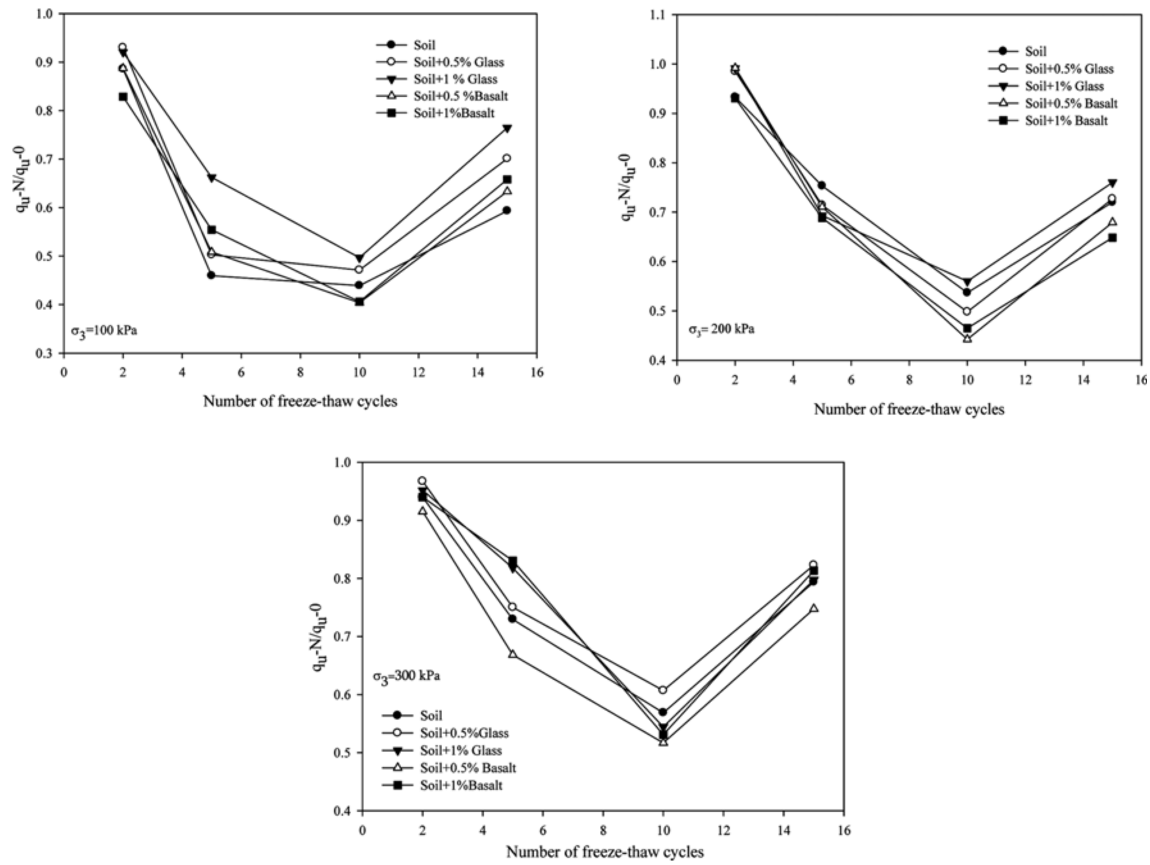


Fig. 12. Failure Strength Ratio of Unreinforced and Reinforced Specimens Versus Number of Freeze-thaw Cycles Under Confining Pressures of 100, 200, and 300 kPa

Table 3. Summary of Calculation Parameters of Cohesion and Friction Angle

	0 F-T cycles		2 F-T cycles		5F-T cycles		10F-T cycles		15 F-T cycles	
	b (MPa)	α (º)	b (MPa)	α (º)	b (MPa)	α (º)	b (MPa)	α (º)	b (MPa)	α (º)
Soil	0.215	26.09	0.178	26.79	0.051	30.28	0.064	25.64	0.080	29.25
S;0.5G	0.211	28.89	0.181	29.81	0.053	32.21	0.075	27.79	0.118	29.73
S;1G	0.206	30.92	0.184	31.25	0.086	32.62	0.12	26.1	0.159	29.56
S;0.5B	0.222	28.37	0.196	28.59	0.081	29.77	0.071	26.06	0.112	28.81
S;1B	0.328	25.17	0.211	28.77	0.078	32.21	0.101	25.41	0.122	29.94

reinforced and unreinforced soil specimens under different number of freeze-thaw cycles. These parameters were determined from the variations of *p-q* as the following:

$$p = ((\sigma_1 + \sigma_3)_f/2) \quad (4)$$

$$q = ((\sigma_1 - \sigma_3)_f/2) \quad (5)$$

where, σ_1 and σ_3 are the failure axial stress and lateral stress, respectively, of the soil specimens.

The general relation between *p* and *q* can be stated as (Wang *et al.*, 2007):

$$q = b + p\tan\alpha \quad (6)$$

where *b* is the intersect of the line with *q* axis, *α* is the slope. Considering the data of *b* and *α* shown in Table 3, cohesion (*c*) and the internal friction angle (*φ*) of the soil can be computed as below (Wang *et al.*, 2007):

$$\varphi = \sin^{-1}\tan\alpha \quad (7)$$

$$c = \frac{b}{\cos\varphi} \quad (8)$$

The cohesion of soil reduced with an increment of the freeze-thaw cycles (e.g., Ogata *et al*., 1985; Ghazavi and Roustaei, 2013; Wang *et al.,* 2007). However, in some cases there was an increase of cohesion with an increase number of the freeze-thaw cycles due to the increasing volume of the specimens, which was related to the voids of clay particles (Wang *et al.*, 2007). According to Fig. 13, the cohesion of the unreinforced and fiber-reinforced soil decreased with increasing number of freeze-thaw cycles; however, the reduction trend of cohesion for fiber-reinforced soil was reduced from 60.73% to 43.14% for 0.5% glass fiber, to 24.90% for 1% glass fiber, to 48.86% for 0.5% basalt fiber, and to 58.57% for 1% basalt fiber. Moreover, the internal friction angle showed an increment as the number of freeze-thaw cycles increased.

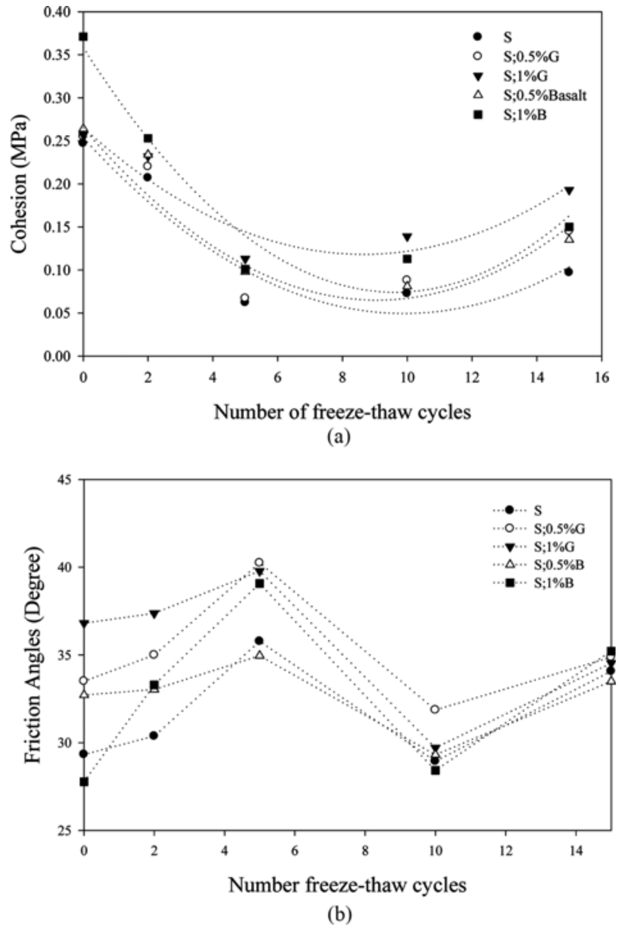


Fig. 13. The Shear Parameters of Unreinforced and Fiber-reinforced Soil: (a) The Cohesion of Glass and Basalt Fiber-reinforced Soil, (b) The Friction Angles of Glass and Basalt Fibers-reinforced Soil

4.5 Effects of Freeze-thaw Cycles on Resilient Modulus

The resilient modulus is a significant key parameter for designing pavement systems to account for soil deformation under repeated traffic loading. Also, it is used to perform the stiffness of materials under variable stress states, densities, and degrees of compaction, and saturation.

The resilient modulus is determined by dividing the deviator stress increment at 1% axial strain to the axial strain increment, which can be stated by:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{1.0\%} - \sigma_0}{\varepsilon_{1.0\%} - \varepsilon_0} \quad (9)$$

where, $\Delta\sigma$ is the inclusion of deviator stress, $\Delta\varepsilon$ is the inclusion of axial strain; $\sigma_{1.0\%}$ is the deviator stress related to the axial strain of 1.0% ($\varepsilon_{1.0\%}$); and σ_0 and ε_0 are the stress and strain at the beginning, respectively (Wang *et al*., 2007).

Figure 14 shows that the common trend of resilient modulus reduces from zero to tenth freeze-thaw cycle, then slowly increases and the largest variation in resilient modulus in all

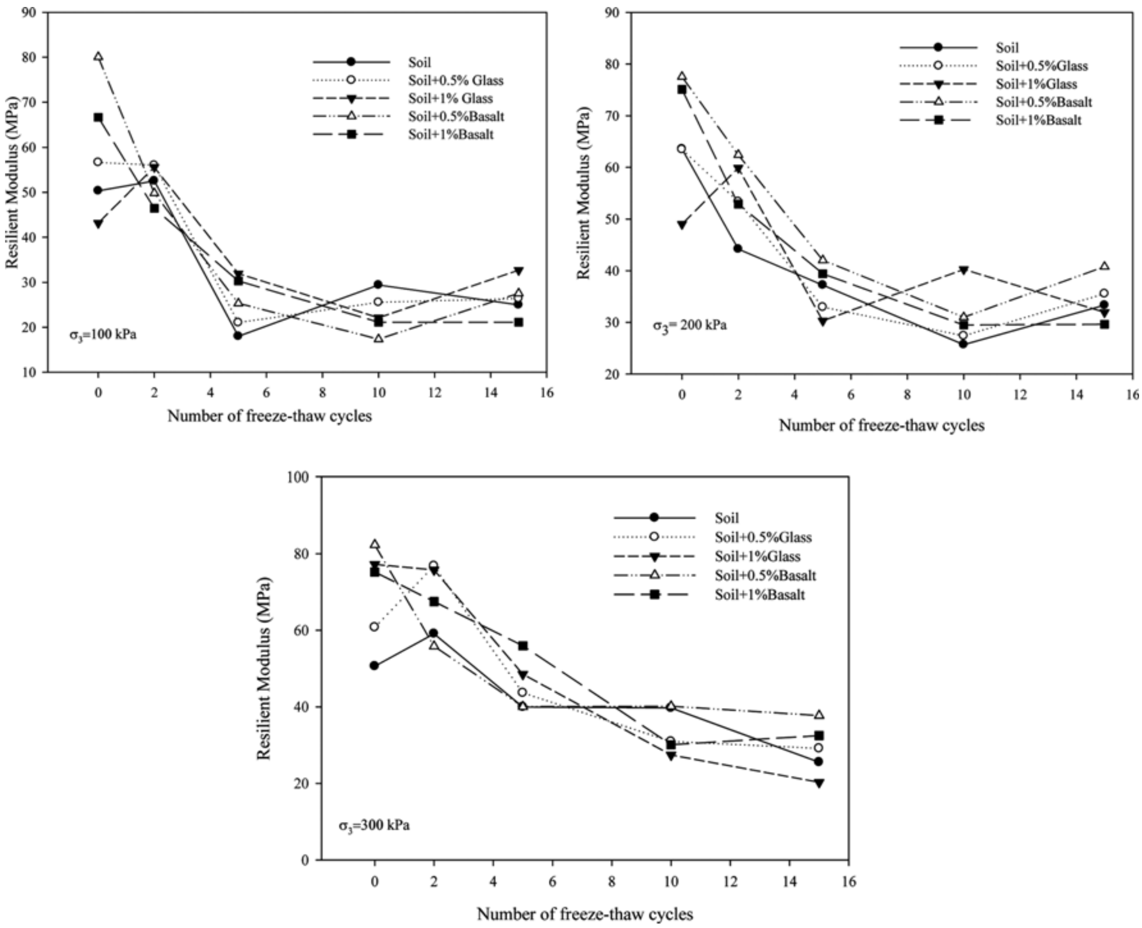


Fig. 14. Variations of Resilient Modulus of Reinforced and Unreinforced Soils Under Different Confining Pressures

confining pressures were determined in 1% glass fiber-reinforced soil after the second freeze-thaw cycles. After all specimens exposed to 10 freeze-thaw cycles, the minimum resilient modulus is seen, in spite of different confining pressures. When the number of freeze-thaw cycles exceed to tenth freeze-thaw cycle, the resilient modulus will arrive to stable point and stay in that point with increasing freeze-thaw cycles. After fifteenth freeze-thaw cycle, the resilient modulus of the unreinforced soil decreased by about 50.34%, as compared with a 53.42% decrease in soil reinforced with 0.5% glass fiber, 24.25% in soil reinforced with 1% glass fiber, 65.60% in soil reinforced with 0.5% basalt fiber, and 68.34% in soil reinforced with 1% basalt fiber.

4.6 Effects of Confining Pressure on Freeze-thaw Cycles

Confining pressure is a parameter which leads soil to consolidate, readjust, and move soil strength in a way. Thus, it has a significant effect on solution of soil strength problems after freeze-thaw cycles.

In this research, when the confining pressures increases, decreasing of the strength during freeze-thaw period reduces. Thus, freeze-thaw cycles greatly damages on surface of highway structure and the foundation of engineering structure. Also, the cracks occurred by freeze-thaw cycles will connect and improve the soil strength in the soil texture. Thus, the effect of freeze-thaw cycles is more noticeable in small rate confining pressures than big rates. Moreover, though the effect of freeze-thaw cycles was determined in the literature papers on reinforced soil with different fibers, no influence was observed in default of unconfined compression strength and confining pressure of fiber-reinforced soil decreased during freeze-thaw cycles. This case was related to inadequate cohesion between soil and fibers (Wang *et al.*, 2007; Ghazavi and Roustaie, 2010).

According to Figs. 6 to 10, using different fibers in the clayey soil influences decreasing of the strength resulted from freeze-thaw cycles. The strength of unreinforced soil reduced by 21%-41% due to the exposed of 15 freeze-thaw cycles while this decreasing is about 30%-17% for 0.5% glass fiber- reinforced specimens, 24%-20% for 1% glass fiber- reinforced specimens, 37%-25% for 0.5% basalt fiber- reinforced specimens, and 34%-19% for 1% basalt fiber- reinforced specimens.

5. Conclusions

An experimental study was performed to demonstrate the effects of freeze-thaw cycles on the physical properties including water content changes and mass loss, and unconsolidated-undrained triaxial compressive strength of clayey soil reinforced with different ratios of basalt and glass fibers. The following results are drawn from this study:

1. The most significant effects of fiber reinforcement were observed on 1% glass fiber-reinforced soil. The mass loss of all fiber-reinforced soils decreased from 7.60% to 3.94%. Moreover, the water content of the specimens reduced with increasing number of freeze-thaw cycles at the beginning, and then slowly steadied after tenth freezing-thawing cycle. It is found that the inclusion of basalt and glass fibers decreases the water content little more than unreinforced soil. Since, woven fibers like basalt and glass fibers layer can drain water in the soil volume. However, this reduction is insignificant.
2. With increasing of the basalt and glass fiber contents, the failure strength of all specimens before and after freeze-thaw cycles increased. As the number of freeze-thaw cycles increased, the failure strength of both the unreinforced and fiber-reinforced soils decreased, but this decrease was observed less in the fiber-reinforced soil than unreinforced soil. Also, the fiber-reinforced soil, with an increment of fiber content, transitioned from strain-softening behavior to strain-hardening behavior with increasing number of freeze-thaw cycles.
3. The failure strength of the unreinforced soil decreased by 20%- 40% after 15 freeze-thaw cycles, whereas this reduction was only about 17% -29% for 0.5% glass fiber- reinforced soil, 20%- 23% for 1% glass fiber- reinforced soil, 25%- 36% for 0.5% basalt fiber- reinforced soil, and 18%-34% for 1%basalt fiber- reinforced soil.
4. The additive content significantly affects the fracture mode. The glass fiber-reinforced soil exhibited the slippage fracture mode comparing with the basalt-reinforced soil. The development of the fracture surface in basalt-reinforced soil was nearly the same with unreinforced soil after fifteenth freeze-thaw cycles. This is because the basalt fiber in clay soil caused a rupture failure mode with smaller failure strain and the clay soil shows nearly the same behavior in deviator stress-strain plots with the smaller strength.
5. The cohesion of the unreinforced and fiber-reinforced soil decreased with increasing number of freeze-thaw cycles; however, the reduction trend of cohesion with fiber reinforcement reduced from 60.73% to 43.14% for 0.5% glass fiber, to 24.90% for 1% glass fiber, to 48.86% for 0.5% basalt fiber, and to 58.57% for 1% basalt fiber. Moreover, the internal friction angle showed an increasing behavior as the number of freeze-thaw cycles increased.
6. With an increment of the number of freeze-thaw cycles, the resilient modulus of the unreinforced and fiber-reinforced soil decreased. After 15 freeze-thaw cycles, the resilient modulus of the unreinforced soil decreased by about 50.34%, as compared with about 53.42% of 0.5% glass fiber-reinforced soil, about 24.25% of 1% glass fiber-reinforced soil, about 65.60% of 0.5% basalt fiber-reinforced soil, and about 68.34% of 1% basalt fiber-reinforced soil.
7. Due to presented figures, the tenth freeze-thaw cycle is a key cycle. The quantity of moving between onward and reversed moving will also attain a dynamic stability. It is seen that this affects *D*, stress-strain behavior, failure stress ratio, cohesion and resilient modulus of specimens after tenth freeze-thaw cycle.

Considering the conclusions of this research, it is suggested to use successfully basalt and glass fibers in range of 0.5% and 1% up to 15 freeze-thaw cycles in reinforcement technology in cold climates to prevent the damaging effect of freeze-thaw cycles. These fibers may be used on foundation technology, road construction and earthwork application to decline the effects of freeze-thaw cycles. The existence of these fibers provides increasing the peak strength of the soil and also reduced the damaging effect of freeze-thaw cycles.

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