Performance of Clay Soil Reinforced with Fly Ash and Lignin Fiber Subjected to Freeze-Thaw Cycles

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Abstract: This paper aims to present the results of an experimental investigation related to the unconsolidated undrained triaxial compression behavior of fine-grained soil as a function of freeze-thaw cycles, and fly ash–lignin fiber volume fractions. All the measurements were carried out for three selected fly ash fractions (0, 4, and 8%), and five selected lignin fiber fractions (0, 0.25, 0.5, 0.75, and 1%). The specimens were exposed to from 0 to 15 freeze-thaw cycles before testing. It has been observed that for the studied soil, the compression strength of unreinforced soil decreased with an increment the number of freeze-thaw cycles. Moreover, the fly ash–lignin fiber–reinforced soil specimens showed greater effect on compression strength after the 15th freeze-thaw cycle. The greatest amount of strength reduction was obtained on the maximum blend ratios of the lignin fiber. Also, the reduction trend of cohesion was declined for the reinforced soil and the resilient modulus of all soil specimens reduced after the 15th freeze-thaw cycle. **DOI:** 10.1061/(ASCE)CR.1943-5495.0000139. © *2017 American Society of Civil Engineers.*

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Introduction

Stress–strain behaviors, failure strength of reinforced soils that are subjected to freeze-thaw cycles, and resilient modulus usually change greatly. Therefore, when

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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 0°C (Andersland and Ladanyi 2004). Thus, a requirement for geotechnical engineering in seasonally frozen soil regions for analysis of stability and solution is the accessibility of engineering properties of subgrade soil exposed to periodic freezing and thawing (Ghazavi and Roustaei 2010; Roustaei et al. 2015; Aubert and Gasc Barbier 2012; Kalkan 2009; Yarbasi et al. 2007; Altun et al. 2009; Olgun 2013; Simonsen and Isacsson 2001).

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. Yarbasi et al. (2007) studied two stabilized granular soils with silica fume–lime, fly ash–lime, and red mud–cement additive mixtures. Their results showed that stabilized specimens with silica fume–lime, fly ash–lime, and red mud–cement additive mixtures have high freezing-thawing durability as compared with unstabilized specimens. Liu et al. (2010) studied triaxial tests on lime and cement reinforced soils with variable blended ratios exposed to freeze-thaw cycles under dynamic loading. Their results showed that the reinforced soils after freeze-thaw cycles exhibited better behavior than before reinforcement. Zaimoglu (2010) showed 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 approximately 50% higher than a reinforced one, and the unconfined compressive strength (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 variable confining pressures on local soil in Itanagar, Arunachal Pradesh, India, without and with jute fiber (0.25, 0.5, 0.75, and 1% ratios). The results showed that with addition of jute fiber, the cohesion, the internal friction angle, and the stiffness modulus of the specimens increased. Ghazavi and Roustaei (2010) studied reinforced caolinite clay with steel and polypropylene fibers exposed to the maximum of 10 closed-system freeze-thaw cycles. The test results showed that a decrease was seen on unconfined compressive strength of clay specimens by 20–25% with an increasing number of the freeze-thaw cycles. Moreover, with the inclusion of fiber fraction in clay specimens the unconfined compressive strength increased and the frost heave decreased. Furthermore, with the addition of the 3% polypropylene fiber, unconfined compressive strength increased. Ghazavi and Roustaei (2013) investigated the effect of freeze-thaw cycles on undrained unconsolidated triaxial compressive strength properties of a fine-grained soil reinforced with geotextile layer. The results showed that unconsolidated undrained (UU) triaxial compressive strength of geotextile-reinforced soil decreased with the increase of freeze-thaw cycles, whereas geotextile-reinforced soil showed better performance and the strength reduction amount decreased from 43 to 14% by reinforcing the soil. 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% 10-mm-long sisal fiber was 20% stronger than unreinforced silty clay. Roustaei et al. (2015) showed the influences of freeze-thaw cycles on UU triaxial compressive strength of the reinforced soil with polypropylene fiber. The results showed that strength of unreinforced soil reduced with increasing freeze-thaw cycles. Also, the reinforced specimens exhibited better strength reduction from 43 to 32%.

Moreover, millions of tons of waste fly ash produced by coal burning in thermal power stations have increasingly become a matter of global concern among researchers. Thus, using fly ash in road and pavement construction with geotechnical stabilization has become important. Understanding geotechnical behavior of soil stabilized with fly ash and determining a proper solution is necessary. Kaniraj and Gayathri (2003) studied compaction, shear characteristics of the pure fly ash, and fiber-reinforced fly ash. The results showed that the shear strength increased and brittle behavior of pure fly ash changed with the addition of fibers. Bin-Shafique et al. (2011) carried out unconfined compression tests, split tensile tests, and vertical swell tests of fly ash and high-plasticity clay soils reinforced with synthetic fiber subjected to freeze-thaw cycles. The unconfined compression strength substantially decreased and the swell potential increased with increasing the freeze-thaw cycles. Also, the compression strength of the losses reduced with the increasing of fiber ratios.

The aim of this 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 fly ash and randomly distributed lignin fiber by performing unconsolidated undrained triaxial tests. For this purpose, investigations of the physical and engineering behaviors of cohesive soils reinforced with fly ash and lignin fiber were performed before and after exposure to freeze-thaw cycles.

Materials

In this paper, clay soil from the Qinghai-Tibet Plateau in China was used to determine the unconsolidated undrained triaxial compression behavior of reinforced soil. Table 1 depicts the particle size distribution and the physical properties of clayey soil.

The specimens were reinforced with fly ash (0, 4, and 8%) and randomly distributed lignin fiber, which were blended at 0, 0.25, 0.5, 0.75, and 1% ratios. In this study, the lignin fiber and fly ash were obtained from Hebei province and Shangdong province in China, respectively, and their engineering properties are presented in Table 2 (Singha 2012) [Fig. 1(a)].

Table 1. Particle Size Distribution and the Engineering Properties of Clayey Soil

Property	Particle size	Value
Grain composition (%)	$d > 0.01$	67.29
	$0.01 \geq d \geq 0.005$	11.16
	$0.005 \geq d > 0.005$	15.95
	$d \leq 0.001$	5.59
Dry density (g/cm^3)	—	1.93
Optimum water content (%)	—	12.90
Plasticity index	—	8.05

Table 2. Engineering Properties of the Studied Lignin Fiber and Fly Ash

Property	Value
Lignin fiber	
Length (mm)	<1
Moisture content (%)	<5
Cellulose content (%)	95
Ash content (%)	<11
Bulk density (g/L)	27
Heat resisting ability (°C)	230
pH	7.0
Purity	99% gray cellulose fiber
Fly ash	
SiO_2 (%)	57.00
Al_2O_3 (%)	28.00
CaO (%)	3.80
Fe_2O_3 (%)	0.70
Volatile (%)	10.50

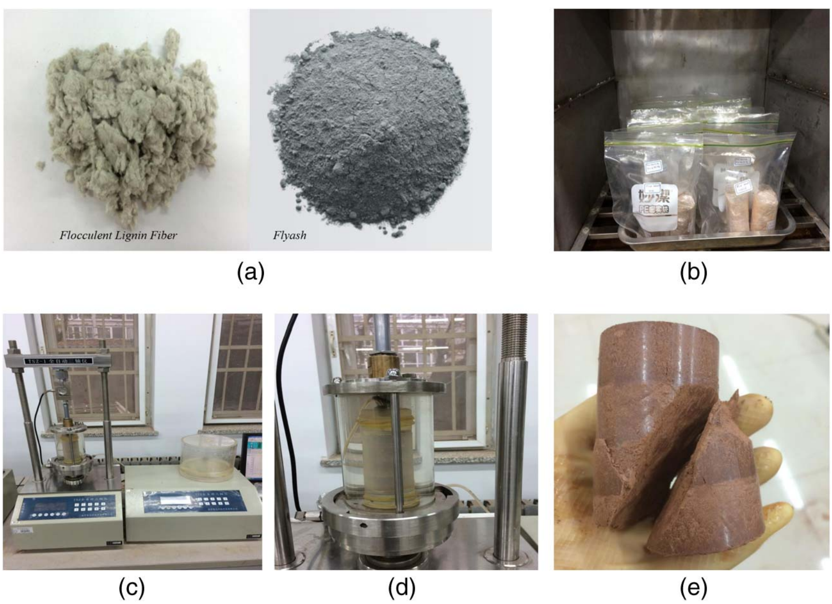

Fig. 1. Preparation of soil specimens for triaxial testing: (a) studied lignin fiber and fly ash in the tests; (b) freeze-thaw cabinet; (c) triaxial compression test system; (d) soil specimen in pressure chamber; (e) specimen after test

Using different fibers in soil reinforcement has significant effects on mechanical properties of soil. The lignin fiber is made of pure fluff fiber through physical action. This was not studied enough in blended soil on the soil engineering properties, though this fiber acts in asphalt and concrete because it can be the main aggregate in the asphalt surface layer to form a layer of asphalt membrane. Thus, this fiber is generally used to enhance the antiaging ability of the asphalt layer, extending its life. Also, the priority of lignin fiber is to strengthen and improve elasticity in subgrade soil. Flocculent lignin fiber is also commonly known as road fibers (Kadla et al. 2002). Due to these useful and advantageous properties of lignin fiber, it was chosen to investigate triaxial compression behavior of blended soil containing this fiber exposed to freeze-thaw cycles.

Testing Procedure

Specimen Preparation

All the soil specimens were formed into columns of 39.1 mm in diameter and 80 mm in height. The different blend ratios of clayey soil in the experiments are presented in Table 3. 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 fly ash were blended in dry conditions, then water was added slowly and the required amount of lignin fiber was added to the mixtures. The mixtures of soil–fly ash–fiber–water were compacted by three layers. Figs. 1(b–e) depict the preparation of soil specimens for triaxial testing.

The results of standard Proctor test are presented in Fig. 2. It is observed that the maximum dry density (MDD) decreased and the optimum moisture content (OMC) increased a small amount with an increment of fly ash content. This is because when fly ash is added to soil, a chemical reaction related to cation exchange occurs. Air voids between soil particles and porous medium are formed by this reaction and the MDD decreases. Furthermore, the soil particles need more water for filling

Table 3. Planning of the Freeze-Thaw Tests for Different Blend Ratios of Soil Specimens before Tests

Dimension of test specimen			*N*		Temperature		
H	*D*	Tested material	0	15	Freezing	Thawing	Tested temperature
39.1	80	S	+	+	−20°C	20°C	Room temperature ~20°C
		S-4%FA	+	+			
		S-4%FA-0.25%LF	+	+			
		S-4%FA-0.75%LF	+	+			
		S-8%FA	+	+			
		S-8%FA-0.5%LF	+	+			
		S-8%FA-1%LF	+	+			

Note: D = diameter (mm); H = height (mm); N = number of the freeze-thaw cycles; S = soil; S-4%FA = reinforced soil with 4% fly ash; S-4%FA-0.25%LF = reinforced soil with 4% fly ash and 0.25% lignin fiber; S-4%FA-0.75%LF = reinforced soil with 4% fly ash and 0.75% lignin fiber; S-8%FA = reinforced soil with 8% fly ash; S-8%FA-0.5%LF = reinforced soil with 8% fly ash and 0.5% lignin fiber; S-8%FA-1%LF = reinforced soil with 8% fly ash and 1% lignin fiber.

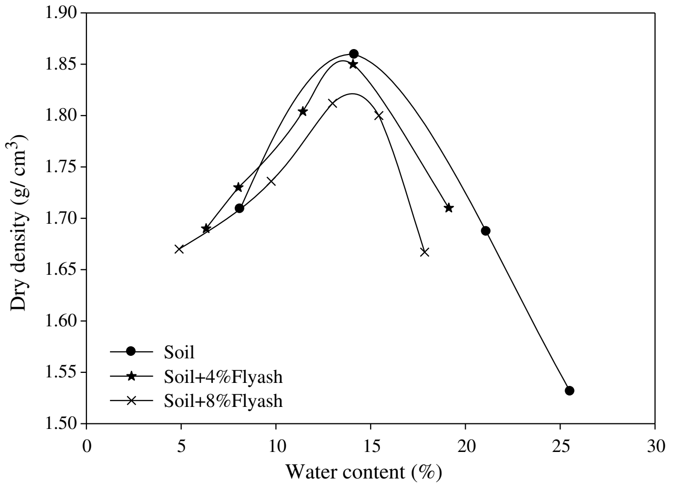

Fig. 2. Variation of water content and dry density with fly ash contents

voids, so the OMC increases. An increment of lignin fiber in soil caused an increase of the OMC and decrease of the MDD (Jafari and Esna-ashari 2012).

Freeze-Thaw Performance

The soil specimens were exposed to 0 and 15 freeze-thaw cycles before testing. The specimens were put in a digital refrigerator with a constant temperature of approximately −20°C for 12 h [Fig. 1(b)]. Then, they were removed from the refrigerator and put in a moisture cabinet maintained at room temperature to provide a thawing period of 12 h. All of these stages were considered as one cycle. The cycles were held to 15 cycles. At the end of the needed freeze-thaw cycles, the static triaxial tests were carried out. Table 3 presents the planning of the freeze-thaw tests for soil specimens before tests.

Static Test Procedure

The soil specimens exposed to freeze-thaw cycles were tested by unconsolidated undrained triaxial compression tests to determine the strength parameters of all soil specimens [Figs. 1(c and d)]. The strain rate was held constant at 0.7 mm/min.

Because the freeze-thaw cycles are usually seen in the interface of soil that is particularly linked with pavement and is exposed to sudden loading resulting from vehicles, the cohesive soil with lesser permeability may not be provided drainage and consolidated. Therefore, applying 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 the subgrade of soil, three confining pressures of 100, 200, and 300 kPa have been chosen for triaxial tests.

Results and Discussion

Effects of Freeze-Thaw Cycles on Stress–Strain Behavior of Unreinforced and Fiber-Reinforced Specimens

In order to show the influence of freeze-thaw on the stress–strain curves of the unreinforced soil and the fly ash–fiber-reinforced soil, the static triaxial tests were performed on the soil specimens before and after freeze-thaw states [Fig. 1(e)]. In this study, the peak strength of the soil specimens was taken as equal to the maximum point before failure on the stress–strain curve.

Figs. 3 and 4 depict the stress–strain behavior of the specimens subjected to freeze-thaw cycles. Before a freeze-thaw cycle, the addition of only fly ash and the mixtures of fly ash–lignin fiber in soil caused an increment on the peak strength at the same confining pressure. The existence of fly ash in clay soil led to it exhibiting the rupture failure mode. In Figs. 3 and 4, it was observed that well-defined peak strength and the failure occurred at a smaller strain ratio than unreinforced soil. However, the failure strain ratio increased with the addition of the lignin fiber, and the fly ash–lignin fiber–reinforced soil exhibited more ductile behavior. Before freeze-thaw cycles, the average increment ratio on the peak strength was obtained as approximately 18% for 4% fly ash–reinforced soil, 21% for 4% fly ash and 0.25% lignin fiber–reinforced soil, 20% for 4% fly ash and 0.75% lignin fiber–reinforced soil, 11% for 8% fly ash–reinforced soil, 16% for 8% fly ash and 0.5% lignin fiber–reinforced soil, and 23% for 8% fly ash and 1% lignin fiber–reinforced soil.

After 15 freeze-thaw cycles, the average increment ratio on the peak strength was observed to be approximately 64% for 4% fly ash–reinforced soil, 53% for 4% fly ash and 0.25% lignin fiber–reinforced soil, 52% for 4% fly ash and 0.75% lignin fiber–reinforced soil, 29% for 8% fly ash–reinforced soil, 58% for 8% fly ash and 0.50% lignin fiber–reinforced soil, and 61% for 8% fly ash and 1% lignin fiber–reinforced soil.

The fly ash–lignin fiber–reinforced soil showed more increase on the peak strength after freeze-thaw cycles. Thus, the freeze-thaw durability of the fly ash–lignin fiber–reinforced soil is approximately three times larger than the peak strengths before freeze-thaw cycles. Also, an increment of lignin fiber ratio increased the peak strength of fly ash–soil mixtures subjected to freeze-thaw cycles. However, it was observed that the peak strength of soil reinforced with fly ash and lignin fiber decreased or remained constant in some cases with an increase of lignin fiber. This is because the lignin fiber has a flocculent structure.

Effect of Freeze-Thaw Cycles on Failure Strength

In this study, soil failure strength was stated using a ratio $[(q_u - N)/(q_u - 0)]$ that is determined as the strength of the unreinforced and the reinforced soil after the required number of freeze-thaw cycles $(q_u - N)$ divided by that of soil that was not exposed to any freeze-thaw cycles $(q_u - 0)$. Many studies have clearly shown that an increment in the freeze-thaw cycles decreases the strength of unreinforced soil and the reinforced soil. Wang et al. (2007) and Ghazavi and Roustaei (2013) explained the soil failure strength using a ratio that is defined as the strength of unreinforced and reinforced soil after a given number of freeze-thaw cycles divided by that of soil that was not subjected to any freeze-thaw cycles.

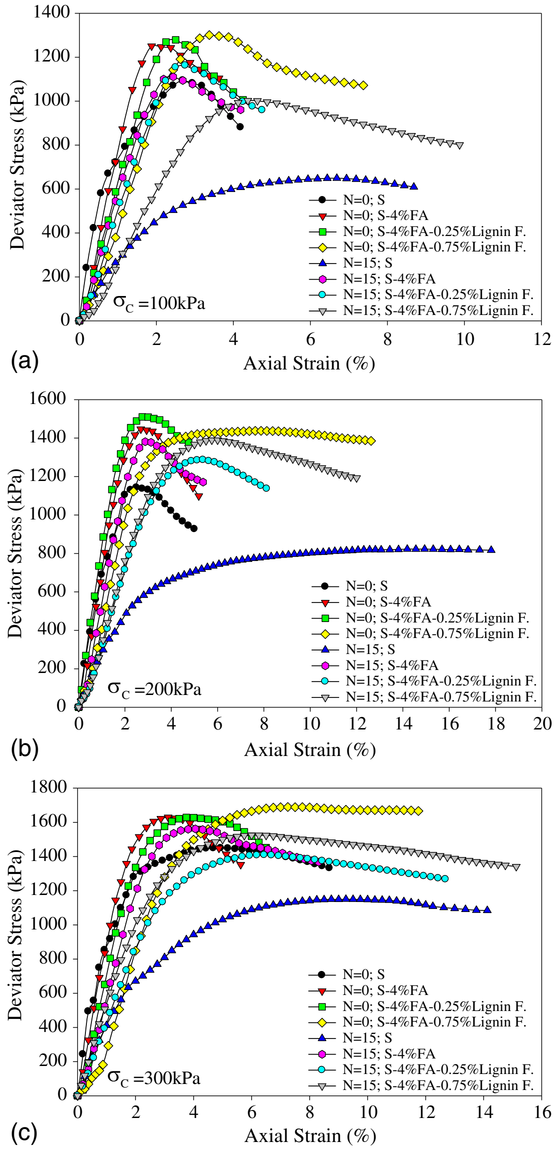

Fig. 3. Stress–strain relationships of unreinforced and 4% fly ash and different blend ratios of lignin fiber–reinforced soil under different confining pressures before the freeze-thaw cycle and after 15 freeze-thaw cycles: (a) $N = 0$ and 15, 4% fly ash, $\chi_w = 0$, 0.25, and 0.75%, $\sigma_c = 100$ kPa; (b) $N = 0$ and 15, 4% fly ash, $\chi_w = 0$, 0.25, and 0.75%, $\sigma_c = 200$ kPa; (c) $N = 0$ and 15, 4% fly ash, $\chi_w = 0$, 0.25, and 0.75%, $\sigma_c = 300$ kPa

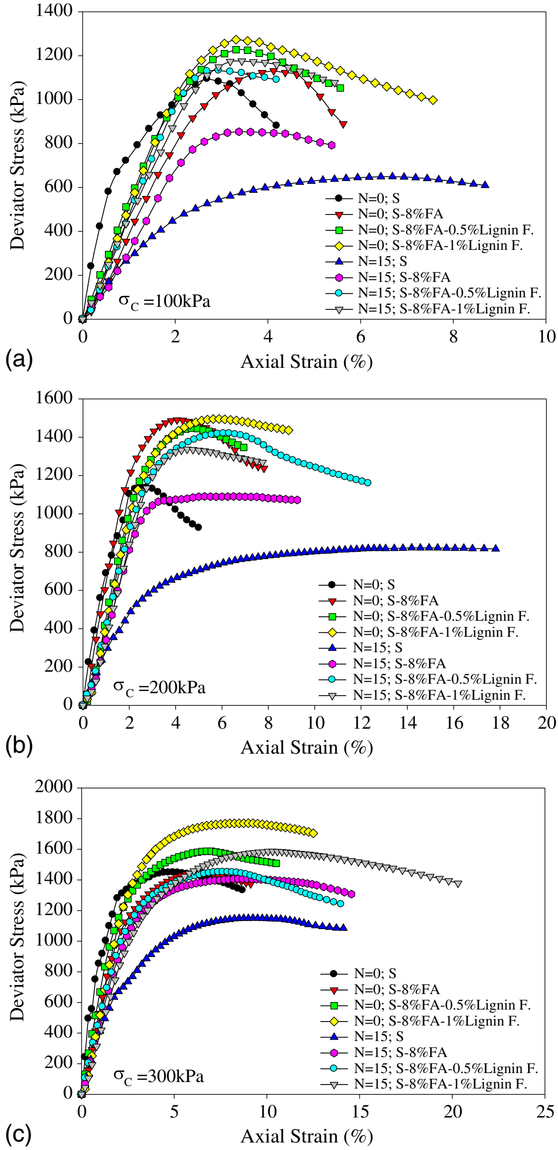

Fig. 4. Stress–strain relationships of unreinforced and 8% fly ash and different blend ratios of lignin fiber–reinforced soil under different confining pressures before freeze-thaw cycle and after 15 freeze-thaw cycles: (a) $N = 0$ and 15, 8% fly ash, $\chi_w = 0$, 0.5, and 1%, $\sigma_c = 100$ kPa; (b) $N = 0$ and 15, 8% fly ash, $\chi_w = 0$, 0.5, and 1%, $\sigma_c = 200$ kPa; (c) $N = 0$ and 15, 8% fly ash, $\chi_w = 0$, 0.5, and 1%, $\sigma_c = 300$ kPa

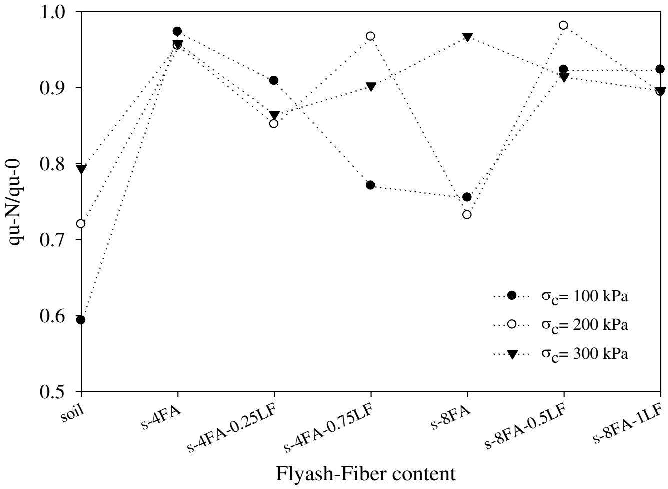

Fig. 5. Failure strength ratio of fly ash and fly ash–lignin fiber–reinforced soil ($N = 0$ and 15, $\chi_w = 4\%$ fly ash, 8% fly ash, and 0, 0.25, 0.75, and 1% lignin fiber, $\sigma_c = 100$, 200, and 300 kPa)

Fig. 5 shows the failure strength ratio of 4% fly ash and 8% fly ash and $\chi_w = 0$, 0.25, 0.75, and 1% lignin fiber–reinforced soil with different confining pressures after 15 freeze-thaw cycles. This reduction amount was observed to have better performance for 4% fly ash and 0.25% lignin fiber–reinforced soil, whereas this reduction was only approximately 2.7–4.6% for 4% fly ash–soil mixtures, 9.15–14.48% for 4% fly ash and 0.25% lignin fiber–reinforced soil, 3.32–22.93% for 4% fly ash and 0.75% lignin fiber–reinforced soil, 20.62–40.67% for 8% fly ash–reinforced soil, 1.90–8.55% for 8% fly ash and 0.5% lignin fiber–reinforced soil, and 7.66–10.59% for 8% fly ash and 1% lignin fiber–reinforced soil.

Effect of Freeze-Thaw Cycles on Shear Strength Properties

Fig. 6 shows the variation of shear strength parameters of reinforced and unreinforced soil specimens under different numbers of freeze-thaw cycles. These parameters were determined from the variations of p-q as follows:

$$p = [(\sigma_1 + \sigma_3)_f / 2] \tag{1}$$

$$q = [(\sigma_1 - \sigma_3)_f / 2] \tag{2}$$

where σ_1 and σ_3 = 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)

$$q = b + p \tan \alpha \tag{3}$$

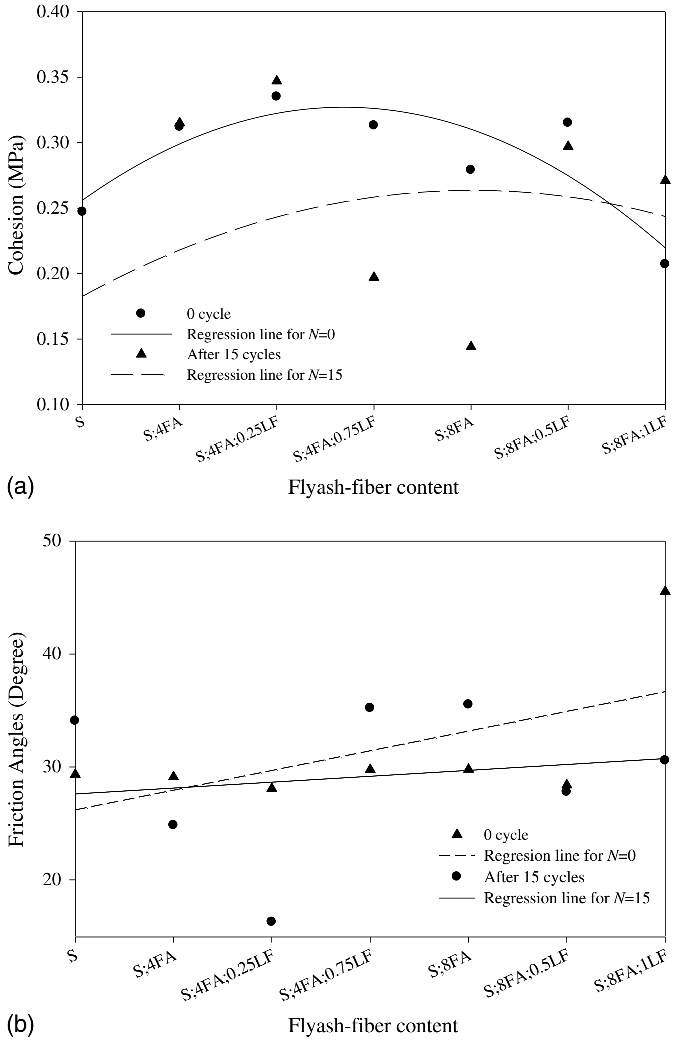

Fig. 6. Shear parameters of soil specimens reinforced with fly ash and lignin fiber: (a) the cohesion of fly ash and lignin fiber–reinforced soil ($N = 0$ and 15, $\chi_w = 4$ and 8% fly ash and 0, 0.25, 0.5, 0.75, and 1% lignin fiber); (b) the friction angles of fly ash and lignin fiber–reinforced soil ($N = 0$ and 15, $\chi_w = 4$ and 8% fly ash and 0, 0.25, 0.5, 0.75, and 1% lignin fiber)

where b = intersect of the line with q-axis; and α = slope. Considering the data of b and α shown in Table 4, cohesion (c) and the internal friction angle (φ) of the soil can be computed as follows (Wang et al. 2007):

$$\varphi = \sin^{-1} \tan \alpha \tag{4}$$

Table 4. Summary of Calculation Parameters of Cohesion and Friction Angle

Tested material	$N = 0$ freeze-thaw cycles		$N = 15$ freeze-thaw cycles	
	b (MPa)	α (degrees)	b (MPa)	α (degrees)
4% fly ash	0.273	25.95	0.279	24.83
4% fly ash, 0.25% lignin fiber	0.296	25.22	0.321	20.85
4% fly ash, 0.75% lignin fiber	0.272	26.38	0.161	30.01
8% fly ash	0.242	26.43	0.117	30.16
8% fly ash, 0.5% lignin fiber	0.277	25.45	0.263	24.98
8% fly ash, 1% lignin fiber	0.145	35.49	0.234	26.93

$$c = \frac{b}{\cos\varphi} \tag{5}$$

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 in the number of freeze-thaw cycles due to the increasing volume of the specimens, which was related to the voids of clay particles (Wang et al. 2007). In Figs. 6(a and b), the cohesion of the unreinforced and the reinforced soil decreased with an increment of the freeze-thaw cycles; however, the reduction trend of cohesion was reduced from 60.73 to 37.208% for reinforced soil with 4% fly ash and 0.75% lignin fiber, to 48.18% for reinforced soil with 8% fly ash, and to 5.64% for reinforced soil with 8% fly ash and 0.5% lignin fiber. Also, the cohesion values decreased with inclusion of fly ash for noncured specimens. This situation can be explained by cementation by pozzolanic activity not being done in the noncured time. The increase in grain size may reduce the cohesion of the reinforced and unreinforced soil specimens. Moreover, under freeze-thaw conditions, excessive fly ash and its contents of different ratios of lignin fiber in clayey soil have no advantages to reduce cohesion. Also, the internal friction angle exhibited a decreasing trend as the number of freeze-thaw cycles increased.

Effect of Freeze-Thaw Cycles on Resilient Modulus

The resilient modulus is defined as a ratio of the deviator stress increment at 1% axial strain to the axial strain increment, which can be expressed by

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{1.0\%} - \sigma_0}{\varepsilon_{1.0\%} - \varepsilon_0} \tag{6}$$

where $\Delta\sigma$ = increment of deviator stress; $\Delta\varepsilon$ = increment of axial strain; $\sigma_{1.0\%}$ = deviator stress corresponding to the axial strain of 1.0% ($\varepsilon_{1.0\%}$); and σ_0 and ε_0 = initial stress and strain, respectively (Wang et al. 2007).

Previous studies related to the effects of freeze-thaw cycles on the resilient modulus showed that cohesive soils with a resilient modulus lower than 55 kPa would exhibit negligible freeze-thaw effects, but those at higher than 103 kPa would exhibit a decrease of more than 50% in this parameter due to freeze-thaw

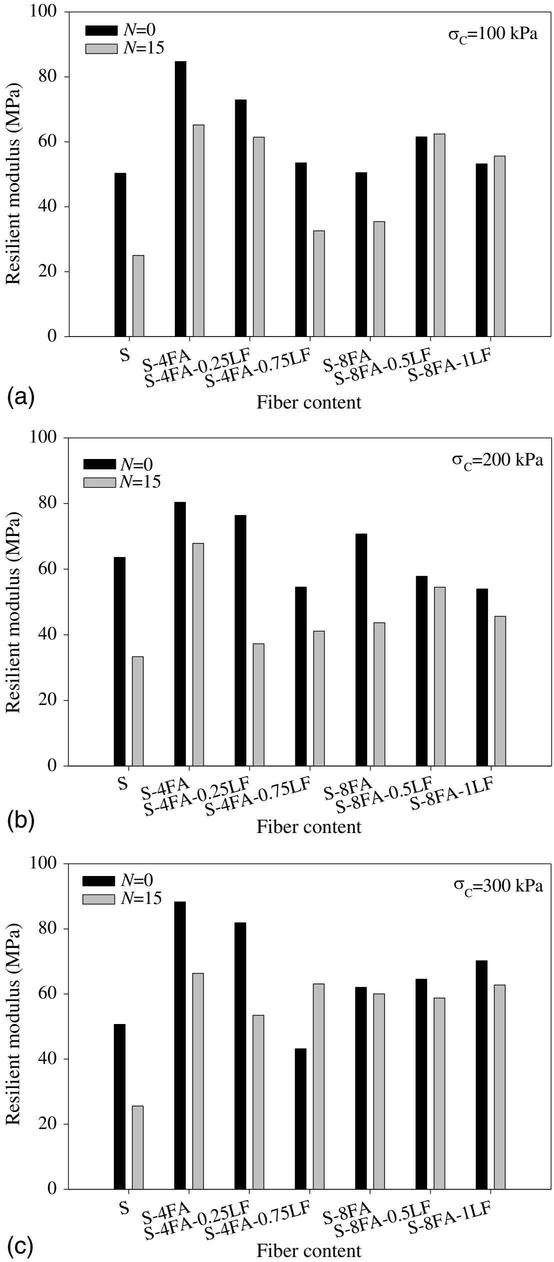

Fig. 7. Variations of resilient modulus of reinforced and unreinforced soils under different confining pressures: (a) $N = 0$ and 15, $\chi_w = 0$, 0.25, 0.5, 0.75, and 1%, $\sigma_c = 100$ kPa; (b) $N = 0$ and 15, $\chi_w = 0$, 0.25, 0.5, 0.75, and 1%, $\sigma_c = 200$ kPa; (c) $N = 0$ and 15, $\chi_w = 0$, 0.25, 0.5, 0.75, and 1%, $\sigma_c = 300$ kPa

cycles (Lee et al. 1995). Ghazavi and Roustaei (2013) found that the magnitude of the resilient modulus decreased by approximately 40% in unfrozen unreinforced soil samples and by 60% in geotextile-reinforced specimens.

Fig. 7 presents the variation of resilient modulus for fly ash–reinforced soil and fly ash–lignin fiber–reinforced soil. The most significant increment was observed on 4% fly ash–reinforced soil before freeze-thaw cycles. The addition of lignin fiber has no important increase in resilient modulus as compared with reinforcement with fly ash. Nevertheless, a small blending ratio of lignin fiber provided less increase in resilient modulus compared with large blending ratios.

Moreover, it is seen that after freeze-thaw cycles, the resilient modulus of unreinforced soil and only fly ash or fly ash–lignin fiber–reinforced decreased as the confining pressure increased. As seen in Fig. 7, after 15 freeze-thaw cycles, the resilient modulus of the unreinforced soil decreased by approximately 20.7%; this decrease was 24.83% in soil reinforced with 4% fly ash, 34.73% in soil reinforced with 4% fly ash and 0.25% lignin fiber, 3.29% in soil reinforced with 8% fly ash, 8.93% in soil reinforced with 8% fly ash and 0.5% lignin fiber, and 10.62% in soil reinforced with 8% fly ash and 1% lignin fiber. Moreover, the reduction of resilient modulus from the maximum freeze-thaw cycle was approximately 49% for unreinforced soil, 21% in 4% fly ash–reinforced soil, 34% in 4% fly ash and 0.25% lignin fiber–reinforced soil, 6.0% in 4% fly ash and 0.75% lignin fiber–reinforced soil, 24% in 8% fly ash–reinforced soil, 5.0% in 8% fly ash and 0.5% lignin fiber–reinforced soil, and 7.0% in 8% fly ash and 1% lignin fiber–reinforced soil.

Conclusion

An experimental study was performed to demonstrate the effects of freeze-thaw cycles on the unconsolidated undrained triaxial compressive strength of clayey soil reinforced with fly ash and lignin fiber. The following results are drawn from this study and Table 5 presents a summary:

- The remarkable effects with increasing confining pressure were found on the peak strength for fly ash–fiber–reinforced soil. The peak strength of 8% fly ash and 1% lignin fiber–reinforced soil showed the maximum increase with increasing confining pressure before the freeze-thaw cycle. After 15 freeze thaw cycles, the maximum increment was obtained on the 8% fly ash–reinforced soil.
- The failure strength ratio of unreinforced soil and fly ash–fiber–reinforced soil decreased with increasing the number of freeze-thaw cycles. On the other hand, it is obvious that with increasing of the confining pressure, the failure strength ratio increased. Moreover, the freeze-thaw cycles have more harmful effects on interface of the ground, which is linked with structure foundations and pavement.
- The reduction resulting from the maximum freeze-thaw cycle in compression strength of the clay soil was observed to be 41%. This reduction trend was decreased with an increase of the lignin fiber ratios. It is obvious that the existence of fiber in clay soil has a great significance on the strength reduction resulting from freeze-thaw cycles. The reduction amount of fly ash–fiber–reinforced soil was observed to be 25% for 8% fly ash–reinforced soil and to be 23% for 4% fly ash and 0.75% lignin fiber–reinforced soil after the 15th freeze-thaw cycle.

Table 5. Summary of the Results of Many Trends of Soil Strength and Behaviors

Calculated value	Confining pressure, σ_c (MPa)	Number of freeze-thaw cycles, N	Tested material					
			4% fly ash	4% fly ash, 0.25% lignin fiber	4% fly ash, 0.75% lignin fiber	8% fly ash	8% fly ash, 0.5% lignin fiber	8% fly ash, 1% lignin fiber
Failure strength	0.1	15	0.970	0.900	0.770	0.750	0.920	0.920
$(q-15/q-0)$	0.2		0.950	0.850	0.960	0.730	0.980	0.890
	0.3		0.950	0.860	0.900	0.960	0.910	0.890
Strength reduction	0.1	15	2.69	9.14	22.93	24.50	7.68	7.65
amount, σ_{Red} (%)	0.2		4.53	14.84	3.32	26.81	1.90	10.59
	0.3		4.20	13.53	9.76	3.22	8.55	10.37
Cohesion, c (MPa)	—	0	0.312	0.335	0.314	0.279	0.315	0.207
		15	0.316	0.348	0.197	0.145	0.298	0.272
Friction angle, φ	—	0	29.12	28.07	29.76	29.78	28.39	45.53
(degrees)		15	24.83	16.26	35.21	35.52	27.77	30.56
Resilient modulus, R	0.1	0	84.70	72.90	53.50	50.50	61.50	53.20
(MPa)		15	65.20	61.40	32.60	35.40	62.40	55.60
	0.2	0	80.38	76.36	54.53	70.72	57.82	53.94
		15	67.85	37.26	41.11	43.68	54.49	45.62
	0.3	0	88.26	81.87	43.15	62.06	64.52	70.20
		15	66.33	53.44	63.08	60.02	58.76	62.75

- The cohesion of unreinforced soil and fly ash–fiber–reinforced soil decreased after experiencing the 15th freeze-thaw cycle. On the other hand, an increase were observed on the cohesion values for some of reinforced specimens. This increment was explained by Wang et al. (2007) and Ghazavi and Roustaei (2013) as the voids between soil particles possibly rising to form ice lenses and the volume of soil increasing. The largest amount of cohesion was obtained on 4% fly ash and 0.25% lignin fiber–reinforced soil before and after the freeze-thaw cycle.
- The largest increment of the internal friction angle was observed on the 8% fly ash and 1% lignin fiber–reinforced soil. This is because the addition of lignin fiber caused slippage in the failure mode, and increased the friction angle with the smaller cohesion. Also, it was observed that the friction angle remained constant with the addition of other ratios of fly ash and lignin fiber before and after freeze-thaw cycles.
- The higher values of resilient modulus were observed on reinforced soil with blending ratios of 0.5 and 0.75% lignin fiber after the 15th freeze-thaw cycle. It is observed that the fly ash content had a significant role on resilient modulus. As the fly ash content increased from 4 to 8% in reinforced soil, the resilient modulus decreased before and after freeze-thaw cycles.

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Notation

The following symbols are used in this paper:

c = cohesion of soil specimen in UU test (kPa);
E = resilient modulus;
N = number of the freeze-thaw cycles;
p = mean stress (kPa);
$q_u - 0$ = strength of soil specimen not subjected to freeze-thaw cycles (kPa);
$q_u - N$ = strength of soil specimen at a given freeze-thaw cycle (kPa);
$(q_u - N)/(q_u - 0)$ = failure strength
$\Delta\varepsilon$ = increment of axial strain;
$\Delta\sigma$ = increment of deviator stress;
ε_0 = initial strain (%);
σ_c = confining pressure;
σ_0 = initial stress (kPa);
σ_1, σ_3 = failure axial stress and lateral stress (kPa);
$\sigma_{1.0\%}$ = deviator stress corresponding to the axial strain of 1.0% ($\varepsilon_{1.0\%}$);
$(\sigma_1 - \sigma_3)_f$ = total deviator stress (kPa);

φ = internal friction angle (degrees); and
χ_w = fiber volume fraction (%).

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