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The effect of freeze-thaw cycles on mechanical properties of fine-grained soil modified by cement and nanocement

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Abstract. Freeze-Thaw (F-T) cycles cause substantial detriment to geotechnical structures, especially roads, every year. Recently, researchers have increasingly used nanomaterials to improve soil resilience. The effect of soil stabilization using nanocement and cement on resistance changes during F-T cycles was investigated in this study. For this purpose, clayey soil was blended with 1, 2, 3, and 4% stabilizers based on dry unit weight. The prepared mixtures were subjected to Atterberg limits and standard compaction tests. Increases in stabilizers improved the optimal moisture content, liquid limit, and plastic limit while decreasing the maximum dry density and plastic limit. Then, the cylindrical specimens of the pure and stabilized soils were prepared and cured within 42 days. Finally, Unconfined Compressive Strength (UCS) tests were performed on the specimens after applying zero, three, six, and nine F-T cycles. The stabilized soil's UCS increased to around 12 times that of the pure soil. By applying nine F-T cycles to pure soil specimens, the UCS value was reduced on average to 49%, which was further reduced to 36% and 31% after adding cement and nanocement, respectively.

1. Introduction

Nanoparticles actively react with other soil constituents, including liquids, cations, organic matters, and clay minerals. The reasons are specific surface area, particle morphology, nanopores, and surface loads that are highly critical in the soil at the nanoscale. Due to the large particle area at the nanoscale, nanoparticles can significantly affect the physical and chemical behaviors and engineering characteristics of soil, even at little levels.

Ouhadi and Bakhshalipour [1] mentioned the reduction in the collapse potential of sandy soil after adding nanoclay. Ghazavi and Abolhasani [2] reported the growth in the Unconfined Compressive Strength (UCS) of clayey soil due to stabilization by 3, 5, and 7% nano-SiO_2. Improvement in USC and reduction in permeability and liquefaction potential in clayey soil were provided through stabilization with nanoclay and nano-silica [3–5]. Mohammadi and Niazian [6] reported that the shear strength, compressive strength, and the California Bearing Ratio (CBR) of soil increased with growing the nanoclay percentage up to 1.5% and decreased at higher percentages. Tabarsa et al. [7] examined the impact of enhancing nanoclay content on loose soil using laboratory and field investigations. The use of nanoclay increases uniaxial resistance and lowers

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wetting-induced collapse, according to the results of research facility tests. Tomar et al. [8] investigated how adding fiber and nano-silica to clayey soil affected its resistance behavior. They used four various combinations of nano-silica at various percentages (1, 3, 5, and 7%) with polypropylene fiber (PPF) at different percentages (0.1, 0.4, 0.7, 1, and 1.3%). They reported that with increasing PPF content, along with nano-silica, UCS also increased. They also observed that the maximum UCS value was obtained at 7% of nano-silica with 0.7% of PPF.

When the air temperature is below 0°C, the soil starts to freeze and the water in the soil pores strands forms ice crystals. The formation of ice in soil pores and the increase in the volume of ice masses change the soil structure and its mechanical and physical properties. Several researchers have reported the detrimental effects of Freeze-Thaw (F-T) cycles on the mechanical parameters of soil, such as permeability and compressive resistance [9–13].

Decreasing the detrimental effects of F-T cycles by adding reinforcing or stabilizing materials has become an exciting subject for researchers. The results of numerous studies have demonstrated the benefits of using metal fibers, polypropylene, geotextile, and crumb rubber in soils to decrease the adverse effects of F-T cycles [14–21].

Adding silica foam to clayey soil, Kalkan [22] described the improved UCS of soils during F-T cycles. Also, soils stabilized with silica foam particles showed a more brittle behavior than natural soils. Luo et al. [23] found that adding lime and cement to clayey soil subjected to F-T cycles raised the critical dynamic stress. Kalhor et al. [24] investigated the effect of nano-SiO_2 on the resistance behavior of clayey soil during F-T cycles. Based on their results, natural soil strength decreased by 64% after applying nine F-T processes, while clayey soil strength decreased by 52, 42, and 49% under the same number of F-T processes when treating the soil specimens with 1, 2, and 3% nano-SiO_2, respectively.

Soil stabilization and reinforcement are considered appropriate strategies to improve the soil strength behavior under F-T cycles. In recent decades, the use of cement with high mechanical properties for soil improvement has become popular. Nanomaterials, on the other hand, have been observed to change the mechanical behavior of soil. Thus, it is necessary to evaluate the effect of nanoscale stabilizers, such as cement, on improving the mechanical behavior of soil during F-T cycles. The current study evaluated the effect of cement and nanocement as stabilizers in reducing the adverse effects of the F-T process on fine-grained soils.

This study investigated the effect of F-T cycles on the mechanical behavior of a clayey soil, as well as the amount of cement and nanocement. Cement has been used as a soil stabilizer in previous research. Nanocement, on the other hand, was employed for fine-grained soil stabilization, and its impact was studied across the F-T cycles.

2. Materials

In this study, research facility tests were carried out on clayey soil from Qazvin Province (Iran), which was classified as CL (ASTM D2478-11 [25]) in the unified classification system. The soil specifications are shown in Table 1 (ASTM D-854-14 [26], ASTM D-4318-10 [27]) and the soil grain size distribution (ASTM D-422-63 [28]) is presented in Figure 1. Standard Proctor compaction tests (ASTM D-698-12 [29]) were conducted on the soil, and a maximum dry mass density of about 1.9 g/cm^3 was obtained at the Optimum Moisture Content (OMC) of about 15.6%. X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) testing and analysis of the soil, cement, and nanocement revealed that the clay fractions predominantly consisted of clinochlore and illite. The result is shown in Figure 2 and Tables 2–4.

Portland Type II cement obtained from the Abeyek Cement Factory of Qazvin Province was used as a stabilizer. Table 5 shows the cement properties. A mechanical milling machine was utilized to make cement nanoparticles by an automated process. The ball mill machine included two cylindrical chambers

Table 1. Specification of clay [30].

Property	Quantity
Specific gravity (G_s)	2.67
Liquid limit (%)	26
Plastic limit	13.5
Plasticity index (%)	12.5

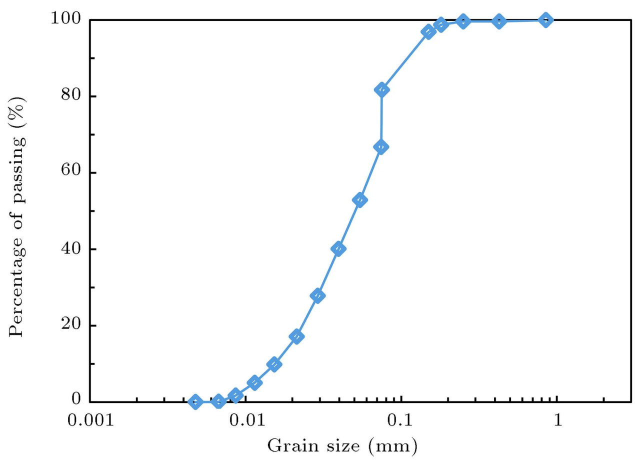


Figure 1. Particle size distribution curve of clay.

Table 2. XRF test result for clay [30].

Compound	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3	SrO	ZrO_2	ZnO
Weight (%)	1.56	9.47	55.34	0.4	0.47	2.28	19.84	1	0.13	7.9	0.13	500 ppm	0.16

Table 3. XRF test result for cement.

Chimical composition	Mgo	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3	L.O.I
Weight (%)	2.57	4.1	19.9	0.08	0.07	0.7	63.1	0.56	0.08	4.5	1.96

Table 4. XRF test result for nanocement.

Chimical composition	Mgo	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3	L.O.I
Weight (%)	2.9	4.26	20.5	0.09	1.7	0.67	61.1	0.55	0.08	4.6	3.6

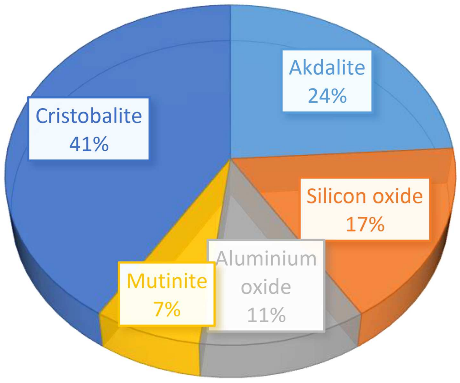


Figure 2. XRD test result for clay.

with a volume of 250 cc. Nano cement process was produced in the chamber, and this process continued until the particle size reached the nanometer scale [30]. Figure 3 shows the ball mill used in the study, Figure 4 depicts the TEM image of the nanocement, and Table 6 shows the specifications of the nanocement.

3. Experimental methods

This study aimed to evaluate the effects of nanocement and cement on the UCS (ASTM D-2166-16 [31]) behavior of clayey soil in zero to nine F-T cycles. The two

Table 5. Physical and chemical analysis of Abeyek Type II cement [30].

Description		**Quantity**
Fineness (Blaine test, cm^2/gr)		3081
Retained on sieve # 170 (90 μm)		5.7
Initial setting time (Vicat test, minutes)		153
Final setting time (Vicat test, minutes)		212
Compressive strength (kgf/cm^2)	2 days	160
	3 days	208
	7days	333
	28 days	492
SiO_2		20.79
AL_2O_3		4.76
Fe_2O_3		3.86
CaO		62.28
MgO		3.22
SO_3		1.89
Na_2O		0.37
K_2O		0.68

following main phases were taken for each specimen to assess the soil resistance changes during F-T cycles.

3.1. Specimen preparation

Samples with diameter and height of 70 mm and 140 mm were provided with the optimum water content and

Figure 3. Planetary ball mill.

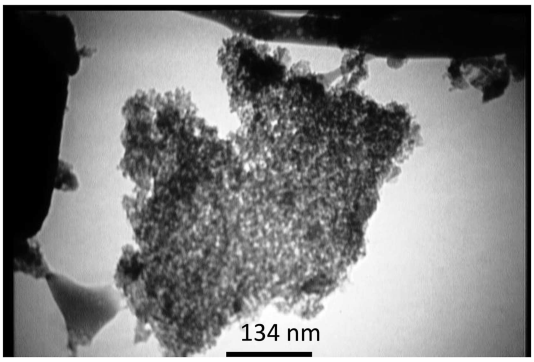


Figure 4. The nanocement TEM image.

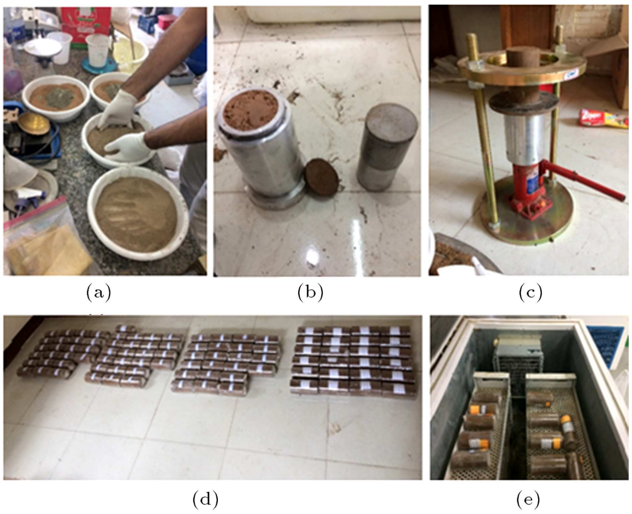


Figure 5. Sample preparation phases: (a) The clayey soil is blended with cement and nanocement, (b) the mixture in metal mold is compacted, (c) specimen is taken out from the mold, (d) specimens are coated with plastic layers for curing, and (e) samples are placed in freeze-thaw cycles device.

Table 6. Physical analysis of nano-cement [30].

Description	Quantity
Purity	99%
APS (average particle size)	80–200 nm
SSA (specific surface area)	200 m^2/g
Color	Gray
Bulk density	< 1 gr/cm^3
True density	2.4 gr/cm^3

maximum dry unit weight was obtained for each mixture based on the standard Proctor test results. After removing each specimen from the mold, it was instantly coated with plastic layers to prevent a reduction in its moisture during definite curing times (7, 14, 28, and 42 days). The stages of preparing soil-nanocement and soil-cement mixture, cylindrical samples, and various prepared pieces are presented in Figure 5.

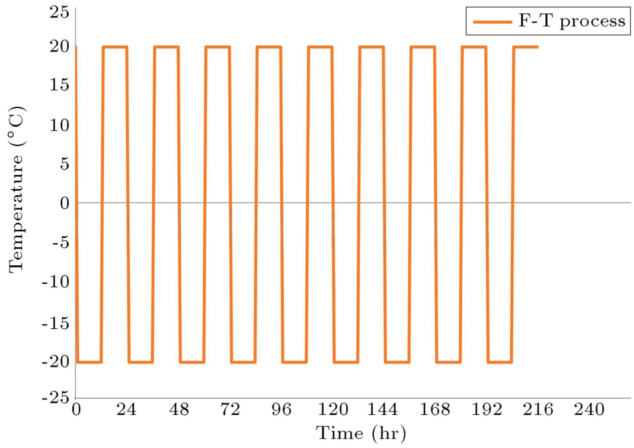


Figure 6. Freeze-thaw cycles process.

3.2. F-T cycles

To apply F-T cycles, the prepared specimens were put in a digital refrigerator. The cylindrical pieces were placed at $-20°$C for 12 hours and $+20°$C for 12 hours [12,20,24], and each F-T cycle lasted 24 hours. Figure 5 depicts the respective phases for preparing soil-stabilizer mixtures, cylindrical representatives, and a group of specimens placed in the F-T cycle device. Figure 6 shows temperature changes over time for an F-T cycle. All the samples were exposed to zero, three, six, and nine cycles. These numbers of cycles were chosen because most changes occur at initial cycles, and a new dynamic equilibrium is reached in the soil mass after five to ten cycles [20,32].

4. Results

4.1. Compaction parameters

On the basis of ASTM D 698 [29], standard compaction tests were performed on all specimens mixed with various amounts of cement and nanocement. In every test, the preferred percentage of stabilizers was treated with pure soil, and the moisture was then added to the mixtures. A rise in OMC and a fall in the maximum dry density were observed due to adding cement and nanocement. The upward trend was continued by an increase in the amount of stabilizers. Figure 7 shows variations in the maximum dry density and OMC after adding cement and nanocement.

The soil became more refined as cement and nanocement were added, and the specific surface area of the soil increased. The mixture particles had a higher tendency to absorb water, which increased OMC and decreased the maximum dry density. However, because nanocement grains are smaller than cement grains, more variations in OMC and maximum dry density were found.

4.2. Atterberg limits

The Plasticity Index (PI) was measured using Liquid

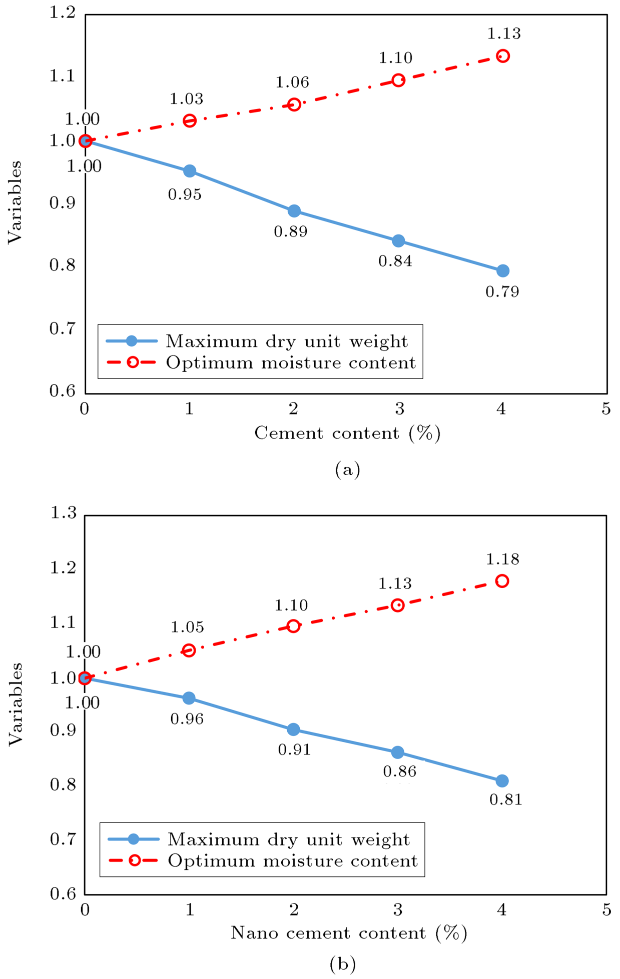


Figure 7. Maximum dry unit weight and optimal moisture content versus: (a) Cement content and (b) nanocement content (Note: the amounts were normalized to that of the pure soil).

Limit (LL) and Plastic Limit (PL) tests on pure soil and soil treated with cement and nanocement, according to the ASTM D 4318-10 [27] standard. Table 7 shows the effects of cement and nanocement on the plastic behavior of clayey soils.

After adding cement and nanocement to pure soil, the PL and LL were incremented. The rising trend continued with increasing the values of stabilizers. Since nanocement has a smaller scale than cement, there can be more changes in LL after adding it. Adding excellent stabilizers increases the soil specific surface area; therefore, the soil particles' tendency to absorb more water increases, resulting in an increase in PL and LL. Furthermore, the increasing trend of PL is greater than that of LL, resulting in a drop in the overall Plastic Limit (PL) [30]. Previous studies have also found alterations in Atterberg limits with the addition of nanoparticles, as mentioned above [24,33,34].

4.3. Dimension changes

After each F-T cycle, a caliper with an accuracy of 0.01 mm was used to measure the height and diameter of each sample to determine the dimension change of pure and treated soil subjected to F-T cycles. The diameter was measured at the top, middle, and bottom of the samples, and the height was measured at three different angles. Table 8 shows the mean diameter and height of the pure and stabilized specimens after varying the number of F-T cycles.

To assess the dimension change in the treated soil at different F-T cycles, the dimension change ratio, R, was defined as follows:

$$R = (D_N - D_0)/D_0 \times 100\%, \tag{1}$$

where, D_N is the sample dimension of the Nth F-T cycle, and D_0 is the initial dimension without F-T cycles. The diameter, length, or volume of the soil sample are commonly used to indicate this dimension. Figure 8 shows the effects of F-T cycles on the height change ratio for the pure and stabilized specimens. As shown in Figure 8, all the treated soil specimens subjected to F-T cycles experienced an expansion in the height direction. The height of the pure and cement-treated soil increased with increasing the number of F-T cycles but showed little change after the sixth F-T cycle. It should be noted that due to soil stabilization with cement and nanocement, height changes were less in the stabilized soil specimens than in the pure soil. The number of height changes was about 1% in the pure sample, while it was 0.58% and 0.52% on average in samples containing cement and nanocement, respectively. As cement content increased, more pore water was used in the hydration reaction, leading to less pore water content in soil samples compacted with OMC. Less pore water means less expansion

Table 7. The effect of nanocement and cement on Atterberg limits.

Mixture	LL (%)	PL (%)	PI (%)	Mixture	LL (%)	PL (%)	PI (%)
0% cement	26	13.5	12.5	0% Nano	26	13.5	12.3
1% cement	27.8	16.2	11.6	1% Nano	28.5	17.3	11.2
2% cement	29.4	18.3	11.1	2% Nano	30.7	19.7	11
3% cement	31.2	20.9	10.3	3% Nano	32.1	21.4	10.7
4% cement	32.3	22.4	9.9	4% Nano	33.4	23.2	10.2

Table 8. The height and mean diameter of the pure and stabilized soil samples at various F-T cycles.

Specimen type	Diameter (mm)				Height (mm)			
	Number of F-T cycles				Number of F-T cycles			
	0	3	6	9	0	3	6	9
Pure soil	70.4	70.29	70.37	70.36	141.25	141.94	142.69	142.56
1% cement	70.06	69.98	69.88	69.92	141.05	141.58	142.12	141.98
2% cement	69.96	69.83	69.82	69.88	141.34	141.81	142.09	142.04
3% cement	70.03	69.91	69.85	69.95	141.22	141.56	141.99	141.85
4% cement	69.93	69.87	69.80	69.84	140.60	140.92	141.28	141.30
1% nanocement	70.03	70.25	70.27	70.26	141.23	141.69	142.21	142.15
2% nanocement	70.05	70.22	70.23	70.22	140.90	141.36	141.68	141.70
3% nanocement	70.01	70.16	70.20	70.17	141.68	142.07	142.37	142.32
4% nanocement	70.03	70.13	70.19	70.18	141.84	142.04	142.40	142.38

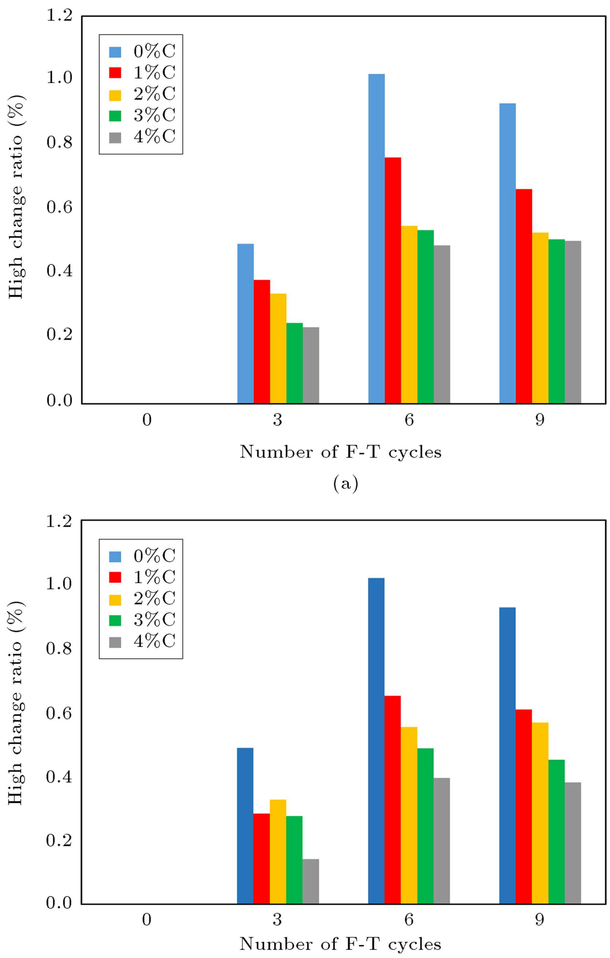


Figure 8. The effects of F-T cycles on height change ratio for stabilized soils: (a) Cement, (b) nanocement varying number of F-T cycles.

during freezing and thus fewer height changes with incrementing cement content [35]. The height of the samples increased sharply at the third and sixth F-T cycles but remained almost constant at the 9th F-T cycle. This trend has been also observed in stabilized clay [24,35] and pure clay [32].

The effects of F-T processes on the volumetric change ratio for pure and stabilized samples are shown in Figure 9. As shown in Figure 9, all the specimens showed expansive behaviors at F-T cycles. The pure sample had the maximum volume change of 1.97%, while the sample containing 4% nanocement and 0.85% had the lowest volume change. The average volume changes in cement and nanocement samples were 1.16% and 1.1%, respectively.

4.4. Unconfined Compressive Strength (UCS)

4.4.1. Before applying F-T cycles

Figure 10 shows changes in peak resistance levels in pure soil specimens. After curing for 7, 14, 28, and 42 days, the specimens were treated with various percentages of cement and nanocement. UCS increased significantly after cement and nanocement were added. For example, after seven days of curing, adding 1, 2, 3, or 4% cement increased the peak resistance in the stabilized specimens to 5.3, 7.6, 9, and 12.4 times that of the pure specimens, respectively. In addition, after seven days of curing, adding 1, 2, 3, or 4% nanocement increased USC in the stabilized specimens to 6.7, 8.2, 10, and 13.4 times that of the pure specimens, respectively. Furthermore, in 28 days, the strength of the stabilized specimens increased with an upward slope before decreasing. In other words, after 28 days, the stabilized specimens had gained roughly 80–90% of their original strength. The increased soil resistance caused by the addition of cement and nanocement could be due to the formation of chemical bonds between the materials and the soil grain, resulting in a cohesive environment. To put it another way, adding water and cement or nanocement to the soil environment creates chemical bonds over time by mixing hydrogen, lime, and silica, increasing soil resistance [30]. The formation of C-H-S bonds

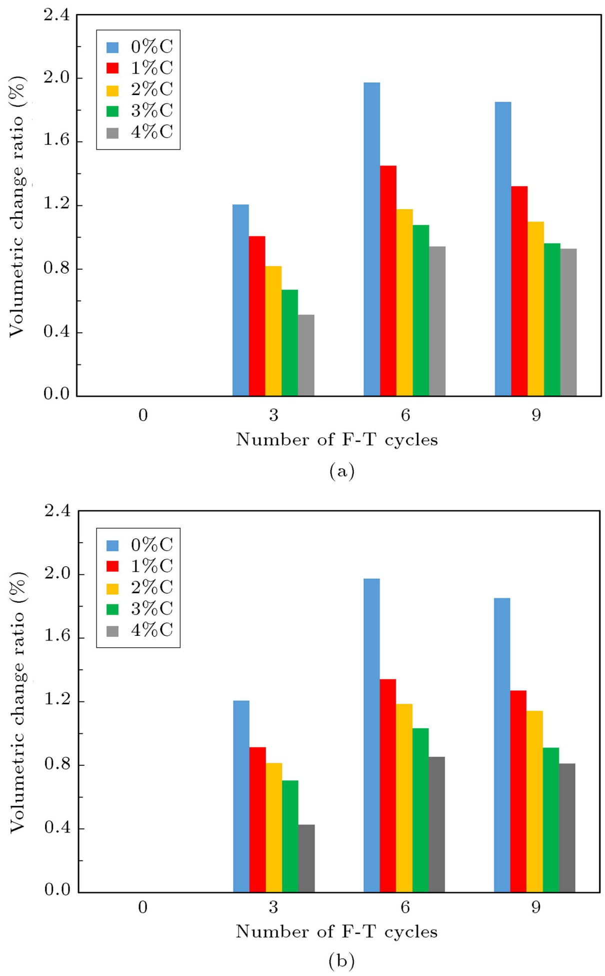


Figure 9. The effects of F-T cycles on volumetric change ratio for stabilized soils: (a) Cement and (b) nanocement varying number of F-T cycles.

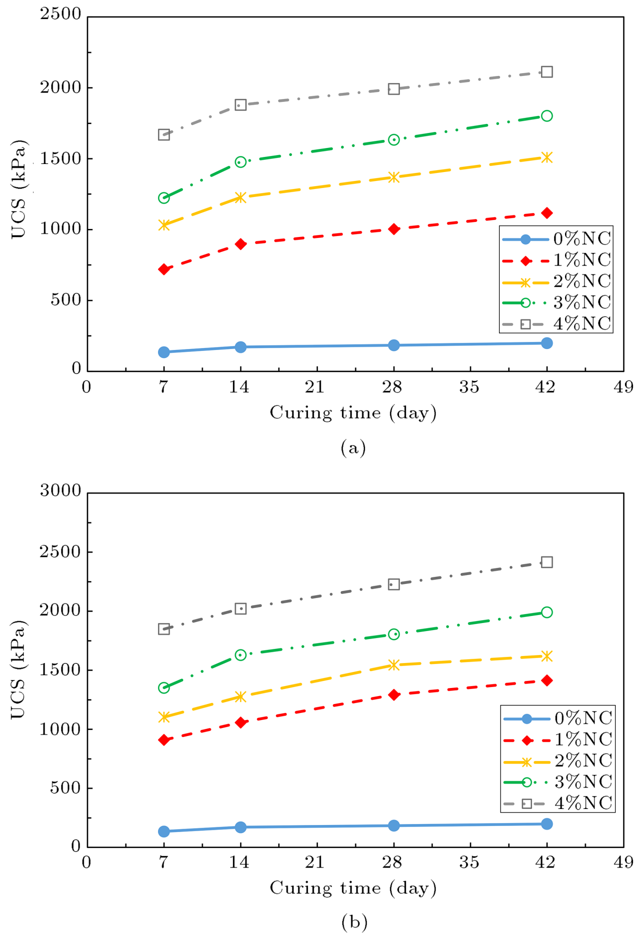


Figure 10. The peak resistance changes of (a) pure soil and soil stabilized with various percentages of (b) cement and nanocement in different curing times.

is a mechanism that has been confirmed in many previous studies [24,30,36]. On the other hand, the strength behavior of the soil changed from ductility to brittleness after adding nanocement. Hence, as the nanocement amount increased, the strain failure decreased and the stabilized specimens failed at lower strain amounts compared to the pure specimens, as can be seen in Figure 11.

4.4.2. After applying F-T cycles

Figure 12 shows the peak resistance changes of each cycle relative to the zero F-T cycles for the pure specimens and specimens treated with cement and nanocement. The ratio of q_c and q_0 represents the UCS amounts, respectively. As seen in this diagram, F-T cycles reduced UCS. Moisture in the soil mass froze, resulting in ice crystals. The soil mass expanded during the freezing stage, and the spacing between soil particles increased. The ice crystals became liquid again during the thawing, and due to the lack of elasticity of the soil particles, these distances remained unchanged. With the repetition of F-T cycles, the distance between the soil particles gradually increased, and the soil resistance was reduced with increasing porosity. It is important to note that adding stabilizers, such as cement and nanocement, reduced the decreasing trend of strength during F-T cycles. This can be due to the formation of strong bonds between soil-cement and soil-nanocement grains. By increasing the cohesion between the soil particles, they prevented the increase in porosity, which leads to the reduction in resistance. Also, the highest reduction in resistance occurred in initial cycles (three to six cycles) and then, the decreasing trend of strength was gradually reduced. The reason for this mechanism is the creation of a new dynamic balance in the soil mass.

As the amount of stabilizers increased, strength decreased with a downward slope during F-T cycles. For example, the peak resistance of the pure specimens was reduced by 63, 53, 41, and 46% by applying nine F-T cycles after 7, 14, 28, and 42 days of curing, respectively. However, the peak resistance of specimens containing 1% cement was reduced by 46, 41, 40, and 34% by applying nine F-T cycles after 7, 14, 28, and 42 days of curing, respectively. Also, the peak resistance

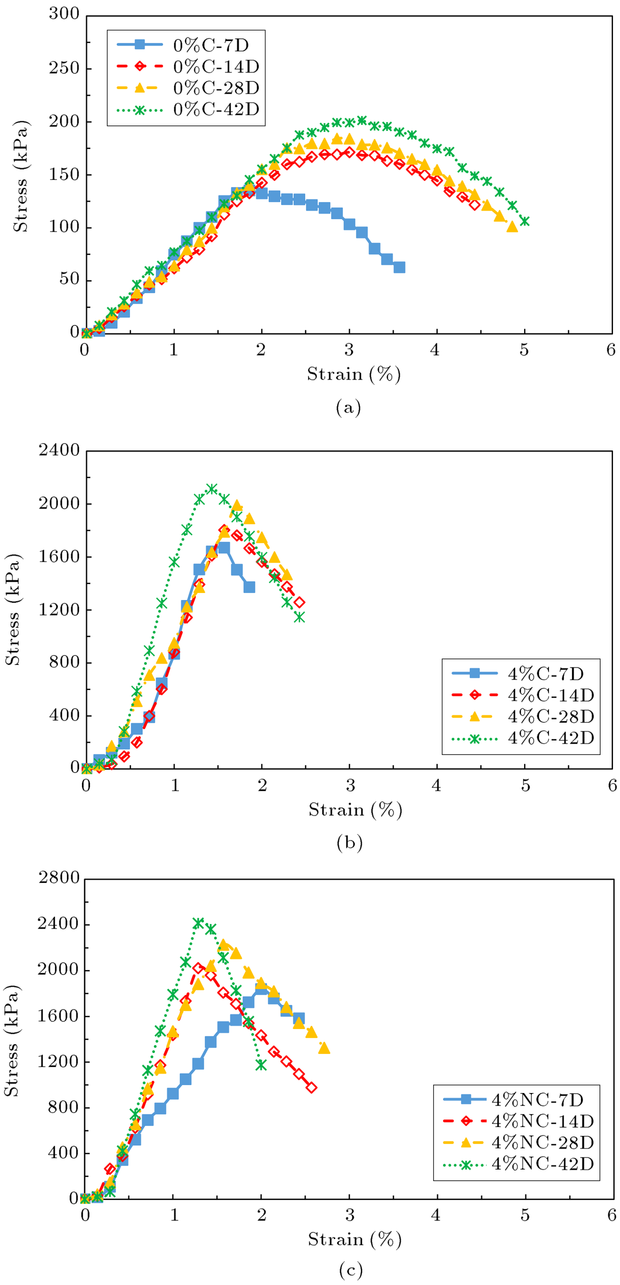


Figure 11. The stress-strain diagrams of (a) pure soil and soil stabilized with (b) 4% cement, and (c) 4% nanocement after 42 days of curing.

of specimens with 1% nanocement decreased by 44, 41, 37, and 32% with applying nine F-T cycles after 7, 14, 28, and 42 days of curing, respectively. After nine F-T cycles, specimens containing 4% cement and nanocement had the lowest strength drop, which was 26% and 18%, respectively, after 42 days of curing. Table 9 shows the strength reduction of the pure and stabilized specimens after applying nine F-T cycles in 42 days.

Also, after applying F-T cycles, the resistance behavior of the specimens changed from brittle to ductile. The reason can be the increased porosity of the

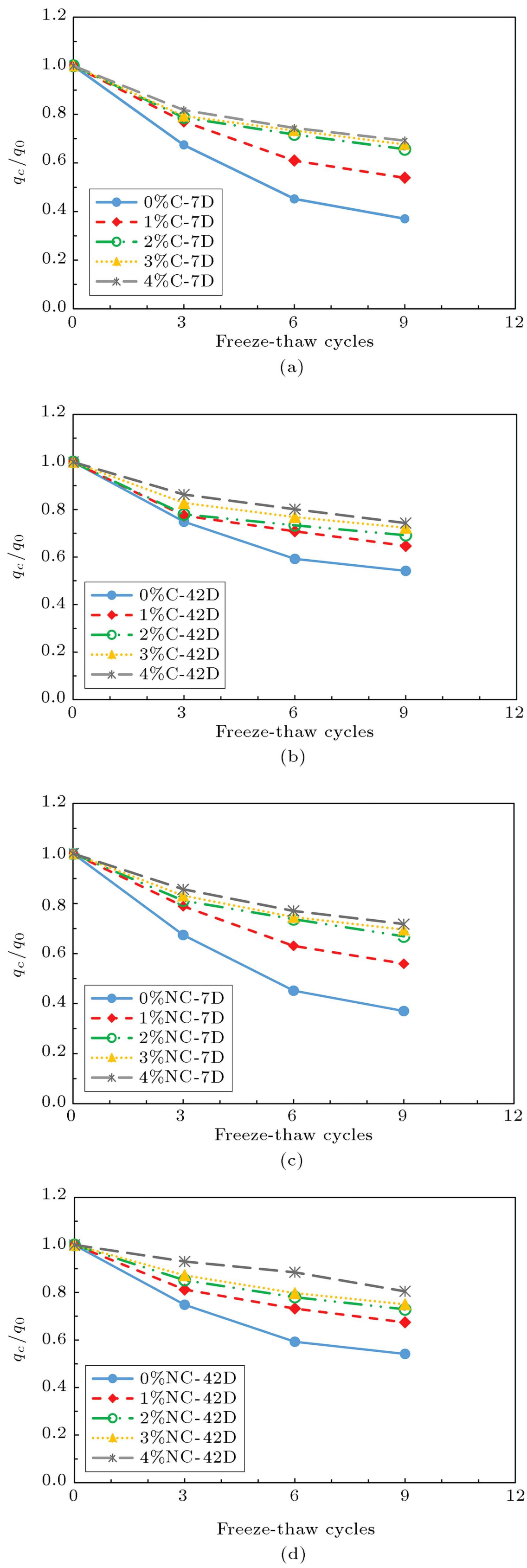


Figure 12. Variation of UCS ratio of pure and stabilized specimens against F-T cycles on different curing times ((a) and (b) for cement, and (c) and (d) for nanocement).

Table 9. The amount of strength reduction after varying F-T cycles.

Specimen type	USC reduction percentage in 3th F-T cycles	USC reduction percentage in 6th F-T cycles	USC reduction percentage in 9th F-T cycles
Pure soil	25	41	46
1% cement	23	29	35
2% cement	22	27	31
3% cement	17	23	28
4% cement	14	20	26
1% nanocement	19	27	32
2% nanocement	15	22	27
3% nanocement	13	20	25
4% nanocement	7	11	18

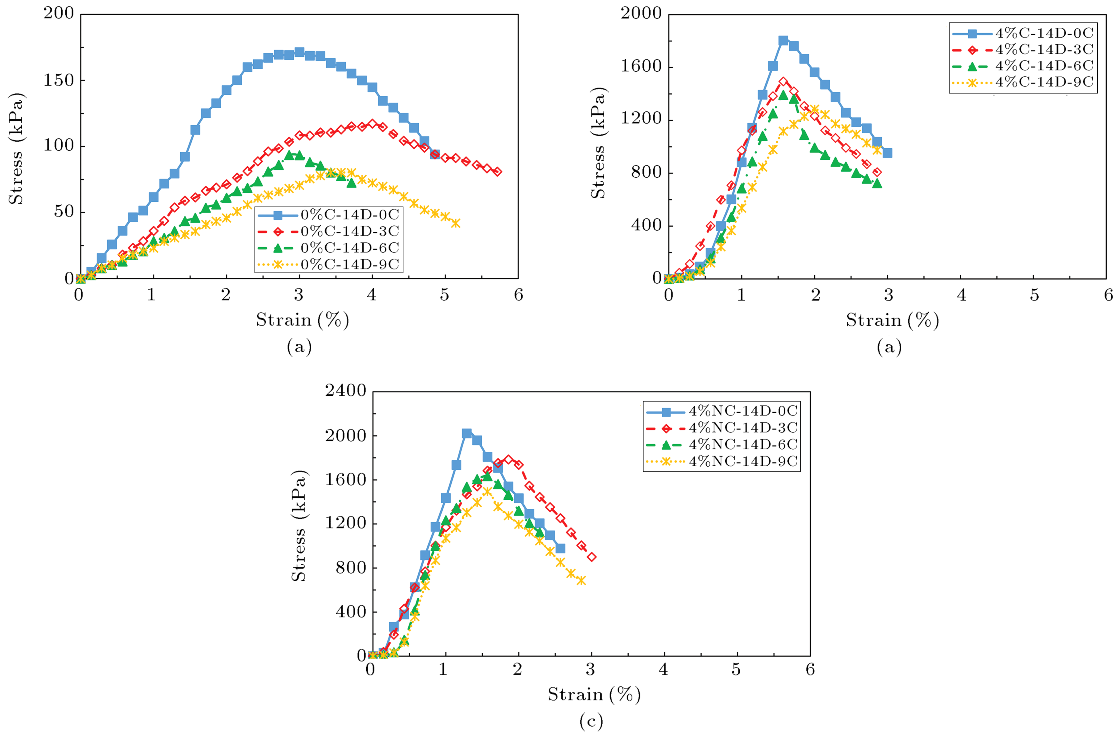


Figure 13. The stress-strain diagrams of specimens: (a) Non-stabilized and stabilized with (b) 4% cement, and (c) 4% nanocement after 14 days of curing under zero, three, six, and nine freeze-thaw cycles.

samples during F-T cycles, resulting in higher failure surfaces when the specimens fail [14,19,24]. This can be seen in Figures 13 and 14.

4.5. Effect of the F-T cycles on resilient modulus

Resilient modulus is a fundamental material property for characterizing unbound pavement materials. It measures material stiffness while facilitating analysis of the stiffness of materials under various conditions, including moisture content, stress level, and density. This input parameter is also required for the mechanistic-empirical pavement design technique. The resilient modulus is defined as an increase in the deviator stress to axial strain increment ratio at 1% axial strain.

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{1\%} - \sigma_0}{\varepsilon_{1\%} - \varepsilon_0}, \tag{2}$$

where $\Delta\sigma$ denotes the increment of deviator stress, $\Delta\varepsilon$ represents the increment of axial strain; $\sigma_{1.0\%}$ is the deviator stress equivalent to the axial strain of 1.0% ($\varepsilon_{1.0\%}$), and ε_0 and σ_0 are the initial strain and stress, respectively [32]. Figure 15 further shows that the resilient modulus magnitude of the unfrozen pure specimens was reduced by roughly 56%.

(a) (b)

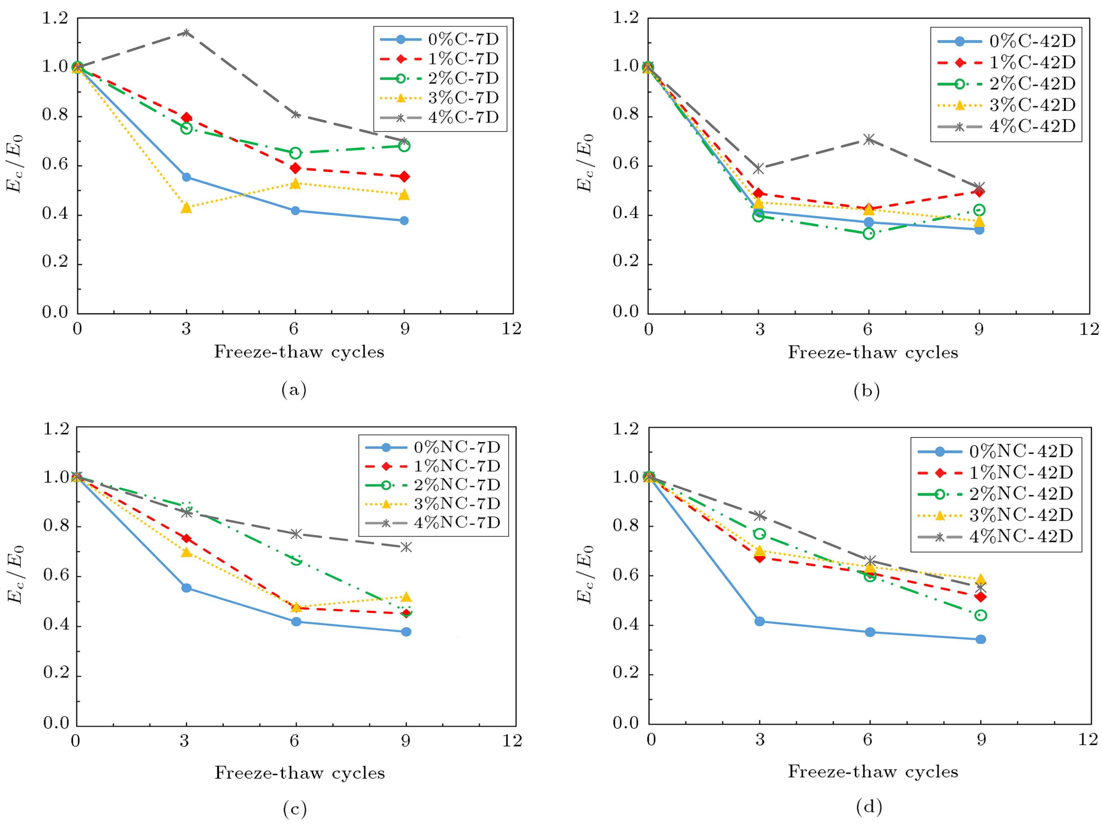
Figure 14. The soil stabilized specimens after the USC test. The increased rupture angle due to the applied freeze-thaw cycles: (a) Stabilized with 3% nanocement before F-T cycles and (b) stabilized with 3% nanocement after nine F-T cycles.

As observed, by incrementing the number of cycles, the resilient modulus of the pure and stabilized specimens decreased, and minimum values were obtained after six F-T cycles. Figure 15 conjointly indicates that the resilient modulus magnitude decreased by about 56% of the unfrozen pure specimens. In specimens stabilized with cement and nanocement, the reduction was on average 46%, and 39%, respectively.

4.6. SEM image

It is essential to evaluate the structural changes in the soil as a result of applying F-T cycles. In the present study, Scanning Electron Microscope (SEM) pictures were utilized to investigate changes in soil mass behavior due to adding stabilizers before and after applying F-T cycles. Figure 13 depicts the SEM pictures of the pure soil and soil stabilized with 4% nanocement before and after applying nine F-T cycles.

The adhesion between soil particles increased with the addition of nanocement, which created chemical bonds, resulting in increased soil strength. This behavior is visible in Figure 16(a) and (c) (circles are shown in Figure 16(c). Because of the repetition of F-T cycles, the space in the soil mass gradually increased, which increased porosity. As shown in Figure 16, porosity increased after applying nine F-T cycles, creating spaces between soil particles (Figure 16(b)). It is important to note that the distance between soil particles during F-T cycles decreased due to adding stabilizers (Figure 16(d)). This phenomenon caused a lower reduction in the strength of the stabilized specimens after applying F-T cycles compared to that of the pure specimens.



(a) (b) (c) (d)

Figure 15. Variation of resilient modulus ratio of pure and treated specimens against F-T cycles on different curing times ((a) and (b) for cement, (c) and (d) for nanocement).

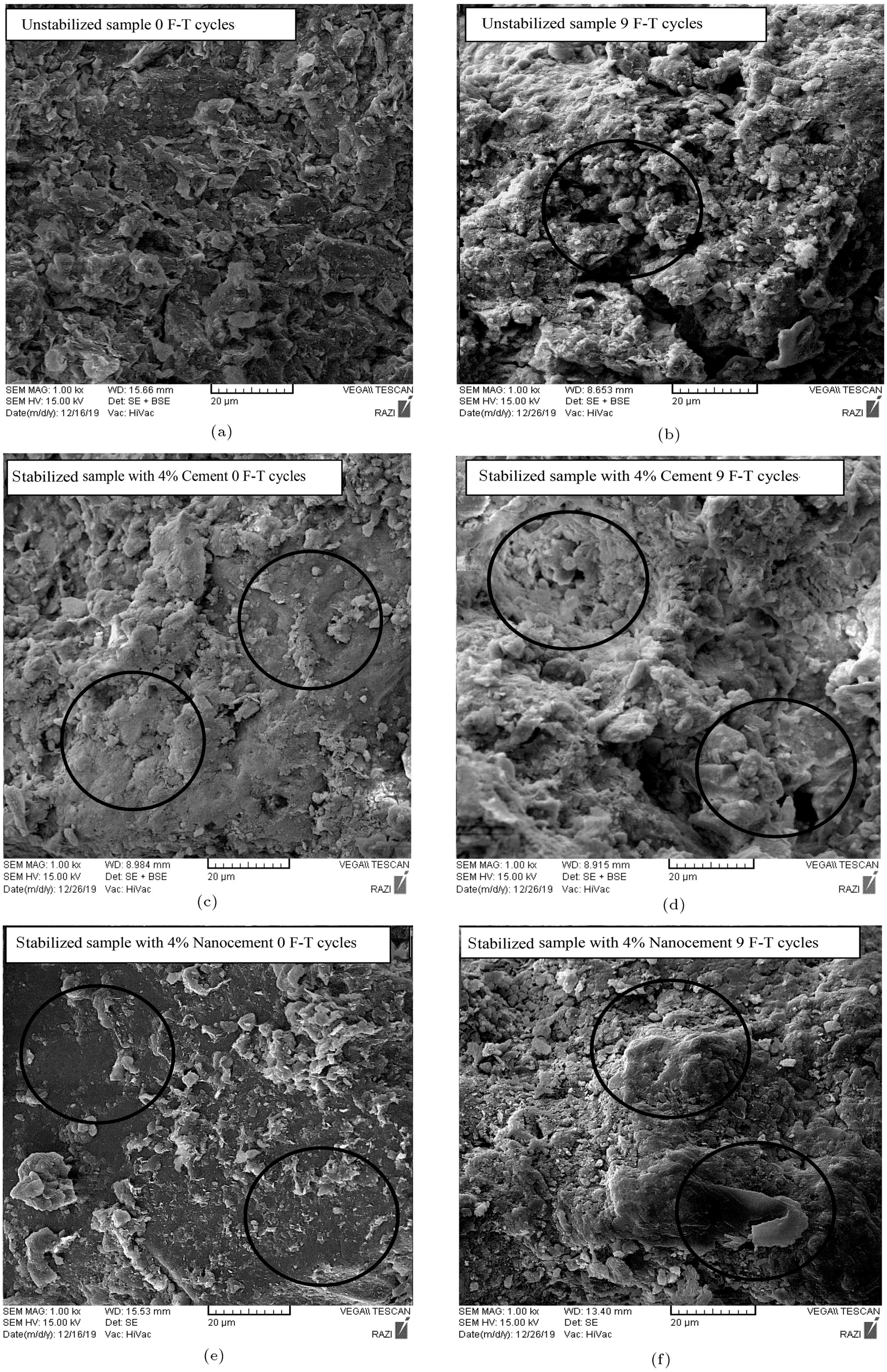


Figure 16. SEM pictures with the magnification of 20 micron: (a) Pure specimens before F-T cycles, (b) pure samples after applying 9 F-T cycles, (c) specimens stabilized with 4% cement before F-T cycles, (d) stabilized specimens with 4% cement after 9 F-T cycles, (e) stabilized samples with 4% nanocement before F-T cycles, and (f) stabilized specimens with 4% nanocement after 9 F-T cycles.

5. Conclusion

Freeze-Thaw (F-T) cycles and Unconfined Compressive Strength (UCS) tests were conducted on the cement and nanocement stabilized clayey soil. The effect of F-T cycles on estimation changes, stress-strain behaviors, and UCS was also investigated. The study's findings are summarized as follows:

- The maximum dry unit weight decreased and the Optimum Moisture Content (OMC) value increased when cement and nanocement were added to clayey soil;
- When the amount of cement and nanocement was increased, the UCS generally increased;
- The Plastic Limit (PL) and Liquid Limit (LL) amount increased after adding cement and nanocement. It should be noted that the increase of LL was less than that of PL, causing a decrease in Plasticity Index (PI);
- The value of USC in the stabilized specimens increased to more than 12 times that of the pure specimens as a result of stabilization;
- The stabilization of clayey soil with nanocement particles caused a delicate performance in the stress-strain diagrams of the specimens since PI was reduced;
- The UCS of all the specimens was reduced by applying F-T cycles. Resistance was reduced the most during the first F-T cycles, and the strength-decreasing trend was reduced after the sixth F-T cycle;
- After applying nine F-T cycles, the strength reduction was 46% in the pure specimens, while it was 26% and 19% in specimens containing 4% cement and nanocement, respectively.

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