Shahrood University of Technology
Iranian Society of Mining Engineering (IRSME)
Journal of Mining and Environment (JME)
journal homepage: www.jme.shahroodut.ac.ir
THOMSON REUTERS
Vol. 10, No. 1, 2019, 257-270.
DOI: 10.22044/jme.2018.7619.1616

Effect of freeze-thaw cycle on strength and rock strength parameters (A Lushan sandstone case study)

M. Hosseini[1*] and A.R. Khodayari[2]

1. Department of Mining Engineering, College of Engineering, Imam Khomeini International University, Qazvin, Iran
2. Department of Mining and Metallurgical Engineering , Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

Received 26 October 2018; received in revised form 25 November 2018; accepted 26 November 2018

Keywords

Freeze-Thaw Cycle

Sandstone

Strength Parameters

Triaxial Compressive Strength

Abstract

In an era of continued economic development around the globe, numerous rock-related projects including mining and gas/oil exploration are undertaken in regions with cold climates. Winters in the Iranian western and northwestern provinces are characterized by a high precipitation rate and a cold weather. Under such conditions, rocks are exposed to long freezing periods and several freeze-thaw (F-T) cycles. It is thus necessary to examine the impact of these cycles on the physical and mechanical properties of rocks. Considering the abundant sandstone resources in Iran, in this work, we focused on the Lushan sandstone by investigating the effects of F-T cycles and freezing temperatures on the uniaxial and triaxial compressive strengths, cohesion, internal friction angle, and elastic modulus of the rocks. To study the impact of the number of F-T cycles on the strength of rocks, the specimens frozen at -16 °C were subjected to 1, 4, 8, 16, and 32 F-T cycles. Similar tests were also carried out on the specimens frozen at -24 °C. Furthermore, a number of tests were undertaken at the ambient temperature (25 °C) on specimens that did not undergo an F-T cycle. According to the results obtained, an increase in the number of F-T cycles and freezing temperatures reduced the uniaxial and triaxial compressive strengths, cohesion, internal friction angle, and elastic modulus due to the growth of the existing cracks and the nucleation of new cracks in the rock. Consequently, the effective porosity increased, whereas the dry specific gravity decreased with more F-T cycles and lower freezing temperatures.

1. Introduction

Rock masses are increasingly used as the substrate in a wide range of human activities. Facilities such as storage depots, wells, tunnels, and underground power plants are exposed to different rocky mechanics conditions in different types of bedrocks [1]. A rock is a complex mechanical medium consisting of joints, cracks, pores, gas, water, and other fluids [2]. In an era of continued economic development around the globe, numerous rock-related projects including mining and gas/oil exploration are undertaken in regions with cold climates [3]. Rocks, as the building materials in engineering works, are always exposed to the freeze-thaw (F-T) weathering phenomenon. Geological disasters can occur in cold areas due to F-T cycles in rocks or soils. For this reason, the impact of F-T cycles on the mechanical properties and penetrability of rocks should be thoroughly studied [4]. The geological disasters include landslide and instability of rocky slopes [5, 6] and instability of tunnels [7].

Rocks in cold areas are exposed to environmental perturbations such as explosion, crushing, piling, earthquake, and landslide. Accordingly, the study

---

✉ *Corresponding author: ma.hosseini@eng.ikiu.ac.ir (M. Hosseini).*

of mechanical properties of rocks under an F-T process provides important theoretical and practical information that helps manage construction projects and prevent disasters in cold areas [8]. The presence of primary cracks and fractures in rocks is inevitable and is considered as a special feature of any substance. As a result, these structures and rock masses are ruptured faster under mechanical loads or by other environmental factors such as F-T cycles [9]. An F-T cycle is a common and serious phenomenon related to the weathering of rocks. Repeated freezing and thawing of water in the pores of rocks leads to the expansion of the cracks and nucleation of small fractures, both quite harmful to rocks [10]. When the temperature is below the freezing point, the volume of pore water inside rocks increases up to 9% as the water phase changes from the liquid to the solid state. This, in turn, leads to a change in the pore structure. When the temperature is above the freezing point, the frozen water is thawed and moves between pores causing a reduction in the cohesion of rock particles. Alternating F-T cycles lead to the gradual exacerbation of the damage and further weakening of mechanical properties [2].

Studies on the effect of F-T cycles on the physical and mechanical properties of rocks are reviewed below.

In an experimental study, Özbek investigated the effects of wetting-drying and F-T cycles on some of the physical and mechanical properties of ignimbrite. Specific gravity, porosity, water absorption, slake durability index, uniaxial compressive strength, and wave velocity (P) in all ignimbrite specimens were determined before and after 10 F-T cycles for each specimen (a total of 50 cycles). In the freezing stage, the specimens were placed in a freezer at -20 °C for two hours. In the thawing stage, the specimens were placed at 20 °C for two hours. The experimental results are suggestive of the impact of wetting-drying and F-T cycles on the physical and mechanical properties of rock specimens [11].

Sarkar Noor-E-Khuda *et al.* conducted an experimental study to investigate the effect of F-T cycles on the bending strength of the weathered granite. They used a controllable F-T chamber in the temperature range of -70--10 °C. Their results indicate the physical erosion of granite subjected to F-T cycles, which significantly reduces the velocity of longitudinal waves, the rock density, and its bending strength [12].

Liu *et al.* proposed a model for estimating the uniaxial compressive strength and the deterioration of rocks in the F-T process. They introduced their model based on the elastic-plastic theory and damage-fatigue mechanics taking into account the real distribution of stress in the rock under an F-T process. The model was validated using the results of the previous F-T experiments on low porous saturated sandstone, highly porous saturated ignimbrites, and unsaturated welded tuffs [13].

Zhou *et al.* investigated microscopic damages of rocks and their dynamic mechanical properties during F-T cycles. They placed the rock specimens in water for 12 h to be saturated, and then at -30 °C for 4 h (freezing stage). The specimens were then placed at 20 °C for 4 h (thawing stage). NMR (Nuclear Magnetic Resonance) spectroscopy is an analytical chemistry technique used for determining the content and purity of a sample. The impact of loading tests were conducted after the F-T process to determine the microscopic properties of sandstone damages and mechanical dynamic parameters of the rock specimen. Their results demonstrated that the porosity increased with increase in the number of F-T cycles. The porosity growth rate decreased at the beginning of the F-T process but increased again after a certain number of cycles. The elastic modulus of sandstone gradually decreased with F-T cycles but the strain increased in proportion to the maximum stress [2].

Li *et al.* conducted NMR studies to examine the deterioration of the sandstone microscopic structure during F-T cycles. Each F-T cycle consisted of four hours of freezing at -30 °C and four hours of thawing at 20 °C. According to the results obtained, with increase in the number of F-T cycles, the density of the rocks decreased and their porosity increased. The porosity of the rock specimens increased after 180 F-T cycles [14].

Martínez *et al.* examined the deterioration of building rocks during the F-T weathering process. They divided the specimens into five groups and tested each group after 0, 12, 24, 48, and 96 F-T cycles. At the end of the experiments, some rock properties including volume reduction, open porosity changes, rock strength, elastic modulus, and velocity of longitudinal waves were determined. The results associated the least durability with the most open porosity (> 10%) in the rocks. Deterioration is non-linear in these rocks as they degrade rapidly in catastrophic F-T cycles [15].

Wang *et al.* studied the static and dynamic mechanical properties of sedimentary rocks subjected to the F-T and thermal shock weathering phenomena. To achieve a deeper understanding of the effects of F-T and thermal shock on rock behavior, they conducted physical property tests, and static uniaxial compressive and dynamic impact (split Hopkinson pressure bar test) tests on red sandstone after freeze-thawing and thermal shock cycles. The results obtained indicated deterioration of red sandstone following the F-T and thermal shock weathering processes [16].

Momeni *et al.* examined the influence of F-T cycles on the physical and mechanical properties of Alvand granitoid hard rocks in the west of Iran. The results of this study showed that with increase in the number of F-T cycles, uniaxial compressive strength, tensile strength, dry density, and P-wave velocity decreased, whereas the water absorption and porosity increased [17].

Khanlari *et al.* investigated the influence of F-T cycles on the physical and mechanical properties of the Upper Red Formation sandstones in the southwestern Qom province in central Iran.

The results of this study showed that an increase in the number of F-T cycles decreased uniaxial compressive strength and P wave velocity, whereas the effective porosity increased [18].

Chen *et al.* examined the effect of freezing and thawing cycle on the mechanical properties. The specimens were collected from the south end-wall slope of the Wulin open-pit mine, and the principal component of the rock specimen was siltstone with a grain size of 0.1 mm. The number of freezing and thawing cycle was set to 1, 2, 3, and 5. The results of this study indicated that the cohesion and the internal friction angle of the specimens reduced exponentially with increase in the freezing and thawing cycle. The reduction of cohesion and internal friction angle slows down significantly after three freezing and thawing cycles [19].

Wang *et al.* studied deterioration of rock properties by F-T weathering using the time-frequency ultrasound method. They used ultrasonic detectors and mechanical tests including uniaxial compressive test, and tensile and shear tests on the red sandstone specimens before and after F-T cycles. After F-T cycles, all indicators of red sandstone including mechanical properties such as uniaxial compressive strength, elastic modulus, tensile strength, cohesion, internal friction angle, and velocity of longitudinal waves were determined. After 25 F-T cycles, uniaxial compressive strength, elastic modulus, tensile strength, cohesion, internal friction angle, and longitudinal waves decreased by 52.5, 63, 87.3, 33.7, 22.6, and 50.6%, respectively [10].

The northwestern and western provinces of Iran have mild summers and cold winters. High precipitation rate and air chill are the winter characteristics of these areas. In these conditions, rocks are affected by long freezing cycles and numerous F-T cycles. Therefore, it is necessary to examine the impact of such processes on the physical and mechanical properties of rocks.

Most studies in this regard have focused on the effect of F-T cycles on the physical properties (such as specific gravity, porosity, and the velocity of longitudinal waves) and mechanical properties (such as uniaxial compressive strength and tensile strength). There are also a few studies on triaxial compressive strength, elastic modulus in triaxial compressive strength, cohesion, and internal friction angle variations including the one by Wang *et al.* According to desk studies, this is the first study on the changes in rock strength properties in the F-T process in Iran. In addition, CT scan images were used to calculate the damage caused by the F-T process. These are considered to be the distinct features of this research work.

This work aims at investigating the effect of F-T cycles on the strength parameters of the Lushan sandstone.

2. Materials

Sandstone is a sedimentary rock that continued forming during all geological periods. It consists mainly of sand and mineral particles in different colors. Sandstone forms in shallow seas, deltas, along beaches, and warm deserts. Clays and silicon dioxide play a key role in the cementation of sandstone particles [20].

The understudied rock (Figure 1) was a limestone sandstone with a calcareous cement. Microscopic studies were conducted on the rock specimen. For this purpose, a thin section of the rock was prepared and observed under a microscope. The microscopic images are presented in Figure 2. The primary and secondary minerals in sandstone included calcite, alkaline feldspar, quartz, and opaque minerals. The rock diagenesis included cerussitation, calcification, and chert. Shaped and semi-shaped quartz with calcite were the primary constituents of the Lushan sandstone.

The minerals are identified with abbreviated symbols on the images.

Experiments were conducted on sandstone to determine the porosity and dry specific gravity. The Brazilian and uniaxial compression tests were also employed to determine the tensile strength, uniaxial compressive strength, elastic modulus, and Poisson's ratio. Table 1 lists the physical and mechanical properties of the rock specimens. The specific gravity, effective porosity, uniaxial compressive strength, and tensile strength were determined in compliance with the standards of the International Society of Rock Mechanics (ISRM) [21].

Figure 1. Lushan sandstone.

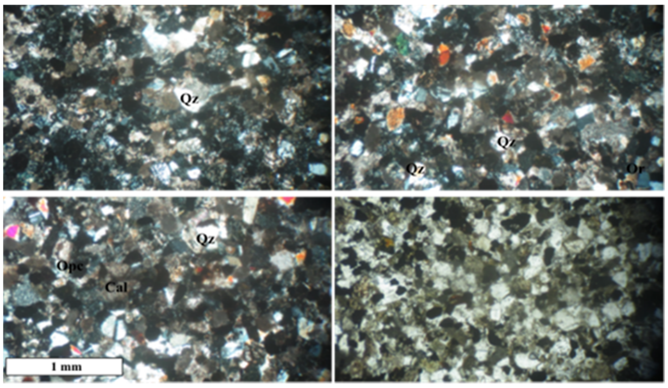


Figure 2. Microscopic images of sandstone (Qz: Quartz, Cal: Calcite, Opc: Opaque Minerals).

Table 1. Physical and mechanical properties of Lushan sandstone.

Effective porosity (%)	Dry unit weight (KN/m^3)	Uniaxial compressive strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Tensile strength (MPa)
10.27	21.88	72.8	17.37	0.26	4.59

3. Specimen preparation

During the specimen preparation, micro-mechanical damages to the rock specimens should be prevented. Micro-mechanical damages may affect fracture propagation, causing a reduction in the mechanical properties. The rock specimens should be prepared with caution by slow coring, cutting, and abrasion to reduce mechanical vibrations [22].

In the first stage, the rock block was placed under the coring device.

In the next step, the cylindrical core was cut by a cutter to pieces with a height of about 100 mm. The rock specimens were then polished using a polisher. Thereafter, the polished rock specimens were placed in a water bath for two days until all the pores were saturated with water (Figure 3).

In the next step, the specimens were placed in a freezer for 18 h at -16 °C (freezing stage). After removing from the freezer, the rock specimens were placed in water at 20 °C for 6 h (thawing stage). An F-T cycle was completed in 24 h. Figure 4 illustrates some rock specimens.

Figure 3. A water bath for saturation of specimens.

Figure 4. Rock specimens.

4. Effect of F-T cycles on rock strength parameters

4.1. Methods

The rock specimens were prepared from five blocks of sandstone (Blocks 1-5) to investigate the impact of the number of F-T cycles on the rock strength. To study how the number of F-T cycles affects the strength properties, the specimens frozen at -16 °C were subjected to 1, 4, 8, 16, and 32 F-T cycles. Moreover, a series of the specimens frozen at -24 °C were tested in one F-T cycle. Furthermore, experiments were conducted at the ambient temperature (25 °C) on the saturated specimens that were not subjected to F-T cycles.

In this work, the specimens were tested at the confining pressures of 0 and 5 MPa. The specimens were connected to a strain gauge to determine the elastic modulus.

After preparation, the specimens were placed inside a Hoek triaxial cell. The cell was then placed under the axial loading jack, and the confining pressure was increased as required. The axial pressure was then continuously increased until the specimen failed.

Figure 5 illustrates the placement of the Hoek triaxial cell below the axial loading jack. Figure 6 illustrates the uniaxial compression test on the rock specimen with the installed strain gauge (at 0 MPa confining pressure).

4.2. Results

The results of the triaxial tests with 1, 4, 8, 16, and 32 F-T cycles with freezing at -16 °C and one F-T cycle with freezing at -24 °C are presented in Table 2. The triaxial tests were also carried out on the specimens that did not undergo an F-T cycle. To determine the cohesion and internal friction angle, the failure envelope was plotted for each specimen (Figures 7-9). sandstone specimens in each F-T cycle [4]. The results obtained are presented in Table 3.

$$\emptyset = \sin^{-1}\left(\frac{m-1}{m+1}\right) \tag{1}$$

$$C = b\,\frac{1-\sin\emptyset}{2\cos\emptyset} \tag{2}$$

where $\emptyset$ represents the internal friction angle in degrees, C is the cohesion in MPa, and m and b are the slope and intercept of the failure envelope in the σ_1-σ_3 diagram.

As mentioned earlier, the confining pressure was set at 0 and 5 MPa to determine the elastic modulus. The results obtained are illustrated in Figure 10.

Figure 5. Triaxial compressive test.

Figure 6. Uniaxial compressive test on a sandstone specimen with a strain gauge.

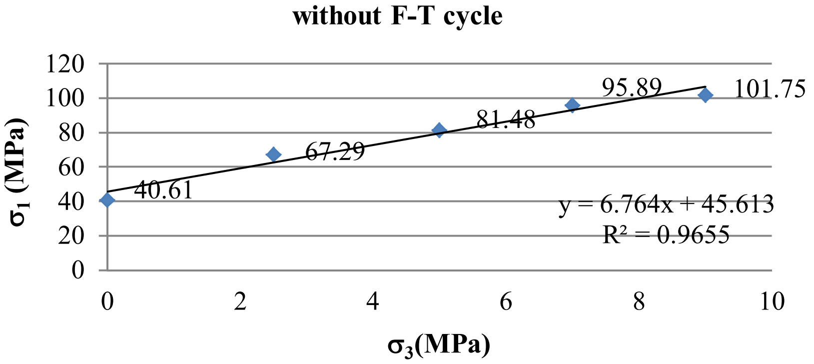


Figure 7. The failure envelope for specimens with no F-T cycle.

Table 2. Triaxial test results in different F-T cycles.

Number of cycles	Freezing temperature (ºC)	Confining pressure (MPa)	Compressive Strength (MPa)
0	25	0	40.61
0	25	2.5	67.29
0	25	5	81.48
0	25	7	95.89
0	25	9	101.75
1	-16	0	33.21
1	-16	2.5	59.05
1	-16	5	77.98
1	-16	7	86.98
1	-16	9	91.86
4	-16	0	31.01
4	-16	2.5	54.54
4	-16	5	74.87
4	-16	7	79.55
4	-16	9	86.83
8	-16	0	28.52
8	-16	2.5	52.65
8	-16	5	71.84
8	-16	7	78.11
8	-16	9	82.05
16	-16	0	27.51
16	-16	2.5	51.25
16	-16	5	69.43
16	-16	7	75.52
16	-16	9	79.69
32	-16	0	25.01
32	-16	2.5	47.14
32	-16	5	67.16
32	-16	7	73.64
32	-16	9	75.87
1	-24	0	30.7
1	-24	2.5	56.86
1	-24	5	75.48
1	-24	7	84.11
1	-24	9	88.93

Table 3. Cohesion and internal friction angle in different F-T cycles.

Number of F-T cycles	Freezing temperature (°C)	Cohesion (MPa)	Internal friction angle (º)
0	-	8.77	47.94
1	-16	7.63	47.30
1	-24	7.22	47.10
4	-16	7.33	46.12
8	-16	7.05	45.54
16	-16	6.92	44.94
32	-16	6.34	44.89

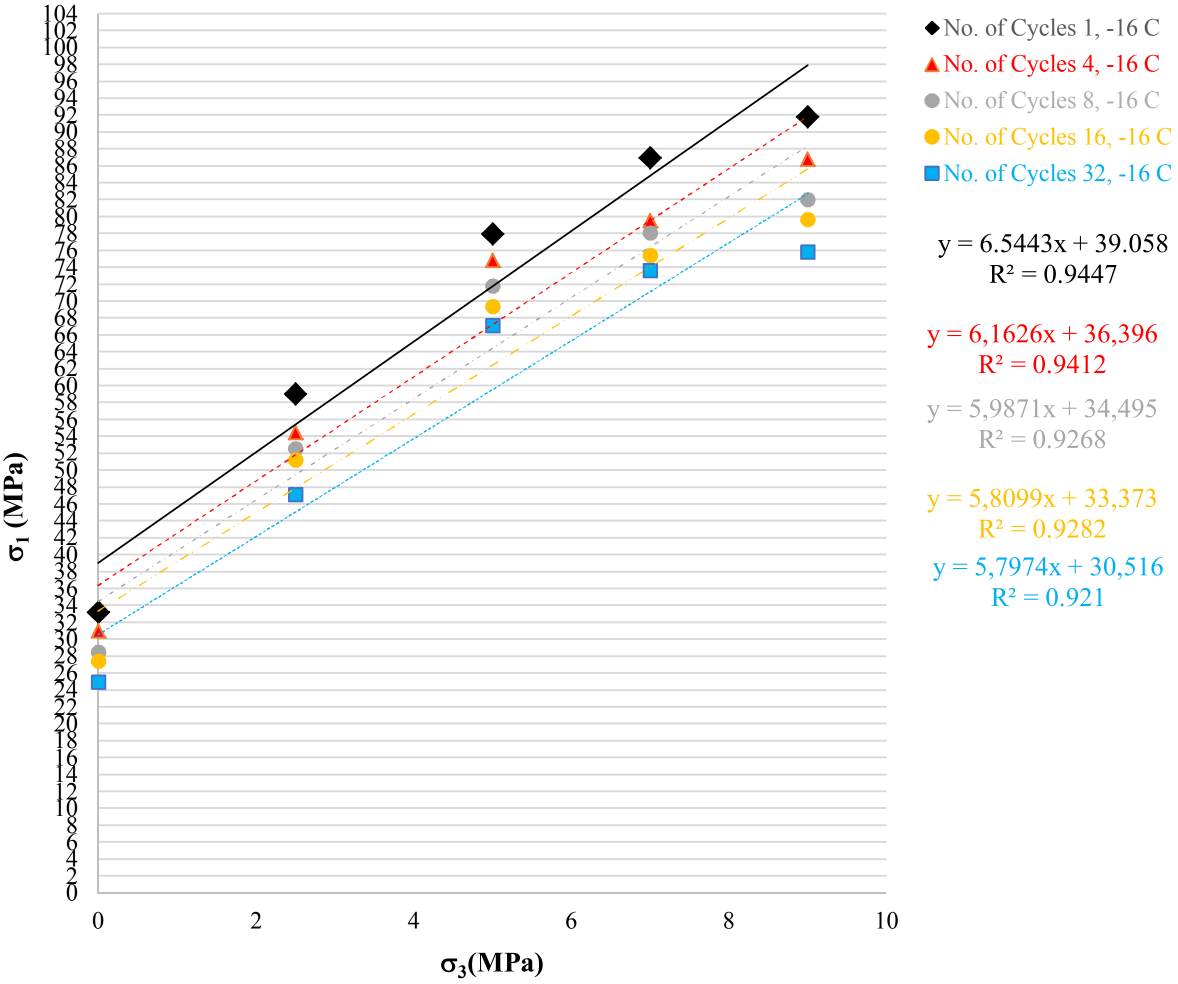


Figure 8. The failure envelope for specimens subjected to different cycles of F-T (freezing temperature: -16 °C).

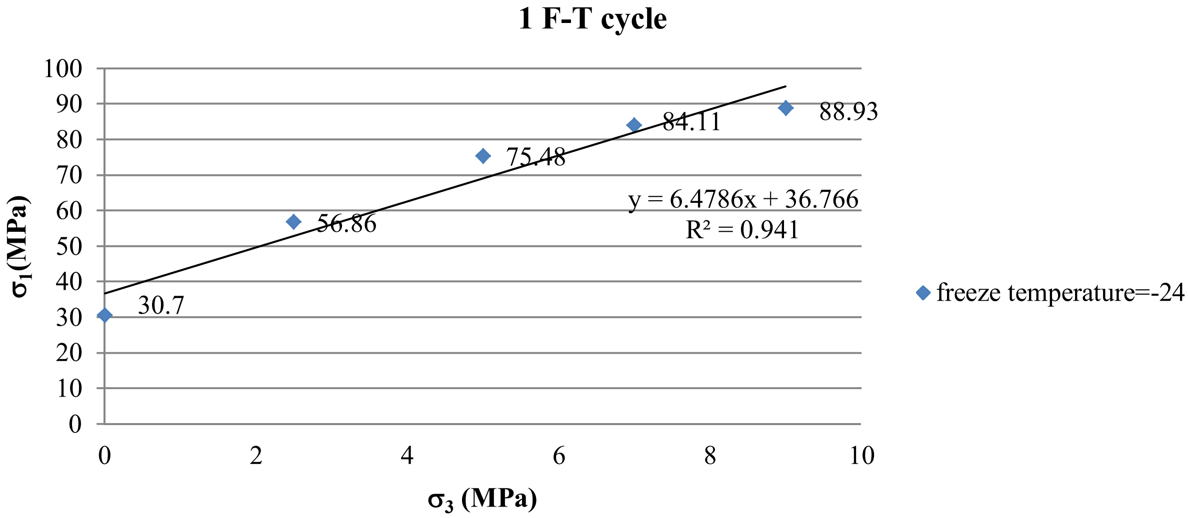


Figure 9. The Failure envelope for specimens subjected to one F-T cycle (freezing temperature: -24 °C).

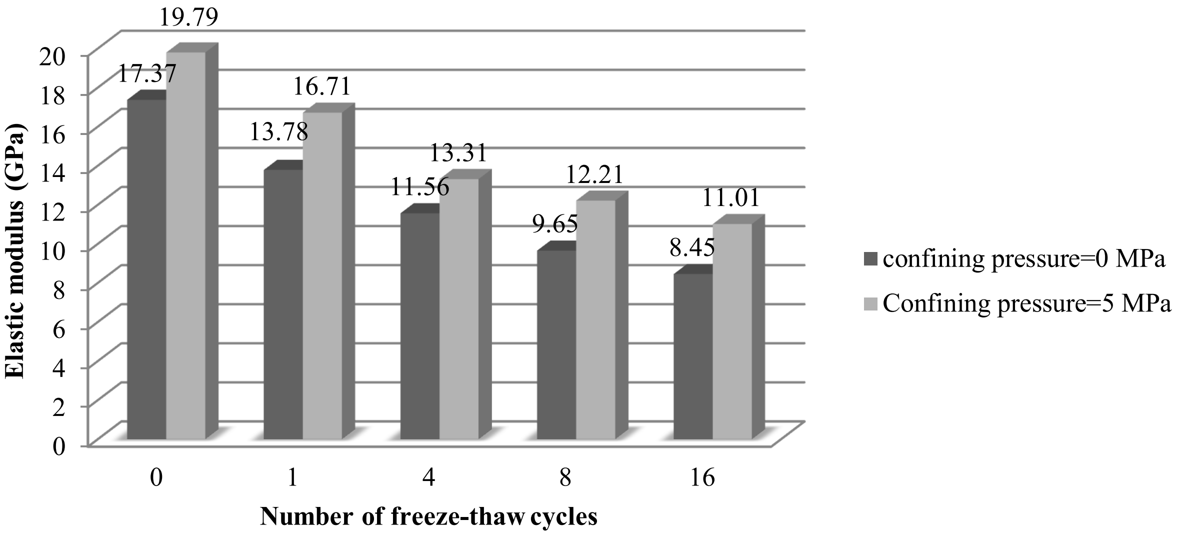


Figure 10. Elastic modulus as a function of the number of F-T cycles.

4.3. Discussion

To investigate the impact of F-T cycles on the uniaxial compressive strength, the ratio of the triaxial compressive strength of the sandstone specimens subjected to the F-T process (σ_1') to that of the specimens that did not experience the cycle (σ_1) was calculated (Table 4). As it can be seen in Table 4, the uniaxial and triaxial compressive strengths of the rock specimens decrease with increase in the number of F-T cycles. Of course, the effect of F-T cycles on the reduction of uniaxial compressive strength is more significant than the triaxial strength so that $\frac{\sigma_1'}{\sigma_1}$ for uniaxial compressive strength decreases from 0.81 to 0.61 by increasing the number of F-T cycles. Furthermore, strength reduction after one F-T cycle is higher than the other cycles. This is consistent with the results of Tan *et al.* [8].

To investigate the effect of freezing temperature in the F-T process on the triaxial compressive strength, σ_1' / σ_1 for an F-T cycle was calculated at freezing temperatures of -16 and -24 ˚C (Table 5). According to the results in this table, uniaxial and triaxial compressive strengths are further decreased at a freezing temperature of -24 than -16 °C. In this situation, the effect of freezing temperature on the reduction of uniaxial compressive strength is more significant than triaxial strength.

Table 6 presents the ratio of cohesion in different F-T cycles (C') to initial cohesion (C) of the rock specimens that did not undergo an F-T cycle and the ratio of internal friction angle in different F-T cycles ($\varnothing'$) to the initial internal friction angle ($\varnothing$). As it can be seen, cohesion and internal friction angles are reduced with increase in the number of F-T cycles. These results are consistent with those obtained by Yu *et al.* [4]. Cohesion reduction is more significant than the internal friction angle. This is in good agreement with the results of Tan *et al.* [8]. Meanwhile, the cohesion of the rock specimens, as seen in Figure 11, further decreases after one F-T cycle. With increase in freezing temperature in the F-T cycle, the reduction of cohesion and internal friction angles is more significant at a freezing temperature of -24 than -16 ˚C.

According to the above tables, the uniaxial compressive strength decreases by 39% after 32 F-T cycles, whereas at the confining pressures of 2.5, 5, 7, and 9 MPa, the triaxial compressive strength decreases by 30, 18, 24, and 25%, respectively. Cohesion also decreases by 28% after 32 F-T cycles. Therefore, one can see the significant impact of the F-T process on the deterioration of rock properties.

According to Figure 10, the elastic modulus increases with increase in the confining pressure. However, the elastic modulus decreases with increase in the number of F-T cycles. The reduction rate of the elastic modulus in the first F-T cycle is higher than that in other cycles, according to Figure 12.

A relationship was obtained to estimate cohesion (Eq. 3) with the help of Table Curve^{2D} software. The relationships were presented to estimate the elastic modulus at the confining pressures of 0 and 5 MPa (Eqs. 4 and 5) in each F-T cycle.

$$\frac{1}{C_N} = 0.118 + 0.0075N^{0.5};\ R^2=0.913 \quad (3)$$

where C_N is the cohesion after N F-T cycles and N is the number of F-T cycles.

$$\frac{1}{E_{N_0}} = 0.057 + 0.0153N^{0.5};\ R^2=0.99 \quad (4)$$

$$\frac{1}{E_{N_5}} = 0.050 + 0.0107N^{0.5};\ R^2=0.98 \quad (5)$$

where E_{N0} is the elastic modulus at a confining pressure of 0 and E_{N5} is the elastic modulus at a confining pressure of 5 MPa after N F-T cycles and N is the number of F-T cycles.

Table 4. $\frac{\sigma_1'}{\sigma_1}$ in different F-T cycles (freezing temperature: -16 °C).

σ_3 (MPa)	$\frac{\sigma_1'}{\sigma_1}$ (for F-T= 1)	$\frac{\sigma_1'}{\sigma_1}$ (for F-T= 4)	$\frac{\sigma_1'}{\sigma_1}$ (for F-T= 8)	$\frac{\sigma_1'}{\sigma_1}$ (for F-T= 16)	$\frac{\sigma_1'}{\sigma_1}$ (for F-T= 32)
0	0.82	0.76	0.70	0.68	0.61
2.5	0.87	0.81	0.78	0.76	0.70
5	0.95	0.91	0.87	0.85	0.82
7	0.90	0.83	0.81	0.78	0.76
9	0.90	0.85	0.81	0.78	0.75

Table 5. $\frac{\sigma_1'}{\sigma_1}$ for one F-T cycle.

σ_3 (MPa)	$\frac{\sigma_1'}{\sigma_1}$ (for T= -16 °C)	$\frac{\sigma_1'}{\sigma_1}$ (for T= -24 °C)
0	0.82	0.75
2.5	0.87	0.85
5	0.95	0.93
7	0.90	0.88
9	0.90	0.88

Table 6. $\frac{C'}{C}$ and $\frac{\tan(\varnothing')}{\tan(\varnothing)}$ as a function of the number of F-T cycles.

Number of F-T cycles	Freezing temperature (°C)	$\frac{C'}{C}$	$\frac{\tan(\varnothing')}{\tan(\varnothing)}$
1	-16	0.87	0.98
1	-24	0.82	0.97
4	-16	0.83	0.94
8	-16	0.8	0.92
16	-16	0.78	0.9
32	-16	0.72	0.89

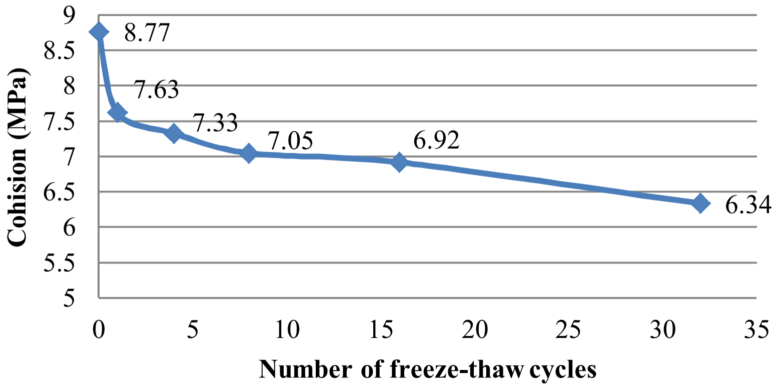


Figure 11. Cohesion as a function of the number of F-T cycles.

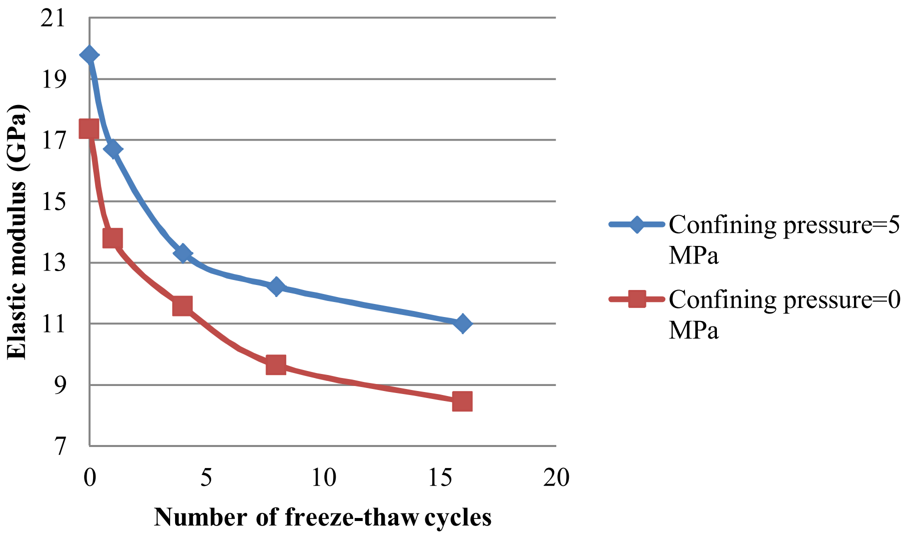


Figure 12. Elastic modulus as a function of the number of F-T cycles.

The reduction of rock strength properties during F-T cycles can be explained as what follows. When the temperature is below the freezing point, the volume of pore water in the rock increases by up to 9% due to ice formation, leading to expansion of pores and cracks in the rock. This, in turn, leads to the expansion of the existing cracks and the nucleation of the new ones. With the ice thawing, water flows through the cracks, reducing the elastic modulus and diminishing the strength properties including uniaxial and triaxial compressive strengths, cohesion, and friction angle.

To prove this reason, the dry unit weight and effective porosity of the rock were determined in different F-T cycles (Figures 13 and 14). As it can be seen, the dry unit weight decreases and the effective porosity increases with increase in the number of F-T cycles, indicating a growth of the pores and micro-cracks in the specimens. The increase in porosity and the decrease in dry unit weight are larger in the first cycle than the others. As a result, the reduction of uniaxial and triaxial compressive strengths, elastic modulus, and cohesion in the first cycle is more significant than the other cycles. The dry unit weight and effective porosity for one F-T cycle were determined at the freezing temperatures of -16 and -24 °C (Figures 15 and 16).

According to Figures 15 and 16, the effective porosity is higher in the F-T process at a freezing temperature of -24 °C than at -16 °C.

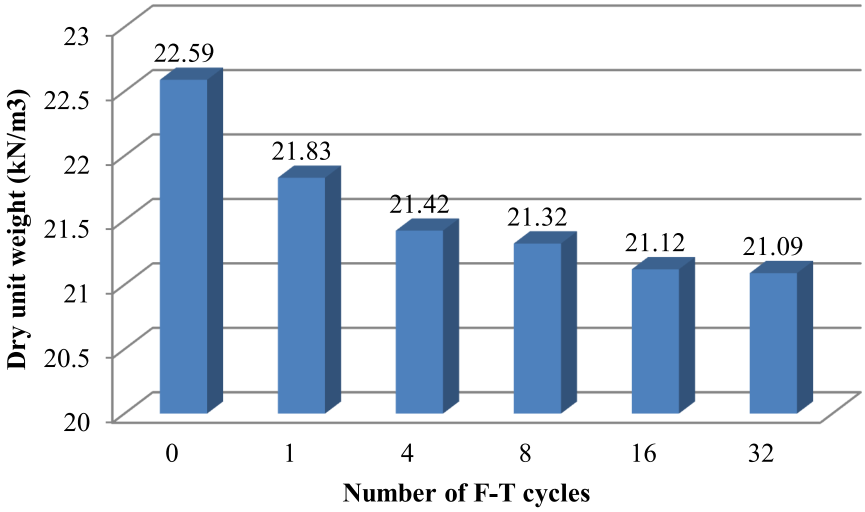


Figure 13. Dry unit weight as a function of the number of F-T cycles.

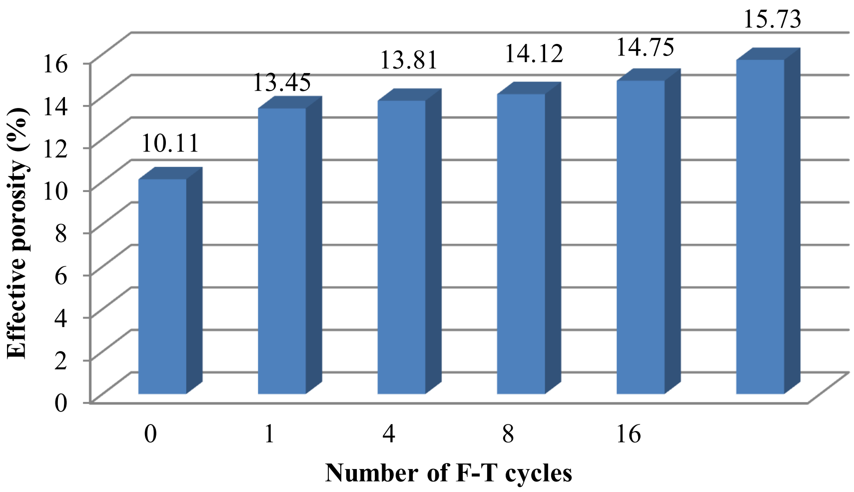


Figure 14. Effective porosity as a function of the number of F-T cycles.

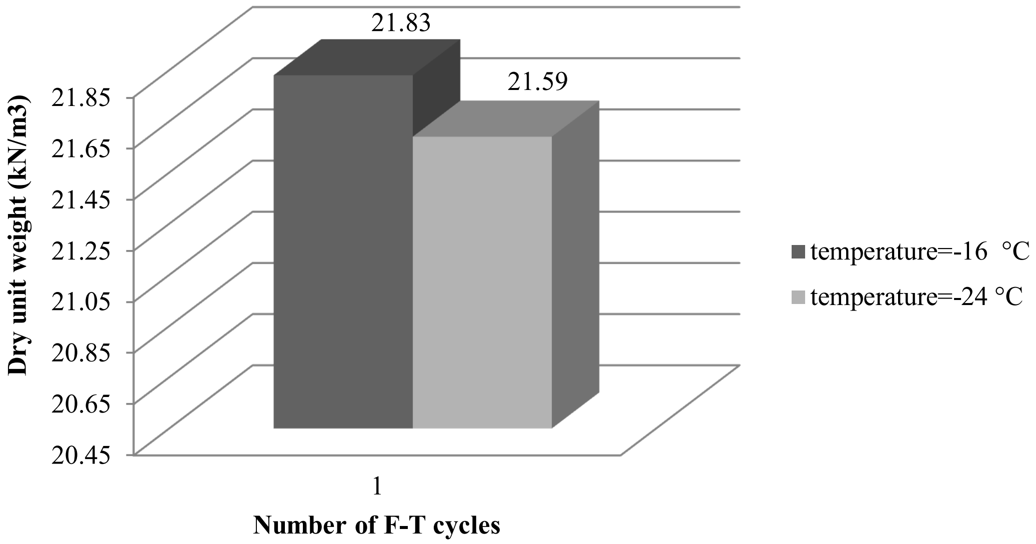


Figure 15. Dry unit weight at freezing temperatures of -16 and 24 °C.

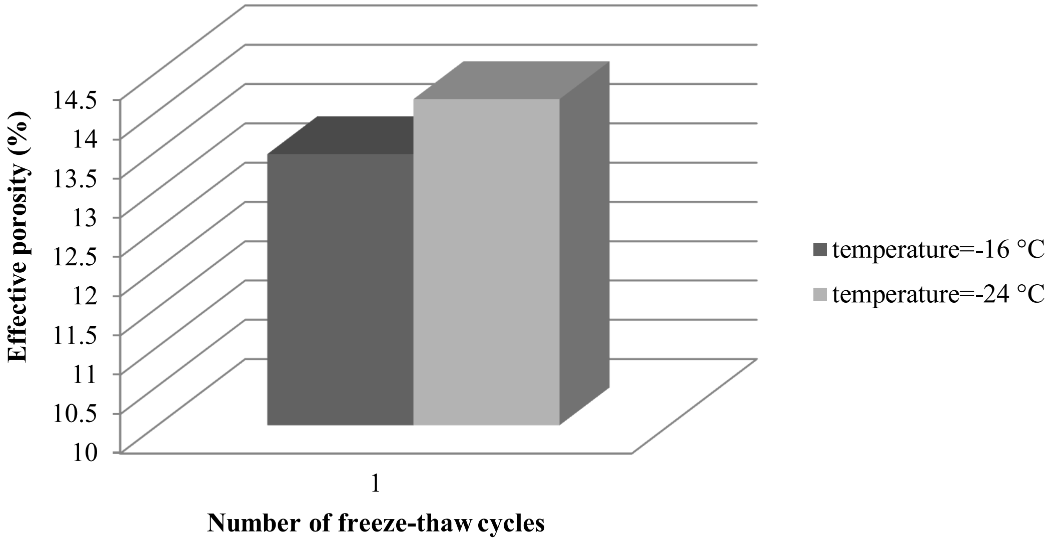


Figure 16. Effective porosity at freezing temperatures of -16 and 24 °C.

In contrast, the dry unit weight is higher at the freezing temperature of -16 °C than at -24 °C due to thermal stress because of the temperature difference. Thermal stress at the freezing temperature of -24 °C is higher than that at -16 °C. As a result, more cracks nucleate at -24 °C, leading to a lower strength and elastic modulus compared to -16 °C.

According to the results presented in Figures 7-16, one can say that F-T cycles have a significant impact on the strength parameters of the rock. Thus the effect of F-T cycles should be considered in numerical modeling for determining the elastic modulus and rock strength properties.

The CT scan images were also used to investigate the damage caused by the freezing process. The CT images of a specimen of sandstone under various F-T cycles are presented in Figure 17. In this technique, the darker region indicates a lower density, whereas the brighter region represents the materials with a higher density [23]. There is no visible difference between the images in Figure 17. Therefore, an appropriate parameter, referred to as the CT value, is required to measure the damage done to the specimen. This parameter is measured in Hu, which bears the name of Godfrey Hounsfield who contributed significantly to the invention of the CT scan. The CT value reflects the composition and the structure of materials [24].

The damage variable (D) (Eq. 6) is used to describe the damage caused by the F-T process based on the average CT [25].

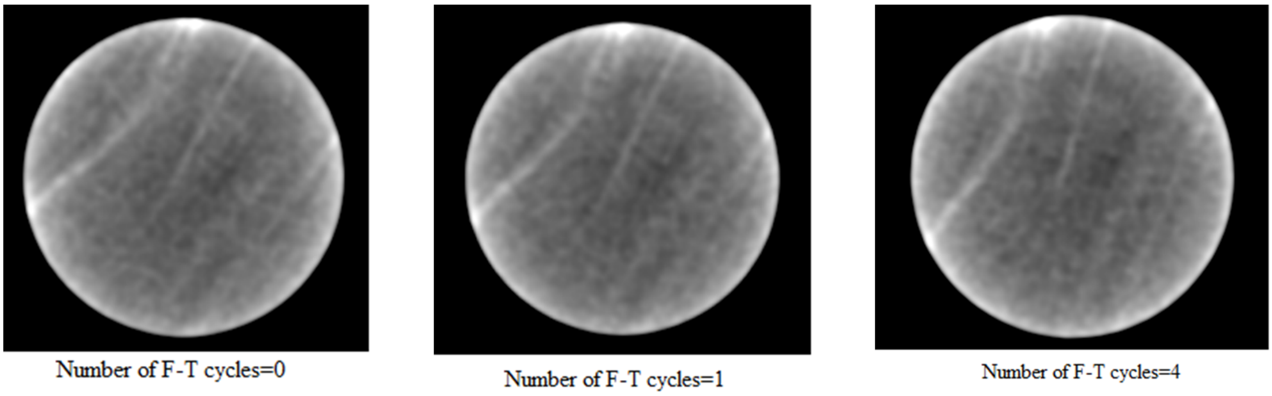
$$D = \frac{H_0 - H}{H_0} \tag{6}$$

where H is the average CT value for a specimen undergoing an F-T cycle and H_0 is the average CT value for a specimen that does not tolerate the F-T cycle.

The calculated values for the damage variable (D) are presented in Table 7. As seen, the damage to sandstone increases with increase in the number of F-T cycles. The CT values were calculated with the help of eFilm Workstation V. 4.2.2.

Table 7. CT values and damage variables after 1 and 4 F-T cycles.

Number of F-T cycles	CT value (Hu)	Damage Variable (%)
0	1764.10	0
1	1745.51	1.05
4	1734.23	1.69


Number of F-T cycles=0

Number of F-T cycles=1

Number of F-T cycles=4

Figure 17. CT scan image of sandstone at different F-T cycles.

5. Conclusions

Rocks are affected by long freezes and numerous F-T cycles in cold regions. This process results in the deterioration of rock strength properties. In this work, we investigated the effect of F-T cycles and freezing temperature on uniaxial and triaxial compressive strengths, and cohesion and internal friction angle of the Lushan sandstone. The results obtained are summarized as follow:

1) Uniaxial compressive strength and triaxial compressive strength decreased with increase in the number of F-T cycles and freezing temperatures. The rate of reduction of triaxial compressive strength was less than the uniaxial compressive strength.

2) The cohesion and internal friction angles of the rock specimens decreased with increase in the number of F-T cycles and freezing temperatures. The rate of cohesion reduction was greater than the internal friction angle.

3) The elastic modulus of the rock specimens decreased with increase in the number of F-T cycles. The rate of cohesion reduction in the first F-T cycle was higher than in other cycles.

4) The dry specific gravity of the specimens decreased with increase in the number of F-T cycles and reducing the freezing temperature. In contrast, the effective porosity increased due to the expansion of the existing cracks and the nucleation of the new ones.
5) The CT values obtained from the CT scan images decreased with increase in the number of F-T cycles, indicating an increase in the damage caused by the F-T process.
6) The relationships were also proposed to estimate the cohesion and elastic modulus after *N* F-T cycles.

Acknowledgments

This paper was funded by the Imam Khomeini International University. Thereby, the author expresses his gratitude to the related authorities (grant number: 11825).

References

[1]. Jabari, A. and Hosseini, M. (2017). An overview of the most common tests of the mode II fracture toughness performed on rock specimens. 10th National Congress on Civil Engineering. Faculty of Civil Engineering. Sharif University of Technology.

[2]. Zhou, K., Li, B., Li, J., Deng, H. and Bin, F. (2015). Microscopic damage and dynamic mechanical properties of rock under freeze-thaw environment. Trans. Nonferrous Met. Soc. China. 25: 1254-1261.

[3]. Nicholson, H., Dawn, T. and Nicholson, F.H. (2000). Physical deterioration of sedimentary rocks subjected to experimental freeze–thaw weathering. Earth Surface Processes and Landforms. 25: 1295-1307.

[4]. Yu, J., Chen, X,. Li, H., Zhou, J. and Cai, Y. (2015). Effect of freeze-thaw cycles on mechanical properties and permeability of red sandstone under triaxial compression. Journal of Mountain Science. 12B(1): 218-231.

[5]. Matsuoka, N. (2001). Direct observation of frost wedging in alpine bedrock. Earth Surface Processes and Landforms. 26: 601-614.

[6]. Mufundirwa, A., Fujii, Y., Kodama, N. and Kodama, J.I. (2011). Analysis of natural rock slope deformations under temperature variation: A case from a cool temperate region in Japan. Cold Regions Science and Technology. 65 (3): 488-500.

[7]. Zhang, S., Lai, Y., Zhang, X., Pu, Y. and Yu, W. (2004). Study on the damage propagation of surrounding rock from a cold-region tunnel under freeze–thaw cycle condition. Tunnelling and Underground Space Technology. 19 (3): 295-302.

[8]. Tan, X., Chen, W., Yang, J. and Cao, J. (2011). Laboratory investigations on the mechanical properties degradation of granite under freeze–thaw cycles. Cold Regions Science and Technology. 68 (3): 130-138.

[9]. Backers, T., Stephansson, O. and Rybacki, E. (2002). Rock fracture toughness testing Mode II punch-through shear test. International Journal of Rock Mechanics and Mining Sciences. 39 (6): 755-769.

[10]. Wang, P., Xu, J., Fang, X., Wang, P., Zheng, G. and Wen, M. (2017). Ultrasonic time-frequency method to evaluate the deterioration properties of rock suffered from freeze-thaw weathering. Cold Regions Science and Technology. 143: 13-22.

[11]. Özbek, A. (2014). Investigation of the effects of wetting–drying and freezing–thawing cycles on some physical and mechanical properties of selected ignimbrites. Bulletin of Engineering Geology and the Environment. 73 (2): 595-609.

[12]. Noor-E-Khuda, S., Albermani, F. and Veidt, M. (2017). Flexural strength of weathered granites: Influence of freeze and thaw cycles. Construction and Building Materials. 156: 891-901.

[13]. Liu, Q., Huang, S., Kang, Y. and Liu, X. (2015). A prediction model for uniaxial compressive strength of deteriorated rocks due to freeze- thaw. Cold Regions Science and Technology. 120: 96-107.

[14]. Li, J., Zhou, K., Liu, W. and Deng, H. (2016). NMR research on deterioration characteristics of microscopic structure of sandstones in freeze-thaw cycles. Trans. Nonferrous Met. Soc. China. 26: 2997-3003.

[15]. Martínez-Martínez, J., Benavente, D., Gomez-Heras, M., Marco-Castaño, L. and García-del-Cura, M.Á. (2013). Non-linear decay of building stones during freeze-thaw weathering processes. Construction and Building Materials. 38: 443-454.

[16]. Wang, P., Xu, J., Liu, S., Wang, H. and Liu, S. (2016). Static and dynamic mechanical properties of sedimentary rock after freeze-thaw or thermal shock weathering. Engineering Geology. 210: 148-157.

[17]. Momeni, A., Abdilor, Y., Khanlari, G.R., Heidari, M. and Sepahi, A.A. (2016). The effect of freeze-thaw cycles on physical and mechanical properties of granitoid hard rocks. Bulletin of Engineering Geology and the Environment. 75 (4): 1649-1656.

[18]. Khanlari, G., Sahamieh, R.Z. and Abdilor, Y. (2015). The effect of freeze-thaw cycles on physical and mechanical properties of Upper Red Formation sandstones, central part of Iran. Arabian Journal of Geosciences. 8 (8): 5991-6001.

[19]. Chen, Y., Wu, P., Yu, Q. and Xu, G. (2017). Effects of Freezing and Thawing Cycle on Mechanical Properties and Stability of Soft Rock Slope. Advances in Materials Science and Engineering.

[20]. Pettijohn, F.J., Potter, P.E. and Siever, R. (1987). Sand and Sandstone. New York Springer-Verlag.

[21]. ISRM, (2007). In: Ulusay, Hudson (Eds.), Suggested methods prepared by the commission on testing methods, International Society for Rock Mechanics. ISRM Turkish National Group, Ankara, Turkey.

[22]. Backers, T. and Stephansson, O. (2012). ISRM Suggested Method for the Determination of Mode II Fracture Toughness. Rock Mech Rock Eng. 45: 1011-1022.

[23]. Yao, W., Xu, Y., Wang, W. and Kanopolous, P. (2016). Dependence of dynamic tensile strength of longyou sandstone on heat-treatment temperature and loading rate. Rock Mechanics and Rock Engineering. 49 (10): 3899-3915.

[24]. Yao, W., Liu, H.W., Xu, Y., Xia, K. and Zhu, J. (2017). Thermal degradation of dynamic compressive strength for two mortars. Construction and Building Materials. 136: 139-152.

[25]. Huang, S. and Xia, K. (2015). Effect of heat-treatment on the dynamic compressive strength of Longyou sandstone. Engineering Geology. 191: 1-7.

اثر سیکل یخبندان- ذوب بر مقاومت و پارامترهای مقاومت سنگ (مطالعه موردی: ماسه‌سنگ لوشان)

مهدی حسینی[1]* و احمدرضا خدایاری[2]

۱-گروه مهندسی معدن، دانشگاه بین‌المللی امام خمینی (ره)، ایران
۲- دانشکده مهندسی معدن و متالورژی، دانشگاه صنعتی امیرکبیر، ایران

ارسال ۲۰۱۸/۱۰/۲۶، پذیرش ۲۰۱۸/۱۱/۲۶

* نویسنده مسئول مکاتبات: ma.hosseini@eng.ikiu.ac.ir

چکیده:

در حال حاضر، با توسعه مداوم اقتصاد در مناطق سردسیر در سراسر جهان، بسیاری از پروژه‌های سنگی از قبیل استخراج معادن و اکتشاف نفت و گاز در این مناطق در حال اجرا است. در استان‌های شمال غرب و غرب ایران که دارای تابستان‌های معتدل و زمستان‌های سرد می‌باشند، بارندگی زیاد و برودت هوا از مشخصات زمستان‌های این مناطق به شمار می‌آید. در این شرایط سنگ تحت تأثیر یخبندان‌های طولانی و چرخه‌های متعدد یخبندان- ذوب قرار می‌گیرند. بنابراین ضروری است که تأثیر این فرایندها بر روی خواص فیزیکی و مکانیکی سنگ بررسی شود. با توجه به گستردگی ماسه‌سنگ در ایران این پژوهش روی ماسه‌سنگ لوشان انجام شده است. هدف این پژوهش بررسی اثر تعداد سیکل‌های انجماد- ذوب و اثر دمای انجماد روی مقاومت تراکم تک‌محوری، مقاومت تراکم سه محوری، چسبندگی، زاویه اصطکاک داخلی و مدول الاستیسیته است. برای بررسی اثر تعداد سیکل‌های یخبندان-ذوب روی مقاومت و خواص مقاومتی سنگ، نمونه‌هایی که تحت دمای ۱۶- درجه سانتی‌گراد منجمد شده‌اند و به ترتیب ۱، ۴، ۸، ۱۶ و۳۲ سیکل یخبندان- ذوب را تحمل کرده‌اند مورد آزمایش قرار گرفتند. یک سری آزمایش هم روی نمونه‌هایی که تحت دمای ۲۴- درجه سانتی‌گراد منجمد شده‌اند و یک سیکل انجماد- ذوب را تحمل کرده‌اند انجام شد. علاوه بر این یک سری آزمایش هم بر روی نمونه‌هایی که سیکل انجماد- ذوب را تحمل نکرده‌اند در دمای محیط (۲۵ درجه سانتی‌گراد) انجام شد. نتایج نشان می‌دهد که با افزایش تعداد سیکل‌های انجماد- ذوب و دمای انجماد، مقاومت تراکم تک‌محوری، مقاومت تراکم سه محوری، چسبندگی، زاویه اصطکاک داخلی و مدول الاستیسیته کاهش می‌یابد. علت این کاهش گسترش ترک‌های قبلی و ایجاد ترک‌های جدید در نمونه است و در اثر آن تخلخل مؤثر با افزایش تعداد سیکل‌های انجماد- ذوب و دمای انجماد افزایش و وزن مخصوص خشک کاهش می‌یابد.

کلمات کلیدی: سیکل یخبندان- ذوب، ماسه‌سنگ، پارامترهای مقاومتی، مقاومت تراکم سه محوری.