International Journal of Mining and Geo-Engineering IJMGE

IJMGE 54-2 (2020) 147-152 DOI: 10.22059/ijmge.2019.271982.594771

The effects of temperature on mechanical properties of rocks

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Article History:
Received: 22 December 2018,
Revised: 27 April 2019 ,
Accepted: 13 May 2019.

ABSTRACT

In a natural condition, temperature variations and phase transition of pore water are the two most effective factors on the mechanical properties of rocks. Instabilities occurred as a result of climate changes, highlight the importance of rock characteristics. This paper conducted a laboratory investigation to study the temperature-dependent mechanical behavior of rocks and to examine the quantity and quality of this relationship. In order to perform laboratory tests, a temperature-controlling apparatus was developed. Studies were conducted on 152 specimens of concrete and three types of rocks, including granite, red travertine, and walnut travertine. Then, the effect of temperature variations, from -30 to +30ºC with 10ºC intervals on the mechanical properties of the rocks, was studied. The results showed that temperature reduction, caused by pore water phase transition, improved the mechanical properties of the rocks. The maximum variation of the mean uniaxial compressive strength from +30ºC to -30ºC belonged to granite (40.1%), while the concrete specimen showed the minimum variation on the test results (33.7%). Red travertine (38.7%) and walnut travertine (34.2%) exhibited lower variations compared to granite. Also, the maximum variation in the mechanical behavior of rocks occurred between -10 and 0 °C. Additionally, variations in the mechanical properties of cracked rock samples were more than the rocks with spherical pore and the same porosity percent.

Keywords : *Temperature, Mechanical behavior, Travertine, Granite, Concrete*

1. Introduction

In recent years, the effect of temperature on the mechanical properties of rocks has attracted the attention of many researchers in the field of rock mechanics [1, 2]. Geological disasters and rock engineering phenomena that involve freezing, thawing, and permeating frequently occur all over the world in many structures, such as rock slopes, sliding, landslides, tunnels, and so on [3]. The physical and mechanical properties of rocks, mineral composition, and microstructure of materials change with temperature variations [4, 5]. Those changes may cause irreparable loss if there are no good remedial measures. The mechanical properties of rocks are influenced by temperature, among other factors, and the results of research on this factor can be valuable for improving the safety of some rock engineering projects [6].

Physical and chemical processes can changes rock engineering parameters. The physical processes that cause disintegration in the rocks are salt bursting, wetting-drying, heating-cooling, and freezing-thawing [7]. In cold regions, pore and fissure waters existing in the rock mass usually cause the freeze-thaw cycle effect, as the temperature changes. This effect is one of the main factors influencing the deterioration of the mechanical properties of rocks in cold regions, affecting the selection of rock mass parameters [8]. When the phase transition of water occurs in rocks, it affects the mechanical properties of the rock mass in two important ways. First, by fully or partially filling pores and cracks with ice, the average of the initial porosity is reduced, and the cracks are immobilized by bridging the side walls. Second, ice in the pores increases the fracture strength of the rock. Celik et al. (2014) [9] showed that with the freezing of water, which happens in the porosities, the strength of building stones is increased. This strengthening may be attributed to an increase in the effective coefficient of static friction for sliding on the cracks [10]. Thus, due to the presence of ice, the frozen rock can adopt different behaviors, as compared with the unfrozen one.

Currently, studies on the effects of the freeze-thaw cycle on the rock mass are mainly focused on laboratory tests [2,11-18]. The effect of the freeze-thaw cycle on the deterioration degree has been proved to be connected with the moisture content [14]. Ruedrich and Siegesmund (2007) [19] emphasized the importance of saturation in the damage caused by the freeze-thaw cycle for porous sandstones. Chen et al. (2004) [20] studied the effect of saturation on the freeze-thaw damage of highly porous welded tuff samples, finding that the porosity and rock damage were increased significantly when the initial degree of saturation exceeded 70 %. Although laboratory research studies have had many valuable achievements, it is still unknown how these results can be used to select rock mass parameters in cold regions for engineering projects.

This paper investigates the effect of temperature variations on the mechanical properties of rocks and their behavior. Investigations were performed on more than 150 specimens of concrete and three rock types, including granite, red travertine, and walnut travertine; then, the mechanical properties were obtained at the laboratory scale. Based on the laboratory tests, the mechanical characteristics were measured at different temperatures ranging from -30 to +30 °C with an increment of 10°C. Also, the stress-strain curves of the samples were analyzed at three temperatures (-30, 0, and +30°c). The rock properties that were selected included: the uniaxial compressive strength (UCS), which is the most important rock property used in rock mechanics; P-wave velocity test that provides an accurate estimation of the pore water phase transition;

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and finally, the stress-strain curves of rocks that can perfectly show the temperature dependency of the rock behavior under uniaxial loading. In this research, after introducing the rock samples and their characteristics, the experimental methods and their results were studied.

2. Test procedure

Thermal balance takes a long period of time to happen in rocks, which are materials with low conductivity, insofar at least 2 hours is proposed for a small rock lab specimen. To control the temperature during the loading process, a temperature-controlling apparatus with a sensibility of ±3° C was produced to control and decrease the temperature down to -35° C.

2.1. Temperature-controlling apparatus

The temperature-controlling apparatus had two containers, the electric container, which surrounded the refrigerator engine, and the cooling system with an outer dimension of 45×50×50 cm and an inner dimension of 20×20×50 cm. The outer dimension of the freezing container was 30×30×60 cm, which could be easily fitted into the loading apparatus with 35 cm width and 40 cm height. In order to place in and remove the samples easily during the tests, there was a gate of 10×15 cm in front of the container. In order to the load samples into the apparatus, two circular holes of 6.5 cm in diameter were devised at the upper and lower surfaces (Fig.1 (a)). To apply load to the samples, two hard steel fixtures were produced as well. These fixtures had two parts with different diameters. One had a diameter of 10 cm and a length of 2.5 cm, and it was in contact with the loading apparatus. The other one had a diameter of 6.4 cm (less than two times the diameter of samples) and a length of 12.5 cm, which was placed into the apparatus to apply a definite load. The sample would be placed between these two parts during the tests. There was a 1 mm difference between the diameter of the fixture and the hole of the freezing containers in order to move them freely and to reduce heat loss within the two parts. When the apparatus stabilized the samples' temperature, a plastic cover would be used to decrease the temperature between the upper jaw and the refrigerator hole (Fig 1 (b)).

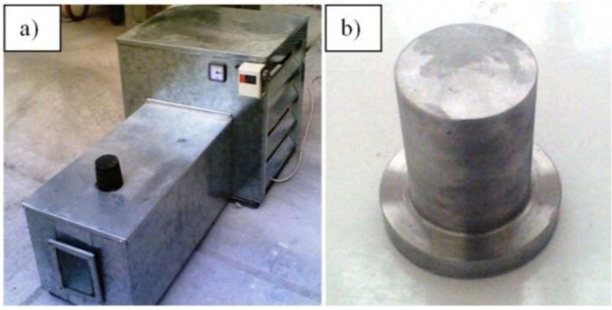

Fig. 1. a) Temperature adjusting apparatus, and b) Loading fixture.

3. Preparation of specimens

This study was performed on four different types of specimens: concrete (artificial rock), granite, and two types of travertine (see Fig. 2). 152 cylindrical specimens were prepared by coring large blocks of rocks in the same directions. In the samples, no artificial crack or joint was created, and the rocks were intact. The description of the samples is given in Table 1.

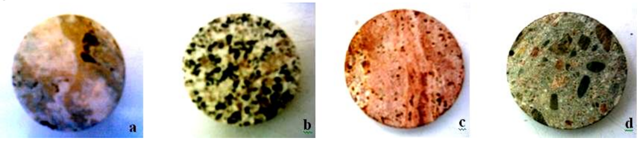

Fig. 2. Sections of rock samples: a) walnut travertine, b) granite, c) red travertine, and d) concrete.

Table 1. Description of the samples.

Rock class	Rock type	Rock name	Location	Number of specimens
Sedimentary	Travertine I	Red Travertine	Ahar	40
Sedimentary	Travertine II	Walnut Travertine	Azarshahr	38
Igneous	Granite	Ahar Granite	Ahar	38
Artificial	Concrete	Concrete	-	36

The ordinary Iran Portland Cement (corresponding to ASTM type 1) was used for the production of the concrete samples. In this study, the compressive specimens of concrete were cast in 150×150×150 mm cubic steel molds, so they had no cracks or flaws. During the first day after casting, the cubes were stored in the molds at a temperature of 30(±5) °C. They were prevented from drying by being covered with a plastic sheet. Freshly cast specimens were kept in the mold for 24 hours during which they were demolded. Then, all of the specimens were stored in the standard curing conditions of the room (30(±5) °C). When the cubes were 28 days old, they were removed, and the cylindrical samples were prepared by coring these concrete blocks. The largest grain size of the composition, W/C, and slump were 9.5 mm, 0.46, and 16 mm, respectively. The ingredient composition of the concrete used in the laboratory studies is given in Table 2.

Table 2. The ingredient composition of the concrete samples.

Material	Weight (kg)	Mixing ratio (kg/m^3)
Gravel	28.5	840
Sand	32.5	957
Cement	14.1	415
Water	6.5	191
Plasticizer	0.212	6.25

4. Petrographic studies

Petrographic studies of the rock samples consisted of routine observations and measurements on thin-section slides under the polarized microscope. The petrographic characteristics that are known to affect the mechanical properties of rocks include grain size, packing density, packing proximity, degree of grain interlocking, void space, and mineral composition. The petrographic characteristics such as mineral composition and microstructures are the important parameters affecting the rock strength. Thin-section slides were prepared in different directions perpendicular, parallel, and a 45-degree angle, relative to the vertical axis of the specimens.

The photomicrographs of the samples are shown in Fig. 3. A comparison of two types of travertine specimens showed that the grain size in the red travertine was finer than that of the walnut one. The voids in the walnut travertine were interconnected, perpendicular to the core axis, but not parallel to it. The pores in the red travertine were larger and scattered in all directions and disjointed. In the walnut travertine, dolomitization was observed. The concrete specimen contained calcium carbonate, which showed the proper congruence with cement. The specimens contained two types of voids: the 1st type between cement and the grains, especially those with a different chemical compound. The 2nd type of pores in cement was due to the presence of air or gas escape. The granite specimens contained high values of the acidic compound with high values of plagioclase, orthoclase, and quartz; other compounds were amphiboles, which were chloritic and weathered. The alteration degree of the specimen was medium. In some crystals, microcracks had been filled with calcite. Microscopic studies verified the presence of structural defects and secondary porosities in granite specimens.

5. Mechanical properties of the samples

This section briefly describes measurement techniques that were used to investigate the mechanical properties of the rock specimens.

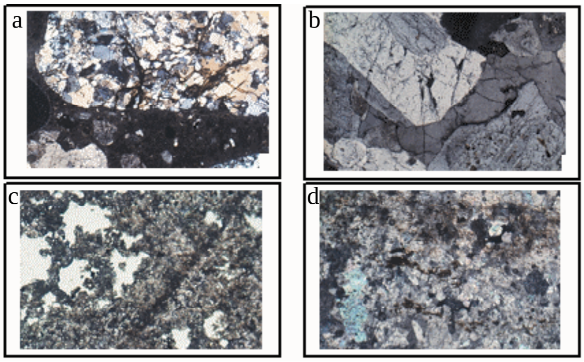

Fig. 3. Photomicrographs of the rock samples: a. concrete b. granite c. red travertine, and d. walnut travertine.

5.1. Uniaxial compressive strength

The uniaxial loading apparatus was used to calculate the uniaxial strength of the specimens. The apparatus applied a maximum force of 2000 KN and elastic energy of 2100 J. The surface area of its loading plate was equal to 400 cm^2. In this study, the uniaxial compression tests were carried out on 152 cylindrical specimens with a diameter of 46 mm and a length of 100 mm. They were prepared by coring and cutting from larger blocks. The bottom of the specimens was flatted about 0.02 mm. The load was applied to the specimens at a constant stress rate of 0.5-1.0 MPa/s. Before starting to test, all of the rock samples were saturated in water because the tests were aimed to investigate the influence of temperature on saturated rocks. For each type of rock, at least three specimens were used at each temperature. The specimens stayed inside the temperature-controlling apparatus with the temperature fluctuation of ±3ºC for at least 2 hours, depending on the experiment temperature.

5.2. P-wave velocity

In practice, the compressional wave velocity is a prominent geophysical parameter for the differentiation of frozen and unfrozen underground spaces [22]. The PUNDIT instruments with a frequency of 54 kHz were used to measure the velocity of the P-wave. The direct transmission method, which is more sensitive than the other methods, was preferred for the measurement of the P-wave velocities of rocks. The faces of the samples were trimmed perpendicular to the axis of the specimens to provide the tight contact of transducers with the face of the specimen. Constant pressure was applied systematically to ensure the tight contact between the rock specimen and the transducers. After fixing the sample temperature in the provided apparatus for 2 hours, the velocity was calculated from the ratio of the travel distance to the travel time of the P-wave through the rock sample. The P-wave velocity was measured at 30 ºC. The study was done on both dry and saturated states. In the saturated state, the specimens were saturated by submerging in distilled water; as for the dry case, the specimens were dried in the oven at 105ºc for a period of at least 24 hours.

5.3. Deformation characteristics (axial stress-strain curves)

UTM apparatus, which is a hydraulic servo-controlling machine, was used to obtain the displacement-load data in this study. The maximum load that could be applied by this apparatus was 50ton. The loading rate was 0.005m/s, and it was controlled by displacement. The test specimens were prepared in the same procedure applied for the specimens used in the UCS tests.

6. Experiment test results and discussion

Many researchers have studied the effects of temperature on the mechanical properties of rocks. These studies have revealed that the phase transition of pore water is the most important factor in this case [10, 23-24]. Here, the results of the study on the samples discussed in the previous section are presented:

6.1. P-wave velocity

The values of P-wave velocity were determined by applying the ultrasonic compression wave pulses to the specimens. The average P-wave velocity and the standard deviation of the dry and saturated specimens at +30 ºC and -30 ºC, as well as their comparison, are given in Table 3.

Table 3. P-wave velocity (m/s) for the dry and saturated rock samples at +30ºC & -30ºC.

Rock type	$V_{p(\mathrm{dry})}$ +30ºC		$V_{p(\mathrm{dry})}$ -30ºC		Increase	$V_{p(\mathrm{sat})}$ +30ºC		$V_{p(\mathrm{sat})}$ -30ºC		Increase
	mean	S.D	mean	S.D	(~%)	mean	S.D	mean	S.D	(~%)
R-Travertine	3901	133	4073	165	4.4	4856	87	5672	104	16.8
W-Travertine	3911	140	4159	171	6.3	4959	102	5563	56	12.3
Granite	4054	177	4190	128	4.6	4984	170	5701	109	14.4
Concrete	4386	55	4486	33	2.3	4541	88	4966	35	9.3

The effect of temperature on the deterioration degree was proved to be connected with the moisture content [14]. The laboratory studies in this research showed that, for the dry cases, the variation of the P-wave velocity at the minimum and maximum temperatures in the walnut travertine (6.3%) was higher than that of the red one (4.4%). However, for the saturated mode, the variation of velocity in the red travertine (16.8%) was higher than that of the walnut travertine (12.3%), which could be was because of the size distribution of pores, as seen in the photomicrographs of the rock samples. The pores in the red travertine were larger, which were distributed almost uniformly in the specimens; therefore, it can be concluded that in saturated rocks, variations of the P-wave velocity due to freezing can be a function of porosity. The results obtained for granite and concrete indicate that the differences in the rock type, grain size, and mineralogical components can affect the temperature dependency of the rocks. Variation of the P-wave velocity in granite with low porosity revealed the differences in the mineralogical composition and texture. Hence, porosity, rock-forming components, grain size, and alteration were effective on the freeze-thaw resistance.

6.2. Mechanical behavior of rock samples under the uniaxial compression tests

Landmark, in his studies on concrete, considered the shape of pores in porous materials and pointed out the importance of the pore radius and connectivity in determining the freezing point. Water-ice transition is defined by the critical radius, which is a function of temperature and energy balance and is dependent on the pore radius. By reducing the pore radius, the freezing point of pure water is decreased. Sammis and Biegel [10] also stated that when water in the cracks of a crystalline rock is frozen, it affects the mechanical properties of the rock mass in two ways. First, by immobilizing some cracks and bridging others, it reduces the average size and density of the initial cracks. Second, ice in the cracks increases the fracture strength of the rock.

The results of UCS at -30 and 30˚C are given in Table 4. The results show that the maximum variation of UCS belonged to granite (40.1%), while concrete (33.7%) showed the minimum variation on the test results. Travertine showed lower variations than granite; the reasons could be the shape of pores or the effect of dimension on this phenomenon. As for the travertine rocks, the variation in the compression strength of red travertine (38.7%) was more than that of walnut travertine (34.2 %). This, as mentioned for the P-wave velocity from photomicrographs, can be attributed to the distribution and size of pores.

Table 4. UCS of the dry rock samples at +30ºC & -30ºC and the increase rate.

No	rock type	σ at +30ºC (MPa)		σ at -30ºC (MPa)		Increase
		mean	S.D	mean	S.D	(~%)
1	Red Travertine	38.31	2.32	53.13	3.54	38.7
2	Walnut Travertine	41.52	2.35	55.71	3.45	34.2
3	Granite	66.16	4.95	92.67	6.61	40.1
4	Concrete	28.81	2.51	38.53	3.67	33.7

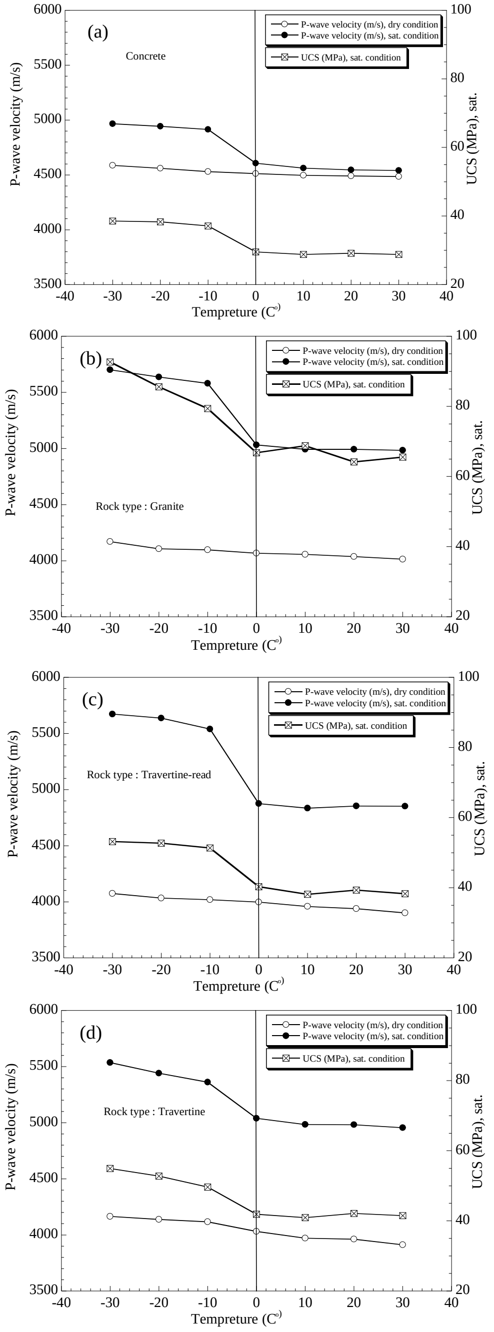

Fig. 4. The effects of temperature on the P-wave velocity and UCS; (a) concrete, (b) granite, (c) red travertine, and (d) walnut travertine.

A significant amount of information about the material can be obtained based on the analysis of the processes and parameters coupled with the propagation of the elastic wave inside the rock [25]. Fig. 4 illustrates the effects of temperature on the P-wave velocity and UCS. The interconnection of the P-wave velocity and UCS is generally a positive relationship, although there have been many exceptions [26]. Laboratory studies in this research also proved this positive relationship. Increasing the temperature and the formation of new cracks, as well as the expansion of existing cracks, decreased the P-wave velocity and UCS.

Numerous researchers have studied the deformation and fracture characteristics of the rocks. Bieniawski [27] defined these stages as follows: crack closure, linear elastic deformation, crack initiation, and stable crack growth, critical energy release, and unstable crack growth, failure, and post-peak behavior. This division is applicable to all rocks. The stress-strain curves of the uniaxial compressive tests at -30 and +30ºC are shown in Fig. 5. Granite samples had a low initial strength, which extremely varied during water pore freezing. On the other hand, travertine, with almost high porosity and low strength, showed more strength variations during freezing. Generally, axial stress-strain curves show that the temperature drop below 0ºC would lead to an increase in strength and elasticity modulus. Comparing the curves indicated that at -30ºC, the section with the elastic behavior was increased, and there was no meaningful difference between the curves between 0 and 30ºC.

6.3. Discussions

In this study, the mechanical properties of different rocks were studied by developing a temperature-adjusting apparatus. The tests were performed on granite, travertine, and concrete samples at [-30, 30] ˚C with 10ºC intervals. The conducted laboratory studies on the mechanical properties of saturated samples showed that the P-wave velocity would increase by decreasing the temperature from +30 to -30˚C (about 10% to 20%), and UCS would be enhanced (about 30% to 40%), in the same condition. These results are consistent with previous studies conducted by Liu and Xu (2015) [2], Hosseini (2017) [16] and Chen et al. (2017) [17] on the mechanical properties of igneous rocks, and those of Kolay (2016) [7], Hosseini (2017) [16] and Lu et al. (2017) [4]on the mechanical properties of sedimentary rocks. The temperature reduction improved rock properties, but the amount of the effect depended on the initial cracks existing in the rock. In this case, one of the most important initial properties was porosity. Since the two types of travertine used in this research had the same genesis, a comparison of their behavior is valuable. The results showed different magnitudes of porosity, and the behavior of these rocks could be improved by freezing the water pore, with a direct dependency on their porosity percentage. However, in granite and concrete samples, with different genesis, other factors such as mineralogy and pores' shape could become more meaningful. The granitic samples used in this investigation showed the maximum dependency on temperature against its minimum porosity. The most significant property discussed as the reason for this phenomenon is the pores' shape and the relationship between the joints and microfractures that could reduce the rocks' strength more than the spherical pores. Nicholson (2000) [14] showed that the presence or absence of rock defects alone could not control the deterioration mode; rather, it was the relationship among these flaws, rock strength, and textural properties, which exerted the greatest influence. So, when water freezes in these joints, a new intact body of rock will be produced, and the probable sliding faces will be prevented; then, the fracturing occurs inside the new body rock, while spherical pores need to be cracked before the formation of the slide surface, in which ice acts as a new mineral. Besides, the nucleation and growth of ice, as well as water migration, can be easier in the cracks than the spherical pores. The mechanism for the rock freeze-thaw damage is as follows. Water in micropores expands about 9% of the original volume; when the rock is frozen at low temperatures, this expansion induces a tensile stress concentration and damages the micropores; when the rock is thawed, water flows through the fractured micropores, which increases the damage.

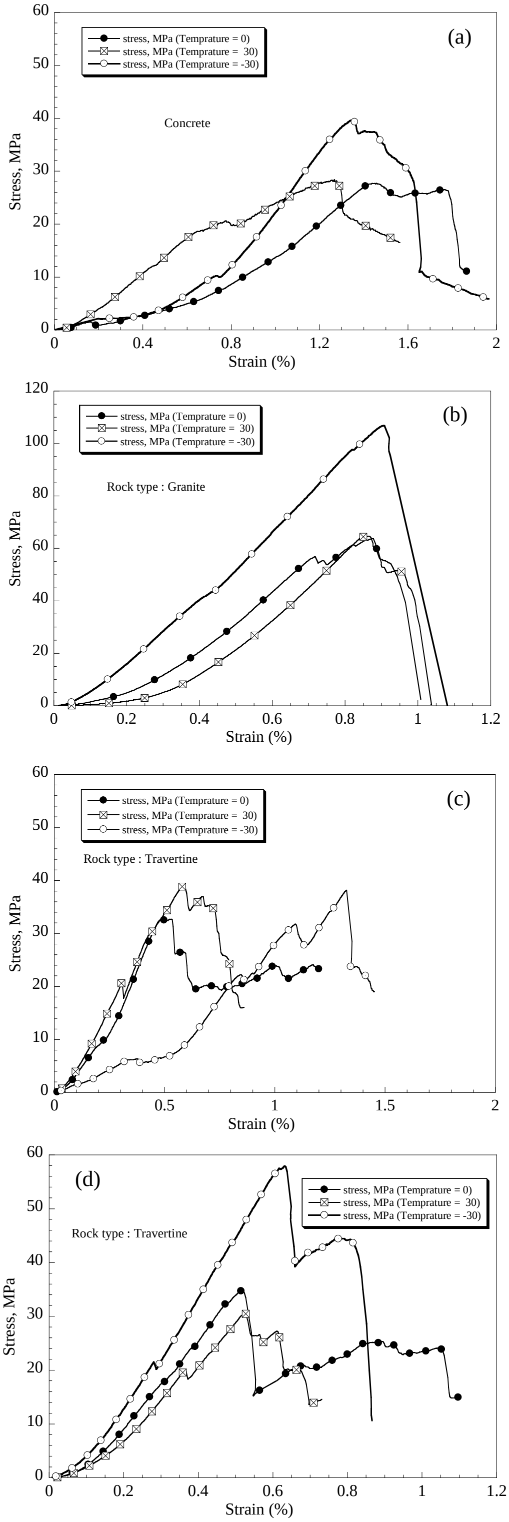

Fig. 5. Stress-strain curves for (a) concrete, (b) granite, (c) red travertine, and (d) walnut travertine.

7. Conclusions

In this research, the dependency of dry and saturated rocks on the temperature was studied using a temperature-adjusting apparatus. Laboratory studies were carried out on 152 specimens of concrete and three rock types, with temperature variations from -30 to +30ºC, and 10ºC intervals. Also, the P-wave velocity and the uniaxial compression strength of different rock specimens were determined.

The laboratory studies on the mechanical behavior of the rock samples showed that the maximum variation of the uniaxial compressive strength from +30ºC to -30ºC belonged to granite (40.1%). The concrete sample, however, showed the minimum variation on the test results (33.7%). The uniaxial compressive strength of the red travertine (38.7%) and the walnut travertine (34.2%) exhibited lower variations compared to granite. Also, in the dry specimens, the variations of the P-wave velocity at the maximum and minimum temperature in the walnut travertine (6.3%) were higher than those in the red travertine (4.4%). Variations of the P-wave velocity in granite (3.4) with low porosity showed the differences in the mineralogical composition and texture. Finally, the concrete specimens exhibited lower variations (2.3%).

Experimental results also revealed that the dependency of the mechanical properties of rocks on the porosity magnitude was not absolute, and other factors such as the shape and form of pores were important as well. Also, the changes in the rock properties were negligible above 0ºC, and considerable below 0ºC. Most of the pore water phase transition occurred in [-10, 0] ºC. Below -10ºC, as the temperature dropped, the property changes decreased, meaning the reduction in the phase transition

REFERENCES

[1] Lu, Z., Xian, S., Yao, H., Fang, R., & She, J. (2019). Influence of freeze-thaw cycles in the presence of a supplementary water supply on mechanical properties of compacted soil. *Cold Regions Science and Technology*, 157, 42-52.

[2] Liu, S., & Xu, J. (2015). An experimental study on the physico-mechanical properties of two post-high-temperature rocks. *Engineering Geology*, 185, 63-70.

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

[4] Lu, C., Sun, Q., Zhang, W., Geng, J., Qi, Y., & Lu, L. (2017). The effect of high temperature on tensile strength of sandstone. *Applied Thermal Engineering*, 111, 573-579.

[5] Su, H., Jing, H., Yin, Q., & Yu, L. (2018). Effect of thermal environment on the mechanical behaviors of building marble. *Advances in Civil Engineering*, 1-8.

[6] Chen, Y.L., Ni, J., Shao, W., & Azzam, R. (2012). Experimental study on the influence of temperature on the mechanical properties of granite under uniaxial compression and fatigue loading. *International Journal of Rock Mechanics & Mining Sciences*, 56, 62-66.

[7] Kolay, E. (2016). Modeling the effect of freezing and thawing for sedimentary rocks. *Environmental Earth Sciences*, 75, 210.

[8] Luo, X., Jiang, N., Fan, X., Mei, N., & Luo, H. (2015). Effects of freeze-thaw on the determination and application of parameters of slope rock mass in cold regions. *Cold Regions Science and Technology*, 110, 32-37.

[9] Celik, M.Y., Akbulut, H., & Ergul, A. (2014). Water absorption process effect on strength of Ayazini tuff, such as the uniaxial compressive strength (UCS), flexural strength and freeze and thaw effect. *Environmental Earth Sciences*, 71(9), 4247-4259.

[10] Sammis, C.G., & Biegel, R.L. (2005). Seismic radiation from explosion in frozen crystalline rock. *27th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, Rancho Mirage, California.

[11] Nicholson, D.T., & Nicholson, F.H. (2000). Physical deterioration of sedimentary rocks subjected to experimental freeze–thaw weathering. *Earth Surface Processes and Landforms*, 25(12), 1295-1307.

[12] Xu, G., & Liu, Q.S. (2005). Analysis of mechanism of rock failure due to freeze–thaw cycling and mechanical testing study on frozen–thawed rocks. *Chinese Journal of Rock Mechanics and Engineering*, 24(17), 3076-3082.

[13] Takarli, M., Prince, W., & Siddique, R. (2008). Damage in granite under heating/cooling cycles and water freeze–thaw condition. *International Journal of Rock Mechanics & Mining Sciences*, 45(7), 1164-1175.

[14] Tan, X., Chen, W., Yang, J., & 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.

[15] Kodama, J., Goto, T., Fujii, Y., & Hagan, P. (2013). The effects of water content, temperature and loading rate on strength and failure process of frozen rocks. *International Journal of Rock Mechanics & Mining Sciences*, 62, 1-13.

[16] Hosseini, M. (2017). Effect of temperature as well as heating and cooling cycles on rock properties. *Journal of Mining & Environment*, 8(4), 631-644.

[17] Chen, S., Yang, C., & Wang, G. (2017). Evolution of thermal damage and permeability of Beishan granite. *Applied Thermal Engineering*, 110, 1533-1542.

[18] Lu, Y., Liu, S., Alonso, E., Wang, L., Xu, L., & Li, Z. (2019). Volume changes and mechanical degradation of a compacted expansive soil under freeze-thaw cycles. *Cold Regions Science and Technology*, 157, 206-214.

[19] Ruedrich, J., & Siegesmund, S. (2007). Salt and ice crystallisation in porous sandstones. *Environmental Geology*, 52(2), 225-249.

[20] Chen, T.C., Yeung, M.R., & Mori, N. (2004). Effect of water saturation on deterioration of welded tuff due to freeze–thaw action. *Cold Regions Science and Technology*, 38(2-3), 127-136.

[21] ISRM. (2007). The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. In R. Ulusay & J. A. Hudson (Eds.), Suggested methods prepared by the commission on testing methods (pp. 137–140). Ankara: International Society for Rock Mechanics, Compilation Arranged by the ISRM Turkish National Group.

[22] Hauck, C. (2001). Geophysical methods for detecting permafrost in high mountains (Doctoral Dissertation). ETH Zurich, Zurich, Switzerland.

[23] Ghobadi, M.H., Beydokhti, A.R.T., Nikudel, M.R., Asiabanha, A., & Karakus, M. (2016). The effect of freeze–thaw process on the physical and mechanical properties of tuff. *Environmental Earth Sciences*, 75, 846.

[24] Hale, P. A., & Shakoor, A. (2003). A laboratory investigation of the effect of cyclic heating and cooling, wetting and drying, and freezing and thawing on the comprehensive strength of selected sandstones. *Environmental and Engineering Geoscience*, 9(2), 117–130.

[25] Concu, G., Nicolo, B.D., & Valdes, M. (2014). Prediction of building limestone physical and mechanical properties by means of ultrasonic P-wave velocity. *The Scientific World Journal*, 1-8.

[26] Ding, Q.L., Song, S.B. (2016). Experimental investigation of the relationship between the P-wave velocity and the mechanical properties of damaged sandstone. *Advances in Materials Science and Engineering*, 1-10.

[27] Bieniawski, Z.T. (1967). Mechanism of brittle fracture of rock, Part I: theory of the fracture process. *International Journal of Rock Mechanics and Mining Sciences*, 4(4), 395-406.