The effects of temperature on mechanical properties of rocks

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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 +30°C with 10°C 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 +30°C to -30°C 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 change 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;...
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 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>
<thead>
<tr>
<th>Rock class</th>
<th>Rock type</th>
<th>Rock name</th>
<th>Location</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary</td>
<td>Travertine I</td>
<td>Red Travertine</td>
<td>Ahar</td>
<td>40</td>
</tr>
<tr>
<td>Sedimentary</td>
<td>Travertine II</td>
<td>Walnut Travertine</td>
<td>Azarshahr</td>
<td>38</td>
</tr>
<tr>
<td>Igneous</td>
<td>Granite</td>
<td>Ahar Granite</td>
<td>Ahar</td>
<td>38</td>
</tr>
<tr>
<td>Artificial</td>
<td>Concrete</td>
<td>Concrete</td>
<td></td>
<td>36</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (kg)</th>
<th>Mixing ratio (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>28.5</td>
<td>840</td>
</tr>
<tr>
<td>Sand</td>
<td>32.5</td>
<td>957</td>
</tr>
<tr>
<td>Cement</td>
<td>14.1</td>
<td>415</td>
</tr>
<tr>
<td>Water</td>
<td>6.5</td>
<td>191</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>0.212</td>
<td>6.25</td>
</tr>
</tbody>
</table>

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.
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 °C. 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 105°C 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 50 tons. The loading rate was 0.005 m/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 °C and -30 °C, as well as their comparison, are given in Table 3.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>( V_{p(dry)+30^\circ C} ) mean (m/s)</th>
<th>SD</th>
<th>( V_{p(dry)-30^\circ C} ) mean (m/s)</th>
<th>SD</th>
<th>( \text{Increase} % )</th>
<th>( V_{p(sat)+30^\circ C} ) mean (m/s)</th>
<th>SD</th>
<th>( V_{p(sat)-30^\circ C} ) mean (m/s)</th>
<th>SD</th>
<th>( \text{Increase} % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Travertine</td>
<td>3901</td>
<td>133</td>
<td>4073</td>
<td>165</td>
<td>4.4</td>
<td>4856</td>
<td>87</td>
<td>5672</td>
<td>104</td>
<td>16.8</td>
</tr>
<tr>
<td>W-Travertine</td>
<td>3911</td>
<td>140</td>
<td>4159</td>
<td>171</td>
<td>6.3</td>
<td>4959</td>
<td>102</td>
<td>5563</td>
<td>56</td>
<td>12.3</td>
</tr>
<tr>
<td>Granite</td>
<td>4054</td>
<td>177</td>
<td>4190</td>
<td>128</td>
<td>4.6</td>
<td>4984</td>
<td>170</td>
<td>5701</td>
<td>109</td>
<td>14.4</td>
</tr>
<tr>
<td>Concrete</td>
<td>4386</td>
<td>55</td>
<td>4486</td>
<td>33</td>
<td>2.3</td>
<td>4541</td>
<td>88</td>
<td>4966</td>
<td>35</td>
<td>9.3</td>
</tr>
</tbody>
</table>

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 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.
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 +30°C & -30°C and the increase rate.

<table>
<thead>
<tr>
<th>No</th>
<th>rock type</th>
<th>(\sigma_{\text{at } +30^\circ\text{C}}) (MPa)</th>
<th>S.D</th>
<th>(\sigma_{\text{at } -30^\circ\text{C}}) (MPa)</th>
<th>S.D</th>
<th>Increase (% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Red Travertine</td>
<td>38.31</td>
<td>2.32</td>
<td>53.33</td>
<td>3.54</td>
<td>38.7</td>
</tr>
<tr>
<td>2</td>
<td>Walnut Travertine</td>
<td>41.52</td>
<td>2.35</td>
<td>55.71</td>
<td>3.45</td>
<td>34.2</td>
</tr>
<tr>
<td>3</td>
<td>Granite</td>
<td>66.16</td>
<td>4.95</td>
<td>92.67</td>
<td>6.61</td>
<td>40.1</td>
</tr>
<tr>
<td>4</td>
<td>Concrete</td>
<td>28.81</td>
<td>2.51</td>
<td>38.53</td>
<td>3.67</td>
<td>33.7</td>
</tr>
</tbody>
</table>

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°C and +30°C 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 0°C would lead to an increase in strength and elasticity modulus. Comparing the curves indicated that at -30°C, the section with the elastic behavior was increased, and there was no meaningful difference between the curves between 0 and 30°C.

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 10°C 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.
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 +30°C to -30°C 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 0°C, and considerable below 0°C. Most of the pore water phase transition occurred in [-10, 0]°C. Below -10°C, as the temperature dropped, the property changes decreased, meaning the reduction in the phase transition

**REFERENCES**


