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Effect of temperature as well as heating and cooling cycles on rock properties

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Abstract

Temperature has a significant role in many actions performed on rocks. An example would be the effect of temperature on rocks in the burial of nuclear waste, geothermal energy extraction, deep oil well drilling, and fires in tunnels. In addition, due to diurnal/nocturnal as well as seasonal temperature variations, rocks undergo a process of heating and cooling. In the present work, the effect of temperature as well as heating and cooling cycles on the rock properties was studied. The utilized samples included tuff, andesite, and sandstone. In addition to natural samples, concrete was also studied in this research work. The aim of this work was to evaluate the effect of temperature on the tensile strength of rocks and the velocity of longitudinal waves in a single heating and cooling cycle of samples as well as evaluating the effect of the number of heating and cooling cycles on the tensile strength of rocks and the velocity of longitudinal waves. In order to investigate the effect of temperature on the tensile strength of rocks as well as the velocity of longitudinal waves in a single heating and cooling cycle, the samples were heated in a furnace. After cooling the samples, the Brazilian and the sound velocity tests were carried out on them. These tests were conducted at the three temperatures of 100, 200, and 300 °C. In order to examine the effect of the number of heating and cooling cycles on the tensile strength and the velocity of longitudinal waves, the samples were heated up to the temperature of 100 °C and then cooled down in order to reach the room temperature. In this case, the work was conducted in the three modes of 5, 10, and 15 cycles. The test results showed that the velocity of longitudinal waves and the tensile strength of samples decreased but their porosity increased. Reduction in the tensile strength varied in different rocks so that the greatest and lowest reduction in the tensile strength was observed in concrete and andesite, respectively.

Keywords: *Temperature, Heating and Cooling Cycle, Rock Properties, Tensile Strength, Velocity of Longitudinal Wave.*

1. Introduction

Rocks are occasionally exposed to elevated temperatures, which create thermal stress and affect their properties. Thermal loading can generate two types of micro-cracks in rocks via different mechanisms: cycling cracks and thermal gradient-induced cracks. The cycling cracks form due to a mismatch between the thermal expansion coefficients of the adjacent mineral grains in a homogeneous temperature field, while the thermal gradient-induced cracks result from the thermal stresses induced by the temperature gradients exceeding the local grain strength [1]. In theory, a maximum thermal stress of $E\alpha\Delta T/(1-\nu)$ could be generated (where E is the Young's modulus, α is the coefficient of thermal expansion, ΔT is the change in temperature, and ν is the Poisson's ratio). For example, for a rock at a depth of 5000 m at a temperature of 160 ^{o}C, and the rapid application of a cooler temperature of 25 ^{o}C, a maximum tensile stress at the boundary of the excavation of about 27 MPa could be generated (assuming E = 30 GPa, $\alpha = 5\times10^{-6}$/^{o}C, and

$\nu = 0.25$). This is sufficient to result in tensile cracking [2].

In cases such as explosion, fire, deep drilling, and geothermal energy extraction, rocks are exposed to high temperatures [3-9].

The historic method of rock excavation by heating-up the rock with a fire and then dousing the rock with cold water is an example of this type of thermal loading. More modern examples include the sudden flow of cold air due to ventilation in a deep underground excavation [10-13]. In addition, due to diurnal/nocturnal as well as seasonal temperature variations, rocks undergo a process of heating and cooling.

Therefore, the mechanical behavior of rocks under thermal treatment is an important aspect for engineering excavation. The basic physical and mechanical properties of thermally-treated rocks under static loading have been studied such as compressive strength (Heuze; Masri et al.) [3, 14], fracture toughness (Nasseri et al.) [15], and tensile strength (Rao et al.) [16].

A majority of global research works on this subject has been carried out in the last decade, four of which are referred to in the present study. Takarli and Prince Agbodjan conducted a study on the effect of temperature on the physical and mechanical properties of granite in 2008. The samples included granite taken from the Pyrenees in France. The grain sizes were in the range of 0.5-3 mm. The rocks were composed of 42% quartz, 46% plagioclase, 8% feldspar (K), and 4% Mica [17].

Granites were heated in a furnace at a rate of 1 °C/min. The samples were heated up to the temperatures of 200, 300, 400, 500, and 600 °C. They were then cooled down at a rate of 1 °C/min in order to reach the room temperature. The effect of temperature on the porosity of samples was initially investigated in this work. The results obtained showed that the porosity of the samples increased from 0.68% at 105 °C to 2.85% at 600 °C. The most intense change was observed when the temperature was increased from 500 to 600 °C so that the porosity at 600 °C was 2.59 times the porosity at 500 °C. This was also true for permeability so that the permeability at 500 °C was 8 times the permeability at 105 °C and more than 100 times at 600 °C. Longitudinal wave velocity decreases with increase in temperature so that in the samples heated to 105, 500, and 600 °C, 12, 30, and 64% reduction was observed, respectively. Similar was the effect of temperature on the uniaxial compressive strength and modulus of elasticity so that the uniaxial compressive strength of the samples heated to 500 °C was 0.8 times the uniaxial compressive strength of the samples heated up to 105 °C. For the samples heated to 600 °C, the uniaxial compressive strength was 0.52 times the uniaxial compressive strength of the samples heated up to 105 °C. The modulus of elasticity also decreased with increase in temperature. The reduction rate was greater when the temperature was increased from 500 to 600 °C. The modulus of elasticity for the samples heated to 600 °C was 0.72 times the modulus of elasticity for the samples heated up to 105 °C. For the samples heated up to 600 °C, the modulus of elasticity was 0.37 times the axial modulus of elasticity of the samples heated to 105 °C. Studies show that the crack network expands with increase in temperature, causing increased porosity and permeability as well as decreased longitudinal wave velocity, uniaxial compressive strength, and modulus of elasticity. At temperatures higher than 500 °C, the rock samples were exposed to greater damages, which could be accounted for by the transformation of quartz α to β at 573 °C. That is why the intensity of changes in the rock properties is greater at 600 °C [17]. Another study was conducted by Dwivedi et al. on the thermal-mechanical properties of Indiana granite [18].

Indiana pink granite is composed of 39.5% quartz, 48% feldspar (feldspar K), 10% plagioclase, 1.5% biotite, and 1% amphibolite [18]. The samples were tested in a high-temperature furnace. They were heated to 100 ° C at a rate of 1 °C/min, after which, the rate of temperature rise increased to 2 °C/min. After reaching the desired temperature, the samples remained at the same temperature for 5 hours, and were then tested. The tests were conducted at 30 °C (ambient temperature), 65 °C, 100 °C, 125 °C, and 160 °C. The results of uniaxial compression tests showed that uniaxial compressive strength and modulus of elasticity decreased at 65 °C and increased at 100, 125, and 160 °C [18]. To account for such a behavior, the researchers examined the micro-cracks previously existing in the samples by an electron microscope. They concluded that the width of micro-cracks increased at 65 °C and decreased at 100, 125, and 160 °C, showing that new cracks were not developed due to heating.

The reason for the decreased uniaxial compressive strength and modulus of elasticity at 65 °C can be attributed to the increase in the width of the pre-existing cracks. The reason for the increased uniaxial compressive strength and modulus of elasticity at other temperatures can be attributed to the decrease in the width of the cracks [18].

Another study conducted in this regard was a laboratory study by Kim et al. on the samples of igneous, sedimentary, and metamorphic rocks. The samples were slowly heated to the temperatures of 100, 200, and 300 °C, and then quickly cooled down with a fan to the room temperature (25 °C). The rate of temperature rise was 1-2 °C/min. The test results including the tensile strength of the samples due to temperature changes on Coconino sandstone showed that the tensile strength reduced from 6 MPa in unheated samples to 5 MPa in the samples that were heated up to 300 °C and cooled rapidly. In addition to this test, the effect of cycles of heating up to 100 °C and then cooling on the tensile strength of Coconino sandstones was also investigated. In this case, the samples underwent 10, 15, and 20 cycles of heating and cooling. On account of these cycles, the tensile strength decreased from 6.3 to 6 MPa [19]. The researcher also investigated the various effects of heating and cooling cycles on different rocks. In this respect, the samples were heated up to 5 cycles at 100 °C. The results of the studies conducted on Sierrita granite showed that the samples undergoing 5 cycles of heating and cooling exhibited a lower longitudinal wave velocity and a greater porosity than the unheated samples. In these examples, cycles of heating and cooling caused increases in the crack widths and densities.

These changes were different in Diabase. The results obtained showed that the samples enduring 5 heating and cooling cycles had a higher longitudinal wave velocity and porosity compared to the unheated ones. Crack density decreased as they were subject to compressive stress, which also led to decreased porosity. The same scenario was observed in Skarn, diabase, and quartzite. For this reason, the samples enduing five heating and cooling cycles exhibited greater tensile strength compared to the unheated samples.

Another study conducted in the past was a laboratory study by Yavuz et al. on five different types of carbonate rocks including two types of marble, and three types of limestone were compared to examine changes in the physical properties of the samples caused by varying temperatures. In this work, 75 cubic samples, 15 from each type of rock, with dimensions of 70 mm were prepared. These samples were subjected to a temperature rise up to 100, 200, 300, 400, and 500 °C. Each sample was first heated to the desired temperature at a rate of 2 °C/min. They were then heated to reach the target temperature for a period of 12, 24, 48, 96, and 144 hours, and were then cooled down. Before heating the samples, their physical properties including bulk density, porosity, and velocity of longitudinal waves were determined. Wave velocity decreased with increase in temperature. The rate of decrease in the wave velocity was much greater at 500 °C compared with the other temperatures. Moreover, the effect of heating duration on the velocity of longitudinal waves was negligible after 24 hours.

The velocity of longitudinal waves was not greatly affected at 100 °C. In all rocks, longitudinal wave velocity decreased with increase in temperature [20]. Changes in the bulk density caused by increasing temperature suggests that effective porosity increases with increase in temperature, and the intensity of increased porosity is greater at temperatures higher than 400 °C. Microscopic studies showed that cracks and detachment between the grains were more visible at 400 °C so that effective porosity approached the total porosity as closed porosities were connected to each other due to the development of new micro-cracks. These changes were more intensive at 500 °C as micro-cracks spread in-between the grains, which led to a further reduction in the longitudinal wave velocity. The safe and successful effectuation of modern geotechnical engineering projects such as nuclear waste disposal requires a knowledge of the thermo-mechanical behavior of rocks [21]. Therefore, in this work, the effect of temperature, and heating and cooling cycles were examined on the rock properties. The utilized samples included tuff, andesite, and sandstone. In addition to the natural samples, concrete was also studied. Most research works conducted around the world has focused on the effect of temperature on the rock properties in a heating and cooling cycle. Little research work has been conducted on the effects of the number of heating and cooling cycles on the rock properties. Moreover, such studies have mostly been conducted on granite and sandstone. This study provides a new perspective in terms of the studied samples as well as the effect of the number of heating and cooling cycles on the properties of rocks.

The Brazilian and the longitudinal wave velocity tests were conducted on the samples. The effect of temperature on these rock properties was also examined.

2. Sample for study

The blocks used for the coring included: Block 1: Sandstone, Block 2: tuff, blocks 3: andesite.

In order to study the mineralogy of the samples used, thin sections were prepared from samples, and their images were taken under a microscope. Figures 1, 2, and 3 show the sandstone microscopic analysis, microscopic analysis of tuff, and microscopic analysis of andesite, respectively. Figure 1 is a section of sedimentary rock (sandstone). Shaped and semi-shaped quartz together with calcite are the main components of this rock. Primary and secondary minerals forming this rock are calcite, alkaline feldspar, quartz, and opaque minerals. Figure 2 is a cross-section of an andesitic tuff that has been strongly silicified. Shaped and semi-shaped Cerrusite and calcified plagioclase in a silicified field are the main components of this rock. Minor minerals forming the rock include alkali feldspar, quartz, and opaque minerals. Figure 3 is a cross-section of andesite. Plagioclase makes up more than 50% of the rock crystals. Plagioclase crystals are usually shaped or semi-shaped, and can be zoned. The size of these crystals could reach 5.1 mm. The quartz and opaque minerals are of the most important minor minerals in the studied rocks.

In the microscope images, Qz, Cal, Am, Pl, and Ope represent the quartz, calcite, Amphibole, Plagioclase, and opaque minerals, respectively.

The cores taken from these blocks all had a diameter of 51 mm, and the core drilling operations were carried out by a Hilti DD200 machine, shown in Figure 4. In addition to the natural samples, concrete samples were also prepared. In these samples, the water-cement ratio was 0.5 and the sand-cement ratio was considered equal. After the cement, sand and water were mixed together, and the mixture was poured into plastic cylindrical samples. Then the samples were extracted from the mold after a day and were put in water for the concrete to become resistant and for the concrete curing to become complete (Figure 5).

Meanwhile, the physical properties were determined before heating, and the ISRM standard was used for determining these properties [22]. These tests were conducted to determine the effective porosity and density of the rock. The results obtained were tabulated in Table 1. As the most common laboratory test for the study of rock mechanics, the uniaxial compression test was carried out on the samples. The aim of this test was to determine the uniaxial compressive strength, the modulus of elasticity, and the Poisson's ratio. For Sandstone, tuff and andesite, and concrete, the uniaxial compressive strength was obtained to be equal to 77.62, 117.85, 145.73, and 18.01MPa, the Young's modulus was equal to 32.77, 33.97, 34.55, and 4.82 GPa, and the Poisson's ratio was equal to 0.25, 0.19, 0.2, and 0.25, respectively.

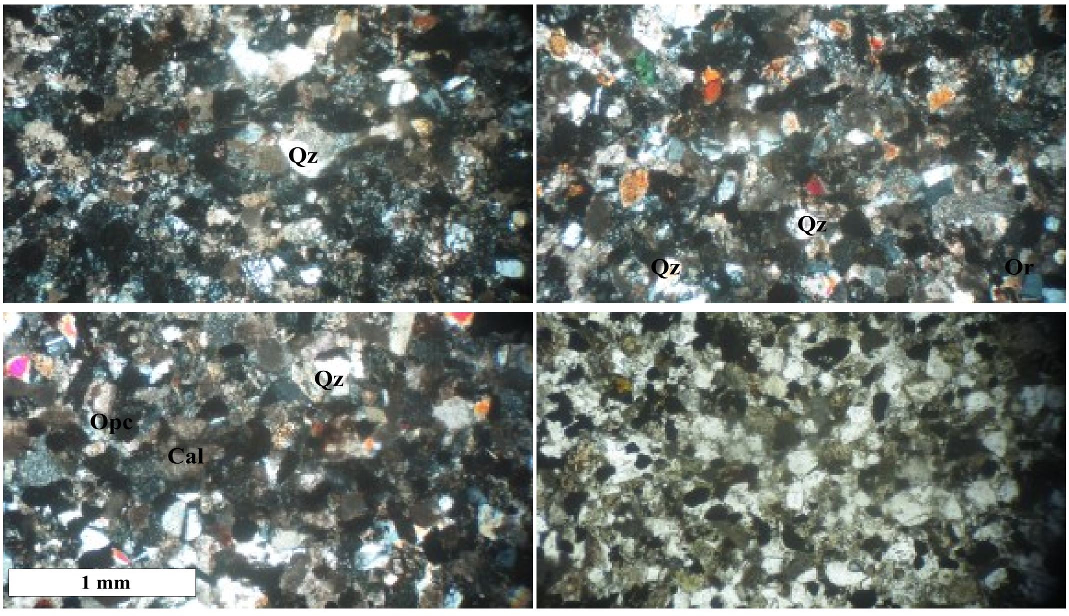

Figure 1. Microscope image of cross-section No. 1 (sandstone).

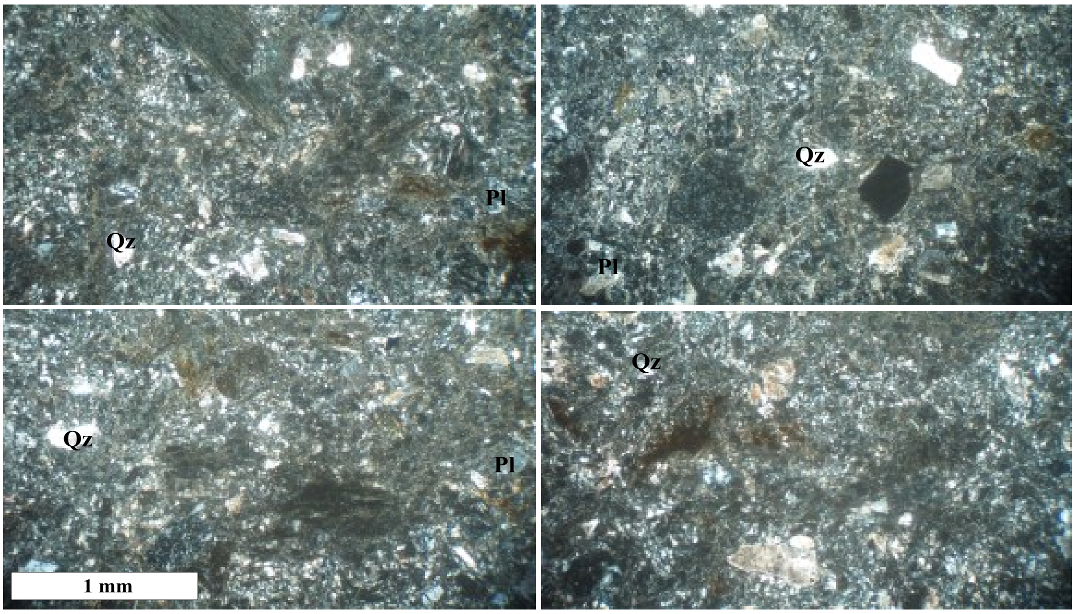

Figure 2. Microscope image of cross-section No. 2 (andesitic tuff).

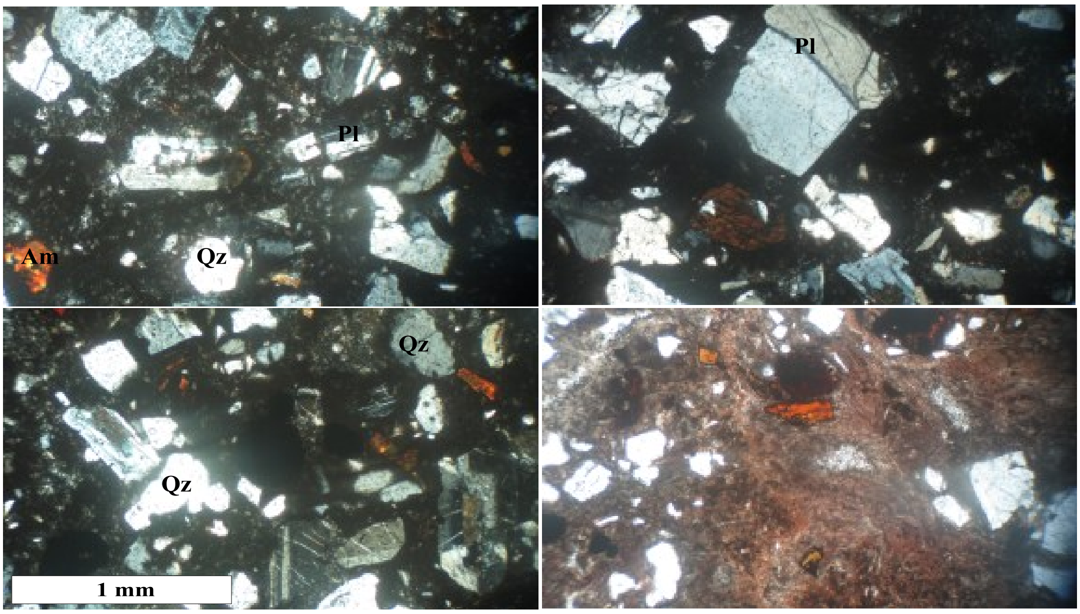

Figure 3. Microscope image of cross-section No. 3 (andesite).

Figure 4. Hilti DD200 core drilling machine.

Figure 5. Concrete samples.

Table 1. Physical properties determined before heating.

Rock type	γ_{sat} (kN/m^3)	γ_d (kN/m^3)	$n(e)$ (%)
Andesite	25.14	25.01	1.30
Tuff	22.78	22.32	4.60
Sandstone	24.51	23.82	6.94
Concrete	21.1	19.72	13.87

3. Conducted tests

The longitudinal wave velocity and Brazilian tests were conducted on the samples. Ultrasonic apparatus was used to test the longitudinal wave velocity. The location of transducers was marked on the samples' end surfaces in a way that the passage from their centers would not differ more than 2 degrees from the central axis of the sample. Then the wave motion distance, which is the distance between the two ends of the specimen, was measured with an accuracy of 0.1%. A thin layer of Vaseline was applied on the location of transducers to prevent the loss of energy passing through the transducers. In order to obtain the dead time between the sample and the transducers, the latter were put on one other and the time shown was subtracted from the time read. Equation (1) was used to obtain the longitudinal wave velocity in the sample [23].

$$V_P = \frac{L}{t} \times 1000 \tag{1}$$

V_P: Compressional wave velocity (m/s)

t: transit time of compressional wave (μs)

L: sample length (mm)

The Brazilian tensile strength test was performed on the samples to determine their tensile strength. The tensile strength of rock samples was calculated by Equation (2) [24]. Figures 6-8 show the disc samples ready to be tested by the Brazilian test.

$$\sigma_t = 0.636 \frac{P}{D.t} \tag{2}$$

P: load at the moment of failure (kN),

D: diameter of specimen (mm),

t: thickness (mm),

σ_t: tensile strength (MPa).

Two series of tests were done on the samples.

In the first series of the tests, the samples endured a heating and cooling cycle. These tests were conducted at the four temperatures of 25 (ambient temperature), 100, 200, and 300 °C. The aim of the first series of the tests was to evaluate the effect of temperature on the tensile strength of rocks and velocity of the longitudinal waves in a single cycle of samples undergoing heating and cooling for considering variation in rock properties in deep underground excavation. In this state, the maximum temperature was generally 200 °C, however, the variation in rock properties was considered in the temperature of 300 °C.

The rate of temperature rise was 3 °C per minute. In the second series of the tests, the effect of the number of heating and cooling cycles on the velocity of longitudinal waves in the samples enduring 5, 10, and 15 cycles of heating to 100 °C and cooling were examined. The aim of the second series of the tests in this study was to evaluate the effect of the number of heating and cooling cycles on the tensile strength of rocks and the velocity of longitudinal waves for modeling the flow of cold air due to ventilation in a deep underground excavation and the effect of daily and seasonal temperature variation in surface rock. In this state, the rock was cooled and heated continuously. The maximum temperature is usually 100 °C. The results of the test for determining the velocity of longitudinal waves were tabuled in Table 2, and the results of Brazilian test are shown in Table 3. All samples of a specific kind of rock had been taken from a single block. To ensure the integrity of the results in each case, the tests were conducted on two samples.

Figure 6. Sandstone disc samples for Brazilian test.

Figure 7. Tuff disc samples for Brazilian test.

Figure 8. Andesite disc samples for Brazilian test.

Table 2. Results from velocity of longitudinal wave test on samples.

Type of rock	Number of cycles	Temperature (°C)	Velocity of longitudinal waves (m/s)
Sandstone, sample 1	1	25	3437.67
Sandstone, sample 2	1	25	3440.56
Andesite, sample 1	1	25	4693.79
Andesite, sample 2	1	25	4685.49
Tuff, sample 1	1	25	3919.42
Tuff, sample 2	1	25	3923.51
Concrete, sample 1	1	25	3521.37
Concrete, sample 2	1	25	3530.1
Sandstone, sample 3	1	100	3417.54
Sandstone, sample 4	1	100	3421.43
Andesite, sample 3	1	100	4615.51
Andesite, sample 4	1	100	4621.55
Tuff, sample 3	1	100	3890.91
Tuff, sample 4	1	100	3883.11
Concrete, sample 3	1	100	3443.22
Concrete, sample 4	1	100	3439.35
Sandstone, sample 5	1	200	3387.65
Sandstone, sample 6	1	200	3390.71
Andesite, sample 5	1	200	4530.21
Andesite, sample 6	1	200	4525.23
Tuff, sample 5	1	200	3845.45
Tuff, sample 6	1	200	3841.37
Concrete, sample 5	1	200	3152.81
Concrete, sample 6	1	200	3155.85
Sandstone, sample 7	1	300	3350.45
Sandstone, sample 8	1	300	3355.35
Andesite, sample 7	1	300	4460.70
Andesite, sample 8	1	300	4467.35
Tuff, sample 7	1	300	3775.21
Tuff, sample 8	1	300	3779.15
Concrete, sample 7	1	300	2843.82
Concrete, sample 8	1	300	2849.86
Sandstone, sample 3	5	100	3407.81
Sandstone, sample 4	5	100	3409.22
Sandstone, sample 3	10	100	3370.65
Sandstone, sample 4	10	100	3375.71
Sandstone, sample 3	15	100	3355.33
Sandstone, sample 4	15	100	3351.47
Andesite, sample 3	5	100	4603.21
Andesite, sample 4	5	100	4601.25
Andesite, sample 3	10	100	4585.87
Andesite, sample 4	10	100	4580.11
Andesite, sample 3	15	100	4570.07
Andesite, sample 4	15	100	4565.91
Tuff, sample 3	5	100	3865.55
Tuff, sample 4	5	100	3870.75
Tuff, sample 3	10	100	3850.26
Tuff, sample 4	10	100	3848.38

Table 2. Continued.

Type of the rock	Number of cycles	Velocity of longitudinal waves (m/s)
Tuff, sample 3	15	3821.47
Tuff, sample 4	15	3817.63
Concrete, sample 3	5	3417.63
Concrete, sample 4	5	3425.41
Concrete, sample 3	10	3400.05
Concrete, sample 4	10	3407.06
Concrete, sample 3	15	3385.12
Concrete, sample 4	15	3380.29

Table 3. Results of Brazilian test on samples.

Type of the rock	Number of cycles	Temperature (°C)	Tensile strength (MPa)
Sandstone, sample 1	1	25	6.19
Sandstone, sample 2	1	25	6.25
Andesite, sample 1	1	25	12.35
Andesite, sample 2	1	25	12.15
Tuff, sample 1	1	25	16.27
Tuff, sample 2	1	25	16.31
Concrete, sample 1	1	25	8.15
Concrete, sample 2	1	25	8.35
Sandstone, sample 3	1	100	5.81
Sandstone, sample 4	1	100	5.69
Andesite, sample 3	1	100	11.78
Andesite, sample 4	1	100	11.91
Tuff, sample 3	1	100	15.51
Tuff, sample 4	1	100	15.35
Concrete, sample 3	1	100	7.15
Concrete, sample 4	1	100	6.93
Sandstone, sample 5	1	200	5.35
Sandstone, sample 6	1	200	5.25
Andesite, sample 5	1	200	11.21
Andesite, sample 6	1	200	11.03
Tuff, sample 5	1	200	13.87
Tuff, sample 6	1	200	13.95
Concrete, sample 5	1	200	5.61
Concrete, sample 6	1	200	5.85
Sandstone, sample 7	1	300	5.05
Sandstone, sample 8	1	300	5.07
Andesite, sample 7	1	300	10.96
Andesite, sample 8	1	300	10.87
Tuff, sample 7	1	300	13.05
Tuff, sample 8	1	300	13.11
Concrete, sample 7	1	300	4.51
Concrete, sample 8	1	300	4.45
Sandstone, sample 3	5	100	5.45
Sandstone, sample 4	5	100	5.35
Sandstone, sample 3	10	100	5.15
Sandstone, sample 4	10	100	5.21
Sandstone, sample 3	15	100	4.91
Sandstone, sample 4	15	100	4.89
Andesite, sample 3	5	100	11.67
Andesite, sample 4	5	100	11.71
Andesite, sample 3	10	100	11.45
Andesite, sample 4	10	100	11.51
Andesite, sample 3	15	100	11.23
Andesite, sample 4	15	100	11.28
Tuff, sample 3	5	100	15.03
Tuff, sample 4	5	100	15.11
Tuff, sample 3	10	100	14.71
Tuff, sample 4	10	100	14.78
Tuff, sample 3	15	100	14.21
Tuff, sample 4	15	100	14.30
Concrete, sample 3	5	100	6.51
Concrete, sample 4	5	100	6.45
Concrete, sample 3	10	100	5.98
Concrete, sample 4	10	100	5.91
Concrete, sample 3	15	100	5.21
Concrete, sample 4	15	100	5.15

4. Analysis of the results

In this section, the test results will be presented in the form of charts in order to examine the effect of a cycle of heating and cooling of samples as well as the effect of the number of heating and cooling cycles on the velocity of longitudinal waves and tensile strength. As at each temperature testing was conducted on two samples of a type of rock, the average test results performed on two samples of a type of rock was considered for drawing the chart of changes in the longitudinal wave velocity and tensile strength of the samples enduring a heating and cooling cycle. Figure 9 shows the changes in the longitudinal wave velocity and Figure 10 shows the changes in the tensile strength.

As it can be seen, by increasing the temperature in a heating and cooling cycle of the rock samples, the velocity of longitudinal waves and the tensile strength were reduced. These results are consistent with the results obtained by Madland et al. [25], Homand-Etienne and Houpert [4], Dwivedi et al. [18], Yin et al. [26], Liang et al. [27], Chaki et al. [28], Chen et al. [29], and Sriapai et al. [30]. Also a decreased longitudinal wave velocity with increasing temperature is consistent with the results of the studies conducted by Takarli and Prince-Agbodjan [17], Yavuz et al. [20], and Kim et al. [19]. Increased temperature causes thermal stress in rocks. Since different minerals have different coefficients of thermal expansion, these stresses are concentrated on the boundaries of various minerals; and if it exceeds the amount of tensile or shear strength of the rocks, new cracks will be developed or previous cracks will be increased [31]. In addition, during the cooling phase of samples, new cracks will be developed due to the contraction of the sample, especially in grain boundaries of various minerals. Therefore, the density of cracks increases and the longitudinal wave velocity decreases due to the increased density of cracks. The effective porosity was calculated in sandstone, tuff, and andesite. As shown in Figure 11, the effective porosity increased with increase in temperature, leading to a decreased longitudinal wave velocity and tensile strength. Of course, this reduction in the tensile strength is different in various rocks. As shown in Table 4, the ratio of tensile strength after a heating and cooling cycle (σ_t) to the tensile strength at room temperature (σ_{t_0}) varies between 0.81 and 0.92 in sandstone, 0.8 and 0.95 in tuff, 0.54 and 0.85 in concrete, and 0.89 and 0.97 in andesite. As it can be seen, the largest reduction in the tensile strength is related to the concrete and the lowest reduction is seen in the andesite.

Figure 12 shows the changes in longitudinal wave velocity and Figure 13 shows the changes in tensile strength caused by the number of heating and cooling cycles. The samples were heated to 100 °C. As shown in Figure 13, with increase in the number of heating and cooling cycles of the samples, the tensile strength was reduced. This reduction in strength was due to the development of new cracks and expansion of the former ones. Development and expansion of cracks were due to the thermal expansion coefficient differences between various minerals at the heating and cooling phase on the boundaries of different minerals. Also longitudinal wave velocity decreased due to the increased density of cracks. As far as the effect of the number of heating and cooling cycles on the tensile strength of the samples is concerned, the study conducted by Kim et al. can be noted. In their study, they observed a reduction in tensile strength in a number of rocks [19]. The results obtained showed that the reduction in tensile strength of various rocks was different. As shown in Table 5, the ratio of tensile strength after a few heating and cooling cycles to the tensile strength after a single cycle of heating and cooling varies between 0.92 and 0.98 in sandstone, 0.85 and 0.94 in tuff, 0.74 and 0.92 in concrete, and 0.95 and 0.99 in andesite. As it can be seen, the largest reduction in the tensile strength was associated with the concrete and the lowest reduction with the andesite.

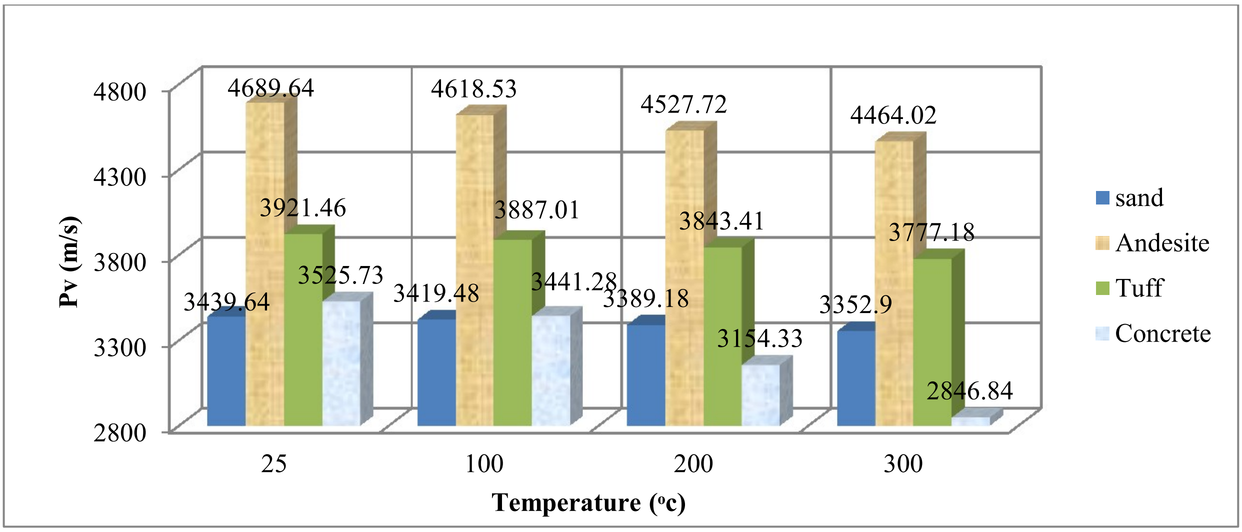

Figure 9. Changes in longitudinal wave velocity of samples as a result of a heating and cooling cycle.

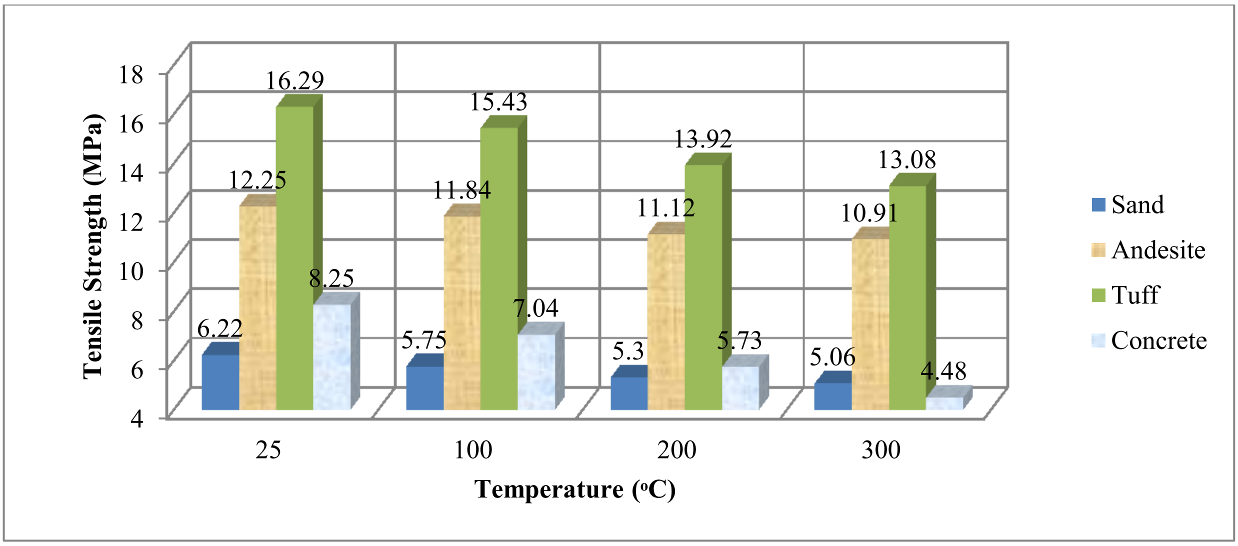

Figure 10. Changes in tensile strength of samples as a result of a heating and cooling cycle.

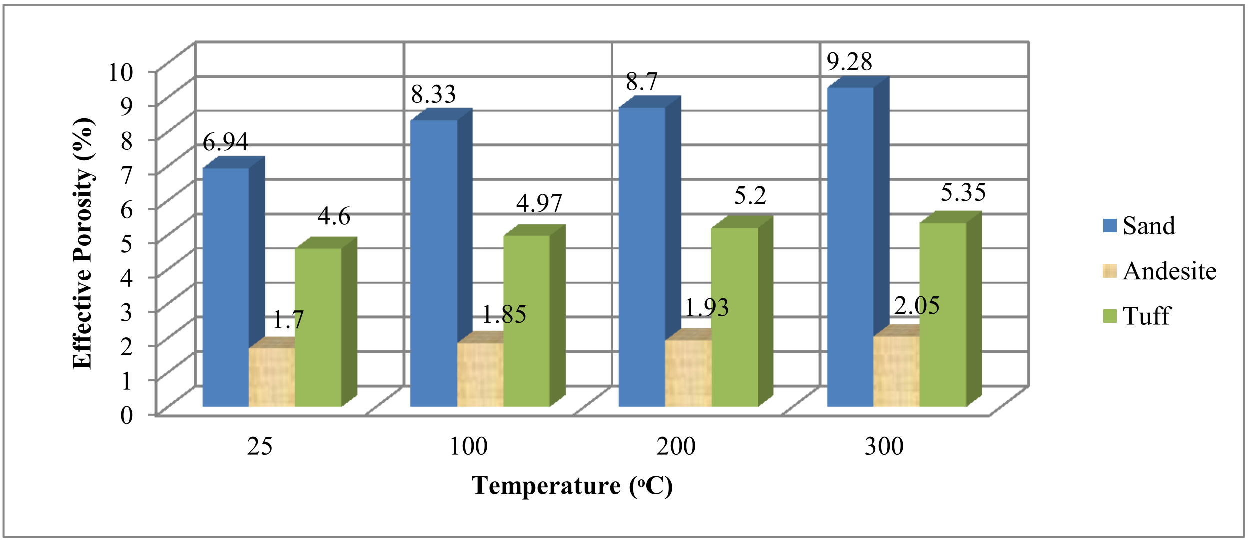

Figure 11. Changes in effective porosity of samples as a result of a heating and cooling cycle.

Table 4. Ratio of tensile strength after a heating and cooling cycle (σ_t) to tensile strength at room temperature (σ_{t_0}).

Temperature (°C)	σ_t / σ_{t_0} (for Concrete)	σ_t / σ_{t_0} (for Tuff)	σ_t / σ_{t_0} (for Sandstone)	σ_t / σ_{t_0} (for Andesite)
25	1	1	1	1
100	0.85	0.95	.092	0.97
200	0.69	0.85	0.85	0.90
300	0.54	0.8	0.81	0.89

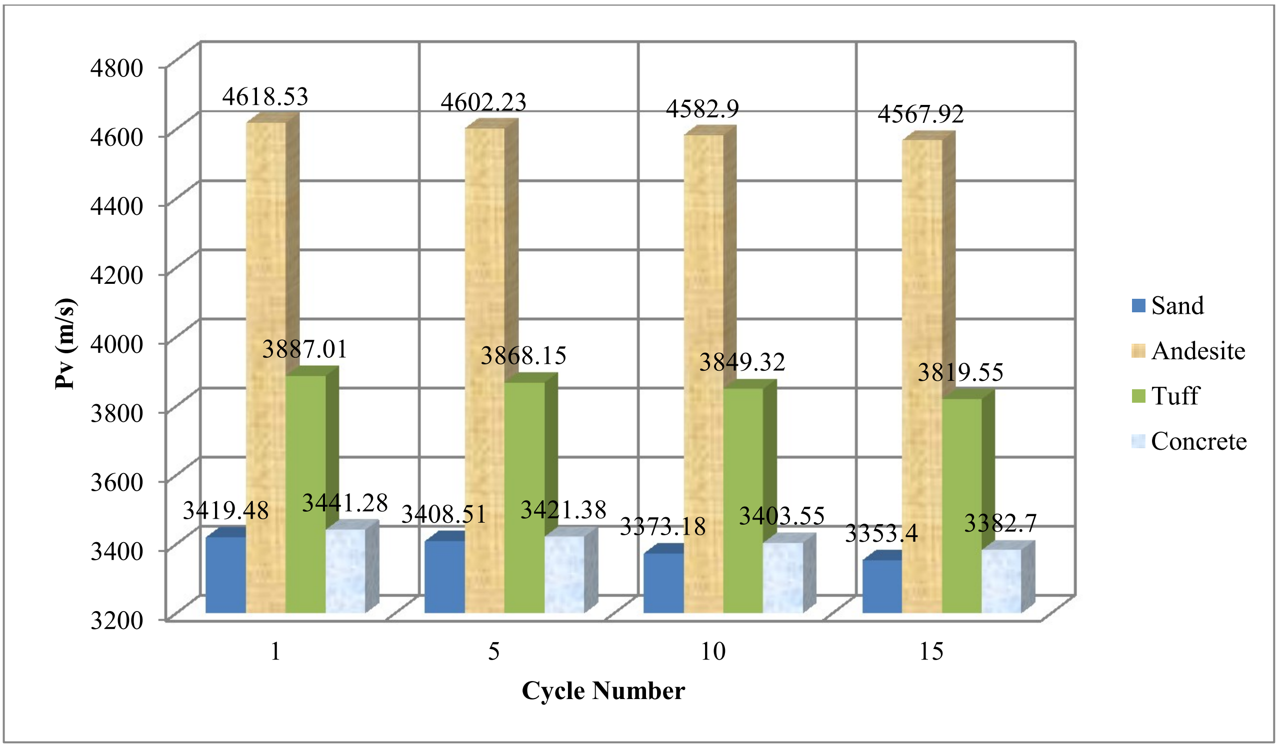

Figure 12. Changes in longitudinal wave velocity of samples as a result of several cycles of heating to 100 °C and cooling.

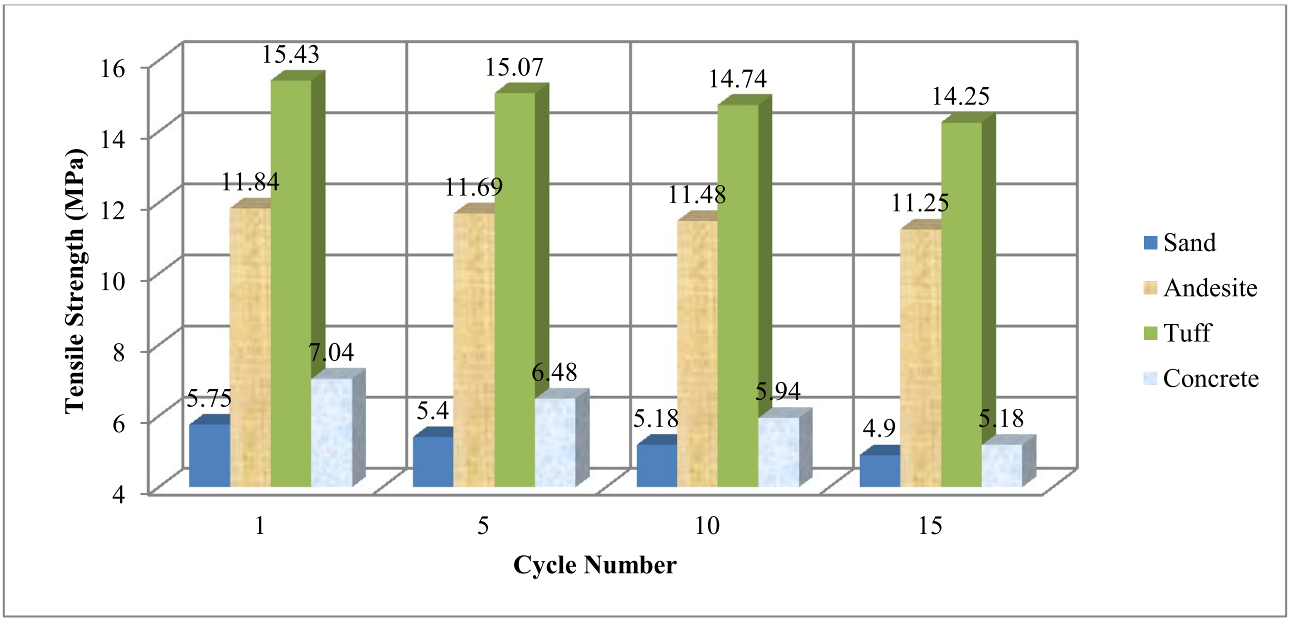

Figure 13. Changes in tensile strength of samples as a result of several cycles of heating to 100 °C and cooling.

Table 5. Ratio of tensile strength after several cycles of heating to 100 °C and cooling (σ_t) to tensile strength after a cycle of heating to 100 °C and cooling (σ_{t_0}).

Number of cycles	σ_t / σ_{t_0} (for Concrete)	σ_t / σ_{t_0} (for Tuff)	σ_t / σ_{t_0} (for Sandstone)	σ_t / σ_{t_0} (for Andesite)
1	1	1	1	1
5	0.92	0.94	0.98	0.99
10	0.84	0.9	0.96	0.97
15	0.74	0.85	0.92	0.95

5. Conclusions

Temperature plays an important role in the engineering of underground projects through changing rock physical and mechanical properties. In this work, we experimentally investigated the effects of temperature on the longitudinal wave velocity and tensile strength of andesite, tuff, sandstone, and concrete. Andesite belongs to the igneous rock; tuff and sandstone belong to the sedimentary rock.

Two series of tests are done on the samples.

In the first series of the tests, the samples endured a heating and cooling cycle. These tests were conducted at four temperatures of 25 (ambient temperature), 100, 200, and 300 °C. In the second series of the tests, the effect of the number of heating and cooling cycles on the velocity of longitudinal waves in the samples enduring 5, 10, and 15 cycles of heating to 100 °C and cooling were examined.

The results of the present study on four types of rocks showed that by a single heating and cooling cycle of samples, longitudinal wave velocity and tensile strength of the samples decreased, while their porosity increased. Reduction in the tensile strength was different in various rocks so that the maximum reduction in tensile strength was seen in the concrete, and the minimum reduction in the andesite. The igneous rocks are formed by cooling magma, and have a massive structure. The sedimentary rocks are formed from sediment deposits through the process of compaction and cementation. The sediment deposit compaction happens due to the overburden pressure. These conditions do not exist during the construction of concrete; so the concrete is weaker than the other three types of rocks. The development and the expansion of the cracks during the heating and cooling phase at mineral boundaries are due to the difference in the thermal expansion coefficients of the various minerals. The cohesion between the cement and the sand in concrete is weaker than the cohesion between the various minerals in andesite, tuff, and sandstone. As a result, development and expansion of the cracks in concrete samples due to the heating and cooling process were more than the other rock samples.

The results of the second series of the tests showed that the longitudinal wave velocity and the tensile strength of the samples decreased. Reduction in the tensile strength was different in various rocks so that the maximum reduction in the tensile strength was seen in the concrete and the minimum reduction in the andesite. Reduction in the tensile strength caused by the number of heating and cooling cycles was less than reduction in the tensile strength caused by heating the samples to 200 and 300 °C and then cooling them. The results of this research work show that the properties of concrete extremely decrease. This issue must be considered during the design of the support systems in the deep underground excavation; otherwise, due to the damaging effect of the cooling and the heating of the concrete, the support system can fail.

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اثر درجه حرارت و سیکل‌های گرمایش و سرمایش بر روی خواص سنگ

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چکیده:

حرارت دارای نقش مهمی در بسیاری از کارهایی که در سنگ اجرا می‌شود، ایفا می‌کند. به عنوان مثال می‌توان به اثر حرارت بر روی سنگ‌ها در دفن زباله‌های اتمی، استحصال انرژی زمین گرمایی و حفاری چاه‌های نفتی عمیق و یا آتش‌سوزی در تونل‌ها اشاره کرد. علاوه بر این، با توجه به تغییرات دما در روز و شب و همچنین تغییرات دما در فصول مختلف، سنگ‌ها تحت فرآیند گرم شدن و سرد شدن قرار دارند. در این پژوهش تأثیر درجه حرارت و سیکل‌های گرمایش و سرمایش بر روی خواص سنگ بررسی می‌شود. نمونه‌های مورد استفاده شامل سنگ توف، آندزیت و ماسه سنگ است. در این تحقیق علاوه بر نمونه‌های طبیعی، بتن نیز مورد بررسی قرار گرفته است. هدف از این پژوهش، بررسی اثر درجه حرارت بر روی مقاومت کششی سنگ و سرعت امواج طولی در یک سیکل گرم شدن و سرد شدن نمونه‌ها و همچنین بررسی اثر تعداد سیکل‌های گرم شدن و سرد شدن روی مقاومت کششی سنگ و سرعت امواج طولی است. برای بررسی اثر درجه حرارت روی مقاومت کششی سنگ و سرعت امواج طولی در یک سیکل گرم شدن و سرد شدن، نمونه‌ها به وسیله کوره گرم می‌شوند و بعد از سرد شدن نمونه‌ها، بر روی آن‌ها آزمایش برزیلی و سرعت صوت انجام می‌شود. این آزمایش‌ها در سه درجه حرارت مختلف ۱۰۰، ۲۰۰ و ۳۰۰ درجه سانتی‌گراد انجام می‌شود. برای بررسی اثر تعداد سیکل‌های گرم شدن و سرد شدن بر روی مقاومت کششی و سرعت امواج طولی نمونه‌ها تا ۱۰۰ درجه گرم و سپس تا رسیدن به دمای محیط سرد می‌شوند. در این شرایط، این بررسی در ۳ حالت ۵، ۱۰ و ۱۵ سیکل انجام می‌شود. نتایج آزمایش‌ها نشان می‌دهد که سرعت امواج طولی و مقاومت کششی نمونه‌ها کاهش و تخلخل نمونه‌ها افزایش می‌یابد. کاهش مقاومت کششی در سنگ‌های مختلف متفاوت است؛ به طوری که بیشترین کاهش مقاومت کششی در بتن و کمترین کاهش در آندزیت مشاهده می‌شود.

کلمات کلیدی: درجه حرارت، سیکل گرمایش و سرمایش، خواص سنگ، مقاومت کششی، سرعت امواج طولی.
