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Effects of temperature and confining pressure on mode II fracture toughness of rocks (Case study: Lushan Sandstone)

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Abstract

The fracture mechanics examines the development and expansion of cracks in solids and how they affect the deformation of materials. The stress intensity factors at the tip of the crack and the critical stress intensity factors or fracture toughness of materials are considered in the relevant criteria. There are three main modes of applying forces to a crack including the tensile mode, shear mode, and mixed mode. Mode II fracture toughness, which is also called the shear mode, is an important parameter for investigating the rock behaviors. This parameter is used in many different areas such as mining and tunneling. Several methods have been proposed for determining the mode II fracture toughness. In this work, the Punch-True-Shear (PTS) test, standardized by the International Society for Rock Mechanics, was used to determine the fracture toughness while the confining pressure is present. The studied sample was the Lushan sandstone. In this work, notchd cylindrical specimens were prepared for PTS testing. In order to investigate the effect of confining pressure, some tests were conducted in the presence of the confining pressures of 0, 3, 5, 7, and 10 MPa, and to check the effect of temperature, some tests were conducted under 1, 5, and 10 heating and cooling cycles at 60, 100, and 150 ˚C as well as at the ambient temperature (25 °C). The confining pressure of 3 MPa was used in all the tests to examine the effect of temperature. The analyses results showed that with increase in the confining pressure, the mode II fracture toughness and the fracture energy would increase as well. By increasing the number of heating-cooling cycles, the mode II fracture toughness as well as the fracture energy would decrease leading to a reduced fracture toughness and energy for all the three modes of heating specimens up to 60, 100, and 150 ˚C. The effect of the number of heating-cooling cycles on reducing the fracture toughness and fracture energy was greater than the effect of temperature.

Keywords: *Fracture Toughness, Mode II, Confining Pressure, Temperature, Sandstone.*

1. Introduction

Installations such as storage depots, wells, tunnels, and underground power plants are located in the bed of different types of rocks under different conditions of rock mechanics. The stability and durability of excavation are essential for all these constructions both in the short and long terms [1].

The initial cracks and fractures in rocks are inevitable and are considered as the special features of any material due to which these structures and rock masses are broken down faster under mechanical loads or other environmental factors [2].

Fracture is the dominant mechanism of brittle rock failure, which is very important in recognizing the efficiency of the structure of rocks [3]. The fracture mechanics examines the creation and expansion of cracks in solids and how they affect the deformation of materials [1]. The fracture mechanics can also be used to identify and predict the sudden fracture of rocks [4]. The principles of fracture mechanics were founded in 1960. Scientists focused their attention on the nature of crack tip plasticity. During this period, several scholars including Irwin (1961), Dejal

(1960), Bernbalt (1962), and Wales (1961) [5] developed analyzes for fracture at the crack tip.
The material resistance to germination and crack development is called fracture toughness, which is used as the most important crack parameter in the fracture mechanics. The toughness is the rate of energy consumption required to form new levels [6]. The abundant applications of this parameter in the fields of rocks' explosion and burst, stability, and non-collapse of mines, hydraulic fracture, and earthquake mechanics have led to extensive studies. Another application of rock fracture toughness is in tunnel excavation. Moreover, the engineering calculations of the rock fracture toughness in the tunnel excavation path must be precise; otherwise, it would increase the possibility of the tunnel collapse due to the load on top resulting in an irreparable damage [7].
In general, the fracture toughness depends upon factors such as temperature, environment, loading rate, material composition, and microscopic structure, along with geometric effects. The fracture toughness for various states is indicated by K_{Ic}, K_{IIc}, and K_{IIIc} [8, 9]. There were many structures with confirmed safety factors based on common regulations but they collapsed during operation. In the recent years, it has been attempted to investigate the actual behavior of structures based on the theories of fracture mechanics [1].
The stress intensity factor (K) controls the size of the stress at the crack tip in the fracture process [1].
When a cracked fragment is exposed to the external load, a lot of stress concentration occurs around the crack tip. Whenever this concentrated stress reaches a critical level, it causes a fragment fracture [7]. The fracture toughness is one of the properties of matter, which means the critical state of the stress intensity factor [1].
Depending on how the external load is applied, the propagation of the crack occurs under three basic fracture modes (Figure 1). Mode I is a crack-opening mode in which the crack dimensions are separated perpendicular to the crack plane [7]. Mode II or shear mode, in which the two cracking regions slip in a direction perpendicular to the crack tip, where the shear stress is parallel to the crack plane and perpendicular to the crack front. Mode III or the mixed mode, in which the two crack planes slip in a direction parallel to the crack profile line [10].

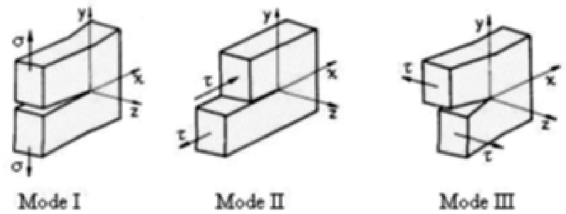

Figure 1. Fracture modes [11].

Previous rock fracture toughness studies have mainly focused on the mode I fracture toughness. The expansion of crack in the rock mass does not occur only in tensile conditions. Therefore, the mode II fracture toughness and stress intensity factors in the mixed modes (II, I) are very important for a proper understanding of the rock fracture [1].
Several test methods have been developed to obtain K_{IIc}. The crack expansion may occur in many brittle materials that are exposed to the pure mode II crack. In such cases, the crack begins to progress when the mode II stress intensity factor reaches the mode II critical stress intensity factor (or the mode II fracture toughness, K_{IIc}). Therefore, it is important to determine a laboratory or theoretical method to obtain the mode II fracture toughness (K_{IIc}) in brittle materials. Previously, some tests have been proposed to determine the mode II fracture including:

1. Confining pressure punch test (PTS);
2. Brazilian disk test with the central gap;
3. Three-point bending test on a semi-circular specimen;
4. Cutting box test;
5. Asymmetric four-point bending tests [1].

The PTS testing method was standardized by the International Society for Rock Mechanics. The desk studies showed that most of the works done in this field were conducted on the effect of temperature on the physical and mechanical properties of rocks, some of which are presented in Table 1. The previous studies show that the increased fracture toughness can be attributed to closure of pre-existing cracks in the rock specimens. The decrease in the effective porosity confirmed the pre-existing closure in the rock specimens.

Table 1. Studies on effect of temperature on mechanical properties of various rocks.

References	Rock type	Test temperature	Sample size	Elastic modulus	Compressive strength	Tensile strength
[12]	Salt	20–240	ISRM SM	Decrease	Increase	
[13]	Granite	20–800	5cm(ϕ) × 10cm	Decrease	Decrease	
[14]	Marble	20–700	ISRM SM	Decrease	Decrease	
[15]	Granite	30–160	ISRM SM	-Decrease increase	Decrease–increase	Decrease
[16]	Granite	25–1300	2.5cm(ϕ) × cm	Decrease	Decrease	
[17]	Gabbro	25–1000	4cm(ϕ) × 9cm	Decrease	Decrease	
[18]	Khondalite	30–250	5.4cm(ϕ) × 3.4cm			-Increase Decrease
[19]	Mudstone	20–750	$2 \times 2 \times 5cm^3$	Increase	Increase	
[20]	Sandstone	25–950	2.3cm(ϕ) × 4.6cm	Increase–decrease	Increase–decrease	
[21]	Salt	4–182	$5.4 \times 5.4 \times 5.4cm^3$	Decrease	Decrease	Decrease
[22]	Granites	20–1000	4cm(ϕ) × 8cm	Decrease	Decrease	
[23]	Calcarenite	60–105	5cm(ϕ) × 12.5cm	Decrease	Decrease	
[24]	Mudstone	25–800	2cm(ϕ) × 4.5cm	Increase–decrease	Increase–decrease	

There are few studies on the effect of temperature on the mode I fracture toughness and, in particular, on the mode II. Some of them are as follow:

Kim et al. [25] conducted experiments to determine the effect of rapid heating and cooling on the mechanical properties of rocks. Their studied samples were from igneous, sedimentary, and metamorphic rocks (granite, igneous rocks with metallic veins, quartz sandstone, igneous rocks without metallic veins and skarn). They placed specimens under rapid heating and cooling cycles. In their experiments, they used the Edged-Notched-Disc (END) test to determine the mode I fracture toughness. They came to the conclusion that rocks of high heterogeneity and coarse grains tend to expand cracks when they are subject to rapid heating and cooling cycles, while rocks with lower heterogeneity and finer grains tend to improve cracking.

Jabari and Hosseini [26] investigated the effect of the number of heating and cooling cycles of rocks on the mode I fracture toughness. They performed tests on semi-circular samples of natural rocks including sandstone, limestone, and andesite using the three-point bending test. They heated the specimens to 700 °C in 1, 5, and 10 cycles, and then cooled them in the laboratory and conducted some experiments at ambient temperatures, where the speed of temperature rise in the process of heating and cooling was 15 ˚C per minute. The results of their tests showed that fracture toughness in andesite, sandstone, and limestone specimens was reduced under cyclic conditions.

Gan Feng et al. [27] conducted tests to determine the effect of temperature on the mode I fracture toughness and the fracture characteristics of sandstone specimens. They used Semi-Circular-Bend (SCB) specimens for their tests. They found that at low temperatures (20-100 °C), the mode I fracture toughness of rock increased by about 11%; at moderate temperatures (100-500 °C), it decreased approximately by about 18%, and at high temperatures (800 °C), it decreased by about 44%.

Mahanta et al. [28] investigated the effect of heating on the mode I fracture toughness of rocks. They conducted their tests on the Manoharpur sandstone, Bellary dolerite, and Dholpur sandstone specimens at temperatures rising from the ambient temperature to 600 °C on the Crack-Straight-Semi-Circular-Bend (CTSCB) specimens. They showed that up to 100 °C, the fracture toughness of Manoharpur, Bellary dolerite, and Dholpur sandstone, respectively, increased by 40%, 25%, and 65% compared to being tested at the ambient temperature; and then with a gradual rise in temperature up to 600 °C, the fracture toughness for Manoharpur sandstone, Bellary dolerite, and Dholpur sandstone,

respectively, decreased by 59%, 36%, and 30% compared to the ambient temperature.
As far as the effect of temperature and confining pressure on the mode II fracture toughness is concerned, a few tests were conducted as what follow.
Bakeres et al. [2] conducted the PTS test to determine the mode II fracture toughness. They used specimens with a diameter of 50 mm and a height equal to their diameter. They obtained the results of laboratory tests on the limestone, marble, and granite specimens. They created circular notchs with different depths but the same diameter at both the upper and lower extremes of the specimens so that a part remained intact in the middle of the specimens. The specimens were then subjected to different confining pressures, and loading was conducted axially onto the rock core. The test results indicated that the mode II fracture toughness increased with increase in the confining pressure, and in applying the confining pressure more than 30 MPa, the mode II fracture toughness reached a constant value.
Meier et al. [29] designed tests to determine the effect of temperature on the mode II fracture toughness through PTS testing with confining pressures. They carried out 30 tests on rock specimens that had a notch with a depth of 5 mm at the upper extreme and a notch with a depth of 30 mm at the lower extreme at a temperature ranging from 25 to 250 °C. The results of their experiments showed that the mode II fracture toughness of rock slightly changed up to 150 °C. With increase in temperature, the mode II fracture toughness slightly increased by 10%, which had a direct relationship with the onset of heating the fine-cracked rock.
In this work, the effects of temperature and confining pressure on the mode II fracture toughness were investigated. The novelty of this research work is investigation of the effect of the number of heating-cooling cycles on the mode II fracture toughness and fracture energy. Furthermore, the effect of confining pressure (by carrying out the PTS test) on the mode II fracture toughness has not been investigated in Iran yet.
This work aimed to investigate the effects of heating-cooling cycles and confining pressures on the mode II fracture toughness of sandstone specimens.

2. Studied material

The specimen examined in this work was the Lushan sandstone. Sandstone is a sedimentary rock that has been formed in all geological periods, mainly consists of fine sand particles and different minerals, and has various colors. This rock has been formed mainly in shallow seas and deltas along the coasts, and in hot deserts. Moreover, materials such as clay and silicon oxide have contributed to the cementation of its particles [30].
The rock sample of Lushan sandstone is a calcareous sandstone with a limestone-silica structure whose cement is calcareous (Figure 2). The main and secondary minerals in this rock include calcite, feldspar alkaline, quartz, and opaque minerals. The Diagenesis of this rock includes sericitization, chertization, and calcification. The main shapers of this rock are shaped and semi-shaped quartzes with calcite.
In this section, a series of microscopic studies were performed on the specimen. For the microscopic study of the specimen, a thin segment of it was prepared and some images were taken under a microscope, as shown in Figure 3. Minerals in this sandstone are marked with acronyms on the images.
Qz: Quartz, Cal: Calcite, Opc: Opaque minerals

Figure 2. Lushan sandstone.

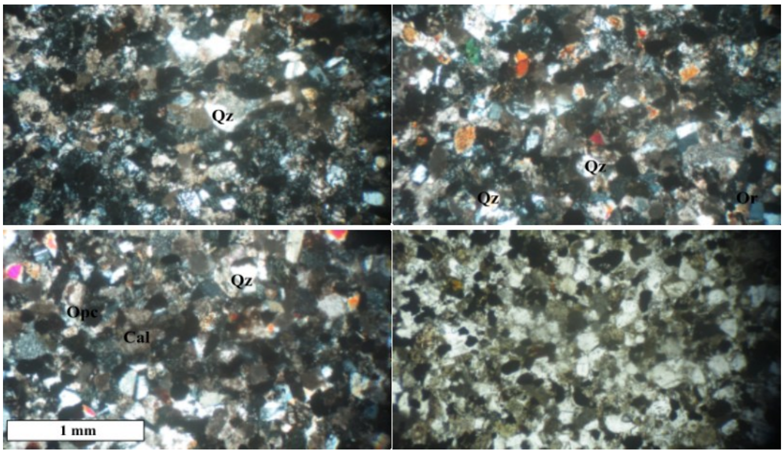

Figure 3. Microscopic images of sandstone specimen.

Experiments were carried out on the sandstone to determine its porosity and dry specific weight, and some other tests such as the Brazilian test and single-axis density test were also carried out. The purpose of the single-axial compression test was to determine the uniaxial compressive strength, Young's modulus, and Poisson's coefficient. The physical and mechanical properties of the specimens are presented in Table 2. Determination of specific gravity, effective porosity, uniaxial compressive strength, and tensile strength were carried out in accordance with the standards of the International Society for Rock Mechanics established in 2007 [31].

Table 2. Physical and mechanical properties of Lushan sandstone.

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

3. Preparation of specimen

During the preparation of the specimen, care should be taken to prevent a micro-mechanical damage to it. Micro-mechanical damage may affect the propagation of fracture and reduce the level of fracture toughness. Cautious preparation of the specimen should involve coring, cutting, and slow abrasion operations to limit vibrations [3].

Figure 4 shows the schematic representation of a prepared specimen.

In order to prepare the notched specimen, a notch 5 mm in height and 25 mm in diameter was created in the center of one base of the rock, and another notch 30 mm in height and 25 mm in diameter was created in the center of the other base of the rock. The following steps were taken to prepare the specimen:

1. Coring the rock blocks;
2. Cutting the core specimens;
3. Polishing the cut specimens;
4. Putting the specimens in the furnace and then cooling them in the laboratory;
5. Creating a notch on the sandstone specimens.

In the first stage, i.e. the coring stage, a stone block was placed under the core drilling machine (using a 54.7 mm core drill). Water was used to cool the specimen, and finally, the cylindrical core was obtained.

In the next step, the cylindrical core was cut into segments with a height of 56 mm using a cutting machine.

In the next step, the specimens were transferred to a polishing machine to be polished. For this, the two sides of the specimens were marked and then polished in a way that their entire surface was flattened and all the colors were wiped.

The next step was to place the specimens inside the furnace to heat them at a temperature of 3 °C per minute to the specified temperature (60, 100 or 150 °C). Additionally, some specimens were tested at 25 °C so there was no need to heat them in the furnace.

In the last and most difficult step, the specimens were transferred to the lathe. The round drill was connected to the mandrel, and the rock specimen was placed on the chuck. Then the notch was created within the rock by bringing the mandrel closer to the chuck (Figure 5). The prepared specimens are shown in Figure 6.

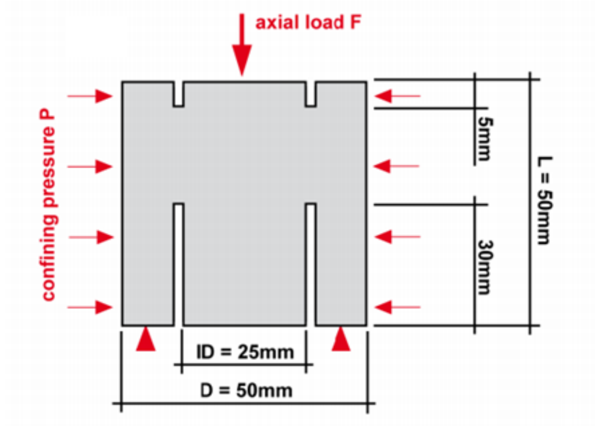

Figure 4. General form of specimen under stress [29].

Figure 5. Creating notches on the base of sandstone specimens.

Figure 6. Prepared sandstone specimens.

4. Investigating effects of temperature and confining pressure on mode II fracture toughness of sandstone

4.1. Testing specimens

The tests were performed on 31 specimens taken from 7 blocks (blocks A, B, C, D, E, F, and G). These tests were carried out to investigate the effects of the confining pressure and temperature on the mode II fracture toughness. The specimens were tested under the pressures of 3, 5, 7, and 10 MPa to investigate the effect of the confining pressure, and a test was conducted in the absence of the confining pressure. In order to test the effect of temperature, the tests were conducted under the 3 MPa confining pressure on the specimens undergoing 1, 5, and 10 heating-cooling cycles. The test conditions are presented in Table 3.

The general schematic representation of loading the specimens is shown in Figure 7.

The load was applied to the upper base with a 5-mm notch height, as shown in Figure 7. In order to perform the test, a specimen was first placed inside the hook cell, and a punch was placed in the hook cell from the side with 5 mm notch to transfer the load from the loading jack to the specimen inside the hook cell. In the part where the base had a notch with a height of 30 mm, a lower retainer was inserted in the cell. Prior to inserting the cell in the axial loading jack, the confining pressure was connected to the cell, the de-airing was done, and a little pressure was applied to the cell to secure the specimen in its place. After applying the oil pressure, the specimen and the Hoek cell were placed in the axial loading jack, and LVDT was attached to the data recording device (as shown in Figure 8).

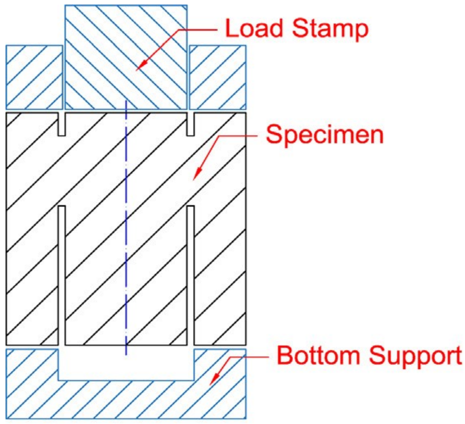

Figure 7. General schematic representation of loading [32].

Figure 8. Testing specimens by triaxial cell.

Table 3. Conditions of tested specimens.

Number of samples	Rate of temperature rise (°C/min)	Temperature (°C)	Number of cycles	Confining pressure (MPa)
A11	-	25	-	3
A41	-	25	-	3
A51	-	25	-	3
A12	3	60	1	3
A13	3	60	1	3
A21	3	60	1	0
A22	3	60	1	7
A23	3	60	1	5
A31	3	60	1	10
B11	3	100	1	3
B12	3	100	1	3
C11	3	60	1	7
D11	3	60	1	10
D32	3	60	1	5
D41	3	150	1	3
D51	3	150	1	3
G11	3	100	1	3
B21	3	60	5	3
B22	3	60	5	3
B32	3	100	5	3
B33	3	100	5	3
D23	3	150	5	3
D61	3	150	5	3
B13	3	100	10	3
B23	3	60	10	3
B31	3	60	10	3
C31	3	150	10	3
D22	3	100	10	3
D42	3	150	10	3
E11	3	60	10	3
F11	3	60	10	3

After installing LVDT, first, the confining pressure and the axial load increased at the same rate. After the confining pressure reached the desired value (the confining pressure device maintaining the pressure during the test), the axial load continued until the specimen was fractured, and the fracture load was recorded by the machine. When the test was performed in the absence of confining pressure, as shown in Figure 9, there was no need to place the specimen inside the cell.

Figure 9. Loading on specimen in the absence of confining pressure.

4.2. Determining the rate of mode II fracture toughness using punch test

The mode II fracture toughness in the PTS test, with the F_{max} value obtained from the tests, could be calculated using Equation 1 [3].

$$K\ IIC = 7.74 \times 10^{-2} \times Fmax - 1.8 \times 10^{-3} \times Pc \quad (1)$$

where:

K IIC: mode II fracture toughness, in $MPa\sqrt{m}$;

F_{max}: fracture load, in kN;

P_c: confining pressure, in MPa.

This equation was applied to the PTS method only when the diameter of the notch in the upper and lower bases was equal to 25 mm, the height of the upper notch was 5 mm, and the height of the lower notch was 30 mm [3].

4.3. Determining rock fracture energy

Equation 2 was used to calculate the fracture energy [33].

$$Gf = \frac{1}{A_{lig}} \times \int f \times dx \quad (2)$$

In this equation, $\int f \times dx$ is equal to the area below the surface of the force-deformation curve.

Deformation was measured by LVDT, and F was measured using the loader of the axial loading machine and recorded by a data recording device. After completing the tests, this graph was plotted by Excel, and then the area under the curve was calculated. A_{lig} is equal to the area of the rock muscle segment whose value can be calculated by Equation 3.

$$A_{lig} = \pi \times \left(h - (a + b) \right) \times D \quad (3)$$

where:
A_{lig}: Area of rock muscle segment, in mm^2;
h: Height of specimen, in mm;
a: Height of upper notch, in mm;
b: Height of lower notch, in mm;
D: Diameter of notch, in mm.

4.4. Test results

4.4.1. Results of PTS test conducted on specimens enduring a heating-cooling cycle in the presence of various confining pressures

All the specimens underwent a heating cycle up to 60 °C and then a cooling cycle in the laboratory before being tested. The results of the PTS test for investigating the effect of the confining pressure on the mode II fracture toughness are presented in Figure 10. For each confining pressure, two tests were carried out whose average results are presented in Figures 10 and 11. A test was carried out in the absence of confining pressure.
Figure 11 shows the results of fracture energy changes in the presence of confining pressure.

4.4.2. Results of PTS test in the presence of 3 MPa confining pressure on specimens undergoing heating-cooling cycles (1, 5, and 10 cycles)

The specimens prepared for this test were divided into three groups: the first group was heated up to 60 °C and then cooled down, the second group was heated up to 100 °C and then cooled down, and the third group was heated up to 150 °C and then cooled down. All specimens of the three groups were divided into three sub-groups. The first sub-group consisted of the specimens undergoing a heating-cooling cycle. The second and third sub-groups were composed of the specimens undergoing 5 and 10 heating-cooling cycles, respectively. Figure 12 shows the results of the effects of temperature and the heating-cooling cycles on the mode II fracture toughness, and Figure 13 shows their effects on the fracture energy. For each case, two specimens were tested whose average results are shown in Figures 12 and 13.
The profile of crack generation and fracture propagation of specimens is shown in Figure 14.

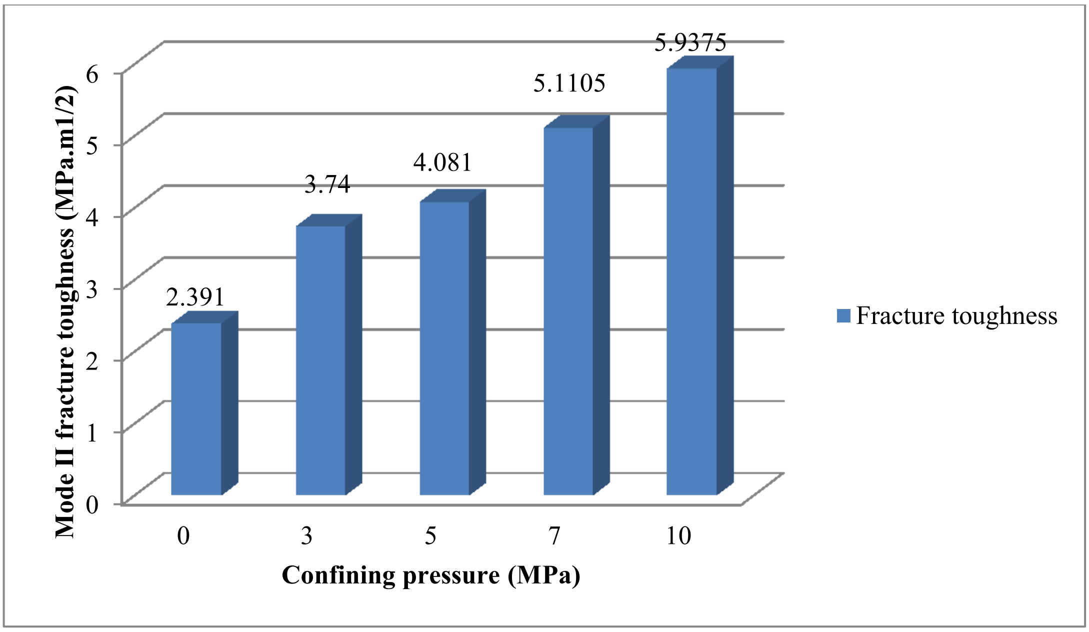

Figure 10. Changes in fracture toughness in the presence of confining pressure.

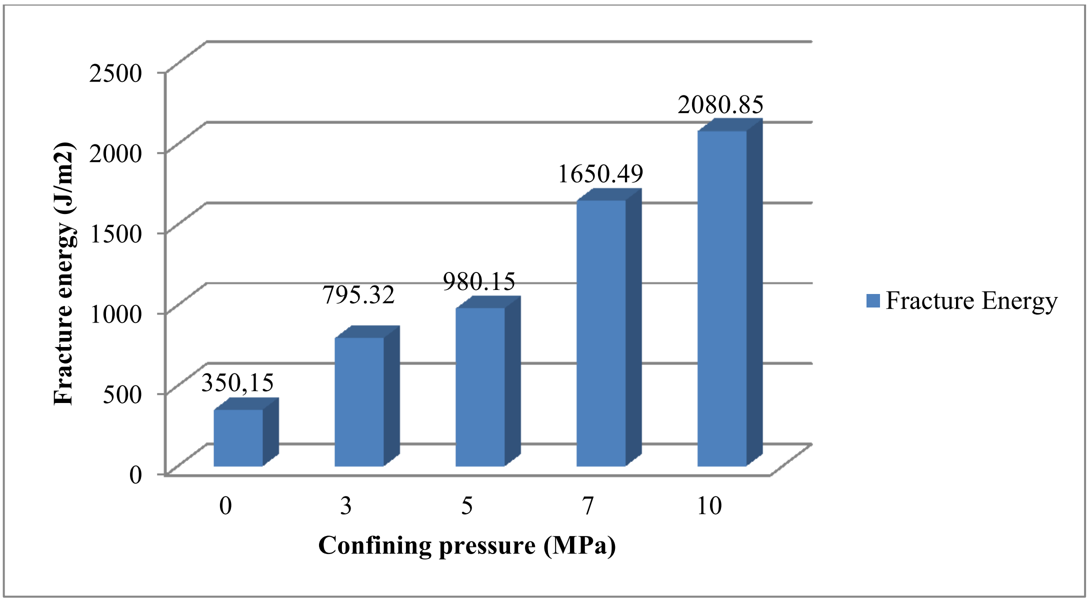

Figure 11. Changes in fracture energy in the presence of confining pressure.

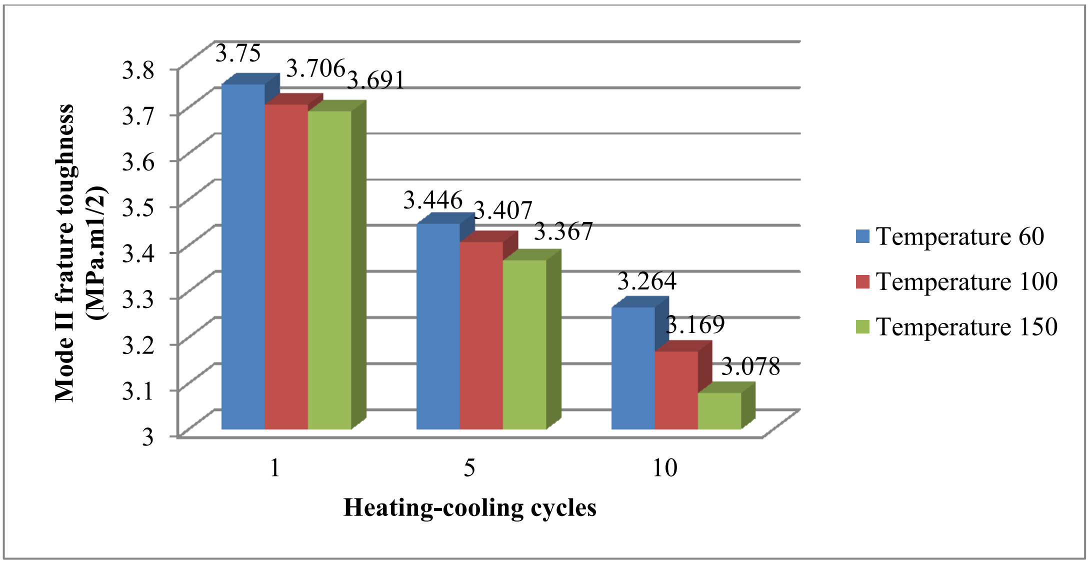

Figure 12. Changes in fracture toughness with temperature and number of heating-cooling cycles.

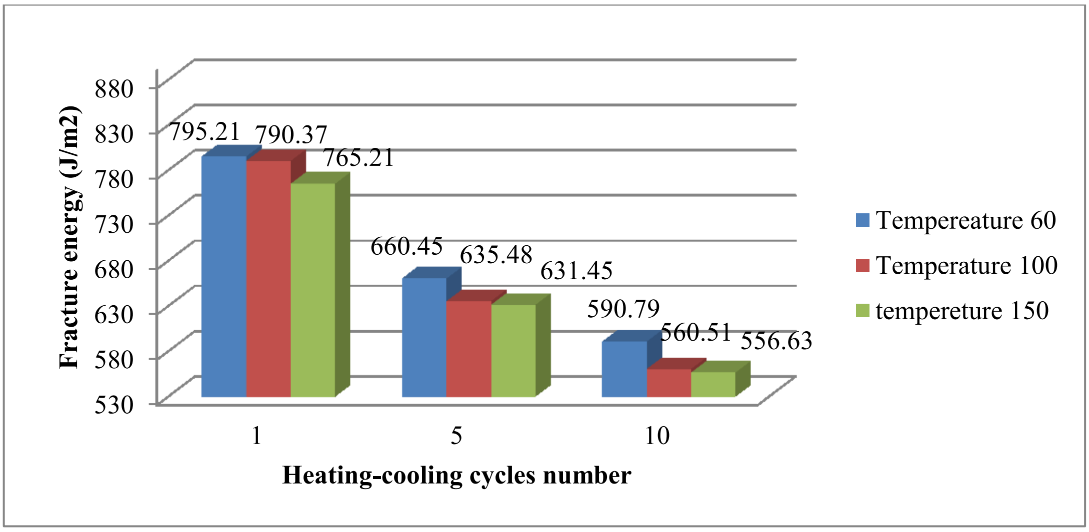

Figure 13. Changes in fracture energy with temperature and number of heating-cooling cycles.

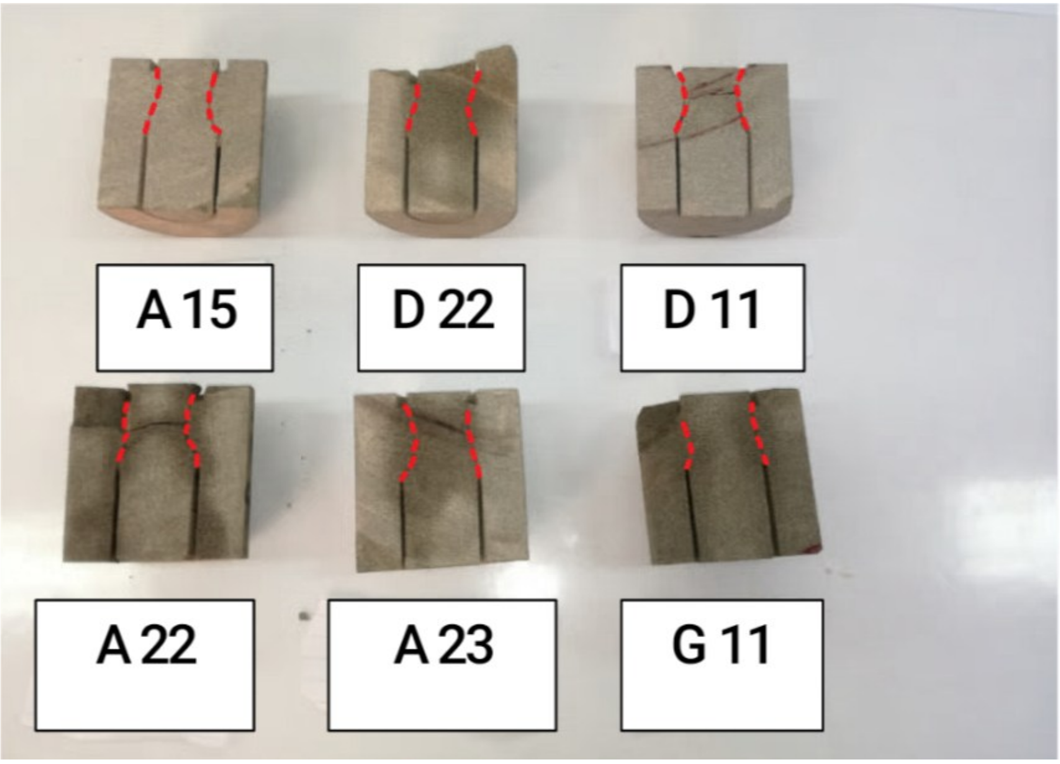

Figure 14. A profile of fracture propagation of specimens (cracks generated after test are marked in red).

4.5. Analysis of results

The analysis results obtained showed that the mode II fracture toughness as well as the fracture energy would intensify by increasing the confining pressure (Figures 10 and 11). These results are consistent with the results of the work performed by Bakeres et al. in 2004 [34] so that by increasing the confining pressure, the stress perpendicular to the cutting surface increases, leading to the increased fracture toughness. It is also clear from Equation (4) [35] that with increased fracture toughness, the fracture energy also increases.

$$K_{IIC}^2 = G_{IIC}.E \quad (4)$$

where:
G_{IIC}: Fracture energy;
E: modulus of elasticity.
Calculation of the fracture energy by Equation (4) also showed that the numbers obtained from this equation were slightly different from the energy calculated by Equation (2), indicating the correctness of the results. For example, the fracture energy in the absence of the confining pressure by Equation (4) was equal to 329.12 J/m^2 and by Equation (3) was equal to 350.15 J/m^2. Table 4 shows the ratio of mode II fracture toughness in the presence of the confining pressure (K IIC) to the rate of mode II fracture toughness in the absence of the confining pressure (K IIC_0) as well as the ratio of the fracture energy in the presence of the confining pressure (G IIC) to the fracture energy in the absence of the confining pressure (G IIC_0). According to this table, the rate of the mode II fracture toughness in the presence of the confining pressures of 3, 5, 7, and 10 MPa was, respectively, 1.56, 1.71, 2.14, and 2.48 times the rate of mode II fracture toughness in the absence of the confining pressure, and the rate of fracture energy in the presence of the confining pressures of 3, 5, 7, and 10 MPa was, respectively, 2.27, 2.79, 4.71, and 5.94 times the rate of fracture energy in the absence of the confining energy.

Table 4. Ratio of fracture toughness and fracture energy in the presence of confining pressure to fracture toughness and fracture energy in the absence of confining pressure.

Confining pressure (MPa)	$K IIC/K IIC_0$	$G IIC/G IIC_0$
0	1	1
3	1.56	2.27
5	1.71	2.79
7	2.14	4.71
10	2.48	5.94

The analysis results of studying the effect of heating-cooling cycles indicated that with increase in the number of heating-cooling cycles, the values for the mode II fracture toughness and the fracture energy decrease. These decreases occurred for all the three modes, i.e. when the specimens were heated up to 60, 100, and 150 °C in the heating cycle, the fracture toughness and fracture energy decreased (Figures 12 and 13). Of course, the effect of heating-cooling cycles on the fracture toughness was very small compared to that of the confining pressure. This reduction in toughness is due to the development of micro-cracks caused by the thermal stress during the heating of specimens and the propagation of these micro-cracks when the specimens contracted during the cooling stage. With increase in the number of heating-cooling cycles, these micro-cracks are further expanded. As a result, toughness decreased with increase in the number of cycles. Meanwhile, as the temperature rised, the thermal stress increased. Therefore, it could be observed that with rising temperature, the rate of toughness decreased due to increase in the density of micro-cracks. For this reason, the toughness of specimens was less when they were heated up to 100 °C, compared with a state in which the specimens were heated up to 60 °C. According to Equation (4), it is also clear that with decreasing toughness, the fracture energy decreases, which is in accordance with the results of this study. Table 5 shows the ratio of mode II fracture toughness for the specimens that endured the heating cycles ($K\,IIC$) to the mode II fracture toughness for specimens that did not endure the heating-cooling cycles ($K\,IIC_0$). It also shows the ratio of mode II fracture energy for specimens enduring the heating-cooling cycles ($G\,IIC$) to the fracture energy for specimens that did not endure the heating-cooling cycles ($G\,IIC_0$). According to this table, the values for mode II fracture toughness at 60 °C for cycles 1, 5, and 10 were, respectively, 0.98, 0.9, and 0.85 times the values for fracture toughness of those specimens that did not endure the heating-cooling cycles. The values for mode II fracture toughness at 100 °C for cycles 1, 5, and 10 were, respectively, 0.97, 0.88, and 0.82 times the values for fracture toughness of those specimens that did not endure the heating-cooling cycles, and the values for mode II fracture toughness at 150 °C for cycles 1, 5, and 10 were, respectively, 0.96, 0.87, and 0.8 times the values for fracture toughness of those specimens that did not endure the heating-cooling cycles. The value for ($K\,IIC_0$) was 846 J/m^2.

The values for fracture energy at 60 °C for cycles 1, 5, and 10 were, respectively, 0.94, 0.78, and 0.7 times the values for fracture energy of the specimens that did not endure the heating-cooling cycles. The values for fracture energy at 100 °C for cycles 1, 5, and 10 were, respectively, 0.93, 0.75, and 0.66 times the values for fracture energy of specimens that did not endure the heating-cooling cycles, and the values for fracture energy at 150 °C for cycles 1, 5, and 10 were, respectively, 0.9, 0.75, and 0.66 times the values for fracture energy of specimens that did not endure the heating-cooling cycles.

As the results of the tests presented in Figures 12 and 13 shows, the effect of temperature on fracture toughness and fracture energy is very small but the number of heating-cooling cycles has more effects on the fracture toughness and fracture energy.

Table 5. Ratio of fracture toughness in different temperatures and heating-cooling cycles.

Temperature (°C)	Heating-cooling cycle number	$K\,IIC/K\,IIC_0$	$G\,IIC/G\,IIC_0$
25	0	1	1
60	1	0.98	0.94
60	5	0.9	0.78
60	10	0.85	0.7
100	1	0.97	0.93
100	5	0.88	0.75
100	10	0.82	0.66
150	1	0.96	0.9
150	5	0.87	0.75
150	10	0.8	0.66

5. Conclusions

The presence of cracks and primary fractures in rocks is inevitable and is a special feature of any material that causes these structures and rock masses to be fractured faster under mechanical loads or other environmental factors. The previous studies on the fracture toughness of rocks have mainly focused on the mode I fracture toughness. The propagation of crack in the rock mass does not occur only in tensile conditions. Therefore, it is very important to study the mode II fracture toughness in order to understand the rock fracture. The sample used in this work was the Lushan sandstone. Notched cylindrical specimens were prepared for PTS testing. In order to investigate the effect of the confining pressure, some tests were conducted in the presence of the confining pressures of 0, 3, 5, 7, and 10 MPa, and to check the effect of temperature, some tests were performed under 1, 5, and 10 heating-cooling cycles at temperatures of 60, 100, and 150 °C as well as at the ambient temperature (25 °C). The confining pressure of 3 MPa was used in all the tests to investigate the effect of temperature. The results of this work are as follow:

- By increasing pressure, the mode II fracture toughness as well as the fracture energy also increased.
- The effect of confining pressure on the changes in the toughness and fracture energy was much greater than the effect of temperature.
- As the number of heating-cooling cycles increased, the values for the mode II fracture toughness and the fracture energy decreased. Reduction of fracture toughness and fracture energy occurred for all the three modes when the specimens were heated up to 60, 100, and 150 °C.
- The effect of the number of heating-cooling cycles on the reduced fracture toughness and fracture energy was greater than the effect of temperature.
- The effect of temperature up to 150 °C on changes of the fracture toughness and fracture energy was very small.

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اثر درجه حرارت و فشار محصور کننده بر روی چقرمگی شکست مود II سنگ (مطالعه‌ی موردی: ماسه‌سنگ لوشان)

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چکیده:

مکانیک شکست به بررسی ایجاد و گسترش ترک در جامدات و نحوه تأثیر آن بر تغییر شکل مصالح می‌پردازد. در معیارهای مبتنی بر ضرایب شدت تنش، ضرایب شدت تنش در نوک ترک، ضرایب شدت تنش بحرانی یا چقرمگی شکست مصالح در نظر گرفته می‌شود. سه مود اصلی اعمال نیرو بر ترک وجود دارد؛ که مود کششی، مود برشی و مود ترکیبی نامیده می‌شود. چقرمگی شکست مود II یا همان مود برشی یک پارامتر مهم برای بررسی رفتار سنگ است، این پارامتر در بسیاری از حوزه‌های مختلف مانند معدن‌کاری و تونل سازی مورد استفاده است. روش‌های مختلفی برای تعیین چقرمگی شکست مود II ارائه شده است، در این تحقیق از آزمایش PTS که توسط جامعه‌ی بین‌المللی مکانیک سنگ استاندارد شده استفاده شده است و امکان تعیین چقرمگی شکست در حالی که فشار محصور کننده وجود دارد میسر است. نمونه مورد مطالعه در این پژوهش ماسه‌سنگ لوشان است. در این پژوهش نمونه‌های استوانه‌ای شیاردار برای آزمایش PTS آماده شده است. برای بررسی اثر فشار محصور کننده، آزمایش‌هایی با فشارهای محصور کننده ۰، ۳، ۵، ۷ و ۱۰ مگاپاسکال و برای بررسی اثر درجه حرارت آزمایش‌هایی تحت سیکل‌های گرم شدن و خنک شدن به صورت ۱، ۵ و ۱۰ سیکل در دماهای ۶۰، ۱۰۰ و ۱۵۰ درجه سانتی‌گراد و همچنین دمای محیط (۲۵ درجه سانتی‌گراد) انجام گرفته است. در بررسی اثر درجه حرارت، فشار محصور کننده ۳ مگاپاسکال در تمامی آزمایش‌ها استفاده شده است. نتایج تحلیل‌ها نشان می‌دهد با افزایش فشار محصور کننده چقرمگی شکست مود II و همچنین انرژی شکست افزایش می‌یابد. همچنین با افزایش تعداد سیکل‌های گرم شدن- خنک شدن مقدار چقرمگی شکست مود II و انرژی شکست کاهش می‌یابد که این کاهش برای هر سه حالت یعنی زمانی که در مرحله گرم شدن نمونه‌ها تا ۶۰ درجه سانتی‌گراد، ۱۰۰ درجه سانتی‌گراد و ۱۵۰ درجه سانتی‌گراد گرم شوند این کاهش چقرمگی و انرژی شکست اتفاق می‌افتد. اثر تعداد سیکل‌های گرم شدن- خنک شدن روی کاهش چقرمگی و انرژی شکست بیشتر از اثر درجه حرارت است.

کلمات کلیدی: چقرمگی شکست، مود II، فشار محصور کننده، درجه حرارت، ماسه‌سنگ.