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The Experimental Investigation of the Effect of Heating-Cooling Cycle Number of Rock on Mode I Fracture Toughness

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ABSTRACT: There are small cracks in rocks; therefore, when rocks undergo loading, stresses are concentrated at the tip of cracks causing rock fracture before reaching its ultimate strength. The critical value of the stress intensity factor at the crack tip is called fracture toughness. The tensile strength of rocks is weak; therefore, Mode I (tensile mode) is the most critical loading mode. In some cases, rocks continuously experience heating-cooling. Therefore, it is necessary to determine the effect of heating-cooling cycle number on mode I fracture toughness, which is the objective of this research. To achieve this objective, we conducted three-point bending test on semi-circular specimens of three types of natural rock including sandstone, limestone and andesite to determine the mode I fracture toughness. A series of concrete specimen was also tested for further investigation. Petrography and X-ray diffraction analysis (XRD) were conducted to understand the rock composition. The specimens were heated up to 700° C in 1, 5 and 10 cycles and then cooled. A series of experiments were also conducted on the specimens at room temperature (25°C). According to the rising of temperature in firing process, the rate of temperature rise for specimens in the electric furnace is determined to be 15 ° C per minute. Fracture toughness of andesite rock, sandstone and limestone specimens decreases under cyclic conditions. Results indicate the generation and expansion of micro fractures in some rocks after undergoing cycles of heating-cooling, which causing an increase in the effective porosity and decrease in the P-wave velocity in rocks.

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1- Introduction

There are three major modes for applying force on cracks. Mode I (opening mode), Mode II (sliding), and Mode III (tearing). Figure 1 schematically illustrates these modes. Any combination of these three major modes is known as a combined mode. Fracture toughness depends on factors such as temperature, loading rate, material composition, the microstructure and geometrical effects. All types of rocks are weak under tension, hence, Mode I (tension) is known as the most critical loading. Given that in some cases, such as an explosion, fire, deep excavations, and geothermal energy recovery, rocks are considerably heated which is effective on the fracture toughness of the rock. The effect of thermal cycles on the fracture toughness has not been widely studied. Kim et al. (2014) experimentally and numerically investigated the impact of cyclic heating on Mode I fracture toughness revealing two different behaviors in the rocks. It was found that cyclic heating reduces fracture toughness in some cases while increasing it in others [1].

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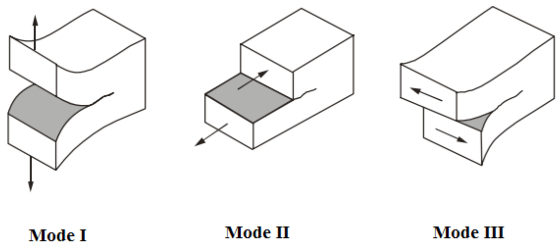

Figure 1. The main fracture modes [2]

2- Experiments and results analysis

Semicircular specimens were analyzed by the three-point bending test in order to find Mode I fracture toughness. Three types of rocks (Andesite, Sandstone, and Limestone) and a number of concrete specimens were investigated. Three different heating scenarios (1 cycle, 5 cycles, and 10 cycles) were investigated for each type of rock, where the specimens were heated up to 700 °C and cooled down to ambient temperature. A few experiments were also conducted on the specimens that were not heated.

Compared to the control specimens that were not heated, fracture toughness was found to be reduced in the specimens that underwent 1 heating cycle, by 41, 9.5 and 42% for limestone, andesite, and sandstone, respectively. Fracture toughness of the specimens that underwent 5 heating cycles (up to 700 °C) was reduced by 12.5, 7 and 13% compared to the case with 1 heating cycle for limestone, andesite, and limestone, respectively.

Compared to the case with 5 heating cycles, fracture toughness was found to be reduced in the specimens that underwent 10 heating cycle, by 61, 36 and 61.5% for limestone, andesite and sandstone, respectively. The variation of fracture toughness is plotted in different cycles for the 3 types of rocks in Figure 2. Increasing the temperature leads to thermal stresses in the rock. Considering the fact that thermal expansion coefficient is different for various minerals, the stresses are focused on the boundaries between minerals and result in crack nucleation or growth if exceeding the shear or tensile strength of the rocks [3]. In addition, new cracks are formed during cooling as a result of contraction, especially on the grain boundaries of different minerals. Therefore, the density of cracks is increased overall [3]

Moreover, microscope and X-ray diffraction (XRD) investigations of the specimens revealed that the rocks are composed of various minerals and compounds, which promotes crack density upon heating. The density of the cracks is in inverse correlation with mineral grain size and small grains are associated with a larger concentration of grain boundary cracks. The mineral composition, which can be determined by XRD, is also effective on fracture toughness variations.

Figure 3 shows the variations of effective porosity for andesite, limestone, and sandstone specimens in various heating-cooling cycles (no heating-cooling, 1, 5 and 10 cycles). Micro-cracks form and propagate in the rock specimens after undergoing heating and cooling cycles, increasing the porosity [4].

3- Conclusion

The impact of heating-cooling cycles on Mode I fracture toughness was studied in this paper for three types of rocks (sandstone, limestone, and andesite) and also concrete. The specimens were heated up to 700 °C and cooled in 1, 5 and 10 cycles. The results are as follows:

- Increasing the number of heating-cooling cycles reduces fracture toughness. Fracture toughness is in inverse correlation with porosity and increased porosity results in reduced fracture toughness.
- The impact of heating-cooling cycles on concrete specimens is more than the rocks and large cracks were formed in concrete specimens after multiple cycles.
- The velocity of longitudinal waves is reduced in the specimens as the number of thermal cycles applied to the specimen is increased. This was the most intense for the concrete specimen.
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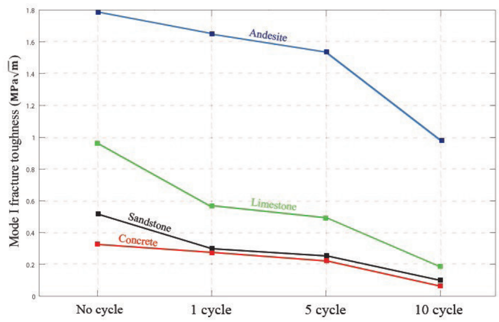

Figure 2. The mode I fracture toughness of andesite, limestone, sandstone and concrete at different heating-cooling cycles

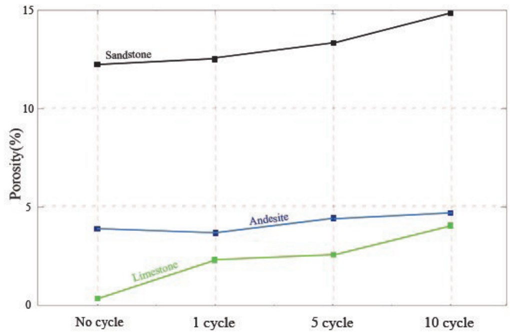

Figure 3. The changes in effective porosity of sandstone, andesite and limestone at different heating-cooling cycles

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