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Investigation Of Rock Fracture Parameters With Hollow Center Cracked Disc Under Quasi-Static Loading Condition

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Abstract: Experiments have indicated that the fracture properties of rocks change with variations of loading rate. In this study, the microstructural properties of two marbles are characterized by three different microscopic techniques including petrographic thin sections method, fluorescent replacement technique, and scanning electron microscopy (SEM). An experimental investigation is conducted to study the quasi-static fracture behavior in different microstructural features of crystalline rocks. The hollow center cracked disc (HCCD) method is employed to determine the fracture parameters with variations of loading rates using a hydraulic machine. Microscopic studies on microstructure deficits reveal that fractal dimension in Maroon marble is higher than in Baghat marble. Variations of toughness, crack propagation speed, and crack tip opening displacement (CTOD) with changes of loading rate are also investigated. The results indicate that toughness and crack propagation speed increase with loading rate, but the effect of microstructure in two marbles reduces the rate of growth. The fracture toughness in Baghat marbles is higher than in Maroon marble, and difference of fracture toughness is magnified with the loading rate.

Keywords: Fracture toughness, High-speed imaging technology, Fracture properties, Quasi-static loading.

INTRODUCTION

Fracture mechanics approaches are have been gaining importance in rock engineering applications. Fracture in rocks is one of the most popular research focuses in geomechanics as a large number of engineering designs and implementations including rock slope stability assessments, tunnel support design, and fluid flow prediction can improve with a greater understanding of fracture. It is particularly useful in geomechanical tests given the scales and frame rates involved.

The fundamental goal of fracture mechanics testing is to obtain a representative value of rock fracture properties. Fracture toughness is known as a fundamental fracture property which represents the potential intrinsic ability of rocks to withstand a given stress field at the tip of a crack and to resist progressive crack extension [1]. Measuring rock fracture toughness under quasi-static loading is a topic of extensive research in fracture mechanics. Measuring fracture properties of rocks such as toughness, crack propagation speed, and crack tip opening displacement (CTOD) and investigating their interdependencies contribute to identifying the rock fracture behavior. In spite of a large number of reported research works about the quasi-static behavior of rocks, rock fracture behavior under quasi-static loading has not been fully characterized.

It has been observed that the fracture parameters of rocks can be performed by high-precision laboratory testing equipment such as high-speed imaging technology. High-speed imaging technology has been used for geometrical research since the 1950s, and various imaging techniques have been applied in parallel. However, due to the difficulties associated with measuring and recording events with short durations, particularly those that are not adequately observable with the naked eye, the dynamic properties of geomaterials have not been well understood for a long period. High-speed imaging technology has been used by numerous researchers in geomaterials engineering application including sand Movement, penetration, static and dynamic fracturing, blasting and impacts, spalling, and fragmentation [2].

Crack speed of the tensile fracture properties of concrete and the dependencies on mechanics' behavior have been investigated in several studies. Wong and Einstein (2006, 2009) examined the crack behavior of prismatic specimens with single flaws via high-speed imaging technology [3,4]. Song et al (2014, 2015) by applying a high-speed camera investigated crack initiation, propagation, coalescence, and final failure of pre-cracked marble samples under loading and unloading conditions [5].

Also, Lim et al. (1993) determined the fracture toughness and crack propagation speed of NSCB specimens under quasi-static loading conditions. Their results indicate no interdependence between the fracture toughness and crack propagation speed at a constant loading rate (0.002 mm/s). However, the crack propagation speed in rocks with higher toughness like Gabbro was faster than that in rocks with lower toughness like marble [6,7] (Lim et al. 1993; Zhang and Zhao 2014). Crack propagation speed of rocks under different loading conditions has been investigated by various researchers. Bieniawski's laboratory studies showed that the crack propagation speed is an important parameter in the brittle fracture of materials [8,9]. In dynamic loading, several laboratory studies have been done to measurement of the crack propagation speed in different samples under shock and explosion loading conditions. The crack propagation speed in different rocks is estimated to range from 0.2 to 0.57 Rayleigh wave speed (Cr).

Fracture toughness can be assessed experimentally using different testing specimens and loading configurations. The International Society for Rock Mechanics (ISRM) suggested use of Cracked Chevron-Notched Brazilian Disc (CCNBD), Chevron-Notched Bending (CB), and Short Road (SR) to determine fracture toughness of rocks. However, the complexity of chevron notch making is another motivation to seek for alternative methods such as Semi-Circular specimens under three-point Bending (SCB) and Flattened Brazilian Disc (FBD) specimen in diametrical compression to determine mode I fracture toughness (KIC) of rocks. Double Edge Cracked Brazilian Disc (DECBD) and Hollow Centre Cracked Disc (HCCD) are other disc-type specimens which are core-based and enjoy comparatively simple preparation and testing. HCCD samples both possess CCNBD's merits and have a far simpler preparation procedure.

Regarding the HCCD, sample, when it is placed under the pure tension mode, two cracked sections are opened with loading. Shiryaev and Kotkis used Mode I of this piece to estimate the magnitude of the mode I fracture toughness (KIC) of rocks [10].

The mechanical properties and fracture behavior of rock materials are influenced by loading rate. Rock fracture toughness in quasi-static loading can also be a function of the fracture properties including crack propagation speed, crack tip opening displacement (CTOD), and the loading rate. This relation or function has been researched in dynamic loading; however, in quasi-static loading no study has been conducted so far.

Since quasi-static loading is achieved within a specific range of loading rate, variations of loading rate can be used to investigate the effect of fracture parameters in a hollow center cracked disc (HCCD) sample.

The macroscopic and microscopic aspects of fracture behavior are closely linked, and thus it is essential to interpret the macroscopic behavior by identifying the failure mechanisms on a microscopic scale (RaviChandar and Knauss 1984b)[11]. Hence, in this study, two crystalline construction marble stones in Iran, Baghat and Maroon, which have a unique mineral composition with different microstructure distributions, were selected as test samples (Figure 1 to 3).

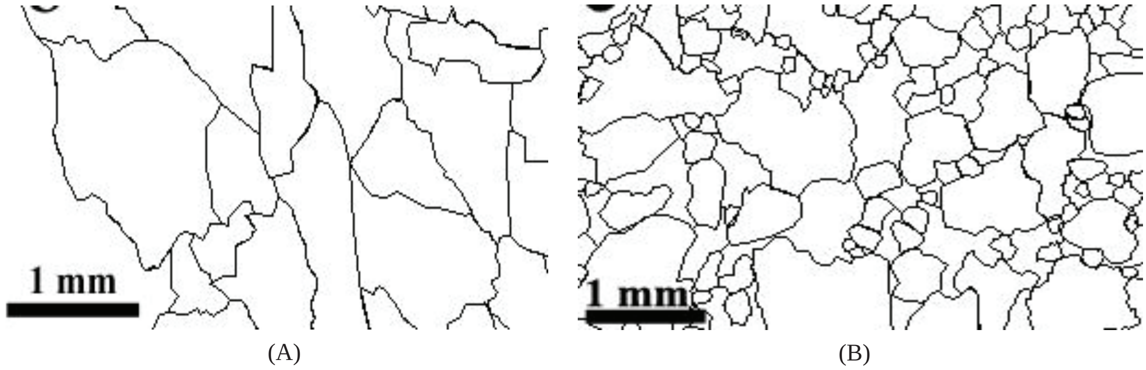

Figure 1. Parts of the polygons of the mosaic of A: Baghat and B: Maroon

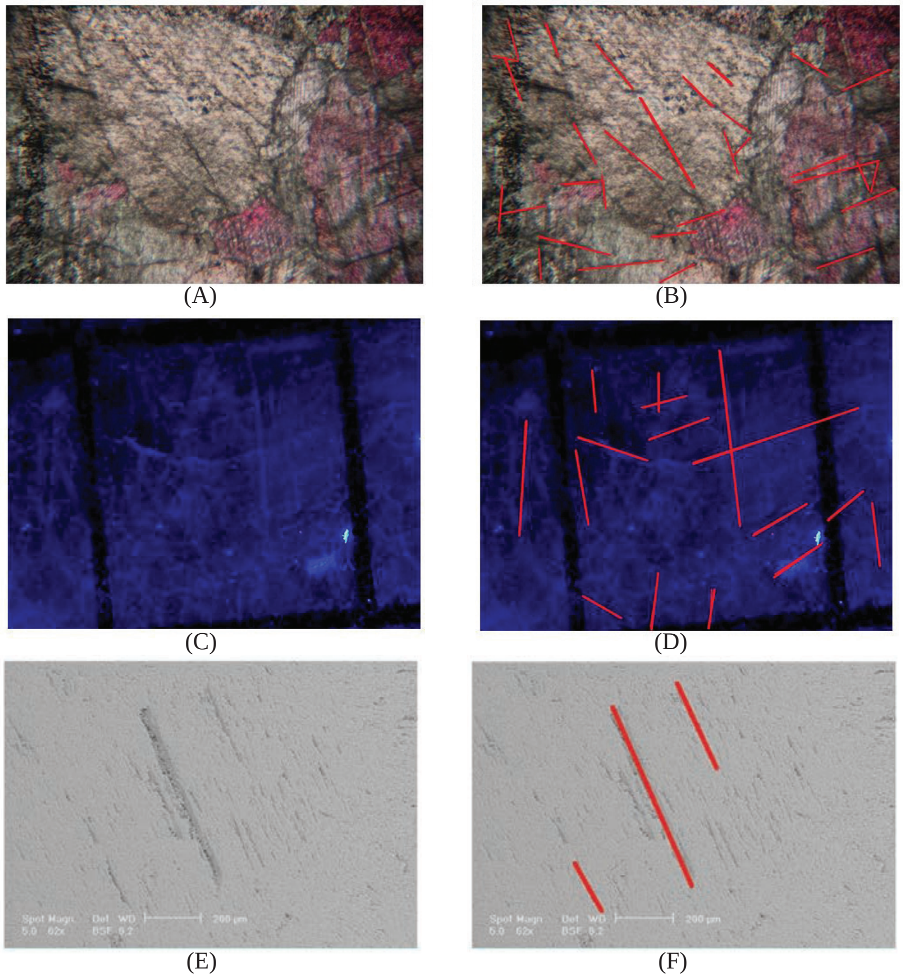

Figure 2. Characterization of micro cracks (red lines) in marbles using A, B: polarizing microscopic FLR

For precise measurement of crack propagation speed and CTOD using high-speed imaging technology and electronic circuitry, the effect of loading rate variation was examined on toughness, crack propagation speed, and CTOD in the two marbles with different microstructures under quasi-static loading conditions.

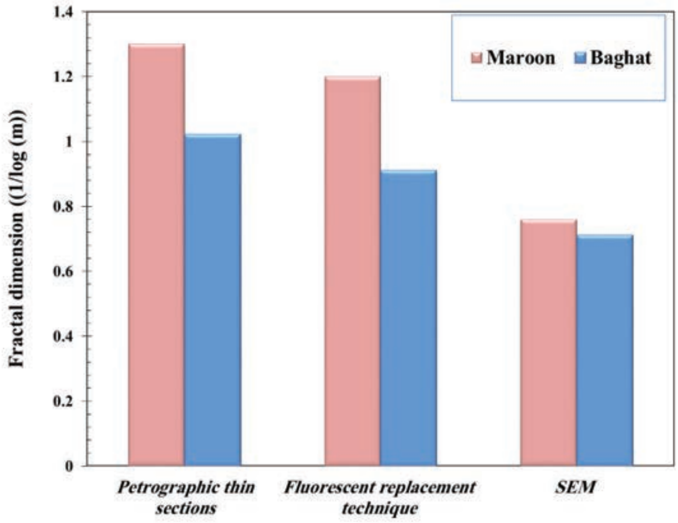

Figure 3. Comparison between fractal dimension of micro cracks in Baghat and Maroon marbles in different measuring techniques

FINDINGS AND ARGUMENT

By comparing consecutive images from the failure time to rock fracturing, using image processing techniques, the CTOD and the crack propagation speed were measured (Figures 4 and 5). Also, the values of the crack propagation speed were verified against the results of the electronic circuitry.

The relationships between fracture toughness (KI) and loading rate, crack propagation speed (v) and loading rate, fracture toughness (KI) and crack propagation speed (v), crack propagation speed (v) and CTOD were investigated and also compared between the two marbles. According to Figure 6, the fracture toughness in Baghat marbles is higher than that of Maroon marble, which was obtained in previous studies [12]. According to Table 1, the difference of fracture toughness in the two marbles, under the low loading rate condition, was 0.42%. However, with elevation of the loading rates, the difference grew and under high loading rate conditions, the difference was 14.78%. The fracture toughness depended on the loading rate,

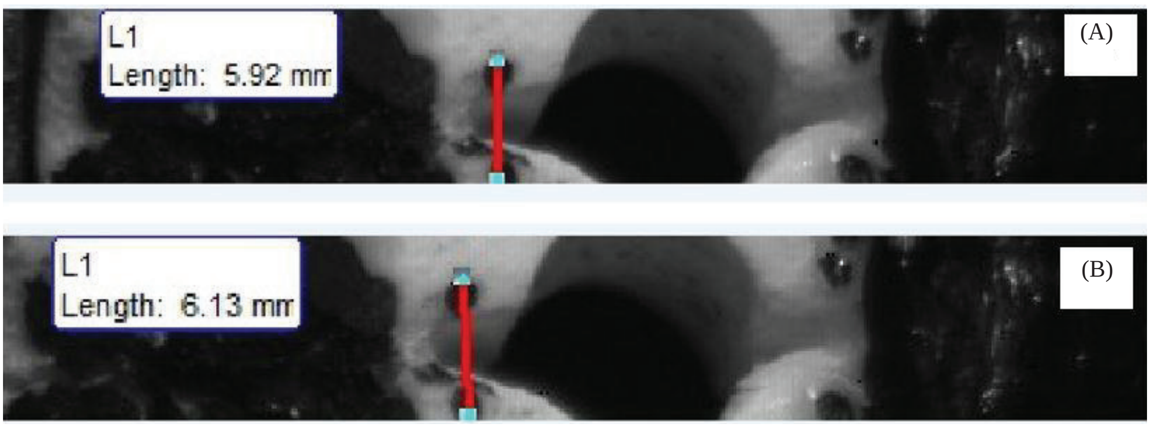

Figure 4. Measuring crack tip opening displacement using high-speed image processing in Maroon marbles in before and after loading

with this dependence being different for Baghat and Maroon marbles. In Baghat marbles, with in the rise of loading rate by 1.8 times, the fracture toughness grew by 1.27 times. However, in Maroon marbles, with an increase in the loading rate by 1.85 times, the fracture toughness was augmented by 1.1 times.

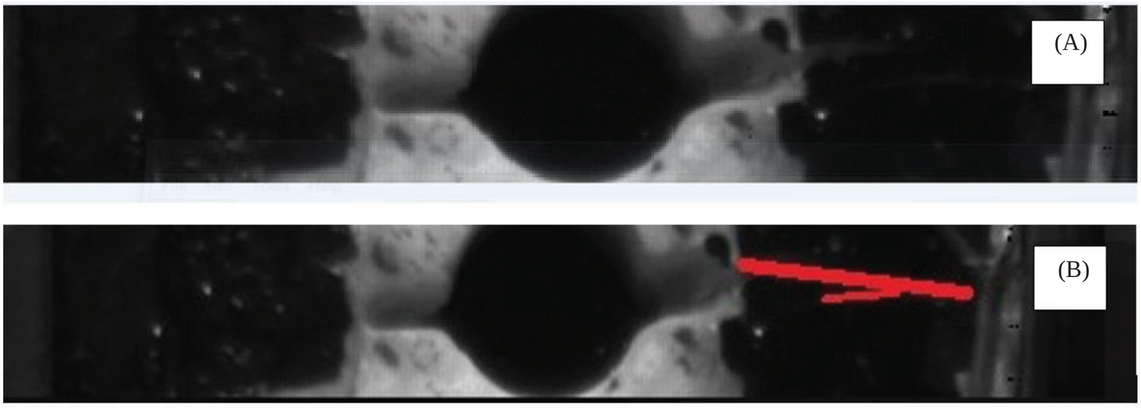

Figure 5. Measuring the crack propagation speed using high-speed image processing in Baghat marbles

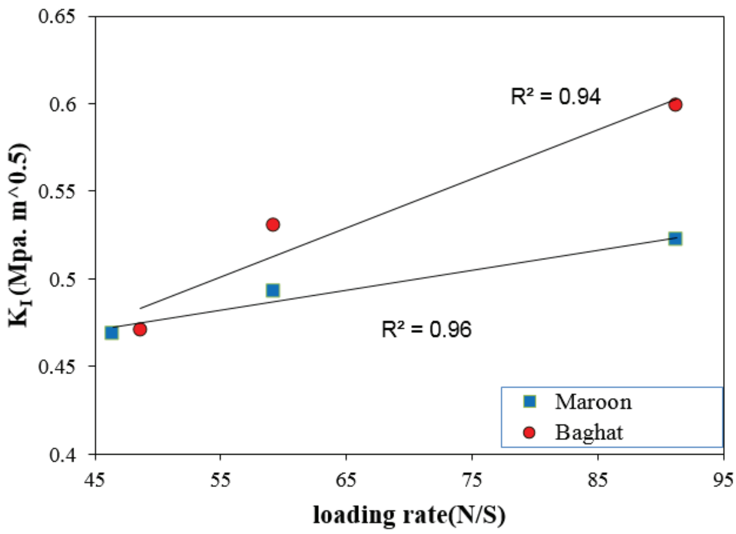

Figure 6. Fracture toughness of Maroon and Baghat versus loading rate

Table 1. Detail of variation of K_{IC} versus loading rate in Maroon and Baghat marbles

Marbles type	Loading rate	$\overline{K}_{IC}$	Repeatability	Error (%)
Baghat	48.62	0.47	2	0.64
	59.29	0.53	3	-2.75
	91.29	0.598	3	0.92
Maroon	46.49	0.468	2	1.41
	59.293	0.493	3	-1.49
	91.29	0.521	3	0.58

According to Figure 7, the rate of crack propagation speed grew with increasing the loading rates on both rocks. The rate of crack propagation in Baghat marble was 1.64 and in Maroon was 2.6. This suggests that the crack propagation speed within the quasi-static loading range depended on the loading rate. The propagation speed in Baghat marble has been more than that of Maroon marble. The difference between them grows with raising the loading rates.

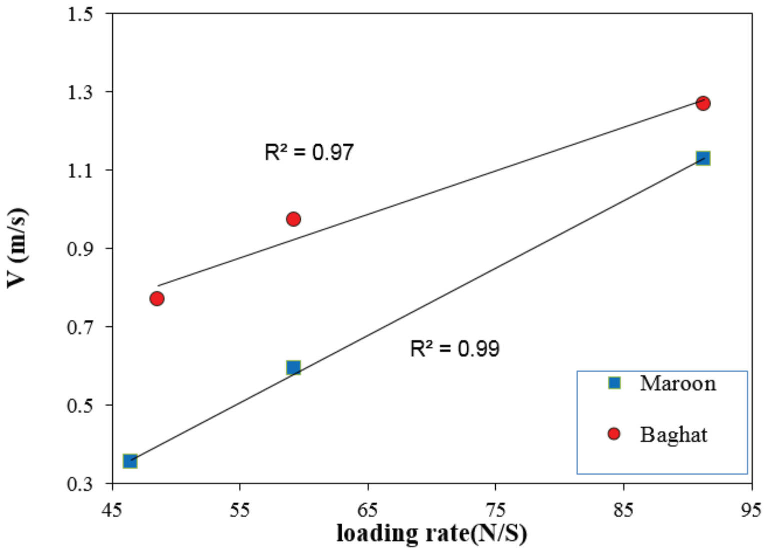

Figure 7. Crack propagation speed of Baghat and Maroon versus loading rate

There is a direct relationship between the fracture toughness and crack propagation speed within the quasi-static loading range, as displayed in Figure 8. Clearly, with the growth of toughness, rocks were fractured within a shorter time (higher rate), but with toughness reduction, the failure time lengthened (lower rate).

In Maroon marbles, with the increase in the loading rate, the crack propagation speed rose. The fracture toughness depended on the loading rate, so with a growth of 1.45 times in the magnitude of fracture toughness, the crack propagation was elevated by 2.54 times. Also, according to Figure 9, in Baghat marbles, with a growth of 1.3 times in fracture toughness, the crack propagation increased by 1.9 times.

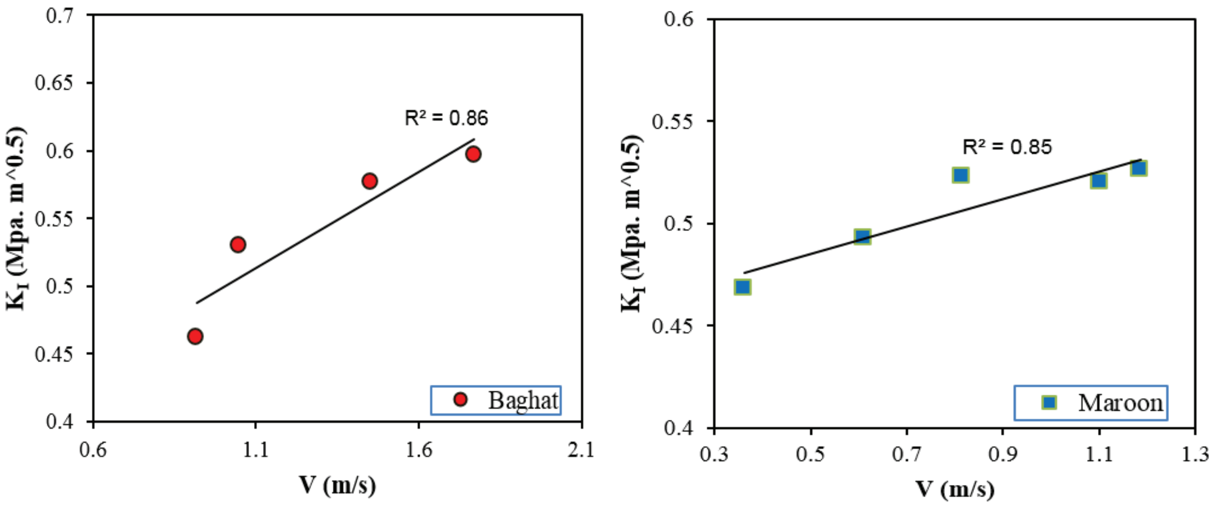

Figure 8. Fracture toughness of Maroon and Baghat, versus crack propagation speed at variable loading rate

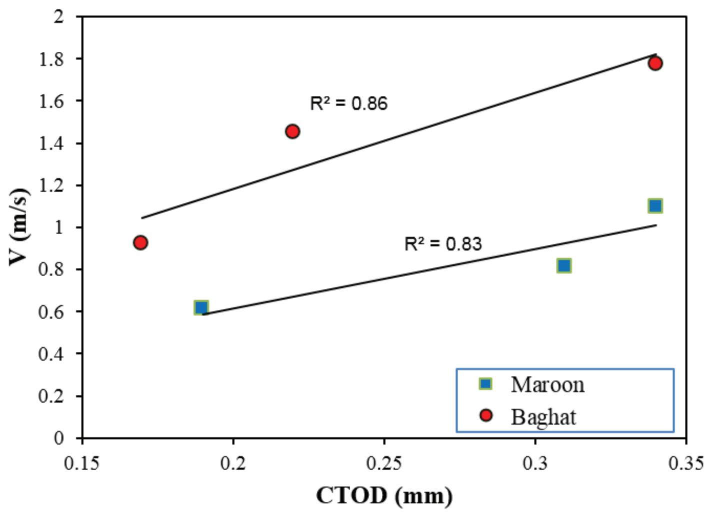

Figure 9. Crack propagation speed of Maroon and Baghat, versus crack-Tip-opening- displacement (CTOD) at variable loading rate

The ratio of toughness growth in Baghat marbles has been 12%, which is lower than the growth percentage of Maroon marbles.

Although CTOD in the tensile failure of materials was discussed earlier, in this study, the specimens were placed under modes I loadings and tensile stress was applied to the tip of cracks, and CTOD was measured. According to the diagram in Figure 8, at lower crack propagation speeds, crack tip opening was less, while at higher crack propagation speed, the crack tip opening grew. The discrepancy of the relationship between these two parameters is related to the microstructural difference of the two marbles.

CONCLUSIONS

The goal of this study has been measuring the rock fracture properties and investigating their relationships in two types of marble with different microstructures under quasi-static loading. Interpretation of the macroscopic behavior is essential by identifying failure mechanisms on a microscopic scale. Thus in this work, the microstructures of two types of marble, Baghat and Maroon, were measured by petrographic thin sections method, fluorescent replacement, and scanning electron microscopy (SEM) techniques. Also, the rock fracture properties of marbles were measured at quasi-static loading conditions in wide range of loading rates with electronic circuitry and high-speed imaging technology.

The interdependency of fracture properties was investigated including toughness, crack propagation speed, loading rate and CTOD in crystalline rocks were investigated by fitting experimental data using a high-speed imaging technology and electronic circuitry. A good correlation was observed between the fracture properties under quasi-static loading among the test results.

The following results were achieved:

- The results of microscopic studies revealed that total elongation and frequency of opened micro cracks were greater in Maroon marbles than in Baghat marbles. It was also observed that the distribution of micro cracks in the surface of grains was greater in fine-grained marbles (Maroon) than in coarse-grained marbles (Baghat).
- The fractal dimension measured by box-counting method indicated that the opened micro cracks were 20% larger in Maroon marbles than in Baghat marbles.
- To measure the crack propagation speed, electronic circuitry with the harvesting capability as precise as 10-9 s was used along with measurement of crack propagation speed on both sides of the central hole in HCCD samples independently.
- In Baghat marbles, with an increase in the loading rate by 1.8 times, fracture toughness grew by

1.27 time. However, in Maroon marbles, with increase in the loading rate by 1.85 times, fracture toughness was augmented by 1.1 times.

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