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Physical and Mechanical Phenomena Associated with Rock Failure in Brazilian Disc Specimens

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Abstract**—**Failure mechanism of rocks is one of the fundamental aspects to study rock engineering stability. Rock is a material that contains flaws, initial damage, micro-cracks, etc. Failure of rock structure is largely due to tensile stress and was influenced by various parameters. In the present study, the effect of brittleness and loading rate on the physical and mechanical phenomena produced in rock during loading sequences is considered. For this purpose, Acoustic Emission (AE) technique is used to monitor fracturing process of three rock types (onyx marble, sandstone and soft limestone) with different brittleness and sandstone samples under different loading rate. The results of experimental tests revealed that brittleness and loading rate have a significant effect on the mode and number of induced fracture in rocks. An increase in rock brittleness increases the frequency of induced cracks, and the number of tensile fracture decreases when loading rate increases.

Keywords**—**Brittleness, loading rate, acoustic emission, tensile fracture, shear fracture.

I. Introduction

FAILURE analysis of rock is a fundamental aspect in rock engineering projects. Micro-cracks, damage zone, and flaws are an inseparable part of natural materials such as rocks [1], [2] and certainly have an influence on the failure mechanism of rocks because of stress concentration on the micro-crack tips. The macroscopic deformation and failure of rock is a dynamic, gradual and cumulative process of nucleation, growth, propagation, coalescence of micro-cracks, which is a non-equilibrium, non-linear evolutionary process. The deformation and failure of rock is its macro-response to accumulated intrinsic micro-damage and cracking [3].

The subject of rock failure analysis is becoming an interesting research area since 1960s and many invaluable research works have been performed to evaluate the mechanisms of deformation and failure of rock or rock-like materials [4]-[8]. There are three separate phases in the failure analysis of intact rocks including: (1) initiation of micro-cracks (2) propagation of micro-cracks and (3) micro-crack coalescence.

Some new procedures for evaluation of failure mechanism of rocks have been developed in recent years. Reference [3] investigated the failure mechanisms of rock under compressive shear loading using real-time laser holography. They found that the real-time laser holographic interferometry is helpful and powerful for real-time observation of the process of deformation and failure of rock. Hence, it can play a role of a bridge to connect macroscopic study and meso-microscopic study on deformation, failure and other behaviors of the rock.

Reference [8] studied the process of initiation, propagation and coalescence on cracks under the influence of the chemical corrosion. They indicated that the effect of chemical corrosion was quite complicated depending on chemical ions and their concentrations and pH values, mineral components of rock, geometry and the number of flows. Their studies were almost the same as weathering studies of micro-crack pattern, but the differences were that they used chemical corrosion as agent of weathering.

Reference [9] studied the mechanism of the intermediate principal stress effect on rock failure behavior through a numerical method using the EPCA3D system and concluded that for a brittle rock specimen, a moderate intermediate principal stress delays the onset of failure propagation, which leads to the increase of the rock strength.

Reference [10] assessed the influence of fissure inclination angle and distribution density on the failure characteristics of rock-like specimens. They showed that the fissure inclination angle was the major influencing factor on the failure modes of fissure bodies.

In the present study, AE technique is sued to evaluate the effect of brittleness and loading rate on the failure mechanism of rocks.

II. AE Parameters

AE is a non-destructive inspection technique utilizing the transient elastic energy which results mainly from crack propagation events inside a material [20]. The dislocation created at the tip of the crack excites elastic waves which propagate outwards and can be captured by sensors on the surface of the material. A typical AE signal with parameters of counts, amplitude, duration, rise time, threshold and hits is shown in Fig. 1.

Counts are the number of sampling times that an AE signal exceeds a certain threshold during one AE signal. Amplitude is the maximum value of the AE signal, usually expressed in decibels. Duration is the time span from the starting point to the end point of the AE signal. Rise time is referred to the time interval starting from the time of AE signal generation to the time of the signal reaching its maximum amplitude. Average

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frequency is defined by the ratio of threshold crossings over the duration of the signal, and raise angle (RA) value is the rise time (RT, delay between the onset and the maximum amplitude) over the amplitude.

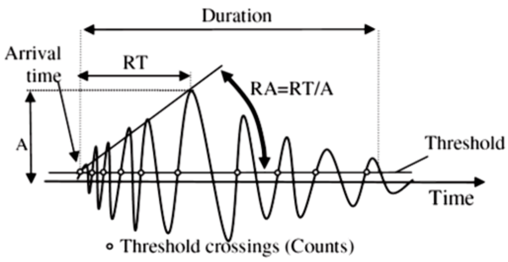

Fig. 1 The typical AE signal features [11]

Reference [12] studied acoustic signal of different fracture modes and revealed that tensile cracking incidents show a preference to higher frequencies and shorter waveforms unlike shear events. In the other words, tensile micro-cracks have high frequency and low RA, while shear micro cracks have low frequency and high RA.

III. Micro and Macro Fracturing in Rocks

Damage processes of brittle materials are driven by the distribution of micro-cracks and their evolution [13]. Nucleation and growth of micro-cracks significantly affect the damage evolution and consequently macroscopic behavior of materials. In recent decades, the AE technique has extensively been adopted, as an excellent diagnostic tool, to monitor fracture damage of geo-materials [14]-[17].

Monitoring and analyzing of the AE response during a loading sequence makes it possible to detect the occurrence and evolution of stress-induced cracks. In fact, cracking is accompanied by the emission of elastic waves which propagate within the bulk of the material [18]. Amplitude of the AE signals, A, is the greatest recorded voltage in a waveform and is measured in either V or dB. Generally, the amplitude corresponds to the scale of fracture, since small scale fracture emits waves with low amplitude and large scale fracture generate signals with higher amplitude [11].

A. b-Value

As mentioned above, micro and macro scale fractures generate different types of AE signals in terms of frequency ranges and amplitudes. A large number of acoustic signals with small amplitude emit from micro scale fractures, while macro scale fractures, compared to the micro ones, generate less number of events with higher amplitude [19].

Cumulative frequency-amplitude distribution, derived from the Gutenberg–Richter (G–R) equation in seismology, can appropriately illustrate the number of events with low and high amplitude. G–R law shows the relationship between the magnitude and total number of earthquakes in any given region and is yielded by (2) [20]

$$\log_{10}(N) = a - bM \tag{1}$$

where a and b are constants, and b is called the ‘‘b-value’’, M is the magnitude, and N is the number of earthquakes that occur in a specific time window with magnitudes larger than M. The b-value is known as the tectonic characteristic and represents the relative abundance of small to large seismic events.

In the case of the AE technique, the G–R relationship between cumulative frequency and magnitude is expressed as

$$\log_{10}(N) = a - b\left(\frac{A_{dB}}{20}\right) \tag{2}$$

where A_{dB} is amplitude of AE in dB, and N is the number of AE hits or events with amplitude greater than A_{dB}. The parameter of the b-value in (2) represents the ratio of small to large amplitude of AE events. In the other words, the b-value indicates the ratio of micro- to macro-crack frequency, occurring in a specific loading sequence [19].

B. AE Monitoring of Brazilian Tests Performed Under Monotonic Loading

In order to assess the effect of rock brittleness on failure of rocks, three rock types with different brittleness were chosen: (1) onyx marble as a high brittle rock with almost no plastic deformation, (2) sandstone as a semi-brittle rock with small plastic deformation and (3) soft limestone as a low brittle rock with a large plastic deformation compared to the other two mentioned rocks.

Fig. 2 Servo-electric loading frame with AE monitoring system

An experimental setup including a servo-electric testing machine supported with a data acquisition system and an AE monitoring system (Fig. 2) was employed to monitor the failure sequence of Brazilian specimens. The Brazilian test was conducted on the three chosen rock types and AE of the rock samples subjected to indirect tension loading were recorded. The testing machine employed for this series of tests was strain controlled and the loading rate was kept at 0.2 mm/min; also, threshold amplitude of the AE signals was adjusted at 38 dB. Cumulative distribution of AE peak amplitude exhibited by the tested specimens of these three rock types is shown in Fig. 3. Each distribution includes all of

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the events recorded during the test. In order to demonstrate the trends, a straight line was fitted for each of the tested rock type samples.

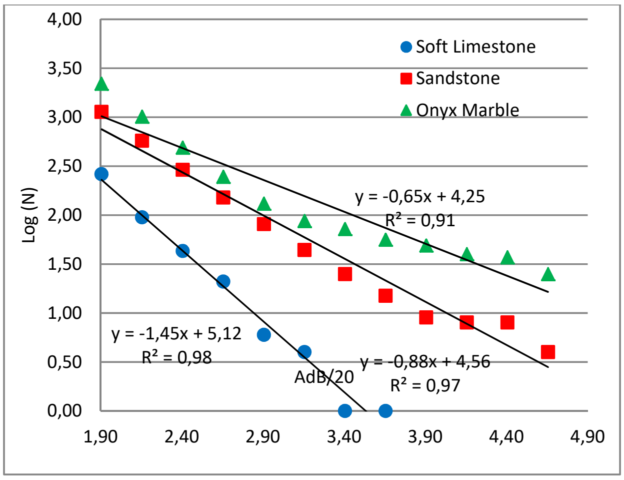

Fig. 3 Cumulative distribution of AE peak amplitude of the studied rocks

Two important notions were inferred from the trend lines illustrated in Fig. 3. The first one was related to the y-intercept of the best-fit straight lines, each of which indicated fracture density during different stages of the failure process. It can be seen that the y-intercept of the line corresponding to the onyx marble is larger than the one for sandstone and both are larger than the line attributed to soft limestone. Variation in number of AE hits with amplitude is depicted in Fig. 4 and it is observed that the number of AE hits generated in onyx marble is more than the number of AE hits of sandstone and soft limestone. This means that the frequency of induced fracture under monotonic loading in onyx marble is more than that in sandstone and soft limestone.

The second important notion concerns the slope of the lines, the b-value, depicted in Fig. 3, which designates the frequency ratio of micro- to macro-cracks. AE of soft limestone, as a low brittle rock, presents a b-value equal to 1.45, while the b-value of sandstone and onyx marble are 0.88 and 0.65, respectively. A smaller b-value indicates AE activity with a higher amplitude. Therefore, during a loading sequence, a highly brittle rock creates more highly energetic fractures compared to a low brittle rock.

A comparison of the AE peak amplitude distribution for the three studied rocks reveals that fracture density and b-value are strongly influenced by rock brittleness. Brittleness affects the density of micro- and macro-cracks generated during the loading sequences. Regardless of micro and macro types of cracks, an increase in rock brittleness increases the frequency of induced cracks and further, the ratio of micro- to macro-crack density decreases with increasing the rock brittleness. However, crystalline structure of onyx marble may tend to intensify generation of micro-crack so as the available cleavages in onyx marble texture increases the number of induced micro-cracks during the loading sequences.

Variation of average frequency with time for the three rock types is depicted in Fig. 5. Average frequency of the signals which emitted from onyx marble is more than the average frequency corresponding to sandstone and soft limestone. It means that the rock with more brittleness contains more tensile fracture during the loading sequences.

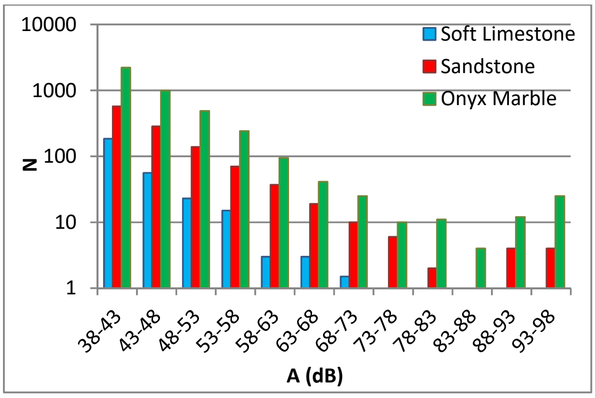

Fig. 4 Variation of number of AE hits with amplitude (dB)

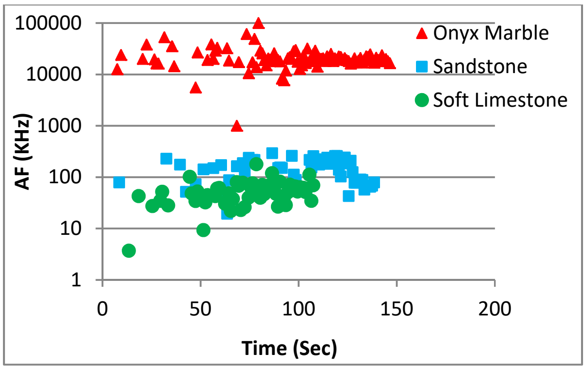

Fig. 5 Variation of average frequency with time for the three rock types

IV. Effect of Loading Rate on the Rock Failure

The effect of loading rate on rock failure has been considered in many rock engineering research works due to its extensive application. Rock peak strength, strain, and elastic modulus rise with the increase of loading rate. Crack branching or bifurcation is a common phenomenon in dynamic fracture which is observed in brittle and ductile materials. With emphasis on the difference between static and dynamic failure, Reference [21] showed that more cracks are developed in rocks under dynamic loading compared to the static loading condition. Under a high state of stress, the propagating crack can split into two or more branches and it can divide into a river delta crack pattern or micro-bifurcation [22].

Several procedures for evaluation of rock failure under different loading rates have been used in the previous studies. In the present study, the effect of loading rate on rock failure mechanism in Brazilian test was considered. For this purpose, some experimental tests were conducted on Brazilian disk specimens of a homogeneous and isotropic sandstone at six different loading rates (0.3, 0.6, 1.2, 2.4, 4.8, and 9.6 mm/min). Fig. 6 shows the failure shape of specimens under different loading rate. In Fig. 6, S1-S6 denote fractured specimens under varied loading rate from 0.3 to 9.6 mm/min. As depicted in the following figure, with increasing loading rates, crack bifurcation or branching increase in rock specimens.

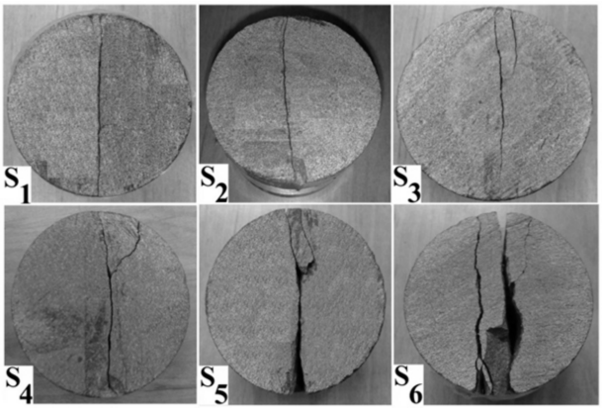

Fig. 6 Failure shape of specimens under different loading rate

During the tests, AE sensors were used to monitor the fracturing process. AE monitoring showed that micro-crack density induced by the applied loads during different stages of the failure processes increases as loading rate increases.

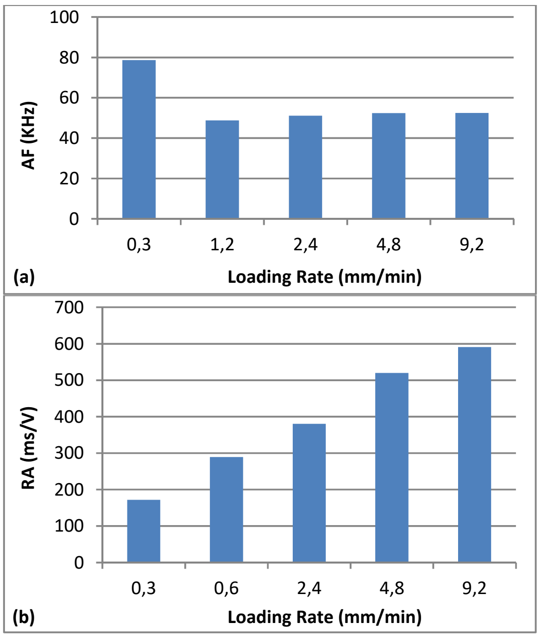

Fig. 7 Variation of (a) average frequency and (b) RA with loading rate

As shown in Fig. 7, with increasing the loading rate, the average of RA increases, but the average frequency has not a significant variation. This finding reveals that loading rate influences the mode of induced fracture, so that the number of tensile fracture decreases when loading rate increases. Therefore, the main reason of increase in failure load with the increase of loading rate may be attributed to changing of the fracture mode from tensile to shear.

V. Conclusion

An experimental study was undertaken in order to investigate the effect of rock brittleness and loading rate on the quantity and quality of induced fracture in rocks during loading sequences. The findings of this study are listed as follows:

AE monitoring while applying a monotonic loading on the three rock types confirmed that micro-fracture density in onyx marble is more than the fracture density in sandstone and soft limestone, respectively.

AE of soft limestone presents a b-value equal to 1.45, while the b-value of sandstone and onyx marble were 0.88 and 0.65, respectively.

Comparison on the AE peak amplitude distribution of the three studied rocks reveals that fracture density and b-value are strongly influenced by rock brittleness. Brittleness affects density of micro- and macro-cracks generated during the loading sequences. An increase in rock brittleness increases the frequency of induced cracks, and ratio of micro- to macro-crack density decreases with increasing rock brittleness. In the other words, during a loading sequence, a high brittle rock creates more highly energetic fractures compared to a low brittle rock.

Average frequency of the signals which emitted from onyx marble is more than the average frequency corresponding to sandstone and soft limestone. It means that the rock with more brittleness involves more tensile fracture during the loading sequences.

The average of RA corresponding to the recorded signals increases with increasing the loading rate, while the average frequency has not a significant variation when loading rate increases. This finding shows that loading rate influences the mode of induced fracture, so that the number of tensile fracture decreases when loading rate increases.

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