Dynamic Fracture Toughness Tests on Limestone

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Abstract: Limestone being sedimentary rock contains multiple bedding planes, which has vertical cracks or joints. As explosives apply high dynamic loading rate during blasting i.e. rock fragmentation & comminution process, the measure of critical SIF (stress intensity factor) is pertinent to be measured and is known as dynamic fracture toughness of limestone. In order to investigate the influence of several factors on the mode-I fracture toughness and fracture behavior of limestone, dynamic fracture toughness tests (mode-I) were conducted under various conditions of loading rate. The microstructure of rocks was also investigated to understand the dynamic fracture toughness and fracture mechanism of limestone. This paper deals with results of 11 limestone specimen subjected to dynamic fracture toughness tests. It was observed that crack surface velocity increases with increase in dynamic fracture toughness. The fracture velocity also increases with increase in dynamic fracture toughness. The fracture velocity in limestone increases between 1.14-5.09 times with increased fracture toughness. The crack surface velocity of limestone increases between 1.39-3.09 times with increase in dynamic fracture toughness.

Key words: Fracture toughness, fracture velocity, crack surface velocity.

1. Introduction

Limestone (basic raw material for cement manufacturing) behaves differently under dynamic loading compared to static loading because of the extremely high loading rate and deformation rate under dynamic loading [1]. During blasting operation, extreme dynamic loading is applied on the in-situ rock mass by explosives loaded in blast holes leading to increase of the dynamic fracture toughness. The purpose of this paper is to demonstrate the dynamic fracture toughness (mode-I) of selected limestone rock samples under various dynamic loading conditions. Eleven (11) rock samples were selected to investigate the impact of dynamic load on dynamic tensile strength of rock specimen. The selected rock sample blocks are labelled as SCW1, SCW2, SCW3, SCW4, SCW5, SCW6, SCW7, SCW8, SCW9, SCW12 and SCW13. In detail, SCW1 is dolomitic limestone; SCW3 is pegmatite; SCW8 is siliceous limestone; and the rests are limestone. SHPB (Split Hopkinson pressure bar) system was used to provide dynamic loads and measure the corresponding dynamic fracture toughness. Moreover, high-speed camera was adopted to record the failure plane development, and laser was used to measure the CSOV (crack surface opening velocity).

2. Materials and Methods

The set up and principle of SHPB system are explained in this section along with basic formula for the data analysis. Since force balance on both sides of the specimens is necessary for a valid SHPB test, pulse shaping technique was applied for each test [2-4]. Such technique is also discussed in this section.

2.1 Experimental Apparatus

SHPB is adopted to test the dynamic fracture toughness test of limestone rock samples, and its setup is shown in Fig. 1. SHPB system consists of three parts: striker bar, incident bar and transmitted bar. These three bars are made of steel and have the same diameter of 25.4 mm but different length as shown in Fig. 1 [5]. Three bars are carefully aligned to ensure the accuracy of measurement, and specimen was sandwiched between the incident bar and transmitted bar.
In the test, the striker bar is launched by the compressive gas in the gas gun, which impacts the incident bar in high speed to create dynamic load and subsequently generates an incident wave, propagated along the incident bar. When the stress wave reaches the end of incident bar and contacts the specimen, part of wave would reflect back called reflected wave, and part of wave transmits through the specimen called transmitted wave [6]. Two strain gauges SG1 and SG2 were tightly pasted on the incident bar and transmitted bar to record the elastic deformation soft the two bars due to the stress wave. The strain signals from SG1 and SG2 are recorded in the oscillo scope. Theoretically, sum of the incident wave and reflected wave should equal to the transmitted wave; therefore, the force acted in the two-end soft specimen should be identical in the test. Such force equilibrium state is called force balance which is base line for a valid SHPB test.

2.2 Sample Description

The schematic of the soft specimen used for dynamic fracture toughness tests is shown in Fig. 2, where $P_1$ and $P_2$ denote the dynamic forces on the both ends of the sample [7]. For dynamic mode-I fracture toughness test, the specimen is a semi-circular disk with a small notch. In the test the radius $R$ is 20 mm; thickness $t$ is 18 mm; notch depth $a$ is around 5 mm; and the distance between two supporting bins $S$ is 22 mm. The specimen preparation strictly followed the suggestion of ISRM to make sure the accuracy of tests [8, 9].

2.3 Pulse Shaping Technique

As mentioned before, force equilibrium at the two ends of the specimen is the fundamental requirement for dynamic testing. Rock is a brittle material which has low wave speed and small failure strains [10]. Therefore, fast loading could lead to the non-uniform fracture which may result in force unbalance [11]. Pulse shaping aims to slow down the loading to achieve the force equilibrium. The loading pulse without pulse shaping is usually trapezoidal shape with apparent oscillation which is induced by the sharp rise of the incident loading wave, and force equilibrium is hard to accomplish. However, with the help of the pulse shaping technique, the loading stage is slowed as the trapezoidal shape wave is modified to a ramp shape wave as shown in Fig. 3 [10].

Various methods could be applied to achieve pulse shaping, and the method used in this paper is to place a thin disk made of soft material between the striker and incident bar. Therefore, the striker would impact the shaper before the incident bar and generate a non-dispersive ramp shape with slow initial rising. Consequently, the strain rate could maintain constant
and force equilibrium condition is easy to obtain [12].
In specific, C1100 copper disc with 7.3 mm diameter and 0.9 mm thickness was used as the pulse shaper material in this paper, and Fig. 3 shows a force equilibrium result of one of the tests.

2.4 Data Processing

According to the 1D wave propagation [2], the dynamic forces act on the incident end ($P_1$) and transmitted end ($P_2$) of specimens, where $E$ is the Young’s modulus of the bar; $A$ is the crosssection of the bar, and $\varepsilon_I$, $\varepsilon_R$, and $\varepsilon_T$ are the incident, reflected and transmitted strain signals. In a valid test, specimen should reach force equilibrium before failure; therefore, $P_1$ should roughly equal to $P_2$ [13].

\[ P_1 = EA[\varepsilon_I + \varepsilon_R], \quad P_2 = EA\varepsilon_T \]

For dynamic tensile strength test, the stress of the specimen is calculated as follow:

\[ \sigma(t) = \frac{P_1(t) + P_2(t)}{2A_s} = \frac{EA}{2A_s}[\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)] \]

In the above equations, $A_s$ is the cross-sectional area of bar. Stress balance could be checked by comparing the stress histories at the two ends of the soft specimen, and one example of dynamic force balance result is shown in Fig. 3. The dynamic loading could be characterized using the loading rate, which is the slope of the loading history curve before the failure point [14].

2.5 Sample Preparation

NSCB (notched semi-circular bend) specimen is used for dynamic mode-I fracture test. To prepare such specimens, 40 mm diameter core samples with 18 mm thickness are prepared. The cylindrical surfaces are kept free from any obvious tool marks. Any irregularities across the thickness of the specimen should not exceed 0.025 mm, and end faces shall be flat to 0.25 mm and square and parallel to within 0.251. Next, the disk is cut and split along the diameter into two semi-circular samples. A notch is subsequently machined to the semi-circular sample, located on the centre of the original disk and perpendicular to the diametrical cut. The photograph of prepared specimens is shown in Fig. 4.
3. Results and Discussion

The dynamic mode-I fracture toughness of each rock specimen responding to different loading rates is shown in Figs. 5-17. Dynamic mode-I toughness is in unit of MPa·m$^{(1/2)}$, while loading rate is in MPa·m$^{(1/2)}$/s.

LGG (laser gap gauge) was used to measure the CSOV (crack surface velocity). Mostly, the CSOV increases with the rise of the dynamic fracture toughness. Table 1 summarizes the test results.

The tested specimens with damage plane during dynamic tensile strength are shown in Fig. 18.
Fig. 6 Loading history of a force balanced dynamic tensile strength test.

Fig. 7 KCW1 SIF (stress intensity factor) $K_{IC}(t)$ vs. loading rate.
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**Fig. 8** KCW2 SIF $K_I(t)$ vs. loading rate.

**Fig. 9** KCW3 SIF $K_I(t)$ vs. loading rate.
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Fig. 10  KCW4 SIF $K_I(t)$ vs. loading rate.

Fig. 11  KCW5 SIF $K_I(t)$ vs. loading rate.
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Fig. 12  KCW6 SIF $K(t)$ vs. loading rate.

Fig. 13  KCW7 SIF $K(t)$ vs. loading rate.
Fig. 14  KCW8 SIF $K(t)$ vs. loading rate.

Fig. 15  KCW9 SIF $K(t)$ vs. loading rate.
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Fig. 16  KCW12 SIF $\kappa_{\alpha}(t)$ vs. loading rate.

Fig. 17  KCW13 SIF $\kappa_{\alpha}(t)$ vs. loading rate.
Fig. 18  Tested NSCB specimens.

Table 1  Variation of fracture toughness with CSOV.

| Sample No. | SIF (MPa·m^(1/2)) | CSOV (m/s) | Fracture velocity (m/s) |
|------------|-------------------|------------|-------------------------|
| KCW1       |                   |            |                         |
|            | 4.46              | 14.3       | 341                     |
|            | 3.93              | 17.0       | 246                     |
|            | 7.65              | 27.6       | 467                     |
|            | 8.14              | 36.0       | 560                     |
|            | 10.17             | 40.1       | 582                     |
| KCW2       |                   |            |                         |
|            | 5.00              | 14.78      | 292                     |
|            | 5.23              | 11.14      | 359                     |
|            | 5.62              | 18.74      | 391                     |
|            | 7.81              | 16.73      | 421                     |
|            | 8.25              | 16.82      | 445                     |
| KCW3       |                   |            |                         |
|            | 3.89              | 12.18      | 268                     |
|            | 4.65              | 9.96       | 239                     |
|            | 6.18              | 22.8       | 424                     |
|            | 8.41              | 24.9       | 483                     |
|            | 9.4               | 36.5       | 622                     |
| KCW4       |                   |            |                         |
|            | 2.98              | 13.3       | 255                     |
|            | 4.95              | 22.1       | 333                     |
|            | 4.6               | 24.5       | 341                     |
|            | 6.39              | 30.9       | 368                     |
|            | 7.48              | 28.7       | 452                     |
| KCW5       |                   |            |                         |
|            | 2.98              | 13.29      | 341                     |
|            | 4.95              | 22.06      | 368                     |
|            | 4.6               | 24.54      | 350                     |
|            | 6.39              | 30.94      | 438                     |
|            | 7.48              | 28.69      | 475                     |
Table 1 to be continued

| KCW6 | 4.24 | 12.43 | 192 |
| 4.14 | 20.96 | 291 |
| 6.30 | 30.21 | 519 |
| 7.61 | 31.05 | 538 |
| 8.99 | 32.41 | 636 |

| KCW7 | 4.37 | 15.8 | 326 |
| 5.81 | 27.0 | 304 |
| 6.56 | 30.1 | 311 |
| 5.99 | 27.1 | 483 |
| 8.41 | 29.6 | 609 |

| KCW8 | 2.68 | 14.9 | 275 |
| 3.57 | 25.5 | 286 |
| 4.61 | 7.70 | 168 |
| 6.66 | 14.1 | 452 |
| 4.95 | 8.40 | 424 |

| KCW9 | 36.9 | 2.68 | 419 |
| 73.7 | 3.57 | 298 |
| 93.7 | 4.61 | 412 |
| 109.9 | 6.66 | 452 |
| 84.7 | 4.95 | 389 |

| KCW12 | 38.8 | 3.50 | 206 |
| 97.8 | 5.02 | 275 |
| 54.8 | 4.33 | 255 |
| 119.2 | 6.84 | 412 |
| 205.1 | 8.04 | 400 |

| KCW13 | 24.9 | 1.81 | 197 |
| 115.8 | 6.34 | 283 |
| 112.7 | 6.45 | 280 |
| 250.1 | 7.46 | 412 |
| 266.1 | 9.22 | 609 |

4. Conclusions

SHPB systems may be used to determine the dynamic fracture toughness of the rock specimen. It may be generalized that crack surface velocity increases with increase in dynamic fracture toughness. The fracture velocity also increases with increase in dynamic fracture toughness. The fracture velocity in limestone increases between 1.14-5.09 times the static loading with increased fracture toughness. The crack surface velocity of limestone increases between 1.39-3.09 times with increase in dynamic fracture toughness. The fracture velocity and crack surface velocity increases by 1.71 and 1.04 times with increase in dynamic fracture toughness in siliceous limestone. The fracture velocity and crack surface velocity increases by 2.80 and 2.10 times with increase in dynamic fracture toughness in dolomitic limestone. The fracture velocity and crack surface velocity increases by 2.99 and 2.32 times with increase in dynamic fracture toughness in pegmatite. It was observed that when the dynamic load is low, the specimen splits equally into two semi-circular disks. It may also be concluded that dynamic fracture toughness increases with loading rate.

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