Dynamic Uniaxial Tensile Strength Tests on Limestone

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Abstract: Dynamic properties of limestone govern the rock fragmentation characteristics. Failure of rock under tension is more likely as compared to failure under compression under static or dynamic loading both. Since the application of explosives creates dynamic loading and is a dynamic event, the determination of dynamic modulus values is technically more appropriate than the static measurement. The rock fragmentation would significantly improve by investigating the dynamic uniaxial tensile strength as specific fracture energy, stress intensity factor, fracture toughness of any detonating blast hole depend heavily on dynamic rock property and not on static rock property. Most of the limestone projects globally are still accustomed with using static tensile strength to understand the rock fragmentation. The present papers deal with determination of dynamic uniaxial tensile property using split Hopkinson pressure bar (SHPB) system. The nano second high speed camera with laser captures the crack surface opening velocity during dynamic loading. It was observed during data analysis that dynamic tensile strength of limestone increases by 1.2-2.3 times of the static strength. It may be concluded by the study that determination of dynamic tensile strength is paramount for understanding the rock fragmentation.

Key words: Rock fragmentation, SHPB, dynamic tensile strength.

1. Introduction

Limestone (basic raw material for cement manufacturing) behaves differently under dynamic loading compared to static loading because of the extreme 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 increasing the dynamic tensile strength. The rock fragmentation in limestone mines is most likely when dynamic tensile stress under dynamic loading exceeds the dynamic tensile strength. The purpose of this paper is to demonstrate the tensile strength 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. Split Hopkinson pressure bar system (SHPB) was used to provide dynamic loads and measure the corresponding dynamic tensile strength. Moreover, high-speed camera was adopted to record the failure plane development, and laser was used to measure the crack surface opening velocity (CSOV).

2. Materials and Methods

The setup and principle of SHPB system is explained in this section along with basic formula for the data analysis. Since force balance on both sides of the specimen 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 tensile strength 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 a 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 deformations of the two bars due to the stress wave. The strain signals from SG1 and SG2 are recorded in the oscilloscope. Theoretically, sum of the incident wave and reflected wave should equal to the transmitted wave; therefore, the force acted in the two ends of the specimen should be identical in the test. Such force equilibrium state is called force balance which is baseline for a valid SHPB test.

2.2 Sample Description

The schematics of the specimen used for dynamic tensile tests are shown in Fig. 2, where $P_1$ and $P_2$ denote the dynamic forces on the both end of the sample [7]. For dynamic tensile test, the specimen is a disk. The diameter $D$ is 40 mm, while the thickness $t$ is 20 mm. The diameter to thickness ratio is approximately 2:1 [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 cross section 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 specimen, and one example of a 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

The geometry of specimen for dynamic tensile strength test is a disk having 40 mm diameter and 18 mm thickness. 40-mm-diameter core samples were cored from the rock block, then the core samples were saw into 18 mm thick cylindrical disk. The cylindrical surfaces were ensured to be free from obvious tool mark. Any irregularity across the thickness of the specimen was ensured not to exceed 0.025 mm. End faces were flat to 0.25 mm and parallel to within 0.25° according to the suggestion by ISRM [2]. To ensure
the accuracy of the tests, two ends of rock specimen must be smooth and parallel. Based on ISRM's suggestion, the ends of the specimen shall be flat to 0.02 mm and shall not depart from perpendicularity to the axis of the specimen by more than 0.001 rad or 0.025 mm in 25 mm. Moreover, the side surface of the specimen shall be smooth and free of abrupt irregularities and straight to within 0.02 mm over the full length of the specimen. The photograph of prepared specimens is shown in Fig. 4.

Fig. 4 Prepared dynamic test specimens.
3. Results and Discussion

It may be generalized that rock strength increases with the rise of loading rate. The dynamic tensile strength of each rock sample responding to various loading rates is shown in Figs. 5-17. Peak point shows dynamic tensile strength, and slope of rising portion is loading rate.

Dynamic tensile strength is in unit of MPa, while loading rate is in unit of MPa/s.

The tested specimens with damage plane during dynamic tensile strength are shown in Fig. 18.

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**Fig. 5** Example of one of the dynamic tensile strength test results.

**Fig. 6** Loading history of a force balanced dynamic tensile strength test.
**Fig. 7** KCW1 loading rate vs. tensile strength.

**Fig. 8** KCW2 loading rate vs. tensile strength.
Fig. 9  KCW3 loading rate vs. tensile strength.

Fig. 10  KCW4 loading rate vs. tensile strength.
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Fig. 11  KCW5 loading rate vs. tensile strength.

Fig. 12  KCW6 loading rate vs. tensile strength.
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Fig. 13  KCW7 loading rate vs. tensile strength.

Fig. 14  KCW8 loading rate vs. tensile strength.
Fig. 15  KCW9 loading rate vs. tensile strength.

Fig. 16  KCW12 loading rate vs. tensile strength.
4. Conclusions

SHPB systems may be used to determine the dynamic tensile strength of the rock specimen. The dynamic tensile strength of the limestone is much higher than static strength. The tensile strength of the limestone increases with the loading rate. Results show that dynamic tensile strength of the limestone varies between 1.2-2.3 times the static loadings. The dynamic tensile strength of dolomitic limestone increases by two times the static strength with increasing loading rate. The dynamic tensile strength of siliceous limestone increases by 1.9 times the static strength with increasing loading rate. The dynamic
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The tensile strength of pegmatite increases by 2.1 times the static strength with increasing loading rate. It may be concluded that under blast induced dynamic loading, the dynamic tensile strength should be considered for determination of the rock fragmentation. It may be observed that when the dynamic load is low, the specimen splits equally into two semi-circular disks under tensile loading. However, when the dynamic load increases, large damaged zone is formed in the middle of rock specimen.

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