Dynamic Uniaxial Compressive Tests on Limestone

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Abstract: The dynamic properties of limestone play a pivotal role while selecting the suitable explosives for any limestone mine. 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 compressive 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 compressive strength to understand the rock fragmentation. The present papers deal with determination of dynamic uniaxial compressive 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 compressive strength of limestone increases by 1.7-4.9 times of the static strength. It may be concluded by the study that determination of dynamic compressive strength is paramount for understanding the rock fragmentation.

Key words: Rock fragmentation, SHPB, dynamic compressive 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. During blasting operation, extreme dynamic loading is applied on the in-situ rock mass by explosives loaded in blast holes leading to increase the dynamic uniaxial compressive strength (UCS). The rock fragmentation in limestone mines depends on the dynamic compressive strength instead of static compressive strength. The purpose of this paper is to demonstrate the uniaxial compressive 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 uniaxial compressive 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 compressive 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 [1-3]. Such technique is also discussed in this section.

2.1 Experimental Apparatus

SHPB is adopted to test the dynamic compressive strength of limestone rock samples, and its setup is shown in Fig. 1. SHPB system consists 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 [4].
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 [5]. 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 compressive tests are shown in Fig. 2, where $P_1$ and $P_2$ denote the dynamic forces on the both end of the sample [6]. For dynamic compressive strength test, the specimen is in form of a cylinder with a length to diameter ratio of 1:1 [7, 8]. The length $L$ and diameter $D$ are around 25 mm, which is a bit smaller than the diameters of incident bar and transmitted bar.

Fig. 1 Schematics of SHPB system.

Fig. 2 Schematics of compressive test specimen.
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 [9]. Therefore, fast loading could lead to the non-uniform fracture which may result in force unbalance [10]. 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.

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 [11]. 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 [1], 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 \( \varepsilon_i, \varepsilon_r, \text{ and } \varepsilon_T \) 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 \( P_2 \) [12].

\[
P_1 = EA[\varepsilon_i + \varepsilon_R], P_2 = EA\varepsilon_T
\]

For dynamic uniaxial compressive 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 [13].

2.5 Sample Preparation

For dynamic UCS strength tests, core samples of 25.4-mm in diameter were cored from each designated rock block with no visible geological weakness. Next, core samples were saw and polished to 25.4-mm long cylinder. Each specimen for dynamic UCS test has a length to diameter ratio of 1:1 which is the recommended geometry suggested by ISRM [1]. To ensure the accuracy of the tests, two ends of dynamic UCS 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 uniaxial strength test specimens.
3. Results and Discussion

It may be generalized that rock strength increases with the rise of loading rate. The dynamic uniaxial compressive strength of each rock sample responding to various loading rates is shown in Figs. 5-17. Dynamic tensile strength is in unit of MPa, while loading rate is in unit of MPa/s.

![Dynamic stress balance (Compression)](image)

Fig. 5  Example of one of the dynamic compressive strength test results.

![Loading rate (Compression)](image)

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

Fig. 8  KCW2 loading rate vs. compressive strength.
Fig. 9  KCW3 loading rate vs. compressive strength.

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

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

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

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

SHPB systems may be used to determine the dynamic compressive strength of the rock specimen. The dynamic compressive strength of the limestone is much higher than static strength. The compressive strength of the limestone increases with the loading rate. Results show that dynamic compressive strength of the limestone varies between 1.7-4.9 times the static loading. The dynamic compressive strength of dolomitic limestone increases by 5 times the static strength with increasing loading rate. The dynamic compressive strength of siliceous limestone increases by 1.9 times the static strength with increasing loading rate. The dynamic compressive strength of pegmatite increases by 1.9 times the static strength with increasing loading rate. It may be concluded that under blast induced dynamic loading, the dynamic compressive strength should be considered for determination of the rock fragmentation.

References

[1] American Society for Testing and Materials. 2008. ASTM D2936-08 Standard Test Method for Direct Tensile Strength of Intact Rock Core Specimens. Philadelphia: American Society for Testing and Materials.
[2] Albertini, C., and Montagnani, M. 1974. Testing Techniques Based on the Split Hopkinson Bar. London: Institute of Physics.
[3] Chen, R., Xia, K., Dai, F., Lu, F., and Luo, S. N. 2009. “Determination of Dynamic Fracture Parameters Using a Semi-circular Bend Technique in Split Hopkinson Pressure Bar Testing.” Engineering Fracture Mechanics 76 (9): 1268-76.
[4] Chen, W., Lu, F., and Cheng, M. 2002. “Tension and Compression Tests of Two Polymers under Quasistatic and Dynamic Loading.” Polymer Testing 21 (2): 113-21.
[5] Goldsmith, W., Sackman, J. L., and Ewert, C. 1976. “Static and Dynamic Fracture Strength of Barre Granite.” International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 13 (11): 303-9.
[6] Harding, J., Wood, E. D., and Campbell, J. D. 1960. “Tensile Testing of Materials at Impact Rates of Strain.” Journal of Mechanical Engineering Science 2 (2): 88-96.
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[7] Hudson, J. A., Brown, E. T., and Rummel, F. 1972. “The Controlled Failure of Rock Disks and Rings Loaded in Diametral Compression.” International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 9 (2): 241-8.

[8] International Society for Rock Mechanics Commission on Standardization of Laboratory and Field Tests. 1978. “Suggested Methods for Determining Tensile-Strength of Rock Materials.” International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 15 (3): 99-103.

[9] Li, M., Wang, R., and Han, M. B. 1993. “A Kolsky Bar: Tension, Tension-Tension.” Experimental Mechanics 33 (1): 7-14.

[10] Lindholm, U. S., and Yeakley, L. M. 1968. “High Strain-Rate Testing: Tension and Compression.” Experimental Mechanics 8 (1): 1-9.

[11] Nicholas, T. 1981. “Tensile Testing of Materials at High-Rates of Strain.” Experimental Mechanics 21 (5): 177-85.

[12] Ogawa, K. 1984. “Impact-Tension Compression Test by Using a Split Hopkinson Bar.” Experimental Mechanics 24 (2): 81-6.

[13] Zhou, Y., et al. 2011. “Suggested Methods for Determining the Dynamic Strength Parameters and Mode-I Fracture Toughness of Rock Materials.” In The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014. Springer, 35-44.