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Dynamic mechanical behavior of some carbonate rocks

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A B S T R A C T

The effects of porosity, unit volume weight and Schmidt hardness on the quasi-static and dynamic compressive behaviors of some carbonate rocks were investigated using classical servo-hydraulic testing machine and split Hopkinson pressure bar (SHPB) testing system, respectively. For dynamic compression testing, cylindrical samples 18 mm in diameter and 11 mm long were obtained from rock samples of light and dark travertines, lymra and beige marbles. For quasi-static compression testing, cylindrical samples were prepared according to the International Society for Rock Mechanics (ISRM) standards. The results of the physical and mechanical properties of the rock samples have shown that the porosity, unit volume weight and Schmidt hardness, have significant effects on the compressive stress–strain behavior of the rock samples under dynamic loading. The results have also shown that the beige limestone samples have significantly higher dynamic compressive strength than the other carbonate rock samples.

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1. Introduction

A variety of techniques are used to extract minerals around the world, including drilling, blasting, excavating, crushing and cutting. The success of these operations often requires knowledge of the relationships between rock properties such as porosity, unit volume weight and Schmidt hardness, and rock dynamic mechanical properties such as compressive strength and elastic modulus. However, in the past, relatively little work has been done to investigate the dynamic mechanical behavior of rock materials [1]. Rock mass properties are of great importance concerning drilling, excavation, blasting, sawing and crushing performance [2]. There are many publications in the rock mechanics literature about selection of equipment by considering geotechnical parameters of the rock mass, and various empirical approaches have been proposed in these publications. One of the parameters that is widely used in those empirical approaches is the quasi-static uni-axial compressive strength of the rock material [3]. Nevertheless, civil engineering structures, designed for either civilian or military use, could be subjected to dynamic loads that they were not originally designed to resist. Such dynamic loads can arise from natural phenomenon (e.g. earthquakes) or from accidental explosions caused by deflagration of natural gas or rapid chemical reaction (e.g. detonation of high explosives) [4].

A considerable number of studies have been conducted in recent years to study cutting, excavating and drilling efficiency in rocks. Most of these studies establish relations between the quasi-static mechanical properties of rocks and the cutting and drilling speed or wear ratio of bead or socket parameters for rocks. Those relations were used to derive the equations that predict the cutting or drilling rates from the quasi-static compressive strength properties of the rock samples. However, dynamic failure of rocks is a commonly observed phenomenon in rockbursts, earthquakes, and mining operations such as drilling, cutting and excavation [5].

The quasi-static compressive strength of rock materials has been used as an important parameter for almost all empirical approaches in the previous studies that predict the efficiency of rock operations and develop the operational parameters such as cutting and drilling rates, wear ratio and blade life. However, as mentioned in the previous paragraphs, dynamic loading conditions are encountered in rock operations, and the mechanical behavior of the rock materials, as other engineering materials, could be significantly different under dynamic loading conditions. Therefore, inclusion of the dynamic compressive strength, rather than the quasi-static compressive strength, into the empirical approaches and the operational parameters might give better results regarding the performance of the rock operations. To accomplish this, it is first necessary to determine the dynamic compressive mechanical properties of the rock materials and their relations with the physical properties such as porosity, unit volume weight and Schmidt hardness.

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The split Hopkinson pressure bar (SHPB), originally developed in 1950s by Kolsky [6] to test metallic materials under compression at high strain rates, has received considerable attention for characterizing the dynamic response of a variety of engineering materials [5]. The materials studied with the SHPB were mostly metals in the past, the plastic behavior and rate dependence of which have been of the main interest. Recently, SHPB has become more popular for the nonmetallic materials such as concrete, rocks, salt-rock, polymers and polymeric foams [7] since it had been modified to test these materials at different loading types such as tension, torsion and shear [8].

In this study, an experimental work was carried out for determining the quasi-static and dynamic compressive mechanical properties of some sedimentary rocks: two limestones (beige and lymra) and two travertines (light and dark). The dynamic mechanical properties of the rocks were obtained using SHPB testing method. The quasi-static mechanical properties and the physical properties such as porosity, unit volume weight and Schmidt hardness of rock samples were also determined according to the International Society for Rock Mechanics (ISRM) standards [9]. Then, the results were analyzed to determine to what extent the quasi-static and dynamic compressive strengths differ from each other and how they are affected by the physical properties of the rock samples.

2. Previous studies

A large number of studies have been carried out for predicting the cutting and drilling performance from the quasi-static compressive strength properties of rocks. These studies were based on various parameters or methods such as Schmidt hammer, point load, cone indenter, shore hardness, drilling rate index, coefficient of rock strength, the rock impact hardness number, the failure energy, and the Protodyakonov impact test [10,11]. The investigators obtained high correlations between the cutability or drillability and the quasi-static uni-axial compressive strength, and suggested different empirical equations. Buyuksagis [12] observed in his investigation that the sawing performance and life of a circular saw blade are affected by many factors such as physico-mechanical and mineralogical properties of the rock. Buyuksagis and Goktan [13] carried out laboratory work to determine the relationships between various rock properties and the cutting performance of a full-scale block-cutter for marbles of medium hardness. Atici and Ersoy [11] indicated that the knowledge of rock properties is essential for the saw blade and drilling bit, drilling rigs and for the selection of their operating conditions. Ozcelik [14] emphasized the importance of the physical, mechanical, textural and structural properties of rocks on the efficiency of diamond wire cutting operation. Ozcelik et al. [15] stated that the mineralogical and petrographical properties of rocks such as percentage of biotite, plagioclase, matrix, opaque minerals and, quartz and plagioclase grain size for andesitic rocks and, only calcite grain size for carbonate rocks significantly influenced the wear and cutting rates in diamond wire cutting operation. Ersoy and Waller [16] studied on sedimentary and igneous rocks to indicate the effects of rock texture on the drillability.

Uni-axial compressive strength and Schmidt hardness have been commonly used for predicting the following parameters for classification of rock excavation and estimation of large-scale in situ strength in a gallery for a variety of specific applications [3,17]: excavator, roadheader and tunnel boring machine performance, machine drilling rate, rock rippability, excavation classification, in-situ strength predictions.

Frew et al. [7] modified the conventional SHPB technique to obtain dynamic compressive stress–strain data for rock materials and conducted experiments with limestone samples. Shan et al. [18] used the SHPB testing system to measure and analyze not only the pre-failure but also the post-failure region of a rock's dynamic stress–strain curve. Christensen et al. [19] investigated the effects of dynamic loading on the stress–strain behavior and failure characteristics of sandstone under confining pressure of 30 kpsi (6.89 MPa). He determined that the characteristics of the dynamic stress–strain behavior were similar to the characteristics of the behavior obtained from the quasi-static testing of the same material. Frew [20] conducted penetration experiments into limestone targets with steel rod projectiles and presented analytical models and experimental techniques that provide procedures to obtain dynamic compressive stress-strain data for brittle materials. Lundberg [21] carried out dynamic compression tests using SHPB and observed fracturing process during testing using a high speed camera.

3. Experimental method

The SHPB device generally consists of an air gun and three lined up cylindrical bars (Fig. 1). The second and third bars, known as incident and transmitted bars, are instrumented with strain gauges and the test sample placed between them. The strain gauges are used in combination with a Wheatstone bridge circuit connected with a digital oscilloscope to monitor the strain during the test. The air gun accelerates the first bar, known as striker bar, which strikes the incident bar. The impact of the striker bar at the free end of the incident bar generates an elastic strain wave, which is called incident wave that propagates through the incident bar and reaches the incident bar-sample interface. While a part of the incident wave is reflected back into the incident bar, the rest propagates through the sample and generates the transmitted wave in the transmitted bar. Those three waves recorded by the gauges attached to the incident and transmitted bars allow reconstructing a stress–strain curve for the sample.

Incident and transmitted bars were made of the same material with equal cross-sectional areas. In the equations below [22,23], the following notations are used: incident (I), transmitted (T), reflected (R), sample (s), density (ρ), modulus of elasticity (E), wave speed (c) and cross-sectional area (A) of the bars and the cross-sectional area (A_s) and length (l_o) of the sample (Fig. 2).

If the sample deforms uniformly, the strain rate $\dot{\varepsilon}_s$ is calculated as

$$\dot{\varepsilon}_s = \frac{d\varepsilon_s}{dt} = \frac{v_1(t) - v_2(t)}{l_0} \tag{1}$$

The velocity at interface 1 (v_1) and interface 2 (v_2) can be written as follows:

$$v_1(t) = c(\varepsilon_I(t) - \varepsilon_R(t)), \quad v_2(t) = c\varepsilon_T(t) \tag{2}$$

By substituting these interface velocities into Eq. (1)

$$\dot{\varepsilon}_s = \frac{c[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)]}{l_0} \tag{3}$$

Stresses at the ends of the sample are

$$\sigma_1(t) = \frac{EA}{A_s}[\varepsilon_I(t) + \varepsilon_R(t)] \tag{4}$$

$$\sigma_2(t) = \frac{EA}{A_s}\varepsilon_T(t) \tag{5}$$

If the sample is in dynamic stress equilibrium

$$\varepsilon_I(t) + \varepsilon_R(t) = \varepsilon_T(t) \tag{6}$$

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