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Different mechanical and cracking behaviors of single-flawed brittle gypsum specimens under dynamic and quasi-static loadings

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ABSTRACT

Besides the strength, other mechanical properties of rock and rock-like brittle materials are also loading-rate/strain-rate dependent over a wide range of strain rate, which in turn affect the cracking behaviors. In order to investigate the variation of the mechanical properties and cracking behaviors under both the dynamic and quasi-static strain rate conditions, rock-like artificially moulded gypsum specimens with and without pre-existing flaw(s) are loaded under different strain rates. A quasi-static loading is applied to the specimens by a uniaxial compression rig. The dynamic loading is produced by the split Hopkinson pressure bar (SHPB). It is found that the compressive strength, the nominal elastic modulus and the failure strain of the gypsum specimens increase apparently with the strain rate. Using the high speed video imaging system, the similarities and differences of the fracturing processes in specimens containing a pre-existing flaw under the quasi-static and dynamic loading conditions are studied. Shear cracks are observed to be the dominant crack types under dynamic loadings while tensile cracks are dominant under quasi-static loadings.

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1. Introduction

In rock engineering, proper determination of strength and deformation behaviors of intact rocks is an important issue. The strength includes both compressive strength and tensile strength. The deformation behaviors are related to modulus, failure strain, elastic limit, plastic strain, etc. However, in practice, rock masses are always not intact. Therefore, the investigation on strength and deformation behaviors of rock masses containing joints, fractures or flaws is highly relevant in rock engineering.

It is also well known that loading rate plays a significant role on the mechanical properties stated above. The compressive and tensile strengths of brittle materials have been proven to be rate-dependent over a wide range of strain rate (Christensen et al., 1972; Cusatis, 2011; Frew et al., 2001; Grote et al., 2001; Kim and Keune, 2007; Mahmutoglu, 2006; Ross et al., 1995; Wang et al., 2006; Wu et al., 2010; Zhao, 2011) including natural rock and rock-like materials (Cho et al., 2003; Kubota et al., 2008; Li et al., 2011; Zhang and Zhao, 2014a; Zhao, 2011; Cusatis, 2011; Kim and Keune, 2007; Mahmutoglu, 2006; Nemat-Nasser and Deng, 1994; Ravichandran and Subhash, 1995; Zhang et al., 1999). Natural rock masses are rarely intact, but containing fractures of varying dimensions. In addition to the strength, the high strain rate also affects the cracking behaviors (Bazant and Caner, 2000; Mahmutoglu, 2006; Ravichandran and Subhash, 1995; Zhang and Zhao, 2014b; Zhang et al., 1999). When an element of any volume within a cracked body is under dynamic loadings, kinetic energy is input into the system. The quasi-static theories of cracks may then not be entirely applicable (Lawn, 1993). Some mechanical properties associated with cracking behaviors like fracture toughness are also influenced significantly by the strain rate (Dai et al., 2010, 2011; Jiang et al., 2004; Hodulak et al., 1980; Kishi, 1991; Kobayashi et al., 1993; Rubio et al., 2003; Zhang and Zhao, 2013b; Zhou et al., 2012).

Gypsum as a rock-like material, which can be molded to any geometry with an easy fabrication of fractures or flaws inside, has been used as a model material of natural brittle rocks for over 40 years at MIT (Bobet and Einstein, 1998; Einstein et al., 1969; Ko, 2005; Motoyama and Hirschfeld, 1971; Nelson and Hirschfeld, 1968; Reyes and Einstein, 1991; Shen et al., 1995; Wong and Einstein, 2006, 2009a). The quasi-static mechanical properties of the molded gypsum have been well-investigated, while these properties under high strain rates have been less investigated. The cracking behaviors of molded gypsum specimens containing a single flaw or multiple flaws are comprehensively studied under quasi-static loadings (Bobet, 1997, 2000; Park and Bobet, 2010; Shen et al., 1995; Wong and Einstein, 2009a, 2009b, 2009c; Wong, 2008; Zou et al., 2012). Crack initiation types and coalescence modes are two main research focuses in rock failure studies. However, in the literature, most of the dynamic impact studies focused on the spalling (Meyers, 1994; Rinehart, 1951, 1952) and fragmentation (Grady and Kipp, 1987; Jaeger et al., 1986; Liu and Katsabanis, 1997; Louro and Meyers, 1989; Lundberg, 1976; Meyers, 1994; Shockey et al., 1974;

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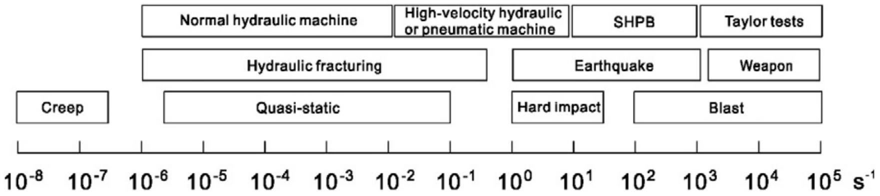

Fig. 1. Strain rate ranges expected for different loading cases.

Taylor et al., 1986) with limited attention on the detailed fracturing processes.

In order to investigate the dynamic strength and the fracturing performances of molded gypsum under high strain rates, intact specimens and non-intact specimens containing a single pre-existing flaw of various inclination angles are studied by using the split Hopkinson pressure bar (SHPB) technique. The SHPB is a widely used experimental instrument to test the dynamic mechanical properties of rock or rock-like materials under high strain rates (Bischoff and Perry, 1991; Chen et al., 2011b; Frew et al., 2001; Gama et al., 2004; Grote et al., 2001; Kim and Keune, 2007; Li et al., 2011; Lu, 2011; Ross et al., 1995; Wang et al., 2006; Xia et al., 2008; Zhao, 2011). The strain rate of the SHPB usually ranges from 50 to 10^3 s^{-1}, and some special setups can produce a strain rate as high as 10^4 s^{-1} on particular specimens (Kaiser, 1998). In SHPB tests, with the assistance of the strain gauges attached on the surface of the incident and transmitter bars, and a multi-channel high frequency precision oscilloscope to record the time-histories of strain in the bars, the engineering strain–stress curve associated with the test specimen can be transformed and calculated (Chen et al., 2011a, 2011b; Davies and Hunter, 1963; Davies, 1948; Kolsky, 1949). The dynamic mechanical properties can then be determined from the engineering strain–stress curve. High speed video cameras are commonly used in the tests to capture the deformation processes and failure of specimens (Chen et al., 2011b; Wong et al., 2013; Wong and Einstein, 2009d; Zhang and Zhao, 2013a, 2013b; Zou and Wong, 2014). In the present study, the entire process of fracturing from crack initiation to the specimen failure under dynamic loading is recorded by a high speed video subsystem.

In the authors' previous study (Zou et al., 2012), the length to height ratio of the gypsum specimens is 1:1, while the ratio in the present studies is adjusted to 2:1, aiming at reducing the end friction effect on the strength and fracture processes. In this paper, the mechanical properties including compressive strength, modulus and failure strain of “non-intact” gypsum specimens containing a single flaw at various inclination angles, and the associated cracking processes of these specimens under both quasi-static and dynamic loadings, are investigated in detail. The results under these two different categories of loading rates are compared and discussed.

The results in the present studies reveal the significantly different cracking behaviors under dynamic loadings as compared with those under quasi-static loadings. The findings contribute to particular areas of rock engineering, where very high strain rates are involved, e.g. rock blasting, military protective structures and earth sciences. The strain rates of common loading cases are given in Fig. 1. The development of shear cracks under dynamic loadings will affect the efficiency of the arrangement of rock blast holes and detonating sequence, as well as the safety of neighboring underground structures. The increase of rock strength under dynamic loading is another factor influencing the design of underground protective structures and the arrangement of blast holes. The relation among the strength of rock containing flaws, the flaw orientation and the strain rate will provide some insights to the blasting in rock mass containing open joints.

2. Methodology

2.1. Specimen preparation

The gypsum specimens in the present study are cast by mixing hydrocal B-11 gypsum powder and diatomaceous earth (or celite) with tap water in a ratio of 175:70:2 (Park and Bobet, 2009). The minute amount of the celite powder can prevent the bleeding (migration of water to the top of the fluid mix) of the gypsum paste to make the artificial material more homogenous. Before the gypsum paste is hardened, steel shims are inserted to create the flaws if needed. When the gypsum paste is hardened, the molds and steel shims are dismantled. The gypsum specimens are then stored in a 40 °C oven to dry the excessive free water in the specimens without evaporating the water of crystallization associated with $CaSO_4 \cdot 2H_2O$. The specimens are finally polished by using a high precision milling machine before being subjected to the both quasi-static and dynamic loading tests.

2.1.1. Dimensions of intact specimens

In order to achieve a high enough strain rate, the size, particularly the length, of specimens should be limited (Chen et al., 2011b; Ravichandran and Subhash, 1994). Therefore, the “normal” size specimens of 152 mm × 76 mm × 32 mm previously tested at MIT and Purdue University (Bobet, 1997, 2000; Bobet and Einstein, 1998; Park and Bobet, 2009; Wong and Einstein, 2006, 2009a, 2009b, 2009c; Wong, 2008) cannot be used in dynamic experiments. “Small” specimens are therefore fabricated for the dynamic tests in order to achieve a higher strain rate. The two different dimensions of “small” intact rectangular gypsum specimens (Group A and Group B) tested are listed in Table 1. The use of two different groups of small intact specimens is to evaluate the size effect, because the dimensions of the single-flawed specimens used in the dynamic tests are different from those of the intact specimens.

2.1.2. Dimensions of single-flawed specimens

The single-flawed specimens have the same length-to-width ratio (2:1) as those used at MIT (Bobet and Einstein, 1998; Einstein and Hirschfeld, 1973; Wong and Einstein, 2009a). However, the actual dimensions of each specimen might be slightly different from those in

Table 1
Dimensions of the gypsum specimens.

		Designed dimensions (length × width × thickness)	Quantities	Strain rate (s^{-1})
Normal specimen		152 mm × 75 mm × 32 mm	9	10^{-6} to 10^{-3}
Small specimen	Group A	35 mm × 35 mm × 26 mm	4	200 to 550
	Group B	19 mm × 19 mm × 35 mm	10	200 to 550
Single-flawed specimens		60 mm × 30 mm × 30 mm	32	10^{-4}
			37	110 to 205

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