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Mechanical properties and failure modes of rock samples with grout-infilled flaws: A particle mechanics modeling

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ABSTRACT

Natural fractures are commonly infilled by the infilling materials, such as sheared-off or broken rock fragments and clay. Grouting has been widely used to improve the wellbore stability in oil or shale gas reservoirs and reduce the permeability of fractured rocks in tunnel vicinity, and thus rock fractures can also be manually infilled by grout. Although a large number of studies focused on the strength and failure behavior of rock samples with open flaws, the research on the mechanical properties and failure modes of rock specimens with infilled flaws is rather limited. In order to understand the effects of fillings on mechanical properties and crack propagation behavior of pre-flawed rocks, a large number of numerical uniaxial compression tests have been conducted for rock samples with single or double flaws which were open or infilled, using a particle mechanics method. The results showed that infillings play a significant role in improving the mechanical properties of pre-flawed rock samples, especially when the inclination angles of flaws are less than 45°. The infillings mainly play a role in transferring stress and reducing stress concentration at the flaw tip and bridge regions and thus infillings can change the crack initiation position, propagation direction and coalescence pattern in rock samples with infilled flaws. The effects of micro-parameters of infillings on the mechanical properties and behavior of rock samples with single flaws were also studied through sensitivity analysis.

1. Introduction

Natural fractures/faults often contain infilling materials, such as sheared-off or broken rock fragments and clay particles, which are termed as gouge. Pre-grouting has been widely used to improve the wellbore stability in oil or shale gas reservoirs and reduce the permeability of fractured rocks in tunnel vicinity, and thus rock fractures can also be manually infilled by grout. Therefore, infilling materials may play an important role in brittle behavior of fractured rocks, in terms of crack initiation, propagation and coalescence and mechanical properties. Although a large number of experimental studies focused on the compressive strength and failure behavior of rock samples with open flaws (e.g., Fujii and Ishijima, 2004; Li et al., 2005; Vásárhelyi, 2006; Wong and Einstein, 2009; Lee and Jeon, 2011; Yang and Jing, 2011), the investigation on the mechanical properties and failure modes of rock samples with infilled flaws has been rare (Zhuang et al., 2014).

A couple of studies contributed to the mechanical behavior of rock samples with closed flaws, which had a zero aperture and internal faces in contact with each other from fabrication to testing (Table 1). Shen et al. (1995) carried out a series of uniaxial compression tests on gypsum specimens with two closed flaws, and they showed that a higher loading was required for crack coalescence in samples with closed flaws than that with open flaws. Bobet and Einstein (1998) performed uniaxial and biaxial compression testing on gypsum specimens with closed flaws, and found that partial debonding and slippage of the flaws is required prior to initiation of a crack. Wong and Chau (1998) investigated the pattern of crack coalescence and uniaxial compressive strength of sandstone-like specimens containing two parallel inclined frictional flaws, and they found that the uniaxial compression strength generally increases with frictional coefficient of the contacting surfaces of pre-existing flaws. Wong et al. (2001) also showed that the pattern of crack coalescence is dependent on the flaw arrangement and the frictional coefficient of the flaw surface. Park and Bobet (2009) tested gypsum specimens with open and closed flaws under uniaxial compression condition, and the main

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Table 1
Review of experimental studies on mechanical behaviors of rock samples with closed/filled cracks.

Shen et al., 1995	Gypsum mixture (152.4 mm × 76.2 mm × 30 mm) with two closed cracks (0.01 mm × 12.7 mm)	Gypsum	Uniaxial and biaxial compression tests
Wong and Chau 1998 Wong et al., 2001	Sandstone-like material (Plaster) (60 mm × 120 mm × 25 mm) with two/three closed cracks (0.3 mm × 20 mm)	Plaster	Uniaxial compression tests
Yang et al., 2008	Marble (φ50 mm × 100 mm) with two closed cracks (0.3–0.5 mm × 24 mm)	gypsum	Triaxial compression test
Bobet and Einstein 1998 Park and Bobet 2009	Gypsum mixture (152.4 mm × 76.2 mm × 30 mm) with two closed cracks (0 mm × 12.7 mm) Gypsum mixture (203.2 mm × 101.6 mm × 30 mm) with three closed cracks (0 mm × 12.7 mm)	gypsum	Uniaxial compression tests
Zhao 2004	Marble (25 mm × 12 mm × 1.6 mm) with one flaw (0.6 mm × 6.0 mm)	cement grout	Uniaxial compression tests
Zhuang et al., 2014	Rock like material (70 mm × 70 mm × 140 mm) with one flaw (1 mm × 15 mm)	Gypsum slurry	Uniaxial compression tests

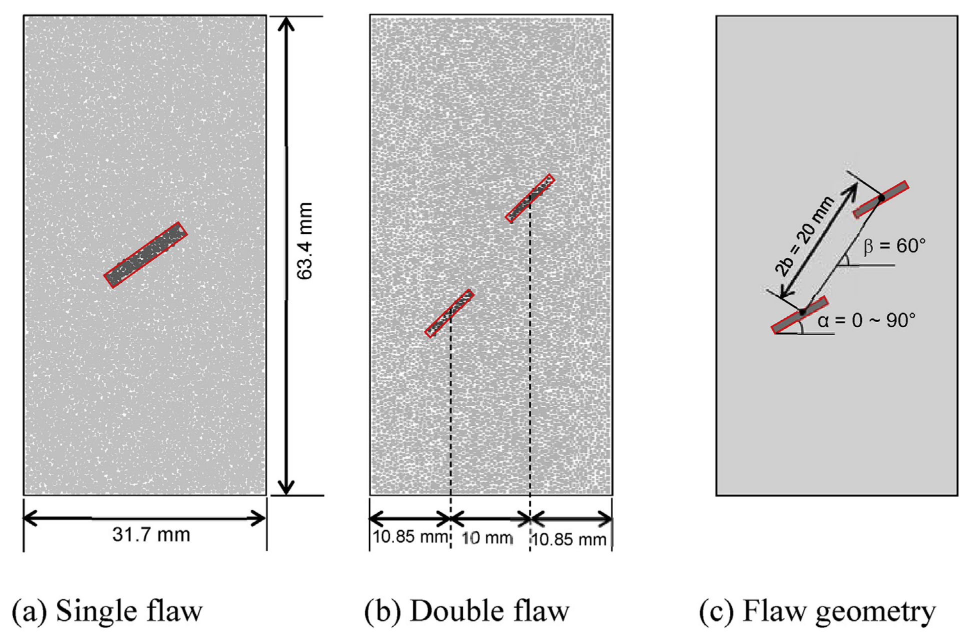

Fig. 1. Particle mechanics models representing the cement particles (dark gray) in pre-flawed rock samples (light gray).

difference between experimental results from open and closed flaws is that initiation stresses and coalescence are higher for closed than for open flaws. The above findings pertaining to closed flaws may provide useful insights for infilled flaws, but they did not consider the interaction between rock and infilled materials at flaw surfaces.

To the authors' best knowledge, only a couple of studies attempted to investigate the brittle behavior of rock specimens infilled by other materials. Zhao (2004) used Scanning Electron Microscope (SEM) to observe the crack initiation and propagation in marble specimens with a single flaw cemented by grout. The results showed that the initiation stress is higher in cemented flaw specimens than in open flaw specimens, and the crack initiation points moved closer to the crack tips in cemented flaw specimens. Yang et al. (2008) carried out triaxial compression tests to study the strength and failure behavior of marble specimens with two flaws infilled by gypsum. Zhuang et al. (2014) compared crack propagation in rock-like specimens with open flaws or flaws infilled by gypsum slurry, subjected to uniaxial compression. They showed that the peak stress for infilled flaws was higher than for the unfilled, and the crack initiation time, initiation location and propagation behavior were different between infilled and open flaws. The micro-mechanisms responsible for the effects of infilling materials on the mechanical properties and failure behavior of pre-cracked rock specimens still remains poorly understood.

The main objective of this study is to examine changes in the macroscopic mechanical properties and failure processes of rock specimens infilled by cement grout, from the point of view of micro-crack development. Particle mechanics method has recently been used to study the crack coalescence in rock specimens with single or multiple flaws (Lee and Jeon, 2011; Zhang and Wong, 2012, 2013; Jiang et al., 2015). The particle mechanics model can