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Shear properties of cemented rockfills

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ABSTRACT

Application of cemented rockfilling to underground mining could not be separated from the corresponding backfill's shear strength properties. The shear of cemented rockfill (CRF)-rock wall and the shear interaction occurring within CRFs both have some disadvantageous failure chances. In this study, we tried to investigate the complete shear properties of CRFs using direct shear and triaxial tests of cemented granite rockfill. Large-scale triaxial testing was held to accommodate the large CRF sample. Direct shear testing on the prepared flat and smooth surfaces was assessed with brief conversions and their corrections were used to approximate the shear strength envelopes of CRF joint interfaces. Two types of CRFs with the same aggregate size and distribution but different unconfined compressive strengths (UCSs) due to different mixture designs indicated insignificant differences between their basic friction angles, and also their asperity inclination angles. Nevertheless, investigation between direct shear test and triaxial test showed that the specimen with higher UCS tended to have a slightly lower friction angle but a higher cohesion than the other one.

1. Introduction

Backfill utilization has been increasingly reported for the recent underground mining sector. As economic resources are being found deeper due to the fact that the surface reserves are almost mined out, backfill utilization even incorporates binder materials such as cement in order to provide more strength. While a number of studies have been carried out on the compressive and tensile strengths of cemented backfills, studies on the shear properties and strength of backfills are rarely reported. In regard to the backfill as a stability support, it is argued that there is no really useful stability analysis for design if the shear strength of the product has been calculated incorrectly (Marachi et al., 1972).

In many Canadian underground mines, the use of cemented rockfill (CRF) as backfill material is a common practice (Yu and Counter, 1983; Reschke, 1993; Shrestha et al., 2008; Emad et al., 2012). Especially in cut-and-fill or blasthole stoping operations, which are usually divided by the primary and secondary stopes, shear properties play an important role (Sepehri et al., 2017a, b). While working on filling the primary stopes, shear interactions occur between the adjacent ore body or rock walls and the placed CRF. A number of studies have verified that stress interaction between the ore body and CRF may be mutually supported (Mitchell, 1989; Belem and Benzaazoua, 2008). On the other hand, mining advancements from the primary to the secondary stopes are supposed to exhibit shear interaction between the primary CRF and the placed CRF at the secondary stope. In this case, this experiment's purpose is to assess the CRF-CRF shear interaction.

Shear interaction in the presence of CRF can be separated into interface between CRF-CRF and interparticle of CRF by means of the mass. A case of sliding failure on the CRF's free-face during the adjacent ore extraction could be the shear interaction between interparticle and/or CRF mass. Fig. 1 shows the mining sequence where the shear interactions of CRF mostly take place.

In rock engineering practice, these two shear interactions are simply assumed to be the shear of discontinuity and shear of an unbroken material. Based on this, the direct shear and triaxial tests may be used to investigate the shear properties of CRF. It should be noted that this study treats CRF as a solid mass instead of loose aggregate accumulation. In this experiment, direct shear and triaxial tests were conducted on two different types of samples. Each sample was tested after 28 d of curing age. This time was selected so that the CRF should completely set and represent its optimum shear strength. Direct shear strength of CRF-CRF interface in this study is based on a flat and smooth surface approach.

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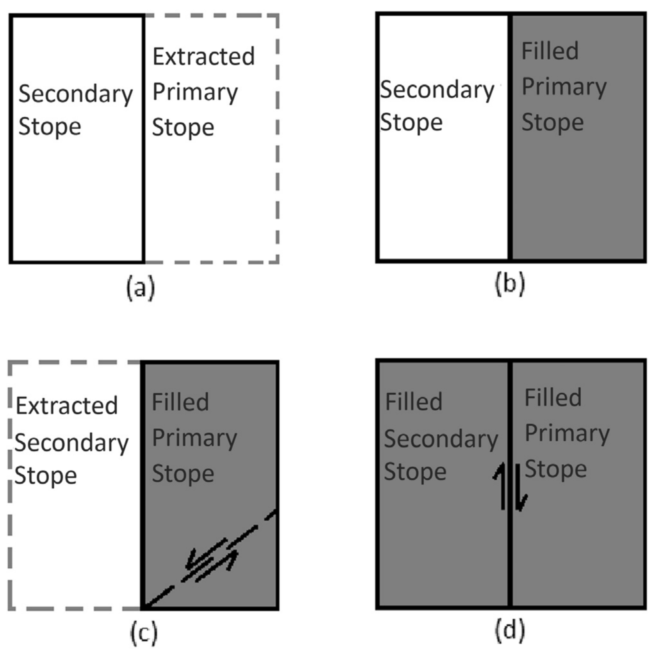

Fig. 1. Mining sequence: (a) primary stope mined, (b) primary stope after backfilling, (c) secondary stope mined and generated interparticle or CRF mass shear at exposed primary stope, and (d) secondary stope after backfilling with CRF-CRF interface shear interaction.

Samples in this study are laboratory-created CRF of granite aggregate rock retrieved from a diamond mine in Northern Canada.

The CRF incorporates a binder which, in setting the CRF, behaves more like concrete or rock than regular compacted or non-consolidated rockfill. This understanding is important to clarify Barton's shear strength criteria (Barton, 2013, 2016) that are used later in this study. Experimental work in this study follows Barton's shear strength of rock joints experiment instead of his shear strength of rockfill interfaces experiment, which is related to loose or non-cemented rockfill. Despite that the triaxial test of CRF is not commonly conducted due to the limited availability of a large triaxial cell for accommodating large CRF sample size, this study delivers the triaxial results of 152.4 mm (6 in) diameter CRF samples. Further details are given in the following sections.

2. Theory, material and experimentation

2.1. Shear strength criteria

Theoretically, a rock's shear strength can be expressed with the Coulomb relationship:

$$\tau = c + \sigma \tan \varphi \tag{1}$$

where τ, c, σ, and φ are the shear strength, cohesion, normal stress, and angle of internal friction, respectively. For rock joints, it is theoretically using the above equation without cohesion value, thus Eq. (1) for rock joints becomes

$$\tau = \sigma \tan \varphi \tag{2}$$

However, Eq. (2) only meets the criteria when any joint's contact is smooth, clean, and planar. Then, the generated shear strength envelope is supposed to be linear. However, in reality, any naturally occurring joint is most likely to undulate. In addition to the fact is that envelope plotting from the shear test is also nonlinear.

Various empirical approximations predicting the nonlinearity of a rock joint's shear strength envelope due to its naturally non-planar characteristics with curve-fitting were found to be more reliable. The initial attempts to interpret the shear strength of rough joints resulted in a bilinear model of shear strength envelope (Newland and Allely, 1957; Patton, 1966):

$$\tau = \sigma'_{\rm n} \tan(\varphi_{\rm b} + i) \tag{3}$$

where $\sigma'_{\rm n}$, $\varphi_{\rm b}$, and i are the effective normal stress, basic friction angle, and asperity inclination angle, respectively.

Patton (1966) configured the relationship using deviation of the shear strength envelope of a joint and $\varphi_{\rm b}$ plus i. The experiment of a wide range of normal stress variations toward a non-planar (artificially controlled undulation) interface sample resulted in a deviating shear envelope plot, in comparison with the smooth surface, which proved Patton's hypothesis.

Further development of the nonlinear shear strength envelope of a joint from bilinear to be more precise as curvilinear had been claimed (Barton, 1973, 1976, 2013, 2016; Barton and Choubey, 1977; Bandis et al., 1981; Barton and Bandis, 1982):

$$\tau = \sigma'_{\rm n} \tan\left[JRC\left(\log_{10}\frac{JCS}{\sigma'_{\rm n}}\right) + \varphi_{\rm b}\right] \tag{4}$$

$$\tau = \sigma'_{\rm n} \tan\left[JRC\left(\log_{10}\frac{JCS}{\sigma'_{\rm n}}\right) + \varphi_{\rm r}\right] \tag{5}$$

$$\tau = \sigma'_{\rm n} \tan\left[JRC_{\rm n}\left(\log_{10}\frac{JCS_{\rm n}}{\sigma'_{\rm n}}\right) + \varphi_{\rm r}\right] \tag{6}$$

where JRC is the joint roughness coefficient, JCS is the joint-wall compression strength, $JCS_{\rm n}$ and $JRC_{\rm n}$ are respectively the corrected JCS and JRC based on the length of observed joint, and $\varphi_{\rm r}$ is the residual friction angle.

In Eq. (4), JRC and JCS are the first two terms introduced by Barton in his earlier study. Upon the development, in consideration of weathering of the natural joint and the difference between a prepared flat surface and natural surface due to residual shear, Barton and Choubey (1977) substituted $\varphi_{\rm b}$ in Eq. (4) with $\varphi_{\rm r}$ as given in Eq. (5). Further, Eq. (6) was developed by Bandis et al. (1981) after Barton and Choubey (1977), where $JRC_{\rm n}$ and $JCS_{\rm n}$ were used to take into account the field scale effect, rather than the derivatives of JRC and JCS.

Barton (2013) suggested that the curvilinearity of the shear strength envelope was affected by how rock behaves under the stress applied. A series of triaxial tests indicated the brittle-ductile behavior of rock as elastoplastic material bended the shear strength envelope (see Fig. 2).

Zhao (1997) proposed an equation (Eq. (7)) based on Barton-Choubey's model (Eq. (5)) by adding a correction factor of interface matching factor or joint matching factor (JMC) to the JRC. He considered the field condition when usually the joint interface was not completely matching as a fresh joint. Therefore, he also used the term residual friction angle instead of basic friction angle.

$$\tau = \sigma'_{\rm n} \tan\left[(JMC)(JRC)\left(\log_{10}\frac{JCS}{\sigma'_{\rm n}}\right) + \varphi_{\rm r}\right] \tag{7}$$

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