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Shear resistance contribution of support systems in double shear test

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ABSTRACT

Rockbolt and surface support systems such as shotcrete and thin spray-on liners (TSLs) are widely used as underground support elements to resist the convergence and maintain the stability of excavations. In order to evaluate the bearing capacity of combined reinforced rockbolt and surface support systems in preventing sliding along discontinuities, double shear tests (DST) was carried out using fully grouted rockbolts installed in three separate blocks. These blocks were covered with a 5 mm layer of TSL followed by a 50 mm layer of shotcrete. Two rockbolts were installed at an inclined angle of 45°, and 20 kN lateral constraining force was applied to clamp together the three blocks. Three different support combinations were tested: 50 mm shotcrete only, 5 mm TSL only, and combined shotcrete and TSL, with and without rockbolts. It was confirmed that the shotcrete plays a mechanical role in resisting the shear load, and TSLs increase the bond strength between shotcrete and substrate replicating the side wall of an excavation. The contribution of rockbolt and surface support system in resisting joint movement was also compared. The failure mechanism of rock substrate, rockbolt and surface support system was also analysed.

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1. Introduction

Design, installation and monitoring support systems are a major consideration in underground mining operations. The use of rockbolts dates back to the late 1900 s in mining and includes mechanically anchored (slot and wedge or expansion shell) bolts, fully grouted bolts and resin bolts. Generally, the purpose of a rockbolt is to develop inherent strength and stiffness in a rock mass by securing the loose surface blocks to deep stable rock masses (Hoek et al., 2000). Rockbolts develop their tensile and shear strength during the convergence of rock mass, in which the rockbolt can be considered as part of a rock mass.

Rockbolts when combined with shotcrete and/or TSLs can cope with almost any ground condition encountered during mining and tunnelling. Thin spray-on liners (TSLs) are multicomponent polymer materials that can be applied to the rock mass surface as a sealant or as a surface support (Darling, 2011). When the shotcrete is sprayed onto the surface of rock, the adhesion strength develops over time. Moreover, any fracture on the surface is filled and sealed by the application of high speed injected shotcrete, helping maintain the integrity of the rock mass. Failure is normally due to adhesion failure between the shotcrete and rock interface that can be initiated after a small displacement.

Over the past four decades, research has confirmed that shear performance can be just as significant as tensile performance. This is evident by a high proportion of rockbolts that have been found to fail in shear in high stress rock masses (Li, 2010) and under rockburst conditions (Haile, 1999). A case study conducted by McHugh and Signer (1999) indicated that shear loading contributed significantly to the failure of anchoring systems. Malmgren and Nordlund (2008) pointed out that the behaviour of shotcrete in interaction with rock is very complex and the performance of shotcrete is influenced by a number of parameters, especially the present of discontinuities. However, there is less known about the effect of discontinuities on the failure of shotcrete.

Many experimental tests have been performed in order to study the mechanical behaviour of rockbolts in resisting the shear force based on single shear tests (Haas, 1976; Haas, 1981; Yoshinaka et al., 1987; Egger and Zabuski, 1991; Holmberg, 1991; Pellet, 1993; Ferrero, 1995; Pellet and Egger, 1996; McHugh and Signer, 1999; Mahony and Hagan, 2006) and double shear tests in the laboratory (Aziz et al., 2003; Grasselli, 2005; Jalalifar, 2006; Craig and Aziz, 2010; Jalalifar and Aziz, 2010; Hyett and Spearing, 2013). The factors that can influence shear resistance include (Hartman and Hebblewhite, 2003):

- Rock mass condition: joint aperture/roughness/dilatancy,
- Strength and size of rock,
- The reinforcement elements system: type/diameter/mechanical properties of anchoring systems,

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- Grout type/thickness,
- Inclination of bolt and joint plane, and
- And loading conditions: pretension, normal pressure, confinement condition.

Hass (1976) studied the 'natural fracture' of shear surface by splitting limestone blocks with 25 mm surface roughness. The results showed that surface roughness increased the initial shear resistance. However, the shear resistance decreased rapidly as the asperities were sheared off. Hass (1976) further compared the anchorage capacity of fully grouted rockbolts in a rifled hole and a smooth hole. He concluded that roughness plays a major role in increasing the tensile capacity and shear force. Grasselli (2005) pointed out that the variation in bolt inclination affects the maximum load mobilised in the rockbolt as well as the rigidity of a jointed system. Spang and Egger (1990) carried out shear tests with bolt diameters of 8 mm, 10 mm, and 40 mm. The results indicated that the maximum shear force and displacement is proportional to bolt diameter. Pull-out capacity of a rockbolt in different resin encapsulation annulus was examined by Hagan and Weckert (2004). They found that pull-out capacity of fully encapsulated rockbolt is not affected by changes in resin annulus of less than 4 mm. However, there was a reduction in pull-out capacity at greater resin thicknesses. There is little research about the resin annulus effect in shear tests. Hard rocks usually have higher shear resistance compared with soft rock and rockbolts embedded in harder rock usually require smaller displacements to attain a given resistance than those in softer rock (Spang and Egger, 1990). Ferrero (1995) mentioned that pretensioning does not influence the maximum resistance of the reinforced shear joint; however, it will heavily influence the magnitude of the shear displacement.

An analysis of double shear testing results shows that the behaviour of a rockbolt under load follows three distinct stages, linear behaviour, non-linear behaviour and unconstrained plastic deformation. The contribution to shear strength is defined as the difference between the applied shear force and the frictional strength normalised to the ultimate tensile load of the bolt. The first and second stage refers to loading up to 75% and 90% of maximum load capacity respectively for a full scale rockbolt (Grasselli, 2005).

Polypropylene-fibre is used to increase the ductility of shotcrete, leading to stress redistribution (Malmgren, 2007). The possible mechanism for shotcrete in interaction with the rock is by block interlock theory. Also the effect of sealing the joints by shotcrete helps to maintain the integrity of the rock mass (Malmgren et al., 2005; Stacey, 2001). The shear-bond strength of TSL was assessed by Yilmaz (2007) and the double-sided shear tests for various TSLs were conducted by Saydam et al. (2004) and Richardson et al. (2009). These researchers examined the capacity of shotcrete or TSLs under shear conditions; however, little is known about the performance of shotcrete and TSLs in combination with rockbolts.

These studies examined shear resistance capacity associated with the movement of rock mass; however, they are insufficient to provide an integrated approach for combined underground support systems. It is common practice that surface support systems are often used in combination with rockbolts. Accordingly, this paper aims to address the mechanical behaviour of combined support systems quantitively, including rockbolt, TSL and shotcrete, through double shear tests.

2. Double shear test

Double shear test is a laboratory test widely used for measuring the shear resistant of support systems in jointed rockmass, including rockbolt, shotcrete, TSLs, and their combinations. In this paper, double shear tests refer to an arrangement of three blocks reinforced with a fully grouted rockbolt at different angles. The two end blocks are fixed and a load is applied to the middle block causing shear loading. Shotcrete and TSLs were applied to the surface of the test blocks, a schematic view of this test is shown in Fig. 1. The strength performance of reinforced element for pull and shear tests was carried out in embedment tubes with a minimum thickness of 10 mm according to British Standard (BS7861-Parts 2:2009), is considered a single guillotine test. The disadvantage of this kind of test as discussed by Li et al. (2014a), is that the steel tube is much stiffer than the rock which may introduce an error into the measurement. A quantitative result reported by Aziz et al. (2015), is the shear load per side for each double shear cable bolt was significantly higher than the results of testing cables in the single guillotine shear test.

2.1. Sample preparation

Blocks used in double shear tests were prepared using a cement mortar to ensure consistency of the test condition. The cementitious mixture was poured into plywood moulds, each measuring 300 mm × 300 mm × 200 mm. A plastic conduit of 24 mm in diameter was placed in the moulds to create a hole for rockbolt installation that was set at either 90° or 45° to the direction of loading. This study sets the inclined angle at 45°. The orientation of the bolt installation is shown in Fig. 1.

The cast samples were left to cure initially in the mould for the first 24 h. The blocks were then removed from the moulds and placed in a water bath for the remaining period of 28 days to cure. Cement was poured into 40 mm diameter cylinder for uniaxial compression strength tests. Three block samples were clamped together two rockbolts, that was fully encapsulated using 77 MPa high strength grout. To ensure that the rockbolt was fully covered, the grout was injected using a grout gun. By doing this, smooth and plane joint surfaces were achieved.

The top surface of the blocks was roughed to ensure good adhesive strength of the shotcrete and TSL. An acrylic-based commercially available TSL was uniformly applied on the surface, that provides a tensile strength of 3.0 MPa within 7 days. Sprayed concrete was applied on the membrane surface after it set, with a typical bond strength (concrete to membrane) greater than 1.0 MPa. A commercially available shotcrete product is a ready-to-use, cement based shotcrete mix with reduced rebound and active corrosion inhibition. Proper curing is extremely important in this process. Wet curing is recommended for 3–5 days. A high performance structural polypropylene fibre was used. It provides resistance to rupture force thereby enhancing concrete toughness and crack control. The usage of fibres was 0.4 kg per bag of shotcrete.

The mechanical properties of the test materials are shown in Table 1.

2.2. Test methodology

A hydraulic universal testing machine with a capacity of 3600 kN was used for double shear testing under static loading, as shown in Fig. 2.The testing machine is comprised of an indicator/control console containing the hydraulic pump unit and valve gear, a dial indicator and electrical controls. The main piston is located within the walls of a cylinder that has hydraulic fluid fed via the top and bottom of the piston. The load is applied from the bottom piston.

Four continuously threaded rods, each 24 mm diameter and two steel plates were used as end constraints as seen in Fig. 1. This differs from a fully enclosed test sample arrangement in which it is assumed the test blocks are under a perfect confining pressure to simulate an infinite rock mass. However, in this situation, the test

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