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AXIAL BEHAVIOUR OF ROCK BOLTS–PART (A)
EXPERIMENTAL STUDY

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ABSTRACT: Several experiments were carried out to investigate the effect of curing time and water to grout ratio on the ultimate load capacity of fully grouted rock bolts subject to pulling out loads. For this purpose, various samples were cast with water to grout ratios of 30%, 36% and 40%. Pull-out tests were conducted on samples with different curing times, ranging from 7 to 28 days. Results indicate that the peak value of the pull out load increased as curing time increased. In contrast, increasing water to grout ratio weakens the pulling out resistance of fully grouted rock bolts.

INTRODUCTION

Fully-grouted rock bolts are widely used to strengthen and support rock walls and tunnels in mining and civil industries (Li, 2017). These reinforcing systems can be designed as temporary or permanent reinforcement to mitigate the risks associated with tunnelling, namely rock falls and structural collapse (Cao, 2012). A typical grouted rock bolt consists of internal and external fixtures such as a ribbed steel bar installed and encapsulated by cementitious grout in a drilled hole. Once grout cures, chemical adhesion, friction and mechanical interlocking provide the bond strength between the grout and bolt (Cao et al., 2016). System debonding may occur at the grout, bolt-grout interface, grout-rock interface or surrounding rocks (Li and Stilborg, 1999). However, failure at the bolt-grout interface is the most common mode according to previous experimental and in-situ studies. Rock bolt systems develop forces in response to rock deformation and displacement. Different stresses are acting on rock bolt systems; these include tension, shear, compression and rotation. Figure 1 illustrates six different loading types that can occur on a rock bolt system depending on the geometric properties of joints and the bolt's spatial position relative to the joint. In this figure, rotation was not taken into account, which creates extra complexities (Thompson et al., 2012).

![Figure 1: Generic reinforcement system (Thompson et al., 2012)](image)

As illustrated in Figure 2, tensile loads within a rock bolt system occur when a discontinuity dilation displaces a rock mass. Tension is produced between stable and unstable rock regions as shown in Figure 3, thus creating shear loads between the rock-grout interface. The tensile strength of steel, the

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bond strength of the bolt-grout interface and the bond strength of the grout-rock interface in combination hold the unstable region in place.

![Figure 2: Loading of reinforcement caused by block translations (Windsor, 1997)](image)

Failure of rock bolt systems can occur in five modes as shown in Figure 4 (Hutchinson and Diederichs, 1996). Mode A represents breakage of a bolt shaft; this form of failure is rare because it requires the bond strength between the grout and bolt to be greater than the bolt's tensile strength. Many studies confirmed that the failure of fully grouted rock bolts occurs at the bolt grout interface as shown in mode B (Chen et al., 2020, Thenevin et al., 2017, Paul Hagan, 2014, Cao, 2012). This type of failure is due to the small contact area between the bolt and grout. However, if the rock strength is relatively weak or if the borehole diameter is relatively small, the rock-grout interface failure is more likely to occur as shown in mode D. Modes C and E depict failure at the grout-rock interface and the surrounded rock respectively (Cao, 2012, Paul Hagan, 2014, Hutchinson and Diederichs, 1996).

![Figure 4: Different failure modes of cable bolts (Hutchinson and Diederichs, 1996)](image)

Grout acts as a medium to transfer the initiated stresses from rock masses to bars. The load-bearing capacity of this reinforcing system depends on numerous factors. The most effective ones are the bolt tensile strength, bolt surface profile, bolt length and diameter, hole diameter, annulus thickness and grout mechanical properties.

There are different types of grout and each has its unique mechanical characteristics. Grout cohesion, shear strength and angle of friction play an essential role in rock bolt systems. Up to now, a large
number of experimental studies have been conducted to investigate the effect of grout mechanical properties on the efficiency of fully-encapsulated rock bolts. Hyett et al. (1995) performed a number of tests on fully-grouted strand cable bolts indicating the sensitivity of the bond strength to the grout properties. Kilic, et al. (2002) conducted numerous pull-out tests on steel bars, encapsulated into basalt rock to study the effects of grout's mechanical properties on the bearing capacity. In this study, besides mechanical properties, bolt length, bolt diameter, bonding area, water to grout ratio and curing time were also investigated. According to the test results, an increase in the bolt diameter and bolt length results in a linearly increase in the ultimate pull-out load. On the contrary, an increase in the water to cement ratio results in a decrease in the ultimate pull-out load. The bond strength of fully encapsulated rock bolts is basically frictional and depends on the shear properties of the grout and bolt-grout or grout-rock interfaces such as cohesion, frictional angle and interface roughness. The results of different studies show that Uniaxial Compressive Strength (UCS) and shear strength of grouts play vital roles in the determination of rock bolts and cable bolts bearing capacity (Hyett et al., 1992, Benmokrane et al., 1995, Miller and Ward, 1998, Rao Karanam and Dasyapu, 2005, Bin et al., 2012, Teymen and Kiliç, 2018, Zhang et al., 2020). Kilic et al. (2002) observed that the bond strength increases logarithmically with an increase in UCS and shear strength of grouts. In another research study, Teymen and Kiliç (2018) investigated the axial stress distribution of rock bolts by applying strain gauges on bolts. The bolts were installed in high strength rock media. Mortar with different mechanical properties was prepared using admixtures with various water to cement ratios. It was concluded that grouts' mechanical characteristics significantly affect shear and axial stress distributions, and consequently the ultimate bearing capacity. Aziz et al. (2017) carried out numerous experiments on commercial grout products (Stratabinder and BU-100) investigating the effects of water to cement ratio and curing time on grout mechanical properties. The results show that an increase in water to grout ratio from 28% to 42% causes a 43% reduction in UCS of Stratabinder samples. In this study, the effect of water to grout ratio is also noted on grouts' shear strength. Kim et al. (2019) evaluated the performance of fully-encapsulated rock bolts using cementitious grout and resin. It was concluded that the grouted bolts' ultimate bearing capacity is a function of water to grout ratio and curing time. Li (2017) illustrated that water to grout ratio is a crucial factor in determination of critical length. For instance, for a sample with water to cement ratio of 0.4, the critical embedment length is 32 cm. This length increases to 36 cm for a water to cement ratio of 0.50. Experiments also indicated a correlation between water to cement ratio and grout UCS as shown in Figure 5. Chang et al. (2017) conducted a series of tests indicating that grouts' UCS influences the interface bond strength. They showed that when UCS of grout increases from 30 to 60 MPa, the interface bond strength increases from 3.8 to 11.5 MPa (Figure 6).

![Figure 5: Relation between mortar UCS and water to cement ratio (Li, 2017)](image)

This paper is the first of two-paper publication in this proceeding. In Part (A), the effects of water to grout ratio and curing time on the axial behaviour of rock bolts were studied by conducting more than 36 pull-out tests. In the subsequent paper (Part B), FLAC 2D was incorporated to simulate numerically the pulling out resistance of fully grouted rock bolts subject to confinement stresses, and by considering various rock bolts surface roughness.
Figure 6: Relation between critical bond strength and grout compressive strength (Chang et al., 2017)

SAMPLE PREPARATION

Short encapsulation was employed to study debonding mechanisms of rock bolts, ensuring uniform distribution of shear stress along the bolt-grout interface (Benmokrane et al., 1995, Blanco Martín et al., 2011). For this purpose, grout samples were prepared with water to grout ratios of 30%, 36%, and 40%, and samples were left to cure for 7, 14, 21 and 28 days. The mixing process of batches (grout and water) followed the instruction recommended by the manufacturer, the Minova Stratabinder. Pull-out loading test was repeated three times on each curing-time and water-grout ratio (36 pull-out tests in total) to obtain accurate and reliable results, and then the average values were taken into account to interpret the results. Firstly, bars with 18 mm in diameter and 500 mm in length were installed in the centre of steel pipes, and then the annulus area between the pipe wall and bar was filled using the mixed grout. Steel pipes with an internal diameter of 50 mm and thickness of 2 mm were used to simulate the surrounding rock and confining material. Pipes were 100 mm in length (equal to the bar encapsulation length) without any internal thread. Samples were left in the laboratory to cure, based on the desired curing times as shown in Figure 7.

Figure 7: Samples prepared for the pull-out test
RESULTS ANALYSIS

Pull-out tests were conducted by setting the servo-controlled MTS 100 kN tensile machine to a strain rate of 1 mm per minute (Figure 8). Samples were threaded into an attachment and subsequently gripped from both the top and bottom by the machine’s jaws. Sample arrangement in the testing machine is shown in Figure 8. The load-displacement interaction was monitored on integrated computer software connected to the pull-out machine. The test was repeated weekly on samples cured in 7, 14, 21 and 28 days.

Results of pull-out tests show that the curing time and water to grout ratio have definitive influences on the bearing capacity of encapsulated rock bolts, albeit some unusual behaviours can be ascribed to the grout mixing procedures (Figures 9 to 11). Figure 12 is a comparative chart showing the ultimate pulling-out loads for the samples with different water to grout ratios and curing times. It is evident that under each curing time condition, the peak values belong to the samples with a 30% of water to grout ratio. It is inferred from the test results that the ultimate bearing load of samples for each curing time decreases with an increase in the water content. For example, samples with 40% of water content fail with lower pulling load (35.6 kN) when compared to the samples prepared with 30% of water content (45.4 kN). Moreover, a general increasing trend in ultimate pulling out resistance is observed with an increase in the curing time. For instance, samples with 36% of water to grout ratio cured for 7 days failed at 33.2 kN whereas samples cured for 28 days failed at 39.95 kN. As mentioned above, in some cases there are strange behaviours observed in the pulling-out results. Figure 9 shows the ultimate load for samples with a 14 day curing time which is slightly higher than those with a 21 and 28 day curing time. This might be associated with the preparation and curing process. The observations also demonstrate that variables, including water to grout ratio and curing time have noticeable effects on the system’s rigidity against shear displacement. According to the results, samples with a water to grout ratio of 30% and a 28 day curing time possess the highest shear stiffness (6.94 kN/mm), however, the lowest belongs to samples with a water to grout ratio of 40% and a curing time of 7 days (3.82 kN/mm). Figure 13 represents an interactive three-dimensional plot between water to grout ratio, curing time and shear stiffness for the grouted bolts with a 100 mm of encapsulation. Figure 14 shows the ultimate bearing loads subjected to the samples and the associated displacement at the maximum load point. From this graph, it is concluded that the highest magnitude of energy is stored in samples with water to grout ratio of 30% in comparison to other tests.

Photos of samples taken after the pull-out test were collected showing tangential and radial cracks (Figure 15). Tangential cracks initiated from the bolt and extended to the steel pipe whereas radial cracks formed a ring around the bolt shaft. All samples showed both types of cracks to various extents. Nevertheless, no correlation between grout properties and the crack type was noted.
Figure 9: Load-Displacement curves for samples with water to grout ratio of 30%

Figure 10: Load-displacement curves for samples with water to grout ratio of 36%

Figure 11: Load-displacement curves for samples with water to grout ratio of 40%
Figure 12: Ultimate bearing capacity based on curing time and water to grout ratio (w:g)

Figure 13: Effects of curing time and water to grout ratio (w:g) on shear stiffness of fully grouted rock bolts

Figure 14: Ultimate loads and relevant displacement
CONCLUSION AND STUDY LIMITATIONS

In this study, experiments were carried out to evaluate the effects of the grout preparation process such as water to grout ratio and curing time on grouted rock bolts' axial bearing capacity. These variables are considered as the main influential factors on the mechanical properties of grouts. The following main conclusions are drawn from this research study:

- The proportion of water in the grout mixture plays an influential role in the ultimate axial bearing capacity of rock bolting systems regardless of other factors. The same effect was observed with respect to the curing time. However, the experimental data showed unusual behaviours in a few cases.

- In all tests, the positive effect of decreasing the water to grout ratio on the ultimate load is evident. As the water to grout ratio decreases from 40% to 30%, the axial bearing capacity increases by 20% on average for each curing time period,

- The maximum pulling-out load (48 KN) was measured for the samples cured for 28 days with a30% of water to grout ratio,

- In terms of failure mechanisms, tangential and radial cracks were observed in all samples regardless of water content and curing time.

- This study was carried out to compare the effects of water to grout ratio and curing time on axial behaviour of rock bolts and may not represent field conditions. 2 mm of steel pipe used as the confinement wall (Figure 8) may cause lateral dilation, thus, affecting the ultimate pulling out capacity. It is recommended to carry out similar research study with confinement tube of 9 mm or more thickness, avoiding lateral displacement during experiment.

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REFERENCE


