Quantifying the increase in adhesion strength of shotcrete applied to surfaces treated with high-pressure water

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Abstract
Research is currently being conducted at the Colorado School of Mines in the use of high-pressure water for scaling down loose rocks in underground mine openings. In addition to improved miner safety, the adhesion strength of shotcrete applied to rock surfaces treated with high-pressure water is also increased significantly, resulting in improved overall support capabilities of the shotcrete layer. Test results show an increase in adhesion strength by a factor of four on a concrete test wall cleaned with water at 21 MPa (3,000 psi) as compared to a surface cleaned at 0.7 MPa (100 psi).

Introduction

Shotcrete (sprayed concrete) is defined as pneumatically applied mortar or concrete projected at high velocity (American Concrete Institute). Shotcrete normally consists of a mixture of Portland cement and fine aggregates and various admixtures, including microsilica, accelerators or retarders, plasticizers and, occasionally, steel fibers for reinforcing. While the use of shotcrete for the support of underground openings was initially developed by the civil engineering industry, the mining industry has in recent years become a major user of shotcrete for underground support.

The main purpose of the shotcrete is to help the rock mass maintain its integrity. Shotcrete works by completely coating the rock surface, thereby reducing rock movement and preventing loosening of rocks around the opening. Good adhesion between the rock and shotcrete layer is crucial. Tests performed in Sweden (Holmgren, 2001) have shown that the primary failure of good-quality shotcrete lining on hard rock is adhesion failure. If the adhesion strength is low, the weight of loose blocks of rock pushing down on the shotcrete layer may cause sections to separate, and gaps can be formed between the shotcrete layer and the rock surface (Fig. 1). The subsequent bending of the shotcrete will cause tensile failure.

To obtain good adhesion, the rock surface must be properly cleaned to remove dust, oil and small pieces of loose rock. A common practice is to clean the rock surface using the shotcrete application equipment by blowing compressed air and water through the shotcrete nozzle. Water pressures greater than 0.7 MPa (100 psi) are difficult to achieve and the effect is more of a wetting down of the surface rather than effective cleaning. While it is possible to use high-pressure water pumps for cleaning, this is seldom done in practice.

As part of a project funded by the National Institute for Occupational Safety and Health (NIOSH) administered through the Western Mining Resource Center, research is being conducted at the Colorado School of Mines (CSM) on the use of high-pressure water for scaling down loose rocks in underground mine openings, (Kuchta, 2001). While the primary purpose of the project is to reduce scaling accidents by removing miners from high-risk areas, the increase in bond strength of shotcrete applied to rock surfaces treated with high-pressure water is also being investigated. An experiment has been set up in the CSM experimental mine with the purpose of quantifying the increase in adhesion strength of shotcrete as a function of the water pressure used to clean the surface.

This paper describes the experiment and summarizes the results obtained as well as similar tests performed by the Swedish mining company LKAB at the Kiruna Mine.

Background

A project with the aim of improving the design of shotcrete as rock support was recently initiated at LKAB's Kiruna Mine (Malmgren and Svenson, 1999). The main support system at the mine is untensioned fully grouted dowels and shotcrete. Ninety percent of the shotcrete is unreinforced. The average thickness of the shotcrete layer is about 40 mm (1.6 in.). Approximately 20,000 m^3 (26,000 cu yd) of shotcrete is used as rock support in the mine per year. The purpose of the shotcrete is to help the rock mass maintain its integrity. Therefore, the adhesion strength between the shotcrete and wall rock is crucial.

A mapping program covering more than 7 km (4.3 miles) of drifts reinforced with shotcrete was carried out. Two basic failure types were identified (Fig. 2): fallout of shotcrete, indicating poor adhesion of the shotcrete to the rock, and fallout of rock and shotcrete together, indicating areas of weak rock.

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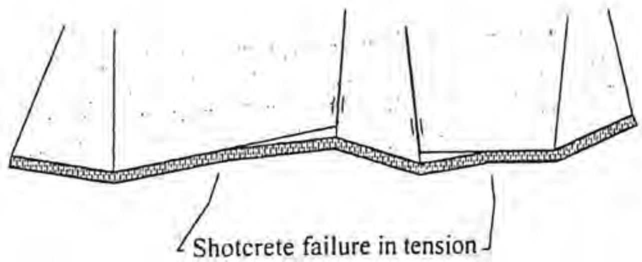

Figure 1 — Tensile failure of shotcrete resulting from insufficient adhesion strength.

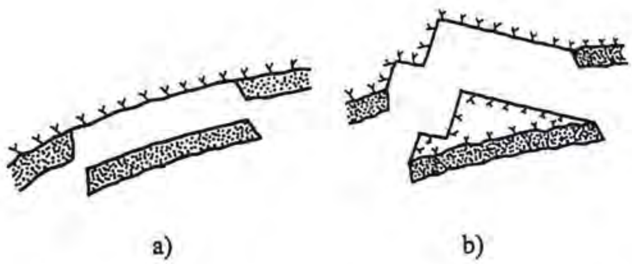

Figure 2 — Two basic types of shotcrete failure: (a) fallout of shotcrete, indicating poor adhesion, and (b) fallout of shotcrete and rock, indicating zones of weak rock (Malmgren, 1999).

2000 psi 13.8 MPa	1000 psi 6.9 MPa	100 psi 0.69 MPa
3000 psi 20.7 MPa	4500 psi 31.0 MPa	6000 psi 41.4 MPa

Figure 3 — Layout and water pressures used to treat the six subpanels on the concrete test panel.

Scaling is performed in all drifts and crosscuts and usually done with a boom-mounted hydraulic scaling hammer. Before application of the shotcrete, the rock surface is cleaned using water at a pressure of about 0.7 MPa (100 psi). This method of surface preparation was called the "normal" treatment. Water-jet scaling was tested as an alternative to mechanical scaling. A prototype rig was built that used a water pressure of 20 MPa (2,900 psi) and a flow rate of 0.21 m^3/min (55 gpm).

These methods of surface preparation were evaluated in seven different crosscuts situated within the iron ore (a fine-grained magnetite). Adhesion tests were performed using test equipment designed according to the Swedish standard SS 13 72 42. The results of the tests are summarized in Table 1.

An analysis of the results indicates that the mean adhesion strength increased from 0.21 MPa (30 psi) with the normal treatment to 0.61 MPa (88 psi) for surfaces treated with high-pressure water-jet scaling. This is an improvement by a factor of about three. It can also be seen that most of the failures for the normal treated surface are within the rock. The distribution of failures shifts towards failure between the shotcrete and the rock with high-pressure water jet scaling. One possible explanation for this is that the outer layer of rock weakened by blasting is cleaned away with water jet scaling. The shotcrete then bonds with a cleaner more homogeneous rock surface, which is of higher strength than the surface cleaned by the normal treatment.

CSM shotcrete adhesion tests

Test area and preparation. An experiment was set up in the Army tunnel (Anonymous, 1984) of the Colorado School of Mines (CSM) Experimental Mine in Idaho Springs, Colorado, with the purpose of quantifying the increase in adhesion strength of shotcrete as a function of the water pressure used to clean the underlying surface. The area chosen for the tests is within a quartz-feldspar gneiss. This unit consists primarily of quartz and potassium feldspar with minor amounts of muscovite. The rock is hard and competent.

A section of rib approximately 2-m (6-ft) high and 6-m (18-ft) long was divided into six vertical panels. The width of each panel was about 1 m (3 ft). Each panel was spayed to thoroughly clean the rock surface using different water pressures. The pressures used were 0.69, 6.9, 13.8, 20.7, 31.0 and 41.4 MPa (100, 1,000, 2,000, 3,000, 4,500 and 6,000 psi). Tarps were used to cover the panels after cleaning to protect them from debris when spraying the neighboring panels.

In addition to the rock test panels, a concrete test panel was also constructed along the rib of the drift directly across from the rock test wall. The purpose of the concrete test panel was to provide a reference to compare results of the adhesion tests. The concrete test panel was about 2-m (6-ft) high and 3-m (9-ft) long. The panel was divided into six subpanels, each about 1 by 1 m (3 by 3 ft). The panels were treated with the same water pressures as the rock panels. The panel was constructed such that the subpanels were completely covered with plywood, which could be removed when spaying the subpanel. The purpose of the plywood covers was to prevent the treated surfaces from being contaminated with debris when spraying the surrounding subpanels. Figure 3 shows schematically the layout of the subpanels and the water pressures used to treat the surfaces.

The compressive strength of the concrete was tested using a total of twelve 300-mm- (1-ft-) high, 150-mm- (6-in.-) diam standard concrete test cylinders. Four cylinders were tested at 7, 14 and 28 days. The final 28-day compressive strength of the concrete was found to be 26.1 MPa (3,780 psi).

High-pressure pump. A high-pressure water pump capable of producing pressures up to 69 MPa (10,000 psi) at about 0.015 m^3/min (4 gpm) was fitted with a pressure gauge and a pressure relief valve that could be used to regulate the water pressure and used for cleaning of the rock panels. It could be seen that at 21 MPa (3,000 psi) a transition occurred in the effectiveness of the cleaning. At 21 MPa (3,000 psi) the water jet was of sufficient power to remove loose rocks fist size and larger. At 41 MPa (6,000 psi) a sandblasting type effect was noted. The wand operator was bombarded by small particles of rock removed from the rock wall. When cleaning the concrete test panel it could be seen that at 41 MPa (6,000 psi) the water jet completely removed the outermost layer of cement creating etched lines along the surface.

Shotcrete application. For application of the shotcrete layer to the rock wall and concrete test panels, a wet mix shotcrete was used. The quantities for a 1 cu yd (0.765 m^3) shotcrete mix used are given in Table 2. According to the supplied specifications, the mix will reach at least 4,000 psi in 28 days with a 4-in. maximum slump and air content of 3% to 5%. The liquid accelerator, Shot-Set 250, provided by Shotcrete Technologies Inc., was mixed at the nozzle while applying the shotcrete.

Table 1 — Results of the adhesion test performed at LKAB's Kiruna mine.

Type of scaling and cleaning method	Number of tests	Adhesion strength, MPa mean	Median	Standard deviation	Failure surface, % Shotcrete to rock	Rock to rock
Normal treatment	41	0.21	0.08	0.27	20	80
Water jet scaling	24	0.61	0.68	0.45	42	58

Table 2 — Quantities for 1-cu yd eight-sac shotcrete.

Cement	(Type I from Holnam)	611 lbs
Fly ash	Class C	141 lbs
Fine aggregate	C-33 washed sand	2141 lbs
Course aggregate	#8 washed rock	511 lbs
Air agent	AirTite 60, WR Grace	as needed
Water reducer	WRDA 86, WR Grace	35 oz
Water	–	38 gal

The compressive strength of the concrete was tested using a total of nine 300-mm- (1-ft-) high, 150-mm- (6-in.-) diam standard concrete test cylinders. The final 28 day compressive strength of the concrete was estimated to be 27.9 MPa (4,050 psi).

Adhesion test equipment. Equipment for testing the adhesive strength of shotcrete was purchased (CGE). The equipment is intended for determining the adhesive strength of sprayed concrete (shotcrete) against rock and between various layers according to the Swedish Standard SS137243. The equipment works in such a way that a circular hole is first drilled through the layer to be tested and a few centimeters into the underlying rock. This produces a core that is still attached to the rock. A cone-shaped friction grip ring is then placed around the core, which is coupled to a tension device. The grip around the core becomes stronger as tension is applied. The equipment consists of four parts: drill bit, core sleeve, tension device and recording unit.

The drill bit consists of an inner drill bit with an inner/outer diameter of 72/86 mm and an outer drill bit, variably adjustable, having an inner/outer diameter of 104/111 mm. The standard drill bit is 160-mm long. The drilling starts with the outer drill bit fixed in its upper position. With the inner bit, a hole is drilled through the adhesion zone and into the lower surface, i.e., the rock. When the lower surface has been penetrated a few centimeters, the drill is stopped and the outer bit is released by means of a socket head cap key and is pushed down to the surface layer and refixed. The rock drill is started and the drilling is terminated when the outer groove is a few millimeters deep. By this procedure, two drill grooves that are completely parallel have been obtained. The drilling process is illustrated in Fig. 4.

When the drilling is complete, a cone-shaped friction grip ring of the core sleeve is then placed around the core.

The tension device consists of three legs, a hand driven worm gear unit run on ball bearings, a tension rod with a strain gauge used to obtain the breaking load, and a threaded sleeve that is threaded into the core sleeve. The three legs of the device are placed in the outer groove. By the fact that the two grooves are completely parallel, a pure tensile force is obtained at loading. The tension device attached to the friction clamp is shown in Fig. 4 (c).

The recording unit is located in a portable case that also carries the tension device. The signal from the strain gauge is connected with a digital display with peak hold function for reading the breaking load. The signal from the strain gauge is also transmitted to a printer with a paper strip where the breaking load is recorded. The loading capacity is 10 kN, which means a tensile stress of up to 2.5 MPa can be measured. Chargeable batteries in the recording unit are large enough to last a normal working day.

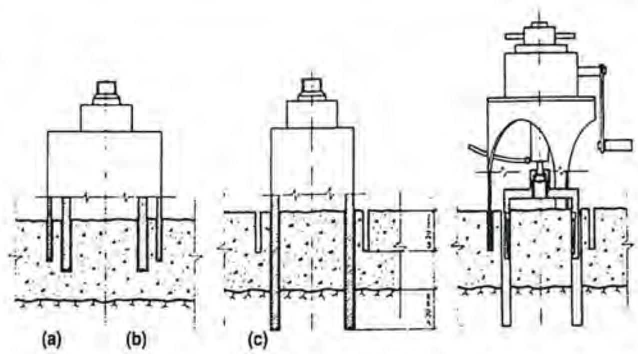

Figure 4 — Double core drilling bit showing the drilling of (a) the outer groove, (b) the inner core and (c) the tensioning device.

Adhesion test results. Approximately 36 cores (six per subpanel) were drilled and pulled on the concrete test wall. The results obtained are shown in Fig. 5. A clear increase in bond strength can be seen from about 0.45 MPa on the surface treated with 0.69 MPa (100 psi) water to about 1.90 MPa on the surface treated with 20.7 MPa (3,000 psi) water jet. This result indicates an increase in bond strength by roughly a factor of four. No significant increase in bond strength beyond this was seen on the panels treated with higher pressure. About half the pull tests at higher pressure resulted in failures within the shotcrete instead of at the bond interface.

Results from the core testing on the rock wall were difficult to interpret. The majority of the breaks on all panels occurred within the rock itself due to the low tensile strength of the rock. Breaks occurred mostly along planes of weakness within the orthoclase feldspar. To obtain meaningful results, future tests should be performed on a host rock with a tensile strength that exceeds the bond strength found with the tests performed on the concrete wall.

Conclusion

Using high-pressure water to prepare surfaces significantly increases the adhesion strength of shotcrete applied to the surface. Test results show an increase in adhesion strength by

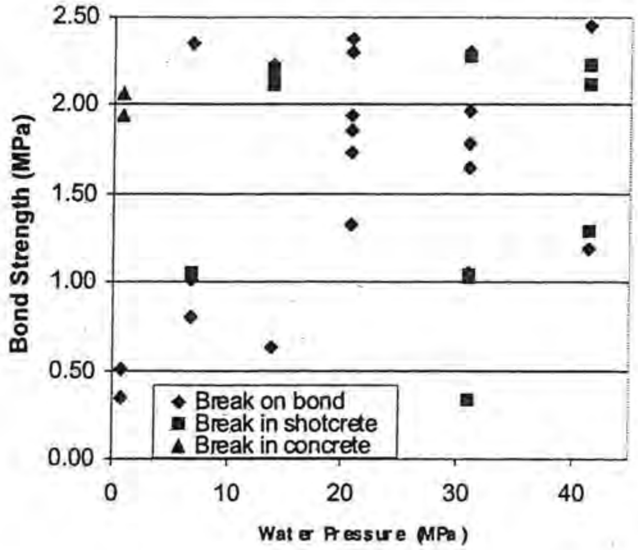

Figure 5 — Shotcrete to concrete bond strength vs. water pressure used to treat concrete wall surface.

a factor of four on a concrete test wall cleaned with water at 21 MPa (3,000 psi) as compared to a surface cleaned at 0.7 MPa (100 psi). It appears that the maximum effect is achieved when a pressure of 21 MPa or greater is used. This pressure greatly exceeds that commonly used in underground mining operations today. Better adhesion should increase the overall support capability of the shotcrete layer. Further studies are required to better quantify the increased support characteristics resulting from better adhesion in mining environments. By combining the use of high-pressure for scaling with shotcrete application, it should be possible to reduce the overall ground-support costs while increasing worker safety.

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