Shotcreting in Australian Underground Mines: A Decade of Rapid Improvement

by Matthew Clements

Over the last decade, dramatic improvements in spraying technology have allowed shotcrete to become the first-choice ground support in many underground mines in Australia. Before 1994, only a very small amount of dry spray shotcrete was used. Since then, the increased use of wet-mix fiber-reinforced shotcrete has been extremely rapid, spurred along by improvements in machinery, admixtures, fibers, and understanding the way shotcrete behaves as a ground support element.

Today, nearly 100,000 m^3 (130,000 yd^3) of shotcrete is applied annually in some 20 underground mines. While volumes have leveled off during a recent period of depressed metal prices, it is almost certain to boom again as metal prices improve and new mines come online. Australian mines are characterized by reasonably shallow ore bodies hosted in hard rock. This made underground mining initially fairly simple with little ground support needed beyond a few rock bolts. As surface deposits have become depleted, however, mine owners are increasingly spending their exploration dollars drilling beneath existing deposits to find new resources. This has led to ever-deepening extraction depths and associated ground support difficulties.

Fiber-reinforced shotcrete has helped to control deforming ground that might not otherwise be minable.

There are two basic types of ground support difficulties encountered. The first is when rock strengths are poor and the ground will not support itself, even with rock bolts. This type of ground can deform easily and quickly after ore extraction begins. Western Mining Corporation's (WMC) Perseverance Mine in Western Australia is a prime example of this. Fiber-reinforced shotcrete is used extensively in this mine to control deformations that are measured in tens of centimeters per month!

The other type of difficulty is encountered when rock strength is high but in-situ rock stresses build up to a level that exceeds the rock strength. This can lead to seismic events or "rock-bursts." This is becoming increasingly common in the deeper Australian mines. This is a worrisome condition for miners as seemingly secure rock faces can explode violently without warning. Fiber-reinforced shotcrete is now seen as the best way of controlling both of these difficulties. In the Western Australian goldfields, Kundana, Bounty, and Junction Mines are using fiber-reinforced shotcrete in ground subject to seismic activity.

At the Perseverance nickel mine, some 2 million tonnes (2.4 million tons) of ore are extracted per annum using a sublevel caving mining process. This involves driving a series of parallel tunnels into the large ore body. Up-holes are then drilled approximately 20 m (66 ft) into the ore above the tunnels and blasted down. The ore is extracted back along the tunnels. The process is then repeated a further 20 m (66 ft) below. This system of mining places huge stress concentrations on the pillars or tunnel walls. The rock mass, which is highly fractured, begins to deform very quickly as the photo to the left shows.

Two layers of fiber-reinforced shotcrete are applied with a sheet of steel mesh between them. The first layer is applied immediately after blasting because collapse can easily occur while the heading is temporarily unsupported. After shotcreting, partially grouted rock bolts are drilled through the shotcrete. Even with all this support in place, deformations of 300 mm (12 in.) can occur in the first 3 months.

The shotcrete used has a typical compressive strength of 50 MPa (7250 psi) and incorporates 50 kg/m^3 (84 lb/yd^3) of hooked end steel fiber. The shotcrete is batched at a nearby commercial concrete producer and driven down underground in 5 m^3 (6.5 yd^3) agitator trucks. These trucks are standard surface trucks with some modifications (exhaust cleaners) to meet underground safety regulations. At Perseverance, the concrete is then transferred into low-level trucks for entry into the smaller mine tunnels. At most other mines, however, standard trucks are suitable to complete delivery to the shotcrete machine. Typically, one 5 m^3 (6.5 yd^3) load is sufficient to spray a 3 m (10 ft) long section of tunnel. This means that the shotcrete operation can be completed in less than 1 h. The shotcrete must then cure for 3 to 4 h before work can continue in that particular heading.

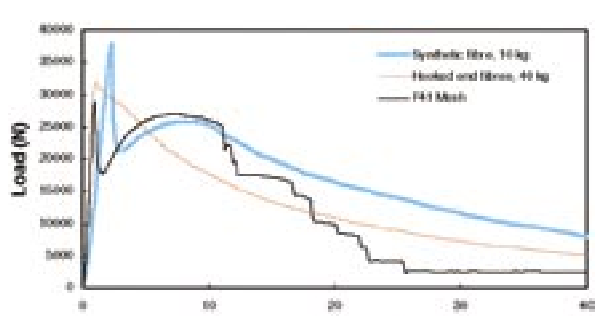
The performance of the shotcrete in both seismic and deforming ground is of great interest to mining engineers who have in recent years become very well informed of the behavior of fiber-reinforced shotcrete. Toughness levels required are now commonly specified by the mine engineer. This has led to the development of a new toughness standard in Australia–the Round Determinate Panel test. Developed by Stefan Bernard, the test has been shown to be less variable and a more user-friendly version of the EFNARC square panel test. ASTM approved the test method in June 2002 with the designation ASTM C 1550-02, "Standard Test Method for Flexural Toughness of Fiber-Reinforced Concrete (Using Centrally-Loaded Round Panel)." Mining engineers now recognize that including fiber reinforcement in shotcrete can enhance the energy-absorbing capacity of the system by 10 times for a cost increase of less than 10%.

The round panel test has also helped to identify the performance characteristics of competing fiber reinforcement products. For instance, synthetic fibers have recently become popular in Australian mines. Recent improvements in the properties of synthetic fibers have allowed them to compete with steel fibers on a performance basis. The ability of synthetic fiber-reinforced shotcrete to "strain-harden" or hold, or even increase, its load-carrying capability under high deformation has attracted the interest of mining engineers.

As a rock-burst can occur immediately after blasting, the early strength of the shotcrete layer is a concern. Work is now being done to investigate how toughness grows in the first few hours after spraying. The shotcrete may have only achieved 5 MPa (725 psi) at his point. To perform in low strength, the fibers must exhibit high bond characteristics.

The Australian round panel test has proven to be a reliable QA tool and has been adopted by ASTM.

The round panel test has highlighted the importance of fiber behavior. It is essential that fibers fail in pullout mode as shown in this photograph. If the fibers snap before pulling out, a fast brittle failure occurs. This must be avoided in a mining environment.



A tremendous amount of energy is absorbed during the pullout process. This energy is measured in the round panel test (25.4 mm = 1 in.; 1 N = 0.22 lb-force).

In-cycle shotcrete application at Perseverance Mine.

In order for the mine to achieve the maximum benefit from a shotcrete ground support system, rockbolting must be carried out after spraying, not before. This allows the bolt plates to be placed over the shotcrete layer that in turn promotes excellent connection between the shotcrete and bolts. When bolting is carried out first, the shotcrete is sprayed over the bolt plates. The connection between the bolts and the shotcrete in this case is very poor. Shotcrete without bolts relies entirely on its adhesion strength to the rock face to transmit its load-carrying ability. The adhesion strength is the weakest link in the shotcrete support chain. Shotcrete is strongest in compression, typically about 40 MPa (5800 psi), whereas the flexural strength is around 5 MPa (725 psi) while adhesion strength is often 0.5 MPa (73 psi) or less. Once the ground starts to deform—virtually a certainty in all large-scale mining extraction methods—the shotcrete/rock bond will easily be broken and the shotcrete will rely on the rock bolts for support interaction.

The practice of spraying shotcrete as the first pass ground support followed by rock-bolting is called in-cycle shotcreting with post-bolting. One practical aspect that stands in the way of post-bolting is scaling. It is standard practice in all underground mines to scale the backs (roof) and walls to remove any loose rocks prior to commencing the installation of ground support. In Australia, this scaling work is typically carried out by the drilling jumbo, the same machine that installs the rock bolts and drills the face for the next round. Therefore, there is a practical imperative towards carrying out all the jumbo-related work in a single visit. For this reason, many mines are still scaled then bolted before shotcreting is carried out. The answer to this may lie in investigative work carried out at the Kiruna Mine in Sweden. The Kiruna Mine, owned by LKAB, is a huge underground mine producing over 20 million tonnes (24 million tons) of iron ore per year. Lars Malmgren, Researcher at LKAB, investigated the suitability of water-jet scaling as an alternative to mechanical scaling. Normal scaling involved the use of a hydraulic pick hammer to remove loose rocks. The rock was then washed with water at a pressure of 7 bar (700 kPa [100 psi]) prior to shotcreting. In the water-jet trial, the rock was sprayed with water at 220 bar (22 MPa [3200 psi]) pressure in lieu of mechanical scaling. Malmgren found that the adhesion strength of the shotcrete to the rock face tripled from a mean value of 0.21 to 0.61MPa (30.5 to 88.5 psi) when water-jet scaling was used. He noted that after water-jet scaling, adhesion failure most commonly occurred at the shotcrete/rock interface, whereas in the mechanically scaled areas, adhesion failure was more commonly seen in the rock mass itself. Malmgren surmised that this was because the strength of the exposed rock face after water-jet scaling was higher than after mechanical scaling. The inference is that mechanical scaling damages the shotcrete/rock interface. Some mines have noted that mechanical scaling can create a relatively poor finished profile. Other mines, such as Perseverance, can derive little benefit from scaling as the heavily jointed rock mass does not improve as each layer is removed.

Based on Malmgren's findings, it appears that water-jet scaling provides an improved scaling method for underground mines. An important point is that there is no reason why the shotcrete machine could not be used to undertake the water-jet scaling work. The shotcrete machine has a suitable remotely controlled boom. The additional equipment required—a high-pressure water pump—is not expensive or large and could easily be adapted to most shotcrete machines. There may be a need to strengthen the shotcrete boom to enable it to resist the impact of rocks that may be dislodged during scaling. With this arrangement in place, the shotcrete machine would become a multifunction tool, enhancing its value to the mine. In turn it would release the drilling jumbo to continue productive work elsewhere in the mine. Best of all, the shotcrete application could readily be undertaken in its correct place in the cycle—before the rock bolts are installed. The jumbo can then enter the heading to undertake rockbolting and can continue immediately to drill the face for the next round of blasting.

The Ridgeway gold mine and Northparkes copper mine in New South Wales are typical of two new underground mines in Australia. They have both specified shotcrete ground support from the beginning. The specifications call for 40 MPa (5800 psi) compressive strengths from cores. Toughness levels are also specified using either the EFNARC Standard or the new ASTM C 1550 Round Panel test. Typically, the toughness levels require about 30 kg (66 lb) of hooked end steel fiber or 7 kg (15.4 lb) of synthetic fiber. Northparkes Mine became the first mine to specifically require only synthetic fibers. This was due to problems encountered with steel fibers penetrating the electrical running cables on the remote control boggers. Both mines have extensive QA requirements to check application and performance parameters.

Shotcrete use in underground mining in Australia is now an integral part of the mining process. Taking its lead from Scandinavian and American experience, the Australian shotcrete industry is now establishing itself as a leader in its own right. Further enhancements to shotcrete and fiber performance will allow shotcrete to play an even larger role in the coming years.

References

Bernard, E. S., "The Behaviour of Round Steel Fibre Reinforced Concrete Panels under Point Loads," *Civil Engineering Report CE8*, UWS Nepean, 1998.

Clements, M. J. K., "Shotcrete in Underground Australian Mines," *International Shotcrete Conference*, Norway, 1999.

Malmgren, L., "Shotcrete Rock Support Exposed to Varying Load Conditions," Dept. of Civil and Mining Engineering, Lulea University of Technology, 2001.

Matthew Clements is a civil engineer specializing in shotcrete. He provides consulting services through his company, Grenz Pty Ltd, and has 20 years of engineering experience in the Australian civil and mining industries. He has a special interest in fiber-reinforced shotcrete and has written many technical papers on the subject. He can be contacted by e-mail at clementsm@bigpond.com or by phone +61 8 9339 7333 or facsimile +61 8 9339 8333.