Fiber-Reinforced Shotcrete in the Australian Underground Mining Industry

By E. Stefan Bernard

The majority of underground metalliferous mines in Australia, comprising more than 60 individual mines, now use fiber-reinforced shotcrete (FRS) and bolts as the primary means of ground stabilization. Numerous underground coal mines also use FRS for portal and decline construction. The popularity of this system of ground control has led to a steady increase in the volume of shotcrete used per annum over the last 15 years, with total consumption estimated at over 17,657,333 ft^3 (500,000 m^3) in 2008. Almost all of the shotcrete used is reinforced with fibers. Macrosynthetic fibers are the dominant form of reinforcement, with a small number of mines continuing with steel fibers, and a minority also including microsynthetic fibers for control of rebound and fall-outs immediately after spraying. Steel mesh is also used either to hold difficult ground in place prior to spraying or as an additional layer over the hardened FRS to enhance high-deformation ductility. The versatility of FRS, both in terms of structural capacity and mixture design, allows miners a higher degree of adaptability in the implementation of ground control and development of underground infrastructure than is possible using any of the currently available alternatives.

The competitiveness of FRS and bolts in a mining environment stems from four pivotal advantages over the alternatives. The first of these is the fact that the one system based on FRS and bolts is capable of stabilizing almost every ground condition encountered. This versatility is unmatched by any other method of ground control. When changes in stability and tunnel geometry occur, the bolt spacing and type will usually be maintained and only the thickness, toughness, and strength of the shotcrete need be altered. This means that the same spraying equipment, personnel, batching plant, and ancillary services are used every day for all ground control requirements and therefore do not stand idle. The result is a substantial improvement in productivity and amortization on equipment.

The second advantage of FRS and bolts is the increase in speed of heading advance possible through rapid ground support installation compared to other systems. Not only is the shotcrete applied quickly, but adaptations to varying conditions can be implemented immediately. Drilling jumbos are normally used to install mesh mechanically. Reliance on FRS frees the jumbos to fulfill their primary role, which is to drill headings. Hydroscaling also frees jumbos from the time-consuming task of mechanical scaling. The robustness of the ground support system based on FRS means that the cycle of excavation and support can proceed reliably in most circumstances. Because most mines employ at least two spraying machines, stoppages due to breakdowns can usually be tolerated through temporary rescheduling, thereby further enhancing the dependability of the system.

The third advantage of FRS and bolts is a substantial reduction in rehabilitation requirements compared to alternatives, especially mesh screens. This is possibly the principal economic advantage of ground control based on FRS, but usually takes at least a year of operation to become apparent. FRS is a highly durable material that can, if required, be designed to exhibit outstanding ductility. The fact that the ground surface is locked together and prevented from unraveling also enhances the stand-up time of ground stabilized using this system. Alternatives such as mesh merely catch the rain of unraveling rocks that fill the screens and require regular removal and replacement. Mesh also corrodes quite rapidly when saline groundwater is present, thereby limiting its life. In addition, FRS provides warning of impending failure by continuing to support localized instabilities even as cracks grow wider, especially when reinforced with high-performance macrosynthetic fibers. Regular inspection can therefore alert geotechnical engineers to a need for rehabilitation prior to failure instead of suddenly finding a pile of rubble blocking a roadway.

The fourth advantage of FRS and bolts is the improved safety of this system compared to alternatives, especially during the installation phase. Shotcrete is always applied remotely and only unmanned equipment such as the front end of boggers and robotic arms are permitted under unsecured ground, which is commonly taken to be any ground lacking shotcrete cover of less than 145 psi (1 MPa) compressive strength and bolts of the required design.[1] Operatives are only permitted to venture under newly excavated ground once the young shotcrete has exceeded this strength (which can be tested using the methods described by Bernard and Geltinger[2]) and bolts have been fully installed. The superior safety of this system has been demonstrated through experience in Australian and South African mines that have made the switch from older systems.[3] Death and injury from rock falls have been reduced from unacceptable levels prior to the introduction of shotcrete to a rarity today. The decline in death and injury has resulted in substantially reduced costs associated with stoppages, downtime, and compensation.

Several secondary advantages are also associated with ground control based on FRS and bolts compared to mesh and bolts. Minimum bolt spacings have been found to be larger when FRS is used, largely because bolt spacing is no longer dictated by mesh geometry, thereby partly offsetting the cost of the shotcrete. Vehicle productivity is also improved as a result of the general reduction in the number of obstructions on

Fig. 1: Successful ground stabilization with FRS and bolts

Fig. 2: Smooth, clean, and free of debris: mining with FRS and bolts

Fig. 3: FRS is not a bandage for poor bolt selection

roadways caused by fallen scats. Finally, the daily use of agitators and the presence of concrete-related personnel make other concreting jobs within a mine quicker and cheaper to implement.

The clean and smooth surfaces characteristic of FRS quickly reveal ground movement that may be problematic, hence geotechnical engineers can easily identify difficult ground instead of wasting their time checking large areas of bare ground obscured behind mesh screens. Observers unfamiliar with FRS are sometimes alarmed by the incidence of cracks in these linings, believing that cracks signal a failure of the system to stabilize the ground and that this requires immediate rehabilitation. This concern is misplaced because the FRS lining does not hold the ground up but instead assists the ground to redistribute stress around the fresh excavation. Continued ground movement is normal for an extended period after excavation due to this redistribution, and thus cracks usually occur throughout the life of the lining. It is only when maximum crack widths continue to increase and tunnel convergence becomes unacceptable that rehabilitation is required. It must be remembered that FRS is not a substitute for inadequate ground control using bolts (Fig. 3). It is the capacity of the FRS and bolt system as a whole that needs to be considered when developing a design for the conditions at hand.

The direct material and labor costs associated with initial ground control using the FRS and bolt system are about 20% higher than for alternatives such as mesh and bolts. When the superior speed, versatility, efficacy, durability, and safety of FRS are considered, however, their combined economic advantage make this system of ground control the most attractive presently available in the majority of circumstances.

Versatility for Ground Control

FRS and bolts are effective for ground control across a broad range of ground conditions, thereby enhancing productivity and competitiveness. The design of an FRS lining can readily be changed as conditions dictate,[4] and experience in the Australian underground mining industry has yielded the following broad guidelines for stabilization based on shotcrete and bolts:

- **Stable ground**—When support requirements are minimal, bolts are still used together with a 1.2 in. (30 mm) lining of FRS containing about 0.12 to 0.19 lb/ft^3 (2 to 3 kg/m^3) of macrosynthetic fibers to lock the surface together and protect the rock from weathering.
- **Moderate instability**—Under conditions typical of mining in shallow to moderate depths, effective stabilization can usually be achieved with 2 to 3 in. (50 to 75 mm) of 5801.5 psi (40 MPa) shotcrete with 0.31 to 0.37 lb/ft^3 (5 to 6 kg/m^3) of a high-performance macrosynthetic fiber. Steel fibers are still used occasionally but have seldom proved competitive against the leading macrosynthetics on the market. Most mines undertake regular quality control (QC) testing for toughness of FRS using the ASTM C1550 round panel test.[5] The benchmark minimum toughness requirement for moderately unstable ground is 360 Joules at 1.6 in. (40 mm) central deflection.[6]
- **Highly unstable ground**—In deep or highly fractured ground, including high stress and seismically active conditions, and when major excavations are undertaken nearby, the minimum thickness and toughness of the FRS must be increased to maintain control of the ground. Lining thickness typically lies in the range 4 to 6 in. (100 to 150 mm), and at least 0.5 lb/ft^3 (8 kg/m^3) of a high-performance macrosynthetic fiber is usually needed. The in-place strength of the shotcrete should be maintained at about 5801.5 psi (40 MPa). Steel FRS has frequently been found ineffective in highly unstable ground because ductility is limited to small maximum crack widths and embrittlement causes the energy-absorbing capacity of the material to fall with age.[7,8] Spraying is sometimes recommended in two or more layers over the first week or two after excavation to limit maximum crack widths.
- **Squeezing ground**—Stabilization becomes more challenging and expensive in very poor ground subject to high stresses. Multiple layers of FRS heavily dosed with high-performance macrosynthetic fibers have been found effective in several mines experiencing squeezing ground in Australia,[9] as shown in Fig. 4 and 5. The layers of FRS are applied progressively over

Fig. 4: FRS with mesh over the top in a high-stress Western Australia mine

Fig. 5: FRS with mesh over the top in squeezing ground at Perseverence Mine

several days following excavation, and this is then augmented by one or two layers of steel mesh installed and left bare over the top of the shotcrete. Numerous bolts are typically required to secure the mesh in place. The high toughness FRS acts as a contiguous membrane under the mesh that must be permitted to slide relative to the surface of the shotcrete until convergence ceases or additional measures are implemented. Such additional measures may involve either stripping out the converged ground and resupporting with new FRS and mesh overlay, or replacement with a thick shell if long-term support is required.

- **Soft nonsqueezing ground**—This type of ground is seldom encountered in a mining environment except during portal construction or excavation through cemented backfill. In these circumstances, the lining can be designed as a thick shotcrete shell in accordance with conventional practice.[10] The versatility of shotcrete means that the same equipment and personnel can be employed to produce this type of lining as are used in hard rock conditions.
- **Vertical shafts**—Ventilation and egress requirements have led to the frequent construction of vertical shafts in many mines, even though declines have supplanted hoists in most operations. The FRS required in shafts is similar to that used for conventional headings, but the equipment used is typically custom-built and remotely operated (Fig. 6). Numerous variations on these shaft lining machines have been constructed depending on the size and depth of the shaft required.
- **Secondary structures**—The versatility that has made shotcrete so widely used in above-ground construction makes it similarly useful for underground structures such as draw points, ore passes, backfill walls, ventilation bulkheads, and door surrounds. All of these can readily be constructed using the same

mixtures, equipment, and personnel used for ground control. In addition, smoothing layers of finely-graded plain shotcrete can be used when required in vents, offices, workshops, and canteens located underground.

Versatility in Mixture Design

The usefulness of FRS in underground mines is also due to the adaptability available in mixture design. Long gone are the days when operations had to be developed around inflexible requirements for spraying and curing shotcrete. Today, the properties of an FRS mixture, in particular the early age strength development characteristics, can be tailored to suit the requirements at hand.

Fig. 6: Shaft lining using a robotic shotcrete rig

Attractive early-age characteristics such as rapid set and strength gain, high stickiness, and resistance to fall-outs generally come at a price, so these properties are designed into a mixture only when they are actually required. Similarly, high later-age performance with respect to toughness and strength also come at a price, so these characteristics are only included when required. Toughness requirements are particularly easy to modify simply by changing the dosage rate of fibers. The other commonly desired characteristics of FRS, however, generally require a more detailed understanding of mixture design technology specific to shotcrete and specialists may need to be consulted.

As an example of the possibilities available for tailoring a mixture design to specific requirements, consider the case of the LGL Goldmine in Ballarat in Victoria, Australia. Using an older mixture design, miners experienced fall-outs in excess of 40% of the 176.6 ft^3 (5 m^3) sprayed in each round when tunneling through difficult ground at 1640 to 1968.5 ft (500 to 600 m) depth. High rates of water ingress combined with weak flaky rock and numerous small clay seams caused slabs of shotcrete up to 10.8 ft^2 (1 m^2) to fall out within 10 minutes of spraying, endangering the lives of operatives and slowing the rate of heading advance (Fig. 7). Stickiness was improved by modifying the aggregate grading curve and reducing the water-binder ratio, and cohesiveness in the young FRS was increased by adding 0.1 lb/ft^3 (1.5 kg/m^3) of synthetic microfiber, with the result that fall-outs were reduced to less than 5% on each round. The superior ductility of the very young shotcrete

Fig. 7: Very poor ground with high water ingress at LGL Ballarat Goldmine, Victoria, Australia

assisted the lining to bridge small areas of adhesion loss to the underlying substrate until strength increased to the point where the lining could support itself, and the ground, several hours later.

Summary

Underground mining is a risky and often dangerous undertaking that places stringent demands on equipment, systems, and personnel. A culture of innovation and boldness in the Australian mining industry has driven it to attempt many new and unproven approaches to mining over recent decades. In the case of ground control based on FRS and bolts, this strategy has reaped rich rewards that have resulted in the near universal adoption of this system in underground metalliferous mines. Versatility is one of the critical factors that have made FRS and bolts the system of choice for stabilization due to the unique range of options that shotcrete provides miners.

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