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In-cycle application of fibre reinforced shotcrete

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ABSTRACT: Ground support in underground mining is an essential aspect of safe mining and ground control. Common rock support systems in use in underground mining operations utilize rock bolts of various designs to bind rock strata together and form a support beam over the excavation. In conjunction with rock bolting, it is common to utilize steel or wire mesh for greater aerial coverage. Although an essential activity, this aspect of the mining cycle is time consuming and expensive. Current practices for mesh and bolting are not conducive to high productivity and continuous mining cycles. As a result of these factors, an alternative to mesh and bolting is required to reduce costs and improve efficiency. Shotcrete has undergone vast technical improvements in recent years and is widely viewed as an alternative to mesh and bolting. In particular, shotcrete is a system capable of supporting rapid application and automation. As a result of advances to date with fibres, Fibre Reinforced Shotcrete (FRS) is a competitive alternative in terms of ground control systems.

In general, shotcrete is extremely effective in controlling spalling or scaling and wedge failure through closure or filling of joints and fractures resulting in transference of the rock load to adjacent stable rock. Shotcrete can be rapidly applied relative to mesh and bolting, and is semi-automated, as such it is far more conducive to efficient inclusion in cyclic operations than mesh and bolting. This paper summarises recent developments in FRS technology and provides a comparison of the practical, economic and productivity aspects of mesh and bolting relative to fibre reinforced shotcrete support methods.

1 INTRODUCTION

Ground support is essential to maintain the integrity of an underground opening while protecting personnel and equipment. In general, the in-situ rock mass tends to be fractured and fragmented as a result of natural jointing and discontinuities. In addition, the development of an opening using explosive techniques results in induced fracturing.

Whichever system of ground support is selected for an operation, it must be selected based on practical applicability, as well as engineering guidelines and economic considerations. In determining whether a system is economical, all aspects affecting the productivity and ultimately the profitability of that system should be considered.

2 GROUND SUPPORT SYSTEMS

When comparing mesh and bolting with Fibre Reinforced Shotcrete (FRS), it is important to verify that each system is capable of meeting the particular rock engineering requirements specific to the conditions of the individual site or development heading. For the purposes of this evaluation, rock conditions are designated to be of average competence with a Laubcher's mining rock mass rating (MRMR) of 50 to 60 (Laubscher 1977). Based on these rock conditions, both mesh and bolting and FRS-based ground support systems will provide the following functions:

- Hold broken rock mass together with the aim of providing a beam of supported rock capable of supporting itself,
- Control the expansion of the rock mass to reduce convergence,
- Provide aerial support coverage to control the spalling of rock into the mine opening.

Depending on predicted conditions the most practical and relevant system or combination of systems would be used.

2.1 *Mesh and bolting*

The combination of rockbolts with wire mesh is a standard feature of Australian underground mining. Bolts are typically mechanical anchor, grouted dowels, friction bolts, or grouted cables. The mesh is used to retain loose rock and the bolts are used to protect against stress-induced slabbing and structural wedge failure.

Depending upon ground conditions, rockbolts are generally installed in a pre-determined and consistent pattern based on rock engineering principles and modeling. In this way a relatively large surface area can be supported at a relatively economical rate per square metre. The system is installed either manually or semi-automatically using standard operating equipment.

Mesh and bolting, although tried and tested and extensively utilized in the mining industry, is relatively slow to install (averaging 18 m^2/man-shift, Archibald et al 1999). In terms of cyclic production, this activity must be completed up to the face of the end prior to advancing the development heading. As such this tends to cause a delay in the entire development cycle and a reduced rate of advance when compared to a system such as shotcrete which has a faster application time.

In some cases the rock competency may require bolting as well as shotcrete. Ideally the bolts should be placed after the shotcrete and this is termed in-cycle shotcrete with post-bolting. Installing bolts as a secondary activity ensures that the bolt plates have better contact with the shotcrete layer forming a better bond than when shotcrete is sprayed over the plates (Clements 2003). In Australia, the meshing and bolting activity is generally undertaken with a jumbo drill rig. Scaling of the backs and washing down is required prior to installation of ground support. The scaling also tends to be done using the jumbo drill rig. Hence a practical restriction to continuous cyclic operations is the need to carry out all the jumbo-related activities together. For this reason, bolting is generally carried out prior to shotcreting. The application of shotcrete over mesh should be avoided whenever possible, as this further hinders adhesion to the rock surface and often results in unacceptable losses due to rebound or fall-out.

A recent development to further integrate shotcrete application into the mining cycle is the use of high pressure water for scaling as an alternative to mechanical scaling. Studies undertaken with hydro-scaling have indicated improved adhesion between the shotcrete and the rock surface by as much as 300 percent (Clements 2003). Adaptation of current shotcrete pumping systems and an alternate nozzle fitting allows water and compressed air in the form of a water blast to be sprayed directly onto the back, hence scaling can easily and inexpensively be carried out by the shotcrete rig making use of the robotic arm. In addition to the benefits of having a multi-function machine, the use of the robotic arm for scaling would be far safer than current practices. In terms of the mining cycle this would ensure that the drilling and support functions would be entirely separated.

2.2 *Shotcrete*

Figure 1. Example of FRS in tunneling applications.

Shotcrete is a mixture of concrete and various admixtures and additives, either applied dry or wet, and is pneumatically projected at high velocity onto rock surfaces requiring area support. The application technique is generally dependent on the controlling aspects of the operation such as accessibility, size of development end, availability of services, and ground water conditions.

Prior to 1993, shotcrete use was limited to small amounts of dry spray applications. In the last 15 years there have been vast improvements in shotcrete application technique and major technological developments in shotcrete constituents. In addition, a much better understanding of the behaviour of shotcrete has led to advances in control and testing of shotcrete. As a result of these developments shotcrete is fast becoming the main support system used in many underground mines in Australia. Currently over 100 000 m^3 of shotcrete is applied on an annual basis in over 20 underground mining operations throughout Australia (MBT 2004).

Added benefits of shotcrete include the filling of joints and fractures, transferring the rock load to adjacent stable rock, and sealing the rock face to prevent further spalling and fracturing. The complete aerial coverage and lining provided by the shotcrete prevents further deterioration of the rock surface due to environmental conditions, and provides less resistance to airflow thereby improving ventilation conditions. On-going improvements in set accelerators ensures rapid hardening and development of load bearing ability of the shotcrete. In recent years the advantages of using shotcrete as a primary support have become increasingly apparent. The process whereby shotcreting operations are undertaken together with excavation is generally termed in-cycle shotcreting.

2.3 *Material components*

Selection of the most appropriate material constituents in the shotcrete mix is essential in order to achieve the required performance and lowest costs. Common constituents include cement binders, variety of cement types and cement extenders, aggregate, sand, water, silica fume, plasticizers and various other admixtures.

Aggregates are added to bulk out the mix and provide additional strength and reduced costs for the final product, the shape size and gradation of the aggregate also affects workability and pumpability of the mix. In selecting the aggregate the main parameters for consideration are the grading and size, particle shape and density, presence of reactive chemicals, compressive strength and the moisture content. In general a maximum 16 mm particle size is recommended, and, depending on the application, this is often reduced to a maximum of 10 mm particularly in wet application processes.

The properties of both aggregate and sand are vitally important in the production of a suitable shotcrete mix. The physical properties of shape, texture, and gradation as well as the chemical properties or type of material used can have a major effect on rebound during application. This factor is critical when evaluating the costs of mixtures as remote sites may require shipping of bulk materials if suitable materials are not available near the site, or, alternatively, processing of material to better suit application.

Water quality is also important, so water should be free of oils and not particularly acidic. Water quality should be tested prior to any application.

The Delvocrete system is a non-chloride chemical system controlling the dynamics of cement hydration, suspending the process and then reactivating it hours or even days later (MBT 2003). The system consists of two products, the stabiliser and the activator. The stabiliser creates a barrier around the cement particles suspending hydration; once the activator is applied it accelerates hydration when added to the stabilised shotcrete.

The addition of silica fume has improved workability, durability, and cohesion, and reduced rebound. Today's powerful combination of ultra high range water reducers and alkali-free accelerators allow slump retention and workability in the mix with true set acceleration at the nozzle, yielding high early bond and compressive strengths.

In recent years there has been rapid development in the technology of shotcrete accelerators, essential in mining to ensure a bond is developed with the rock as soon as possible. The accelerant assists in generating strength quickly and allows shotcrete to be placed in a single thick application, if necessary. Shotcrete acting as a primary support for mining and development activities must rapidly achieve active support status in order to shorten the waiting periods for mining operations to continue. Common accelerators used in Australia are alkali-free accelerators, while in the USA, sodium silicates are still commonly used for economic reasons. Before selecting an accelerator, compatibility tests must be carried out with the cement.

Concrete is brittle and generally weak in tension, reinforcement is provided either through the addition of fibres or alternatively mesh. The introduction of steel fibres into the shotcrete has a significant effect on the overall support characteristics of the shotcrete particularly with respect to the load deformation aspects. However, due to the abrasive nature of steel fibres, as well as their rigidity and a higher tendency to create blockages during application, macro-synthetic fibres are rapidly replacing steel fibres in many mines in Australia (EPC Asia Pacific, 2004). When selecting a fibre fit for purpose it is important to evaluate the desired end use properties. These properties are generally defined according to an energy absorption rating (measured in Joules) when tested using the ASTM C-1550 round panel test or alternative tests (Clements 2003). High performance macro-synthetic fibres are specifically designed to enhance the load bearing capability of the concrete and improve performance after cracks have developed. The use of polypropylene fibres for mining applications has increased tangibly due to the increased performance of these fibres. Macro-synthetic fibres have the added benefit of greater flexibility and reduced wear on equipment.

Tests have proven that including macro-synthetic fibres in a shotcrete mix can enhance the energy-absorbing capacity of the system by 10 times, when compared to plain shotcrete, for a cost increase of less than 10% (Clements 2003, MBT 2004). The addition of fibres has advantages over the use of mesh in that the reinforcement is evenly distributed throughout the shotcrete, less labour intensive to apply, and less time consuming. The principal benefits of fibres over mesh are:

1. Improved durability,
2. Improved ductility,
3. Increased resistance to impact,
4. Reduced surface cracking,
5. Safer application and improved productivity,
6. Reduced costs,
7. Simplified logistics.

A practical consideration in the use of fibre-reinforced shotcrete is the cleaning of rebound or fall-out of macro-synthetic fibres. During application a percentage of the fibres separate from the mix under velocity. In order to minimise contamination of water when washing out sprayed areas, a half metre of blasted rock flattened out by the LHD is left in the drive. The majority of fibres are collected when the drive is mucked out at the end of the shotcreting.

Fibre reinforced shotcrete (FRS) can be rapidly applied relative to bolt and mesh support systems (manual dry spraying systems typically spray shotcrete in the range of 3–4 m^3/hr, or 60–80 m^2/hr). Wet-mix equipment predominantly involves a double cylinder swing-tube pump. Based on operational constraints in mines, this equipment will typically produce between 12 and 15 m^3/hr (average of 260 m^2/hr, Schallom et al 2003, Sturgeon 2004). The constraint is generally the feed rate of dry and wet materials rather than the application rate of the machine (current equipment can process up to 60 m^3/hr, if the supply is fast enough).

2.4 *Application process*

The application of the shotcrete and the techniques employed are fundamental to achieving an effective result. Techniques for application are either wet or dry processes.

2.4.1 *Wet and dry processes*

The wet technique involves the batching and mixing of cement, aggregate and water, which is conveyed through a pipeline or hose before being pneumatically and continuously projected into place. The mixture may contain admixtures which may include fibres (steel, macro-synthetic fibres depending on application) and accelerants for rapid hardening.

In the wet mix process all the constituents are fed into a mixer and water added to achieve a consistency to allow for pumping. The amount of water used is very important with respect to the workability as well as the final strength of the product. Nozzle design is important as this is critical to the spray velocity and distribution, the nozzleman also controls the amount of accelerant added.

There are a number of fundamental differences between the application processes and it is essential that the right method be applied for the relevant application. In general, the wet process is best suited to requirements with high continuous application volumes while the dry process is better suited to low volume applications and stop start operations. In selecting the application process, the site-specific conditions, the overall cost, and the required result as well as volumes required must be considered.

For successful shotcrete application the following aspects are required:

1. Adequate mix design,
2. Adequate material supply at the machine,
3. Matched equipment and infrastructure for the application,
4. Trained and fully accredited (by a competent trainer) crews,
5. Correct preparation of surface prior to spraying,
6. Correct application techniques,
7. Appropriate quality control and remedial actions,
8. Safety measures and procedures,
9. Adequate services.

Service requirements include compressed air at adequate pressure and volume, water of suitable quality, and adequate lighting.

Figure 2. Wet application, robotic controlled spray rig.

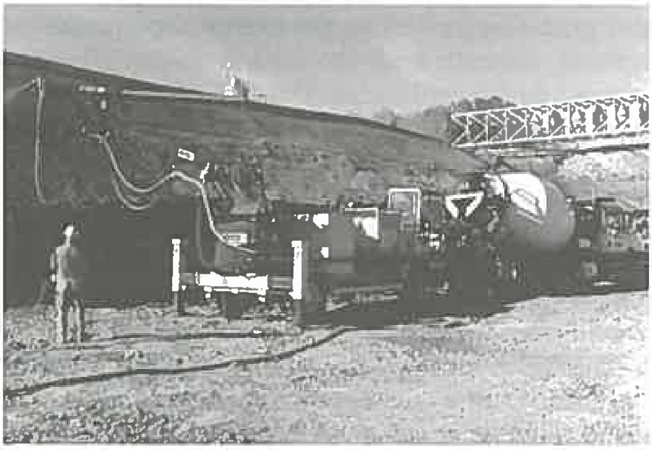

Figure 3. Surface application.

2.4.2 *Logistics*

Having adequate quantities of material available to the shotcrete equipment is essential to the successful implementation of shotcreting in mines. There are several ways of transporting the materials to the site which are usually dependent on the mine infrastructure, material handling system, location of the work place and the quantity of shotcrete required. The following is a list of options:

1. Large bags for pre-proportioned dry-mix,
2. Bulk containers,
3. Mobile mixers,
4. Cased boreholes,
5. Slicklines,
6. Combinations of the above (Rispin 2003).

The preferred method would be to batch concrete on the surface and transport it using agitator trucks to the shotcrete rig. It is important to match the number of underground agitators and/or surface agitators to the shotcrete requirements as the transport of shotcrete is generally the controlling factor governing the quantities applied on a daily basis. The access route will determine whether low profile vehicles are required.

Figure 4. Underground application.

Table 1. Typical performance requirements.

Performance parameter	Performance range (MPa)
Compressive cube strength	30–60
Flexural strength	3–8
Bond strength to competent rock	0.5–1.5
Toughness	400–1000 Joules*

* EFNARC panels to 25 mm central deflection.

A good alternative for shallow underground mines is the use of slick lines, however these need to be rigidly controlled in order to maintain a consistent feed. In deep underground mines, the principal problems arising from slick lines are mixture separation, degradation of aggregate, wear and damage to pipes and equipment, poor cleaning leading to blockages and poor management leading to material wastage. Slick lines generally comprise a 200 mm diameter pipe (or 150 mm, depending on depth), pressure dissipater at bottom of pipe, discharge to concrete pump or agitator vehicle. Due to the high wear experienced in pipes, it is advisable to have a second borehole as a backup; staggered slick line design is recommended in order to reduce the velocity of the load.

In cases where access height is very limited, dry application techniques may have to be utilised with transport of materials in bulk bags using underground vehicles suitable for the height restrictions.

2.4.3 *Shotcrete as a support element*

In order for shotcrete to be fully effective all aspects of the design and ultimate purpose must be considered. Table 1 indicates the normal properties to be expected from shotcrete after placement (28 days curing time).

Shotcrete provides a passive support on application, however due to its high Young's Modulus and stiffness it has significant resistance shortly after application. In addition, it has a micro-reinforcing effect as it penetrates cracks and micro-fissures on the rock surface. Shotcrete has a significant rock reinforcement capability brought about through reduced scaling and rock weathering while confining the rock surface and filling fractures.

Poorly designed and/or applied shotcrete can be costly and ineffective. Ineffective application of shotcrete is usually a result of one or a combination of poor design mix, unsuitable equipment, inadequate services, or poor quality control.

3 ECONOMIC COMPARISON

3.1 *General assumptions*

For the cost exercise below, the following assumptions are made:

- Shotcrete, refers to a 50 mm thick FRS shotcrete lining with post bolting. It is assumed that only half the bolts will be required relative to normal mesh and bolting support patterns. FRS is a wet mix, delivered by agitators. Post-bolting is undertaken with the Jumbo.
- The mesh and bolting includes the installation of 15 bolts per cut, with 5 additional bolts installed for holding the mesh.
- Durations are based on observations from site personnel from actual operations.
- Meshing is undertaken with the jumbo during bolting.

3.2 *Capital costs*

The price of a manual shotcrete unit for underground mining averages AU\$35,000 to AU\$50,000 (MBT 2003), depending on capacity and power source. Remote-controlled wet-mix shotcrete application can be achieved with a shotcrete rig (Jacon or Normet for example), which have an estimated capital cost of AU\$250,000 to AU\$550,000 (Jacon 2004). The added cost of agitators for delivery of wet mix shotcrete from surface to underground is an additional AU\$375,000 per 5 m^3 unit (Wagner 2003). In the case of dry-mix operation, forklifts would be required for material handling.

For mesh and bolting systems, a mechanical bolter which performs semi-automated mesh and bolt installation has a capital cost of AU\$650,000 to AU\$1, 1 million (Atlas Copco 2004). Manual installation of bolts and mesh requires several pieces of equipment, from scissor-lift trucks to pneumatically driven drills, such as rising feeds. The scissor-lift trucks have a capital cost of AU\$275,000 (WCG 2004) while rising feeds typically cost AU\$5500 to AU\$7500 (WCG 2003).

Based on the above costs, it can be shown that the capital outlay for semi-automated mesh and bolting is equivalent to that of semi-automated shotcrete with post bolting. In terms of manual systems the capital cost for shotcrete is far less than the equivalent for mesh and bolting.

3.3 *Direct costs*

In order to evaluate the two support methods, a mine development heading model 5 m in height by 5 m in width advancing at 3 m per blast will be considered. Each support system has the sidewall supported from 2.5 m above the floor to the roof, and full coverage of the roof, a total of 30 m^2. Galvanised friction type bolts, 2.4 m in length (15 bolts per 3 m advance), with a rockbolt plate, and 5.6 mm wire mesh is used for the mesh and bolt support.

In this example, normal ground conditions are defined as having a Mine rock mass rating of 50–60 or Rock Mass quality ranging between 1 and 4 (Rock class D to C) (Barton et al 1974). Under these conditions the recommended support pattern for mesh and bolting is a 1 m spacing. The recommendation for a shotcrete support system is a 50 mm lining thickness with bolting on a 2 m spacing. A 10% wastage factor due to rebound is applied to shotcrete cost calculations.

The shotcrete mix below (Table 2) is used for this exercise, however mixtures will be site-specific and dependent on the ground conditions at each site. This mixture is suitable for ground conditions classed as poor to average. The material costs used in the mixture design are generally for remote mine sites and carry a weighting for freight (Wagner 2003).

The final profile of the blasted heading will depend on the integrity of the country rock which is highly variable from area to area and site to site. In order to fill the voids and the undulations and provide a smooth finished profile, an allowance for shotcrete use is applied in terms of m^2 per m^3. From general experience the factors in Table 3 are normally applicable. Fibre reinforced shotcrete costs are calculated based on these utilization factors.

Table 2. General shotcrete mix costings.

Shotcrete component	Unit	Cost A\$/unit	No/ m^3	Cost A\$
10 mm RD aggregate	tonne	\$30.00	0.52	15.60
Course sand/loam blend	tonne	\$30.00	0.7	21.00
Fine sand/loam blend	tonne	\$30.00	0.4	12.00
Cement GP	tonne	\$198.00	0.44	87.12
Delvocrete	litre	\$1.20	1.54	1.85
Admixtures				
Plasticiser	litre	\$3.10	4.4	13.64
Accelerator	litre	\$3.00	15	45.00
Fibres (macro-synthetic)	kg	\$9.36	12	112.32
Silica fume	kg	\$1.00	40	40.00
Total cost				348.53

The major components of the direct costs are the labour and materials for each support system. The two most critical specifications for rockbolts, in terms of cost, are their length and their relative spacing. As the bolt length increases, not only does the cost per bolt increase, but so too does the cost and the time of drilling each hole. The number of bolts required depends on the selected pattern and spacing for the ground conditions. Mesh costs vary based on the particular gauge of mesh, whether heavy duty steel or light duty wire mesh. For this exercise a line of 5 bolts is placed 1 m apart, or 15 bolts per 3 m advance and an additional 5 bolts installed for holding the mesh.

Shotcrete costs vary depending primarily on the thickness of the coating and on whether or not it is reinforced by fibres or steel mesh. Only FRS will be considered in this analysis, with 7 bolts installed as part of the support criteria.

In this exercise a labour rate of AU\$30 per hour is used for all general mining labour, with AU\$3.33 added for various occupational allowances and 50% on costs, totalling AU\$50 per hour. Table 4 summarises the cost

Table 3. Shotcrete application factor for coverage m^2 per m^3.

Shotcrete thickness	Coverage m^2/m^3
25 mm	28
50 mm	14
75 mm	10

Table 4. Direct cost comparison.

Area of support (30 m^2)	25 mm	50 mm	75 mm
Shotcrete cost			
Shotcrete	\$410.77	\$ 821.53	\$1,150.14
Bolts	\$105.00	\$105.00	\$105.00
Application cost	\$33.33	\$50.00	\$75.00
Bolting cost	\$66.67	\$66.67	\$66.67
Transport of shotcrete	\$25.00	\$25.00	\$37.50
Total	\$640.77	\$1068.20	\$1,434.31
Cost per m^2	\$21.36	\$35.61	\$47.81
Cycle time (mins)	30	30	45
Mesh & bolt space	1 m	1.5 m	2 m
Bolts	\$187.50	\$162.50	\$125.00
Plates	\$37.50	\$32.50	\$25.00
Mesh	\$246.00	\$246.00	\$246.00
Labour	\$600.00	\$562.50	\$525.00
Transport of materials	\$50.00	\$50.00	\$50.00
Additional bolting for mesh, labour	\$66.67	\$66.67	\$66.67
Additional bolts for holding mesh	\$75.00	\$75.00	\$75.00
Total	\$1,262.67	\$1,195.17	\$1,112.67
Cost per m^2	\$42.09	\$39.84	\$37.09
Cycle time (mins)	240	225	210

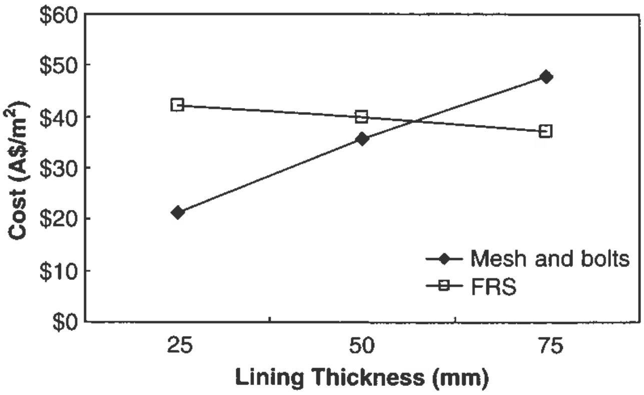

Figure 5. Graphical representation of direct costs for FRS and bolt and mesh.

comparison for the two systems. Assumptions are made for the cycle time and labour requirements based on generally accepted productivity rates.

Based on direct costs, the price for the shotcrete system for thin linings is much lower per square metre than mesh and bolting (50%). In the case of 50 mm shotcrete thickness with post bolting the cost per square metre is 20% lower than a 1 m pattern mesh and bolting system primarily due to the savings in the cycle time. However as the shotcrete thickness increases the cost for mesh and bolting becomes more economical (greater than 65 mm thickness). These observations are based on direct costs alone, and do not take into account other savings.

FRS is shown to be competitive with mesh and bolting in normal conditions on a direct cost basis.

3.4 *Cycle time evaluation*

In the following analysis, estimated durations for activities are applied for both the mesh and bolting and shotcrete support systems.

Mining cycle with mesh

Bore face	2.0 hours
Charge & fire	1.5 hours
Clear smoke	0.5 hours
Hose & scale	0.5 hours
Bog	2.0 hours
Bolt & mesh	4.5 hours
(4 sheets mesh & 15 bolts)	
Face clean up	0.5 hours
Total (average time)	**11.5 hours**

Mining cycle with shotcrete

Bore face	2.0 hours
Charge & fire	1.5 hours
Clear smoke	0.5 hours
Hose & scale	0.5 hours
Bog 4 buckets	0.5 hours
Shotcrete to face	0.5 hours
($1 \times 5\,m^3$ load)	
Bog remainder	1.5 hours
Bolt to face	0.5 hours
Total (average time)	**7.5 hours**

It is difficult to measure the cost savings associated with improved productivity as a result of shorter mining cycles. It is, however, reasonable to suggest that the cost attributed to financing a major project and the savings due to earlier return on investment, reduced operating costs, and overheads would be significant in a major mining operation. The overall cycle times are estimated to be 20 to 30 percent shorter when applying the shotcrete support system. It is obvious that based on these estimates the potential savings on a major project are very significant.

3.5 *Other costs*

One of the greatest advantages associated with shotcrete comes with maintenance management of the development later in the life of a mine. Mesh and bolting requires extensive maintenance; as the ground deteriorates, regular bleeding of the mesh is often required. Bleeding of the mesh requires additional labour and resources as well as cleaning of the material after bleeding. Mesh and bolting is also susceptible to corrosion. With shotcrete it is no longer necessary to conduct manual scaling checks in these areas of the mine, only visual inspections are required.

In addition to the previous costs discussed, equipment operation and maintenance costs should also be considered. Operating costs for a semi-automated shotcrete rig are very low compared to that of a jumbo drill rig used for mesh and bolting activities. In Australia the use of the drilling jumbo for mesh and bolting as well as scaling activities has a major implication in terms of equipment maintenance. These activities consistently cause damage resulting in high repair and maintenance costs. Typically these costs are in the order of AU$5 to AU$10 for shotcrete and AU$40 to AU$50 per operating hour for mesh and bolting (Archibald et al 1999, Sturgeon 2004).

4 SAFETY

Tunnels excavated in jointed rock mass, particularly shallow excavations, are most likely to experience wedge failure from the roof and sidewalls. Wedges are formed at the intersection of geological features such as joints, bedding planes, discontinuities and fractures. Unless supported, wedges will fall out further reducing the restraint and causing more wedges to fall. Any underground movement may cause the unsupported wedges to fail resulting in rockfalls.

Shotcrete provides immediate stability. As it fills in cracks and joints, it increases the restraint and provides a mechanism for holding the blocks together. In addition, water ingress is reduced. This would otherwise reduce the natural restraint and possibly lubricate the contact points of the rock mass. When loaded, FRS shows an initial failure upon occurrence of the first crack, but then recovers and regains some strength as the embedded fibres allow the shotcrete to flex or deform and thereby absorb energy in the process of deformation. FRS will eventually fail when all the fibres have been pulled out of the cracks but at this stage the shotcrete has absorbed much of the deformation energy of the rock mass. FRS provides for a controlled failure, which is ideal in an unpredictable environment and offers the highest level of safety to the work force.

In addition, through the use of semi-automated systems the amount of time spent under unsupported ground is greatly reduced as a result of shotcreting. When compared to mesh and bolting, the potential for accidents is greatly reduced, particularly in relation to material handling, mobile equipment, and working from heights. Using a fibre reinforced shotcrete support system has an enormous practical benefit in terms of increased underground operational safety.

5 CONCLUSIONS

This evaluation has demonstrated that mesh and bolting support is comparable to fibre reinforced shotcreting from the perspective of capital costs as well as direct costs. However, mesh and bolting is not as productive as shotcrete with respect to cycle times and is not readily automated.

Shotcrete is significantly more productive and more compatible to reducing cycle times than mesh and bolting. Applied correctly, and incorporated into cyclic production, shotcrete has the potential for major cost reduction in the direct project and overhead costs, finance costs, and quicker returns on investment. Additional savings can arise in areas of drive maintenance and equipment operating costs. Reduced airflow friction as a result of smooth shotcreted surfaces and improved insulation results in improvements in environmental conditions as well.

The arguments in favour of replacing mesh and bolting with high performance fiber reinforced wet-mix shotcrete as the primary support (where conditions permit) are strong. In all fields of evaluation, including quality, safety and environment, and time and economy, the conclusions are consistently the same. Embracing the concept of this ground support technology has obvious benefits. With ongoing improvements in technology and reduction in costs as FRS shotcrete usage increases, it is the way of the future and is therefore an immediate challenge for progressive mine management.

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