



Shotcrete support

Introduction

The use of shotcrete for the support of underground excavations was pioneered by the civil engineering industry. Reviews of the development of shotcrete technology have been presented by Rose (1985), Morgan (1993) and Franzén (1992). Rabcewicz (1969) was largely responsible for the introduction of the use of shotcrete for tunnel support in the 1930s, and for the development of the New Austrian Tunnelling Method for excavating in weak ground.

In recent years the mining industry has become a major user of shotcrete for underground support. It can be expected to make its own contributions to this field as it has in other areas of underground support. The simultaneous working of multiple headings, difficulty of access and unusual loading conditions are some of the problems which are peculiar to underground mining and which require new and innovative applications of shotcrete technology.

An important area of shotcrete application in underground mining is in the support of 'permanent' openings such as ramps, haulages, shaft stations and crusher chambers. Rehabilitation of conventional rockbolt and mesh support can be very disruptive and expensive. Increasing numbers of these excavations are being shotcreted immediately after excavation. The incorporation of steel fibre reinforcement into the shotcrete is an important factor in this escalating use, since it minimises the labour intensive process of mesh installation.

Trials and observations suggest that shotcrete can provide effective support in mild rockburst conditions (McCreath and Kaiser, 1992, Langille and Burtney, 1992). While the results from these studies are still too limited to permit definite conclusions to be drawn, the indications are encouraging enough that more serious attention will probably be paid to this application in the future.

Shotcrete technology

Shotcrete is the generic name for cement, sand and fine aggregate concretes which are applied pneumatically and compacted dynamically under high velocity.

Dry mix shotcrete

As illustrated in Figure 1, the dry shotcrete components, which may be slightly pre-dampened to reduce dust, are fed into a hopper with continuous agitation. Compressed air is introduced through a rotating barrel or feed bowl to convey the materials in a continuous stream through the delivery hose. Water is added to the mix at the nozzle. Gunitite, a proprietary name for dry-sprayed mortar used in the early 1900's, has fallen into disuse in favour of the more general term shotcrete.

Shotcrete support

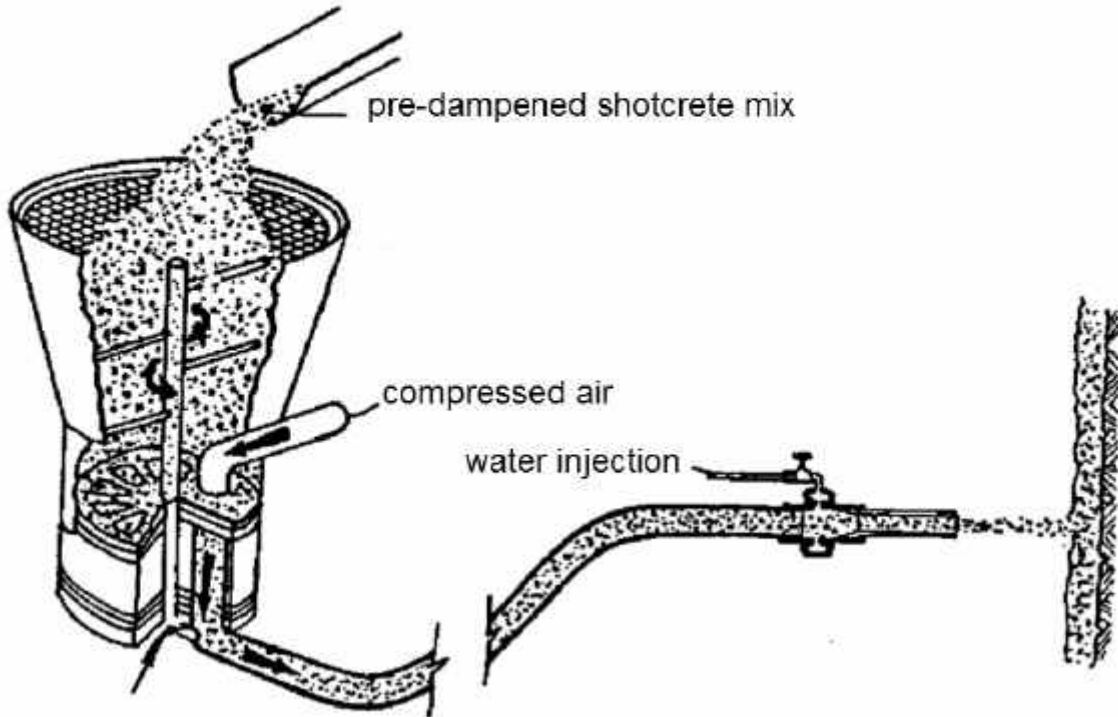


Figure 1: Simplified sketch of a typical dry mix shotcrete system. After Mahar et al (1975).

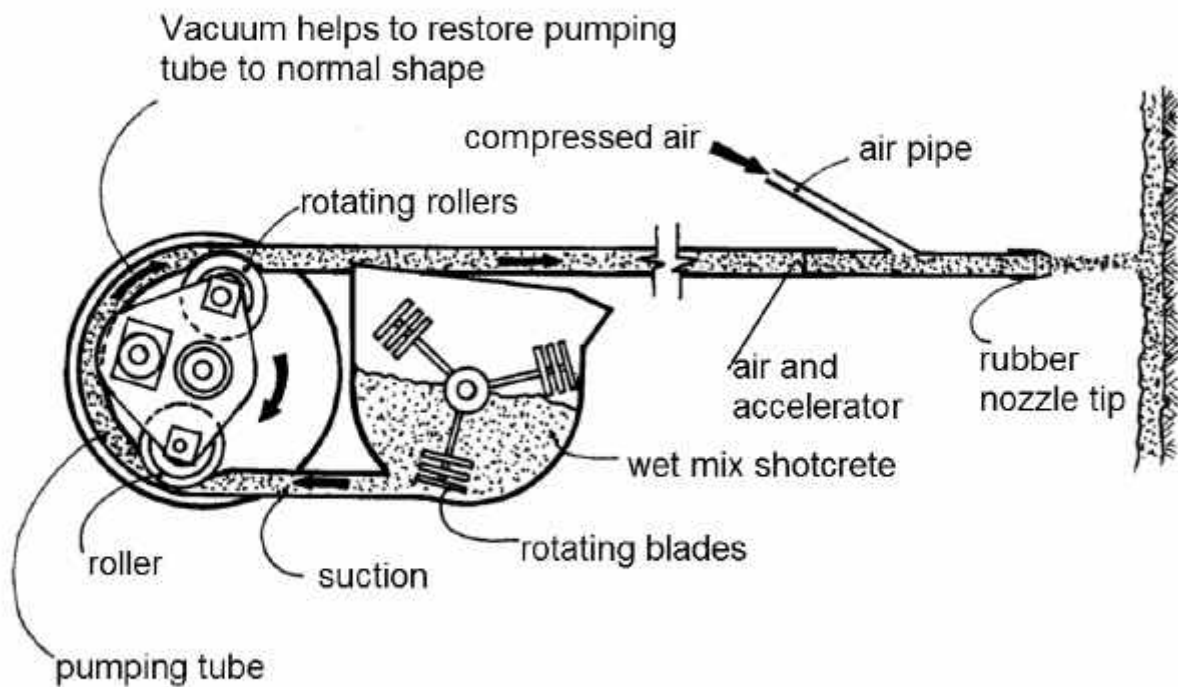


Figure 2: One typical type of wet mix shotcrete machine. After Mahar et al (1975).

Shotcrete support

Wet mix shotcrete

In this case the shotcrete components and the water are mixed (usually in a truck mounted mixer) before delivery into a positive displacement pumping unit, which then delivers the mix hydraulically to the nozzle where air is added to project the material onto the rock surface.

The final product of either the dry or wet shotcrete process is very similar. The dry mix system tends to be more widely used in mining, because of inaccessibility for large transit mix trucks and because it generally uses smaller and more compact equipment. This can be moved around relatively easily in an underground mine environment. The wet mix system is ideal for high production applications in mining and civil engineering, where a deep shaft or long tunnel is being driven and where access allows the application equipment and delivery trucks to operate on a more or less continuous basis. Decisions to use the dry or wet mix shotcrete process are usually made on a site-by-site basis.

Steel fibre reinforced micro silica shotcrete

Of the many developments in shotcrete technology in recent years, two of the most significant were the introduction of silica fume, used as a cementitious admixture, and steel or polypropylene fibre reinforcement.

Silica fume or micro silica is a by-product of the ferro silicon metal industry and is an extremely fine pozzolan. Pozzolans are cementitious materials which react with the calcium hydroxide produced during cement hydration. Silica fume, added in quantities of 8 to 13% by weight of cement, can allow shotcrete to achieve compressive strengths which are double or triple the value of plain shotcrete mixes. The result is an extremely strong, impermeable and durable shotcrete. Other benefits include reduced rebound, improved flexural strength, improved bond with the rock mass and the ability to place layers of up to 200 mm thick in a single pass because of the shotcrete's 'stickiness'. However, when using wet mix shotcrete, this stickiness decreases the workability of the material and superplasticizers are required to restore this workability.

Steel fibre reinforced shotcrete was introduced in the 1970s and has since gained world-wide acceptance as a replacement for traditional wire mesh reinforced plain shotcrete. The main role that reinforcement plays in shotcrete is to impart ductility to an otherwise brittle material. As pointed out earlier, rock support is only called upon to carry significant loads once the rock surrounding an underground excavation deforms. This means that unevenly distributed non-elastic deformations of significant magnitude may overload and lead to failure of the support system, unless that system has sufficient ductility to accommodate these deformations.

Typical steel fibre reinforced, silica fume shotcrete mix designs are summarised in Table 1. These mixes can be used as a starting point when embarking on a shotcrete programme, but it may be necessary to seek expert assistance to 'fine tune' the mix designs to suit site specific requirements. For many dry mix applications it may be

Shotcrete support

advantageous to purchase pre-mixed shotcrete in bags of up to 1,500 kg capacity, as illustrated in Figure 3.

Table 1: Typical steel fibre reinforced silica fume shotcrete mix designs (After Wood, 1992)

Components	Dry mix		Wet mix	
	kg/m ³	% dry materials	kg/m ³	% wet materials
Cement	420	19.0	420	18.1
Silica fume additive	50	2.2	40	1.7
Blended aggregate	1,670	75.5	1,600	68.9
Steel fibres	60	2.7	60	2.6
Accelerator	13	0.6	13	0.6
Superplasticizer	-	-	6 litres	0.3
Water reducer	-	-	2 litres	0.1
Air entraining admixture	-	-	if required	
Water	controlled at nozzle		180	7.7
Total	2,213	100	2,321	100



Figure 3: Bagged pre-mixed dry shotcrete components being delivered into a hopper feeding a screw conveyor, fitted with a pre-dampener, which discharges into the hopper of a shotcrete machine

Shotcrete support

Figure 4 shows the steel fibre types which are currently available on the North American market. In addition to their use in shotcrete, these fibres are also widely used in concrete floor slabs for buildings, in airport runways and in similar concrete applications.

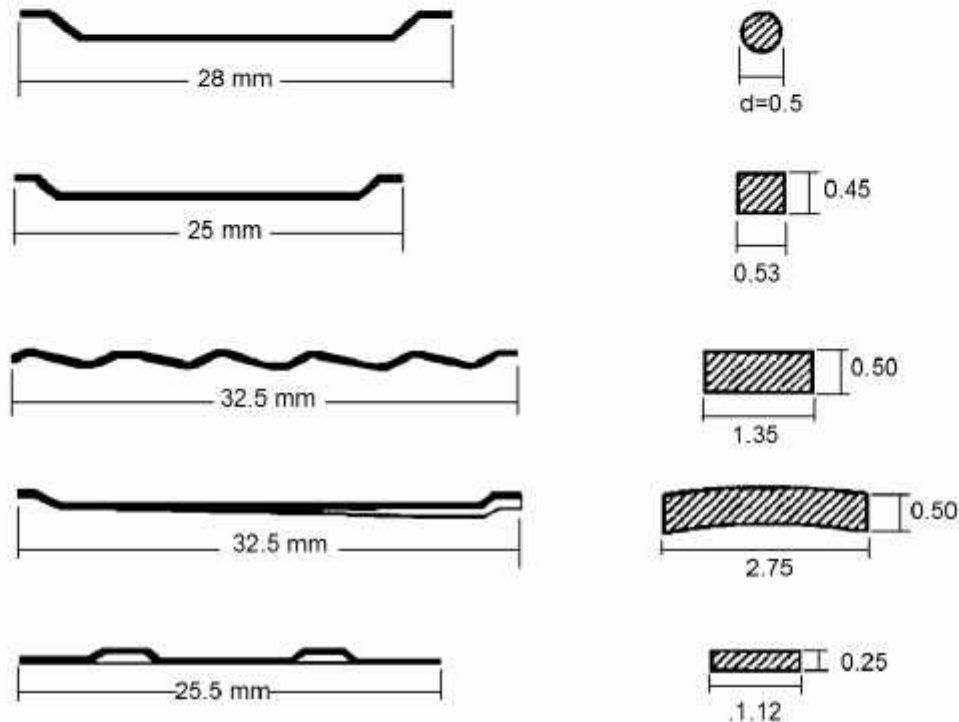


Figure 4. Steel fibre types available on the North American market. After Wood et al (1993). (Note: all dimensions are in mm).

Wood et al (1993) have reported the results of a comprehensive comparative study in which all of the fibres shown in Figure 4 were used to reinforce shotcrete samples which were then subjected to a range of tests. Plain and fibre reinforced silica fume shotcrete samples were prepared by shooting onto vertical panels, using both wet and dry mix processes. The fibre reinforced samples all contained the same steel fibre dosage of 60 kg/m^3 (see Table 1). All the samples were cured under controlled relative humidity conditions and all were tested seven days after shooting.

These tests showed that the addition of steel fibres to silica fume shotcrete enhances both the compressive and flexural strength of the hardened shotcrete by up to 20%. A significant increase in ductility was also obtained in all the tests on fibre reinforced samples, compared with plain samples. While different fibres gave different degrees of improvement, all of the fibres tested were found to exceed the levels of performance commonly specified in North America (i.e. 7-day compressive strength of 30 MPa for dry mix, 25 MPa for wet mix and 7-day flexural strength of 4 MPa).

Shotcrete support

Kompen (1989) carried out bending tests on slabs of unreinforced shotcrete and shotcrete reinforced with ‘Dramix’¹ steel fibres, shown in Figure 5. The shotcrete had an unconfined compressive strength, determined from tests on cubes, of 50 MPa. The results of these tests are reproduced in Figure 6. The peak strength of these slabs increased by approximately 85% and 185% for 1.0 and 1.5 volume % of fibres, respectively. The ductility of the fibre reinforced slabs increased by approximately 20 and 30 times for the 1.0 and 1.5 volume % of fibres, respectively.

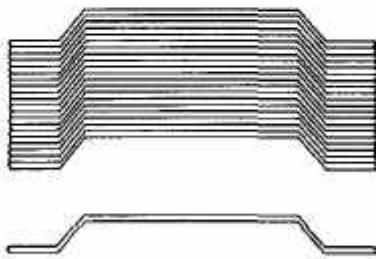


Figure 5: ‘Dramix’ steel fibres used in slab bending tests by Kompen (1989). The fibres are glued together in bundles with a water soluble glue to facilitate handling and homogeneous distribution of the fibres in the shotcrete.

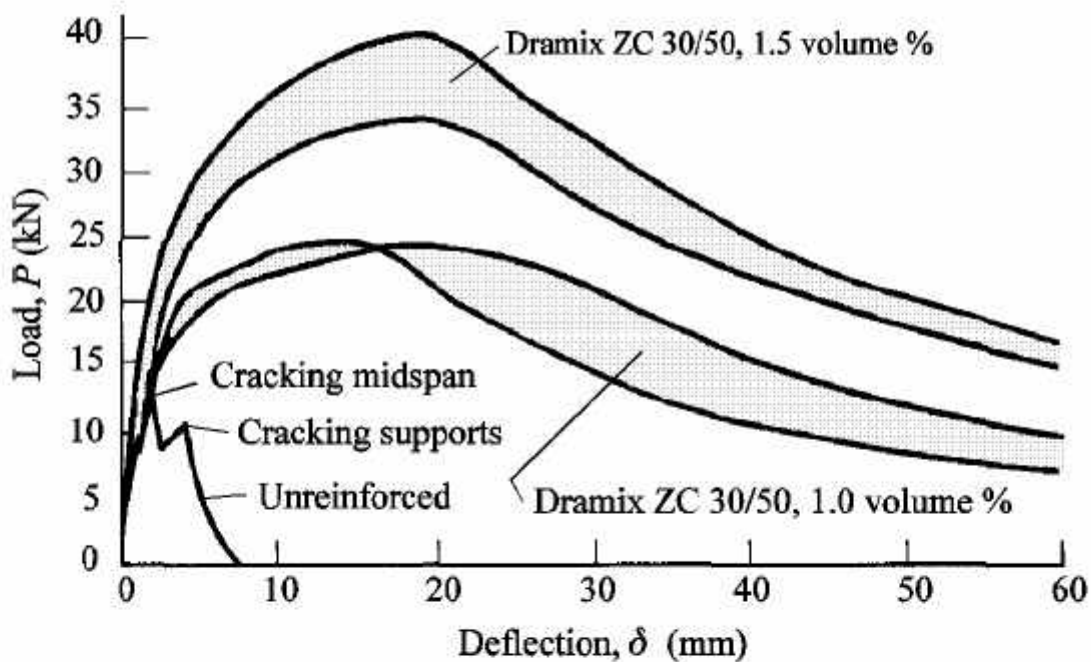


Figure 6: Load deflection curves for unreinforced and steel fibre reinforced shotcrete slabs tested in bending. After Kompen (1989).

In recent years there has been a move towards using fibres other than steel for reinforcing shotcrete. Morgan et al (1989) have reported on the comparative performance of polypropylene and steel fibre reinforced shotcrete and Papworth (2002) discussed a number of other non-metallic fibres that have been used successfully for shotcrete reinforcement. The interested reader can find a large number of papers on recent development in this field on the Internet by searching for “fiber reinforced shotcrete”.

¹ Manufactured by N.V. Bekaert S.A., B-8550 Zwevegem, Belgium.

Shotcrete support

Mesh reinforced shotcrete

While steel fibre reinforced shotcrete has been widely accepted in both civil and mining engineering, mesh reinforced shotcrete is still widely used and is preferred in some applications. In very poor quality, loose rock masses, where adhesion of the shotcrete to the rock surface is poor, the mesh provides a significant amount of reinforcement, even without shotcrete. Therefore, when stabilising slopes in very poor quality rock masses or when building bulkheads for underground fill, weldmesh is frequently used to stabilise the surface or to provide reinforcement. In such cases, plain shotcrete is applied later to provide additional support and to protect the mesh against corrosion.

Kirsten (1992, 1993) carried out a comprehensive set of laboratory bending tests on both mesh and fibre reinforced shotcrete slabs. The loads versus deflection curves that he obtained were similar to those reported by Kompen, reproduced in Figure 6. He found that the load carrying capacity of the mesh and fibre reinforced shotcrete samples were not significantly different, but that the mesh reinforced samples were superior in bending with both point loads and uniformly distributed loads. He concluded that this was due to the more favourable location of the mesh reinforcement in the slabs subjected to bending.

Kirsten also concluded that the quality control, required to obtain a consistent dosage and uniform distribution of fibres in shotcrete, is more easily achieved in civil engineering than in mining applications. This is a reflection of the multiple working headings and the difficulties of access that are common problems associated with many mines. Under these circumstances, more reliable reinforcement will be obtained with mesh reinforced rather than fibre reinforced shotcrete. However, in large mines, in which many of the 'permanent' openings are similar to those on large civil engineering sites, these problems of quality control should not arise.

Chainlink mesh, used in many underground mining excavations to support loose rock, is not usually suitable for shotcrete reinforcement. This is because penetration of the shotcrete is inhibited by the twisted joints as illustrated in Figure 7. This allows air cavities to form behind the mesh and these may allow water to enter and cause corrosion of the mesh.

On the other hand, weldmesh, tightly pinned against the rock face as illustrated in Figure 8, is generally ideal for shotcrete applications. Typically the weldmesh should be made from 4 mm diameter wire welded into a 100 mm x 100 mm grid. This type of mesh is strong enough for most underground applications and the sheets are light enough to be handled by one man.

Shotcrete applications

The quality of the final shotcrete product is closely related to the application procedures used. These procedures include: surface preparation, nozzling technique, lighting, ventilation, communications, and crew training.

Shotcrete support



Figure 7: Chainlink mesh, while very strong and flexible, is not ideal for shotcrete application because it is difficult for the shotcrete to penetrate the mesh.



Figure 8: Welded wire mesh, firmly attached to the rock surface, provides excellent reinforcement for shotcrete.

Shotcrete should not be applied directly to a dry, dusty or frozen rock surface. The work area is usually sprayed with an air-water jet to remove loose rock and dust from the surface to be shot. The damp rock will create a good surface on which to bond the initial layer of shotcrete paste. The nozzleman commonly starts low on the wall and moves the nozzle in small circles working his way up towards the back, or roof. Care must be taken to avoid applying fresh materials on top of rebound or oversprayed shotcrete. It is essential that the air supply is consistent and has sufficient capacity to ensure the delivery of a steady stream of high velocity shotcrete to the rock face. Shooting distances are ideally about 1 to 1.5 metres. Holding the nozzle further from the rock face will result in a lower velocity flow of materials which leads to poor compaction and a higher proportion of rebound.

Shotcrete support

A well-trained operator can produce excellent quality shotcrete manually, when the work area is well-lit and well-ventilated, and when the crew members are in good communication with each other using prescribed hand signals or voice activated FM radio headsets. However, this is a very tiring and uncomfortable job, especially for overhead shooting, and compact robotic systems are increasingly being used to permit the operator to control the nozzle remotely. Typical robotic spray booms are illustrated in Figures 9, 10 and 11.



Figure 9: A truck mounted shotcrete robot being used in a large civil engineering tunnel. Note that the distance between the nozzle and the rock surface is approximately one metre.



Figure 10: Compact trailer-mounted robot unit for remote controlled shotcrete application.

Shotcrete support



Figure 11: Shotcrete operator using a remotely controlled unit to apply shotcrete to a rock face in a large civil engineering excavation.

Figure 12: Plastic pipes used to provide drainage for a shotcrete layer applied to a rock mass with water-bearing joints.



Shotcrete support

When shotcrete is applied to rock masses with well-defined water-bearing joints, it is important to provide drainage through the shotcrete layer in order to relieve high water pressures. Drain holes, fitted with plastic pipes as illustrated in Figure 12, are commonly used for this purpose. Where the water inflow is not restricted to a few specific features, a porous fibre mat can be attached to the rock surface before the shotcrete layer is applied. When practical to do so, the water from these drains should be collected and directed into a drainage ditch or sump.

Design of shotcrete support

The design of shotcrete support for underground excavations is a very imprecise process. However, one observation, which is commonly made by practical engineers with years of experience in using shotcrete underground, is that it almost always performs better than anticipated. There are many examples (very few of which are documented) where shotcrete has been used as a last act of desperation in an effort to stabilise the failing rock around a tunnel and, to most people's surprise, it has worked. The complex interaction between the failing rock mass around an underground opening, and a layer of shotcrete of varying thickness with properties which change as it hardens, defies most attempts at theoretical analysis. It is only in recent years, with the development of powerful numerical tools, that it has been possible to contemplate realistic analyses, which will explore the possible support-interaction behaviour of shotcrete. A clear understanding of shotcrete behaviour will require many more years of experience in the use of and in the interpretation of the results obtained from these programs. It is also important to recognise that shotcrete is very seldom used alone and its use in combination with rockbolts, cablebolts, lattice girders or steel sets further complicates the problem of analysing its contribution to support.

Current shotcrete support 'design' methodology relies very heavily upon rules of thumb and precedent experience. Wickham et al (1972) related the thickness of a shotcrete tunnel lining to their Rock Structure Rating (*RSR*). Bieniawski (1989) gave recommendations on shotcrete thicknesses (in conjunction with rockbolts or steel sets) for different Rock Mass Ratings (*RMR*) for a 10 m span opening. Grimstad and Barton (1993) have published an updated relating different support systems, including shotcrete and fibre reinforced shotcrete, to the Tunnelling Quality Index *Q*. Vandewalle (1993) collected various rules of thumb from a variety of sources and included them in his monograph.

Table 2 is a compilation of current shotcrete practice, combining all of these empirical rules and adding in my own practical experience. The reader is warned that this table can only be used as an approximate guide when deciding upon the type and thickness of shotcrete to be applied in a specific application. Modifications will almost certainly be required to deal with local variations in rock conditions and shotcrete quality.

Shotcrete support

Table 2: Summary of recommended shotcrete applications in underground mining, for different rock mass conditions.

<i>Rock mass description</i>	<i>Rock mass behaviour</i>	<i>Support requirements</i>	<i>Shotcrete application</i>
Massive metamorphic or igneous rock. Low stress conditions.	No spalling, slabbing or failure.	None.	None.
Massive sedimentary rock. Low stress conditions.	Surfaces of some shales, siltstones, or claystones may slake as a result of moisture content change.	Sealing surface to prevent slaking.	Apply 25 mm thickness of plain shotcrete to permanent surfaces as soon as possible after excavation. Repair shotcrete damage due to blasting.
Massive rock with single wide fault or shear zone.	Fault gouge may be weak and erodible and may cause stability problems in adjacent jointed rock.	Provision of support and surface sealing in vicinity of weak fault of shear zone.	Remove weak material to a depth equal to width of fault or shear zone and grout rebar into adjacent sound rock. Weldmesh can be used if required to provide temporary rockfall support. Fill void with plain shotcrete. Extend steel fibre reinforced shotcrete laterally for at least width of gouge zone.
Massive metamorphic or igneous rock. High stress conditions.	Surface slabbing, spalling and possible rockburst damage.	Retention of broken rock and control of rock mass dilation.	Apply 50 mm shotcrete over weldmesh anchored behind bolt faceplates, or apply 50 mm of steel fibre reinforced shotcrete on rock and install rockbolts with faceplates; then apply second 25 mm shotcrete layer. Extend shotcrete application down sidewalls where required.
Massive sedimentary rock. High stress conditions.	Surface slabbing, spalling and possible squeezing in shales and soft rocks.	Retention of broken rock and control of squeezing.	Apply 75 mm layer of fibre reinforced shotcrete directly on clean rock. Rockbolts or dowels are also needed for additional support.
Metamorphic or igneous rock with a few widely spaced joints. Low stress conditions.	Potential for wedges or blocks to fall or slide due to gravity loading.	Provision of support in addition to that available from rockbolts or cables.	Apply 50 mm of steel fibre reinforced shotcrete to rock surfaces on which joint traces are exposed.
Sedimentary rock with a few widely spaced bedding planes and joints. Low stress conditions.	Potential for wedges or blocks to fall or slide due to gravity loading. Bedding plane exposures may deteriorate in time.	Provision of support in addition to that available from rockbolts or cables. Sealing of weak bedding plane exposures.	Apply 50 mm of steel fibre reinforced shotcrete on rock surface on which discontinuity traces are exposed, with particular attention to bedding plane traces.
Jointed metamorphic or igneous rock. High stress conditions.	Combined structural and stress controlled failures around opening boundary.	Retention of broken rock and control of rock mass dilation.	Apply 75 mm plain shotcrete over weldmesh anchored behind bolt faceplates or apply 75 mm of steel fibre reinforced shotcrete on rock, install rockbolts with faceplates and then apply second 25 mm shotcrete layer Thicker shotcrete layers may be required at high stress concentrations.

Shotcrete support

Bedded and jointed weak sedimentary rock. High stress conditions.	Slabbing, spalling and possibly squeezing.	Control of rock mass failure and squeezing.	Apply 75 mm of steel fibre reinforced shotcrete to clean rock surfaces as soon as possible, install rockbolts, with faceplates, through shotcrete, apply second 75 mm shotcrete layer.
Highly jointed metamorphic or igneous rock. Low stress conditions.	Ravelling of small wedges and blocks defined by intersecting joints.	Prevention of progressive ravelling.	Apply 50 mm of steel fibre reinforced shotcrete on clean rock surface in roof of excavation. Rockbolts or dowels may be needed for additional support for large blocks.
Highly jointed and bedded sedimentary rock. Low stress conditions.	Bed separation in wide span excavations and ravelling of bedding traces in inclined faces.	Control of bed separation and ravelling.	Rockbolts or dowels required to control bed separation. Apply 75 mm of fibre reinforced shotcrete to bedding plane traces before bolting.
Heavily jointed igneous or metamorphic rock, conglomerates or cemented rockfill. High stress conditions.	Squeezing and 'plastic' flow of rock mass around opening.	Control of rock mass failure and dilation.	Apply 100 mm of steel fibre reinforced shotcrete as soon as possible and install rockbolts, with face-plates, through shotcrete, Apply additional 50 mm of shotcrete if required. Extend support down sidewalls if necessary.
Heavily jointed sedimentary rock with clay coated surfaces. High stress conditions.	Squeezing and 'plastic' flow of rock mass around opening. Clay rich rocks may swell.	Control of rock mass failure and dilation.	Apply 50 mm of steel fibre reinforced shotcrete as soon as possible, install lattice girders or light steel sets, with invert struts where required, then more steel fibre reinforced shotcrete to cover sets or girders. Forepoling or spiling may be required to stabilise face ahead of excavation. Gaps may be left in final shotcrete to allow for movement resulting from squeezing or swelling. Gap should be closed once opening is stable.
Mild rockburst conditions in massive rock subjected to high stress conditions.	Spalling, slabbing and mild rockbursts.	Retention of broken rock and control of failure propagation.	Apply 50 to 100 mm of shotcrete over mesh or cable lacing which is firmly attached to the rock surface by means of yielding rockbolts or cablebolts.

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Shotcrete support

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Shotcrete support

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