The use of steel fibre reinforced shotcrete for the support of mine openings

by M. Vandewalle*

Synopsis

What separates the support of mining openings from the support of similar civil engineering structures is the fact that mine openings have to survive large deformations as a result of changing stress conditions induced by progressive mining.

Steel fibres impart to concrete and shotcrete a high degree of ductility which not only allows the shotcrete and concrete linings to absorb important rock movements but also to increase its bearing capacity by a redistribution of the loads.

A range of applications will be discussed technically and economically.

Rock support design

The potential for instability in the rock surrounding mine openings is an ever-present threat to both the safety of men and equipment in the mine.

In addition, because of dilution of the ore due to rock falls, the profitability of the mining operations may be reduced if failures are allowed to develop in the rock surrounding a stope.

The classical approach used in designing engineering structures is to consider the relationship between the capacity C (strength or resisting force) of the element and the demand D (stress or disturbing force). The factor of safety of the structure is defined as $F = C/D$ and failure is assumed to occur when F is less than 1.

The value of the factor of safety, which is considered acceptable for a design, is usually established from previous experience of successful designs. A factor of safety of 1.3 would generally be considered adequate for a temporary mining opening while a value of 1.5 to 2.0 may be required for a permanent excavation, such as an underground crusher station.

What separates the support of mining openings from the support of similar civil engineering structures is the fact that mine openings may have to survive large deformations as a result of changing stress conditions induced by progressive mining. The support has to remain effective in gradually degrading rock, and it may have to sustain dynamic loads.

In general, the design of support for permanent openings tends to be conservative in that the designer will generally err on the side of specifying more, rather than less support, to take care of unforeseen conditions. Rehabilitation of permanent openings can disrupt mine operations and can be difficult and expensive. Consequently, the aim is to do the job once and not have to worry about it again.

The support requirements tend to be more conservative than those for the support in normal mine openings, since safety of men and equipment is a prime consideration in these permanent openings.

Designing underground openings

In mining openings excavated in jointed rock masses at relatively shallow depth, the most common type of failure are those involving wedges falling from the roof or sliding out of the sidewalls of the openings.

A characteristic feature of wedge failures in blocky rock is that very little movement occurs in the rock mass before failure of the wedge. Consequently, the support system has to provide a stiff response to movement.

For roof wedges the total force, which should be applied by mechanically anchored or fully grouted rockbolts, should be sufficient to support the full dead weight of the wedge, plus an allowance for errors and poor quality installation.

Shotcrete can be used for additional support of wedges in blocky ground and can be very effective. This is because the base of a typical wedge has a large perimeter and hence,

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even for a relatively thin layer of shotcrete, a significant cross-sectional area of the material has to be punched through before the wedge can fail.

It is important to ensure that shotcrete is well bonded to the rock surface in order to prevent a reduction in support capacity by peeling-off of the shotcrete layer.

If a minimal number of rock bolts are placed to ensure that the short term stability of the rock mass is taken care of, a layer of shotcrete will provide additional long term security. The ideal application of shotcrete is in more closely jointed rock masses. In such cases wedge failure would occur as a progressive process, starting with smaller wedges exposed at the excavation surface and gradually working its way back into the rock mass. In these circumstances, shotcrete provides very effective support and deserves to be much more widely used than is currently the case.

Rock at depth is subjected to stress resulting from the weight of the overlying strata and from locked-in stresses of tectonic origin.

When a mine opening is excavated in this rock, the stress field is locally disrupted and a new set of stresses are induced in the rock surrounding the opening.

One of the major problems in designing underground openings is that of estimating the strength and deformation properties of the in *situ rock* mass.

Support design for overstressed rock

The failure of a rock mass around an underground opening depends upon the *in situ* stress level and upon the characteristics of the rock mass.

Failure around openings in lightly stressed rock masses progresses from brittle spalling and slabbing, in the case of massive rocks with few joints, to a more ductile type of failure for heavily jointed rock masses.

Deformation of rock mass

The plastic behaviour of the rock mass surrounding the tunnels does not necessarily mean that the tunnel collapses. The failed material still has considerable strength and, provided that the thickness of the plastic zone is small compared with the tunnel radius, the only evidence of failure may be a few fresh cracks and a minor amount of ravelling and spalling.

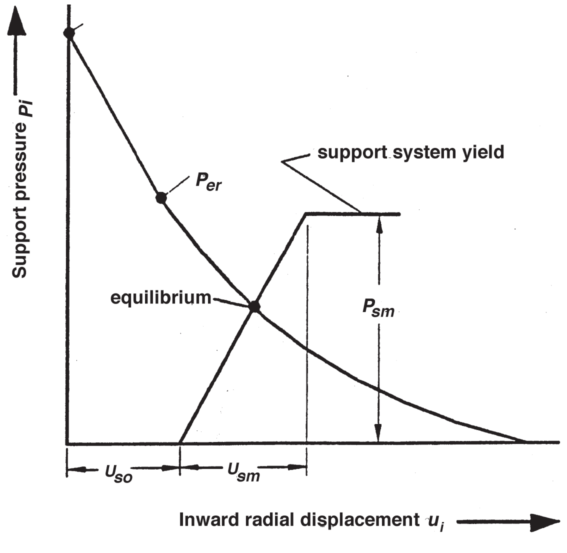


Figure 1—Response of support system—tunnel wall displacement

On the other hand, when a large plastic zone is formed and when large inward displacements of the tunnel wall occur, the loosening of the failed rock mass will lead to severe spalling and ravelling and to an eventual collapse of an unsupported tunnel.

The primary function of support is to control the inward displacement of the walls and to prevent the loosening, which can lead to the collapse of the tunnel. The installation of rockbolts, shotcrete lining or steel sets cannot prevent the failure of the rock surrounding a tunnel subjected to significant overstressing.

But these support types do play a major role in controlling tunnel deformation.

Deformation characteristics of support

Once the support has been installed and it is in full and effective contact with the rock, the support starts to deform elastically. The maximum elastic displacement which can be accommodated by the support system is u_{sm} and the maximum support pressure p_{sm} is defined by yield of the support system.

Depending upon the characteristics of the support system, the rock mass surrounding the tunnel and the *in situ* stress level, the support system will deform elastically in response to the closure of the tunnel, as the face advances away from the point under consideration.

Equilibrium is achieved, if the support reaction curve intersects the rock mass displacement curve before either of these curves have progressed too far. If the support is installed too late, the rock mass may already have deformed to the extent that loosening of the failed material is irreversible.

On the other hand, if the capacity of the support is inadequate, then yield of the support may occur before the rock mass deformation curve is intersected. In either of these cases the support system will be ineffective, since the equilibrium condition will not have been achieved.

Progressive spalling in massive brittle rock

One of the problems which is encountered in mining and civil engineering is slabbing or spalling from the roof and sidewalls. This can take the form of popping, in which dinner plate-shaped slabs of rock can detach themselves from the walls, or gradual spalling where the rock slabs progressively, and fall away from the roof and floor. In extreme cases the spalling may be severe enough to be classed as *rockburst.*

The spalling process tends to start very close to the face of the tunnel and, while the full extent of the failure zone may take time to develop, small rockfalls can occur close to the face and can pose a threat to work crews.

The purpose of the support is to carry the dead weight of the broken rock and to prevent rockfalls close to the working force.

Support applications

The wide variety of orebody shapes and rock mass characteristics which are encountered in underground mining mean that each mine presents a unique design challenge. 'Typical' mining methods have to be modified to fit the peculiarities of each orebody.

Factors controlling the performance of the support system are abrasion, vibration, secondary blasting damage, stress changes due to stoping.

Safety - Support Systems

The simplest form of underground excavation support is that which is installed solely for 'safety' reasons.

This support is not called upon to carry very heavy loads due to the large wedge failures or to massive stress-induced instability, but its function is to provide an acceptable level of safety for personnel and equipment in the mine.

The decision on when support is required in such tunnels is a very subjective one, since there are very few guidelines and those which do exist vary widely from country to country. Possibly the only consistent guideline is that heavily trafficked openings, such as shafts, ramps and haulages, should have rockbolts and/or reinforced shotcrete installed to protect personnel and equipment from rockfalls.

The expense of this support is justified because very little maintenance or rehabilitation would be required for the life of the tunnel. Such rehabilitation can be very expensive and, in the case of a conveyor tunnel or a similar critical route in the mine, the suspension of operations due to rockfalls would be a serious problem.

Permanent mining excavations

Shafts, shaft stations, underground crusher chambers, underground garages are examples of 'permanent' mining excavations.

Because of the frequent use of such excavations by mine personnel and because of the high capital cost of the equipment housed in these excavations, a significantly higher degree of security is required than for other mine openings.

These excavations are usually designed for an operational life of tens of years. Consequently, corrosion is a problem which cannot be ignored. Fibre-reinforced shotcrete is used on exposed surfaces and, in many cases, the thickness of the shotcrete may be of the order of 100 to 150 mm.

Drawpoints and orepasses

Draw-points and orepasses require special considerations in terms of support design. These openings are generally excavated in undisturbed rock. Consequently mining is relatively easy and little support is required to stabilize the openings themselves.

Once mining starts and the drawpoints and orepasses are brought into operation, the conditions are changed dramatically and serious instability can occur if support has not been installed in anticipation of these changes.

Abrasion, due to the passage of hundreds of tonnes of broken ore can pluck at loose rock on opening surfaces and can cause progressive ravelling and eventual collapse. Stress changes, due to the mining of adjacent or overlying stopes, can result in failure of support. Secondary blockings of hangs-up in the drawpoints or orepasses can cause serious damage to the surrounding rock.

As the rock surrounding these openings requires considerable assistance if it is to remain in place for the working life of the opening, there is a considerable economic incentive to install the correct reinforcement during development of the openings in order to avoid costly remedial work later.

The design support for orepasses is similar to that for drawpoints, except that access to install the support is generally not as simple as for drawpoints. In addition, an orepass is required to handle much larger tonnages of ore and may be required to remain in service for many years.

Support, which will retain the rock close to the orepass surface without obstructing the passage of the ore, is required.

Shotcrete support

The use of shotcrete for the support of the underground excavations was pioneered by the civil engineering industry.

In recent years the mining industry has become a major user of shotcrete for 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 the support of permanent openings such as ramps, haulages, shaft stations and crusher chambers. Rehabilitation of conventional support systems 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 minimizes the labour-intensive process of mesh installation.

The design of shotcrete support for underground excavation is a very imprecise process.

The complex interaction between the failing rock mass around an underground opening, and a layer of shotcrete of varying thickness with properties that change as it hardens, defies most attempts at theoretical analysis.

It is also important to recognise that shotcrete is very seldom used alone and its use in combination with rockbolts, cable bolts, 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: Grimstad & Barton have published an updated chart relating different support systems, including shotcrete and Steel Fibre Reinforced Shotcrete (SFRS).

SFRS can not prevent deformation from taking place, especially in high stress environments. It can, however, assist in controlling deformation, particularly when used in combination with rockbolts, dowels or cables.

SFRS becomes very effective when bolt or cable installations are carried out after an initial shotcrete support application. This allows the face plate loads to be transmitted over a large area to the underlying rock mass.

Steel fibre reinforced shotcrete

Definition

Steel fibres are added to shotcrete to improve energy absorption, impact resistance and to provide ductility. The latter property is the ability to continue to carry load after the shotcrete matrix has cracked. It is obvious that all three properties are of great importance for support systems designed for mine conditions.

Steel fibres

Steel fibres are available in different sizes, shapes and qualities.

The length of the fibre needs to be at least three times the size of the maximum aggregate in order to bridge the cementitious gap and to provide sufficient bond of the steel fibres in the shotcrete matrix.

A small diameter increases the number of fibres per unit weight and densifies the fibre network. The fibre spacing is reduced when the fibre gets thinner and the fibre reinforcement becomes more efficient.

Tensile stresses induced in the shotcrete are transferred to the steel fibres thanks to the durable bond characteristics between both basic materials. The adherence can be improved by enhancing the mechanical anchorage and choosing a suitable shape of the steel fibres. Hooked ends, enlarged ends, crimped wire,... are different shapes which are available on the market.

An efficient load transfer will result in a high tensile stress in a small diameter steel fibre. Efficient steel fibres need to have a high tensile strength to avoid fibre fracture. The steel fibre high load-resisting capacity after the shotcrete has cracked guarantees the degree of ductility.

The use of high strength shotcrete in long life final linings of underground constructions have enhanced the need to develop high tensile steel fibres.

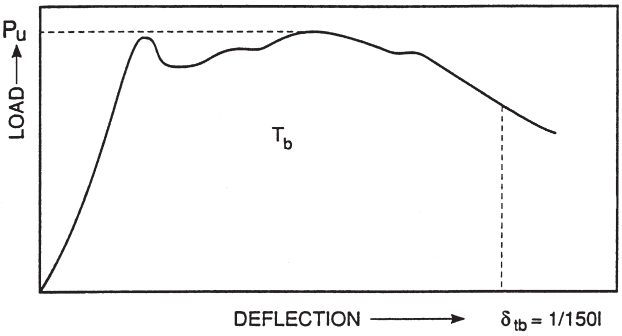
Steel fibres with different sizes and shapes will all have their own effect on the shotcrete behaviour and quality.

The required steel fibre dosage to meet design and structural requirements has to be related to the steel fibre performance.

Ductility

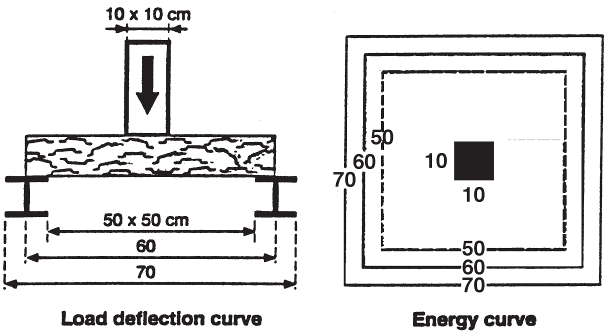
In order to be able to quantify the benefits of fibre addition, a variety of different measuring systems have been developed in different countries. Most commonly used are flexural toughness systems which determine load versus deflection responses of a beam subjected to bending. From this, the area under the curve is determined (an energy quantity) and mostly translated in an absolute index parameter or in one without dimensions. The two oldest systems are the Japanese code (JSCE-SF4, 1984) and the American Standard (ASTM C1018-85, 1985).

Figure 2 represents a typical load-deflection behaviour curve for a SFRS and the definition of the equivalent flexural strength according to the Japanese standard. For practical dosages of steel fibres (40-50 kg/m^3), the flexural strength of concrete is not, or only, marginally increased. The main reason for incorporating steel fibres in concrete is to impart ductility to an otherwise brittle material.



$$f_u = P_u \cdot \frac{l}{b \cdot h^2} \qquad f_e = \frac{T_b}{\delta_{tb}} \cdot \frac{l}{b \cdot h^2}$$

Figure 2—Represents a typical load-deflection behaviour curve for a SFRS and the definition of the equivalent flexural strength according to the Japanese standard. For practical dosages of steel fibres (40-50 kg/m3), the flexural strength of concrete is not or only marginally increased. The main reason for incorporating steel fibres in concrete is to impart to an otherwise brittle material.



Load deflection curve **Energy curve**

Figure 3—French slab test

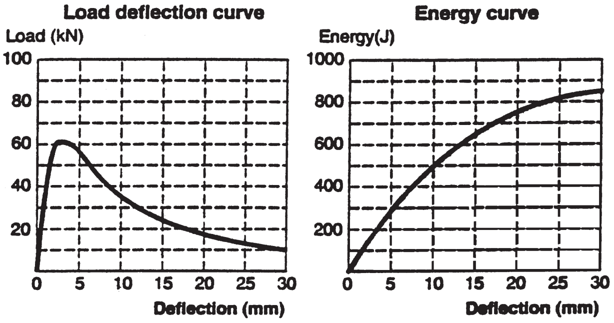


Figure 4—Load deflection and energy absorption curve

The beam test is not the most appropriate test to simulate the membrane action of a SFRS-lining. A more appropriate test has been developed in France to measure the performance of a SFRS lining (M. Legrand, 1984). A test slab of 600 x 600 x 100 mm^3 is supported on the four edges and a central point load is applied through a contact surface of 100 x 100 mm^2 (Figure 3). The load deflection curve is recorded and the test is on-going until a deflection of 25 mm at the central point of the slab is reached (Figure 4). From the load-deflection curve a second curve is drawn resulting in the absorbed energy as a function of the slab deformation or deflection (Figure 5).

The slab test is more appropriate than the beam test to determine the performance of SFRS lining for the following three reasons:

- A slab test corresponds much better than a beam test with a real tunnel lining; the slab support on the 4 edges simulates the continuity of the shotcrete lining;
- As in reality, steel fibres act in at least two directions and not just in one direction as in a beam test; the fibre reinforcing effect in a slab is very similar to the real behaviour of a SFRS lining;
- SFRS can be compared very easily with a mesh reinforced shotcrete to be tested in the same way.

For the same concrete matrix, the amount of absorbed energy is significantly influenced by the fibre type (e.g. the aspect ratio length diameter) and fibre dosage. The higher the aspect ratio and fibre content, the better the performance of the SFRS (A. Lambrechts, 1996).

Interaction with rock bolts

Comparative tests (J. Holmgren, 1985) have been conducted on bolt-anchored shotcrete linings reinforced with steel fibres and mesh by the BeFo (Swedish Rock Engineering Research Foundation) and the FortF (Royal Swedish Fortifications Administration). The tested shotcrete structures were subjected to a punch load from a single block. Support for the shotcrete layer was provided by two rock anchors, one on each side of the punching block. The mesh reinforced linings were tested with a stiff spherical washer of 12 mm thickness, while the SFRS linings were tested with a cheaper flexible washer of 5 x 160 x 160 mm^3. The test set-up is represented in Figure 6. The SFRS linings contained 40 and 50 kg/m^3 of a hooked steel wire fibre. Two mesh types were investigated, a cold tensioned welded steel mesh with 5 mm bars spaced 100 mm and a tensile strength of 500 N/mm^2 and an annealed welded steel mesh with 6 mm bars spaced 150 mm and a tensile strength of 220 N/mm^2.

Figure 7 shows the displacement of the loading block as a function of the forces that act at each joint, i.e. one-half of the force from the hydraulic cylinders minus the gravity force of the loading block The test results show that the SFRS linings are at least equally strong and ductile as conventional reinforced ones.

Batching, mixing and placing

SFRS can be used for the dry shotcreting method as for the wet one. The SFRS can be applied by the conventional equipment. When steel fibres glued together in compact bundles are used, no special equipment is required for mixing. The bundles can be added to the dry aggregates, as well as to the already mixed concrete. As soon as the mixing process starts, these bundles spread immediately throughout the entire mass and owing to the action of the moisture of the mixture and also the scouring effect of the aggregates, they separate into individual fibres. When all fibre bundles are separated, the shotcrete mixture is homogeneously reinforced. By contrast, loose fibre types, particularly those with high aspect ratios, are difficult to add to the concrete and to spread evenly in the mixture.

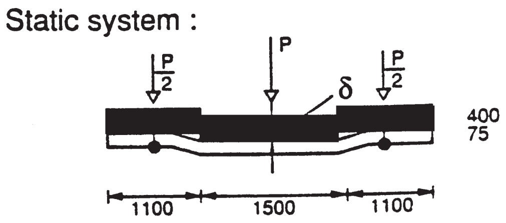


Figure 5—Falling block test

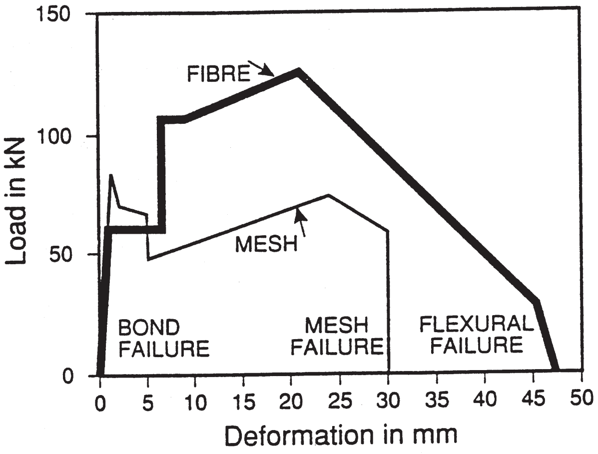


Figure 6—Comparison of load bearing capacity of mesh reinforced shotcrete compared to SFRS

Recently an appropriate dosing equipment has been developed for glued steel fibres which allows the addition of steel fibres in an automatic way. This equipment can be connected to any standard concrete batching or mixing plant. The use of automatic dosing equipment makes it possible to eliminate the need for additional personnel but makes it also possible to have a clear control of the added fibre dosage.

SFRS versus mesh reinforced shotcrete

One of the factors which makes SFRS particularly appealing to contractors is the ability to do away with the need to install mesh. Fixing mesh to a wall is difficult, time consuming, costly and sometimes hazardous. Another advantage is that SFRS follows the exact contours of the rock, while even on a regular excavated surface, the mesh is pinned mostly at spots that project from the surface. It is pinned back inside large depressions, but it is draped over most small ones (see Figure 8).

Mesh reinforced shotcrete requires 30 to 50 mm cover as well as filling in all the voids behind the mesh with shotcrete. Filling the voids behind the mesh in draped-over areas takes extra shotcrete, more than what is required by the minimum specified thickness. It may happen even that the mesh

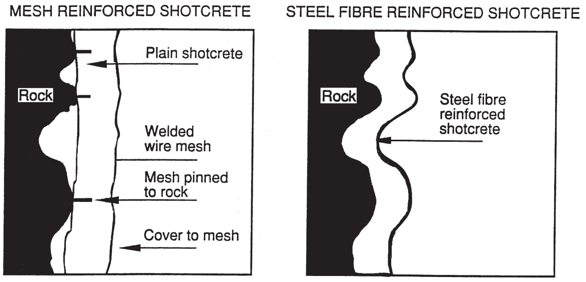


Figure 7—Comparison of a lining built up of mesh reinforced shotcrete vs SFRS

remains uncovered. With SFRS, there is no need anymore to thoroughly encapsulate the reinforcing mesh with shotcrete. An improper nozzling technique can be costly too. If the correct pressure is not used or the nozzle is not held at the correct distance from the rock face, shotcrete can build up on the face of the mesh, leaving voids and sand pockets behind. Not bonded to the rock, this shotcrete will deteriorate quickly and the reinforcing mesh will rapidly start corroding especially if exposed to groundwater, aggressive atmosphere or freezing conditions.

The wire of the mesh causes a much higher rebound of the bigger aggregates, creating poor quality shotcrete behind the wires and, as such, preferential drains for groundwater. Big size aggregates hitting the wires make the mesh vibrate, which affects in a negative way the bond between rock and shotcrete layer. However, the bond is an essential parameter for the shotcrete layer efficiency.

Another big advantage of SFRS is its homogeneous composition. As such, it is able to sustain tensile and shear stresses in each part of the cross-section. A further advantage is that by immediate application of the consolidating layer, adequate protection against falling rocks is provided. Particularly when using a robot, a reinforced shotcrete layer can be applied from outside the danger area.

SFRS in rockburst conditions

The occurrence of a rock- or strain-burst in the immediate vicinity of an excavation results in fracturing and often large displacements of the rock. A rockburst further away from an excavation can still cause heavy damage on mining excavations and tunnels by the passing waves and by the resulting rock displacements. The rock mass is fragmented and ejection velocities of rock blocks can reach 5 to 10 m/sec. Hence, support requirements in mining areas prone to rockbursts should have a larger energy-absorbing capacity. The support installed should also allow large displacements and a good surface coverage should be provided too.

Steel Fibre Reinforced Shotcrete (SFRS) conforms to these support requirements, at least if the fibre content is sufficiently high and evenly distributed, and if the fibres are oriented in all directions. In comparison to plain shotcrete, which is rather brittle, SFRS shows a ductile behaviour and the ability to absorb a significant amount of energy during large deformations.

SFRS should be considered as a part of the support system, e.g. in combination with yielding anchors. Attention should be paid to the adhesion between SFRS and the anchors.

Based on the intrinsic properties of SFRS, one can state that SFRS is, at least in a conceptual way, a support or part of a support system adequate for rockburst conditions. What still has to be discussed is if SFRS is the most optimal support for all rockburst conditions.

First of all, for strainbursts without major displacement, being the least severe rockburst conditions, SFRS is from a theoretical point of view an adequate support system to replace locally installed bolts or plain shotcrete. However, due to economic considerations, more conventional support types are in most cases preferred, except if a good surface cover is required.

Secondly, for the rockburst conditions with a potential of rock fall, SFRS in combination with an adequate anchoring system (cone bolt or yielding anchor) is, however, more than just an alternative for wire mesh in combination with anchors, certainly if the latter systems has to be combined with shotcrete. In the previous paragraph, some practical considerations are given why SFRS is preferred above with mesh reinforced shotcrete.

Thirdly, for rockburst conditions with very large displacements and/or violent ejection, the cracks induced during rockbursts could be too large to keep a sufficient strong steel fibre bridging effect.

Specifying SFRS

Introduction

For many years shotcrete was considered as a second choice material which was only used for temporary linings and preliminary sealing layers. However, a lot has changed in the last 10 years.

Shotcrete equipment has been adapted to job conditions, including mechanized spraying arms, and nozzlemen are trained and certified to use it in the proper way.

Technology and mix design have called for the right basic components. Aggregates need to have a continuous grading. As a result of thorough research in recent years a lot of admixtures have been offered to the market, such as accelerators to reduce rebound and increase early shotcrete strength development, set retarders and activators to increase shotcrete life, silica fume to improve shotcrete characteristics.

Actually shotcrete having the proper mix design and being applied by a certified nozzleman using the right equipment has been upgraded to a high quality material. Improved characteristics to extend the shotcrete applications, including structural use.

Steel fibres

Steel wire fibres, added as one more component to the shotcrete mix, guarantees a uniform reinforcement and an end product with homogenous characteristics.

Steel fibres do reinforce the whole shotcrete matrix resulting in

- an efficient crack control and
- a ductile behaviour.

Structural applications however, require a tougher quality control. The proper characteristics have to be checked depending on the application of the steel fibre reinforced shotcrete :

- preliminary control is needed on the production level of each component, such as cement, admixtures, steel fibres
- before starting up a job preliminary testing has to be done using the mix and the equipment selected for the job to check compatibility of all components and factors involved
- this allows to start the job in a well prepared way to keep quality control easy and simple during tunnelling.

Control in advance includes material testing. Steel fibres should have an official quality label, such as ISO.

Preliminary testing has to check the proper steel fibre reinforced shotcrete characteristics, such as crack control and/or ductility.

Crack control

Steel fibre length has to be in the range of 3 times the maximum aggregate size in order to bridge the gap between two aggregates, where a crack starts, and to have enough bond to withstand the tensile stresses.

Taking into account considerations on rebound, aggregates should have a maximum size of 10 to 12 mm.

Hence steel fibres need to have a length between 30 and 35 mm.

Additionally, in order to achieve a homogeneous reinforcement, the spacing between fibres must be smaller than 0.45 l_f, where l_f is the length of the fibres.

For a given fibre length the spacing depends on the fibre dosage and its diameter.

Crack control requires

- minimum steel fibre length, which should be for shotcrete in the range of 30 to 35 mm
- a small diameter to keep the fibre spacing reduced.

Consequently, specifications for crack control have to ask for a minimum fibre length and should not call for a minimum dosage but for a maximum spacing.

Toughness

Steel fibres transform shotcrete from a brittle material into a highly ductile one. Toughness is an important characteristic which provides a steel fibre reinforced shotcrete lining with a higher bearing capacity by the effect of load redistribution.

Toughness can be determined based on the results of a flexural beam test.

In many countries local standards and/or recommendations include full description of the test itself, such as beam size, span, rate of loading... but only few numerical data are available as to the values to obtain.

ASTM - testing method (C1018)

Toughness indices are determined based on the ratio of energy absorption between first crack and first crack-related deformations.

Accurate measuring of first crack deformation is highly complicated and due to the uncertain behaviour of testing equipment at the cracking stage results may be completely wrong or manipulated.

D. Wood therefore recommended to skip I_5 and I_{10} indices and to use higher toughness indices (I_{20}, I_{30} and I_{60}).

Toughness factors have been defined as

- $R_{30,10} = 5\ (I_{30} - I_{10})$
- $R_{50,30} = 5\ (I_{50} - I_{30})$.

Recommended values for both toughness factors are in the range of 50 - 75

Equivalent flexural strength

The equivalent flexural strength is designed as an average value based on the load-bearing capacity of steel fibre reinforced shotcrete considering large deformations.

A larger part of the load-deflection diagram of the beam test is taken into account, giving a better idea of the real ductile behaviour.

The equivalent flexural strength is a material characteristic which has to be applied in the proper design method.

This requires however, the right design assumptions as to loading conditions and lining dimensions. This can be done for inner linings having a uniform thickness.

The German DBV Recommendations have published a design method based on the MN-method using the equivalent flexural strength.

Project specifications have to include the required equivalent flexural strength values which were introduced in the lining design.

Residual values

Norwegian recommendations define four steel fibre reinforced classes based on 1 mm and 3 mm residual flexural strength values. There is no link, however, between the values and any design method.

In Sweden residual strength factors are defined as a combination of shotcrete flexural strength and a toughness factor based on the American standard.

Slab test

As to the shotcrete linings it is hard to make design assumptions which have a good chance to cope with the real conditions.

Due to the irregular rock surface the thickness varies a lot and the ground movement is difficult to predict.

As a shotcrete lining behaves much more as a thin slab rather than as a strong beam it is not obvious at all to relate data from beam tests to the lining behaviour.

Anyhow, the primary function of an outer lining is to help the underground to stabilise and find a new state of equilibrium.

The French approach of trying to simulate the lining behaviour by loading a four edges supported shotcreted slab by a centre point load, gives a good idea of the load-bearing capacity and the energy absorption of a shotcrete lining.

A Norwegian test program has clearly described the loading conditions of a shotcrete lining in combination with rock bolts. Slab testing, allowing load redistribution by mobilising the steel fibre reinforced shotcrete ductile behaviour in hyperstatic conditions provided good and reliable values to characterize the load-bearing capacity of the lining.

Instead of determining a material characteristic, which requires a proper design model in order to calculate the allowable sollicitation of a structure, the French approach allows to skip that step and to check immediately the energy absorption and the load bearing capacity of the lining.

Numerical values to be recommended were obtained from corresponding slab tests using steel fibre types and dosages, which had proven in the past to be efficient under given loading conditions.

Depending on rock conditions and application type, specified values in the draft European shotcrete standard are in the range of 500 and 1.000 Joule.

Recommendations

Due to efforts from several parties involved in shotcrete development shotcrete has been upgraded to a high quality material to be used for structural purposes.

Quality also requires a thorough check of the relevant characteristics related to the material's application.

Specifications have to call for the required numerical values to be obtained from the appropriate testing methods.

Steel fibre reinforced shotcrete properties depend largely on the steel fibres specific characteristics. Steel fibre should have a quality label.

The effect of steel fibres on crack control depends on steel fibre dosage and aspect ratio. Specifications have to mention a minimum fibre length and a maximum fibre spacing. Based on this value a minimum dosage can be specified for each fibre type.

Toughness should be specified based on

- the French slab test energy absorption values (Joule) for outer linings
- beam test equivalent flexural strengths (N/mm^2) for designed inner linings.

References

1. Nemegeer D., Vandewalle L., Van Nieuwenburg D., Van Gysel A., Vyncke J., and Deforche E. Design of Concrete Structures—Steel wire fibre reinforced concrete structures with or without ordinary reinforcement. *Infrastructuur in het Leefmilieu*, no. 4, 1995.
2. EFNARC. European Specification for Sprayed Concrete. 1996.
3. Wood D. A comparative study of different steel fibres in shotcrete.
4. DBV - Merkblätter Faserbeton
   Merkblatt Technologie des Stahlfaserbetons und Stahlfaserspritzbetons
   Merkblatt Bemessungsgrundlagen für Stahlfaserbeton im Tunnelbau.
5. Vandewalle M. Tunnelling the World.
6. D. Moyson. Steel fibre reinforced concrete (SFRC) for tunnel linings: A technical approach. Proceedings of the International Congress on Tunnelling and Ground Conditions, Cairo (Egypt). 3– 7 Apr. 1994. pp. 673–679.
7. Garshol K. High Performance Wet Mix Shotcrete, Proceedings of the Conference on Design and Construction of Underground Structures, New Delhi (India). 1995. pp. 375–387.
8. Barton *et al*. Engineering Classification of Rock Masses for the Design of Tunnel Support, Rock Mech. §4, pp. 189–239.
9. Grimstad, E and Barton N., Updating the Q-System for NMT, Proceedings of the International Symposium on Sprayed Concrete - Modern Use of Wet Mix Sprayed Concrete for Underground Support, Fagernes (1993), Norwegian Concrete Association (eds.). Opsahl, Kompen and Berg. pp. 46–66.
10. Hoek E., Kaiser P.K., and Bawden W.F. Support of Underground Excavations in Hard Rock. 1995.
11. AFTES-Working Group No.6. Sprayed Concrete. Recommendations on Fibre Reinforced Sprayed Concrete Technology and Practice. *Tunnels et Ouvrages Souterrains* No.126. Nov./Dec. 1994.
12. Vandewalle M., Specifying Steel Fibre Reinforced Shotcrete. Proceedings of the Tunnelling 97 Conference. London 1997.
13. Vandewalle M.,Steel Fibre Reinforced Shotcrete Design. Proceedings of the Engineering Foundation Conference on Shotcrete for Underground Support VI, Niagara-on-the-Lake (Canada). 1993. pp. 99–109.
14. M. Vandewalle. Early Strength of Steel Fibre Reinforced Shotcrete. Proceedings of the Second International Symposium on Sprayed Concrete, Gol (Norway). 1996. pp. 313–315. ◆

Department of Chemical Engineering
University of Stellenbosch

General

The University of Stellenbosch is situated in scenic surroundings in Stellenbosch and traces its origin to the Stellenbosch Gymnasium which was founded in 1866. The Stellenbosch Gymnasium became known as the Victoria College in the following year which marked the 50th anniversary of Queen Victoria's reign. The college achieved university status in 1918 and was renamed the University of Stellenbosch, the first Afrikaans university in the country. Today the university has 12 faculties and more than 16 000 students of which Faculty of Engineering has approximately 1400 students and the Department roughly 200 students.

The Faculty of Engineering was established in 1944. The original Departments of Civil, Mechanical and Electrotechnical Engineering, today known as Electrical and Electronic Engineering, and Applied Mathematics, were later augmented by the Departments of Chemical, Metallurgical and Industrial Engineering. The Faculty is housed in large modern buildings and has fine teaching and research laboratories.

Bachelor degrees have been awarded in the Department of Chemical Engineering since its inception in 1969. The Department offers two degree programmes, i.e. Chemical Engineering and Chemical Engineering with Mineral Processing as an option. The Department has a wide range of research and teaching interests and is supported by the well-developed infrastructure of the university, including the library system, computer centres and analytical and other laboratory equipment. In 1994 the Departments of Chemical and Metallurgical Engineering merged to form the Department of Chemical Engineering. The Department is involved in the activities of the Western Cape Branch of SAIMM since its inception as well as the organization of the Annual Mineral Processing Symposium.

Research Programmes

The Department is actively involved in diverse research programmes covering a wide spectrum of industrial activities, the majority of which are sponsored by industry. Besides the industrial orientation of research, the Department maintains close ties with other academic institutions, both locally and internationally. ◆