THE USE OF STEEL FIBER-REINFORCED SHOTCRETE FOR THE SUPPORT OF MINE OPENINGS

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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 fibers 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 their bearing capacity by a redistribution of the loads.

The use of shotcrete for the support of 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 fiber reinforcement into the shotcrete is an important factor in this escalating use, since it minimizes the labor-intensive process of mesh installation.

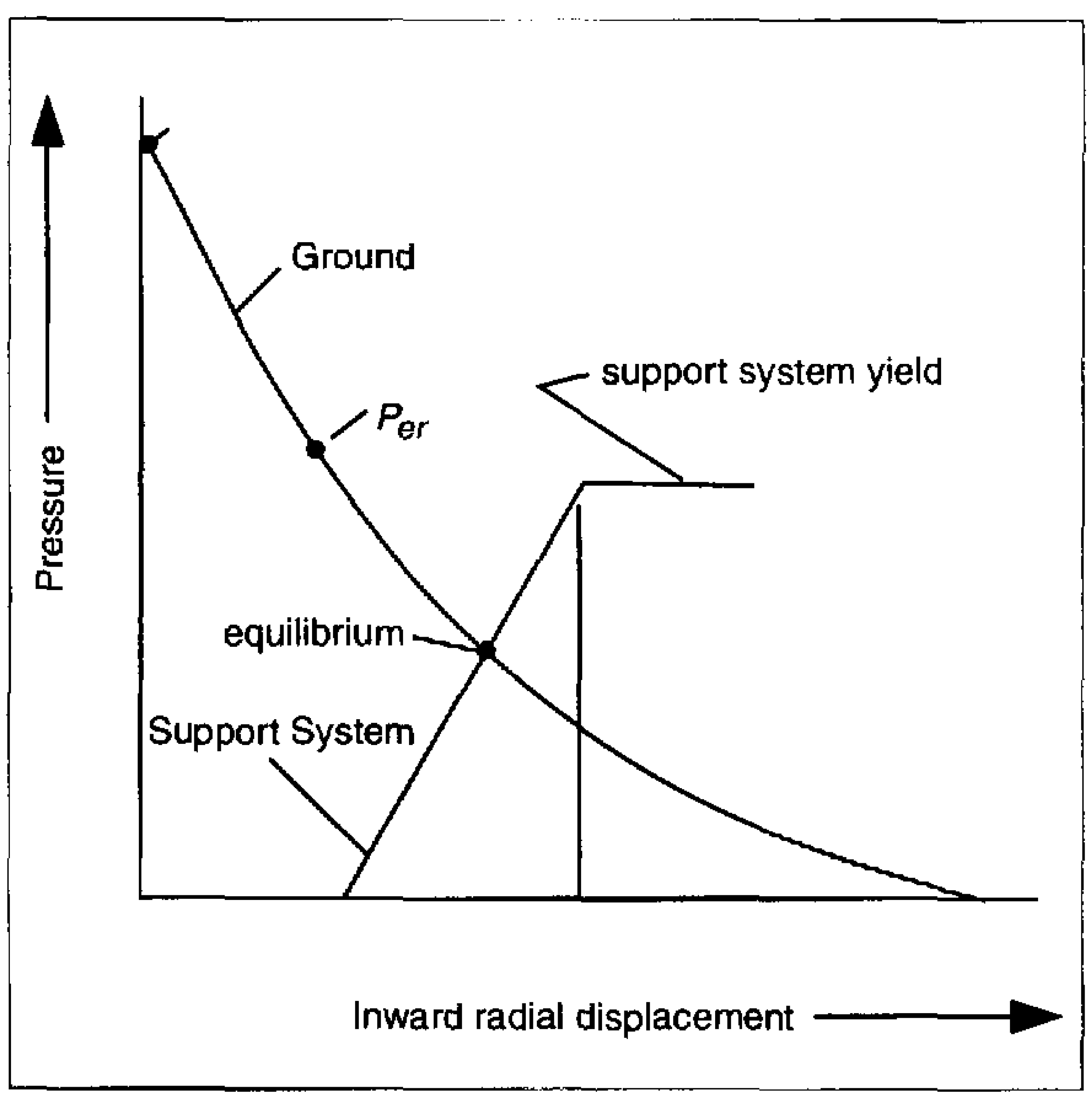

Figure 1. Response of support system – tunnel wall displacement.

DESIGN OF SHOTCRETE SUPPORT

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 (Figure 1). It is also important to recognize 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 analyzing its contribution to support. Current shotcrete support design methodology relies very heavily upon rules of thumb and precedent experience: Grimstad and Barton (1993) have published an updated chart relating different support systems including shotcrete and steel fiber-reinforced shotcrete (SFRS). SFRS cannot 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 FIBER-REINFORCED SHOTCRETE

Steel fibers are added to shotcrete to improve energy absorption and 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 fibers are available in different sizes, shapes, and qualities. The length of the fiber 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 fibers in the shotcrete matrix. A smaller diameter increases the number of fibers per unit weight and densifies the fiber network. The fiber spacing is reduced when the fiber gets thinner and the fiber reinforcement becomes more efficient. Tensile stresses induced in the shotcrete are transferred to the steel fibers 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 fibers. Hooked ends, enlarged ends, and crimped wire are different shapes that are available on the market. An efficient load transfer will result in a high tensile stress in a small diameter steel fiber. Efficient steel fibers need to have a high tensile strength to avoid fiber fracture. The steel fiber 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 has enhanced the need to develop high tensile steel fibers. Steel fibers with different sizes and shapes will all have their own effect on the shotcrete behavior and quality. The required steel fiber dosage to meet design and structural requirements has to be related to the steel fiber performance.

TOUGHNESS

In order to be able to quantify the benefits of fiber addition, a variety of different measuring systems have been developed in different countries. Most commonly used are flexural toughness systems that 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 behavior curve for SFRS, and the definition of the equivalent flexural strength according to the Japanese standard. For practical dosages of steel fibers (40-50 kg/m³ [67-84 lb/yd³]), the flexural strength of concrete is not at all, or only marginally, increased. The main reason for incorporating steel fibers in concrete is to impart ductility to an otherwise brittle material.

The beam test is not the most appropriate test to simulate the membrane action of an SFRS lining. A more appropriate test has been developed in France to measure the performance of an SFRS lining (Legrand 1984). A test slab of 600 x 600 x 100 mm³ (24 x 24 x 4 in.³) is supported on the four edges, and a central point load is applied through a contact surface of 100 x 100 mm² (4 x 4 in.²) (Figure 3). The load-deflection curve is recorded until a deflection of 25 mm (1 in.) 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 with a real tunnel lining much better than a beam test; the slab support on the four edges simulates the continuity of the shotcrete lining;

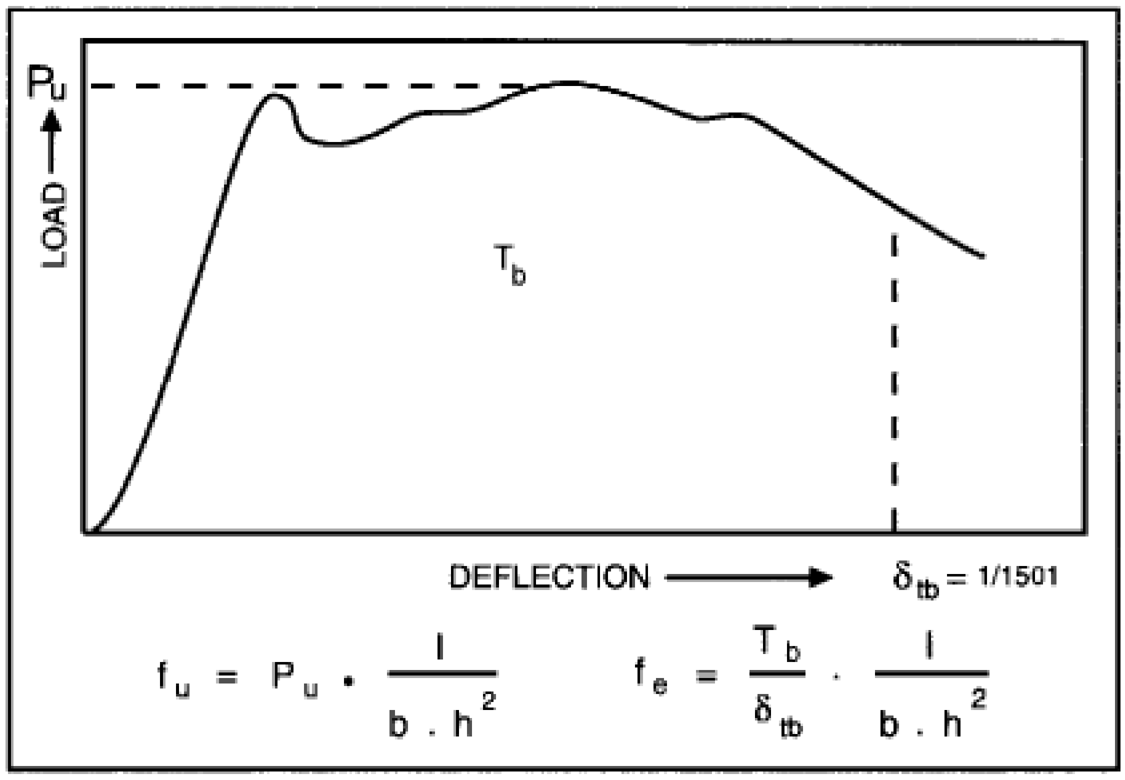

Figure 2. A typical load-deflection behavior curve for a SFRS and the definition of the equivalent flexural strength according to the Japanese standard.

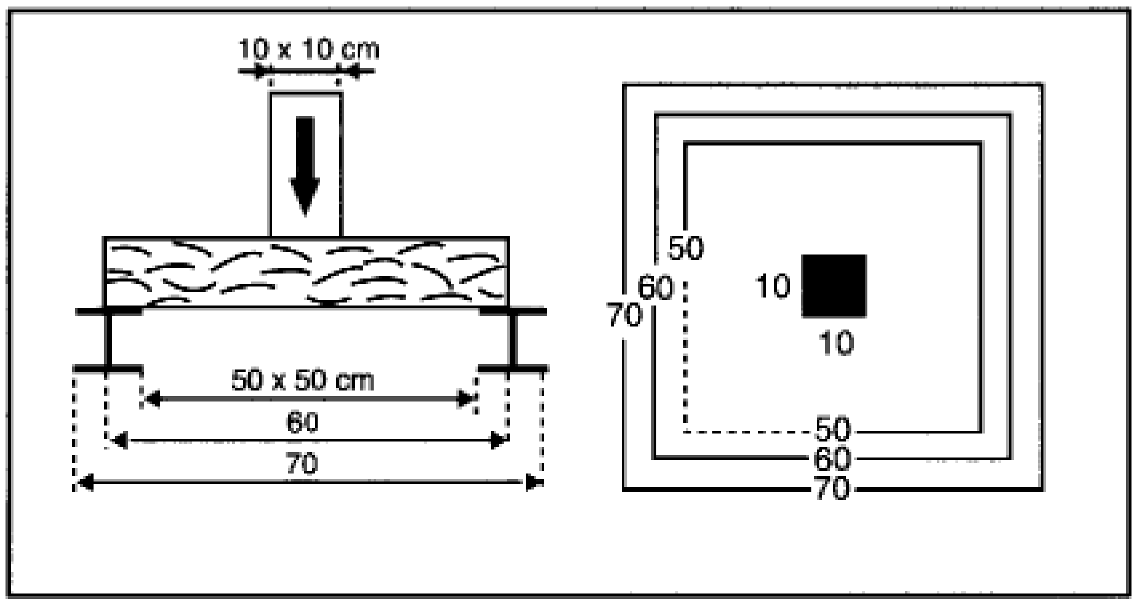

Figure 3. French slab test setup.

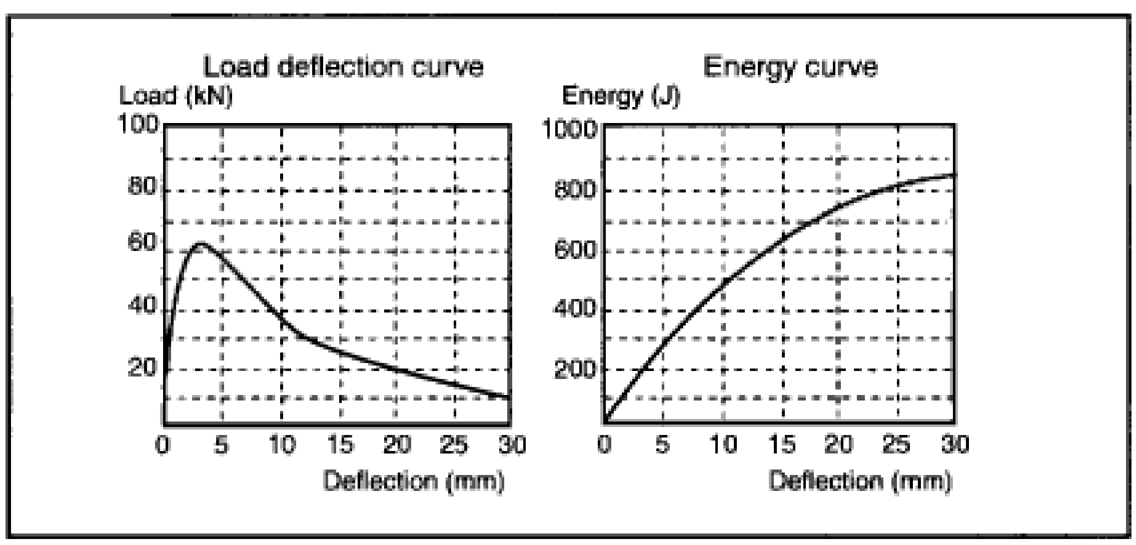

Figure 4. Load deflection and energy absorbtion curve.

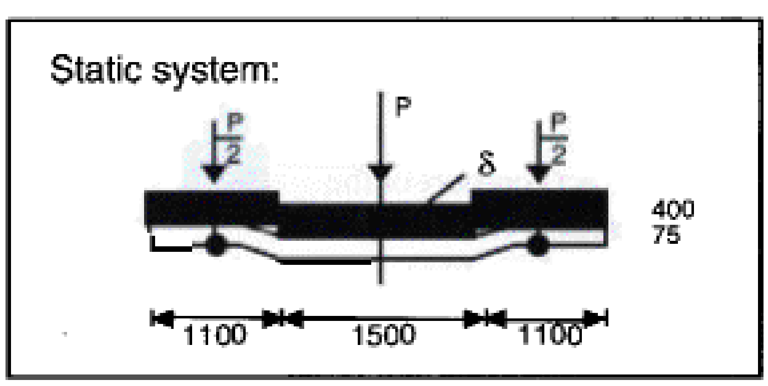

Figure 5. Falling block test.

- As in reality, steel fibers act in at least two directions—not just in one direction, as in a beam test; the fiber reinforcing effect in a slab is very similar to the real behavior of an SFRS lining;
- SFRS can be compared very easily with 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 fiber type (e.g., the aspect-ratio length diameter) and fiber dosage. The higher the aspect ratio and fiber content, the better the performance of the SFRS (Lambrechts 1996).

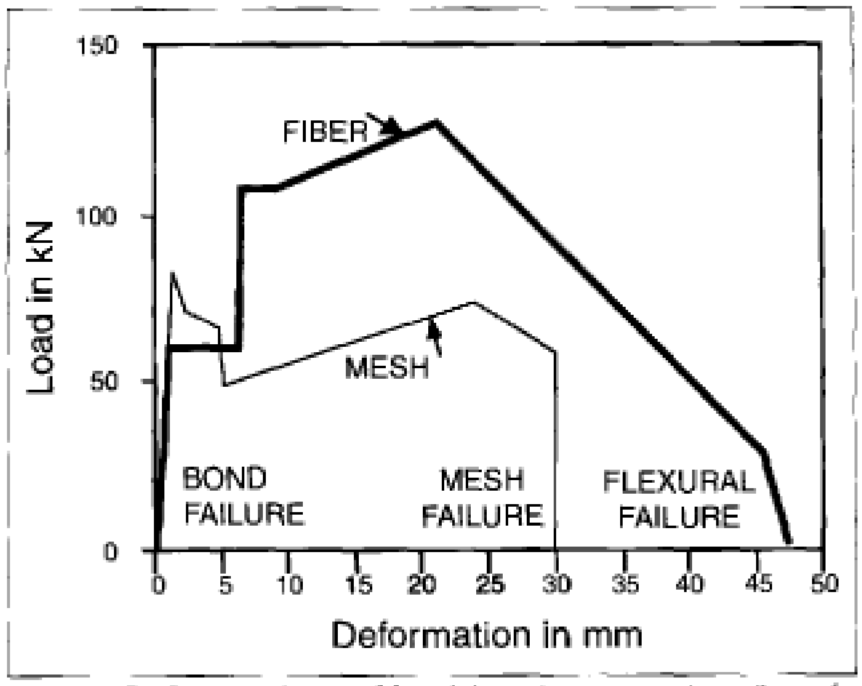

Figure 6. Comparison of load-bearing capacity of mesh reinforced shotcrete compared to SFRS.

INTERACTION WITH ROCK BOLTS

Comparative tests (Holmgren 1985) have been conducted on bolt-anchored shotcrete linings reinforced with steel fibers and mesh by the Swedish Rock Engineering Research Foundation (BeFo) and the Royal Swedish Fortifications Administration (FortF). 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 SFRS linings contained 40 and 50 kg/m³ (67 and 84 lb/yd³) of a hooked steel-wire fiber. Two mesh types were investigated: a cold-tensioned welded steel mesh with 5 mm (0.2 in.) bars spaced 100 mm (4 in.), and with a tensile strength of 500 MPa (72,500 psi); and an annealed welded steel mesh with 6 mm (0.24 in.) bars spaced 150 mm (6 in.), and with a tensile strength of 220 MPa (31,900 psi).

Figure 6 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 mesh-reinforced linings.

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, whereas 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 7).

Mesh-reinforced shotcrete requires 30 to 50 mm (1.2 to 2 in.) 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 even happen that the mesh remains uncovered. With SFRS, there is no longer a need to thoroughly encapsulate the reinforcing mesh with shotcrete. An improper nozzling technique can be costly as well. If the correct velocity 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 conditions, 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. Large aggregates

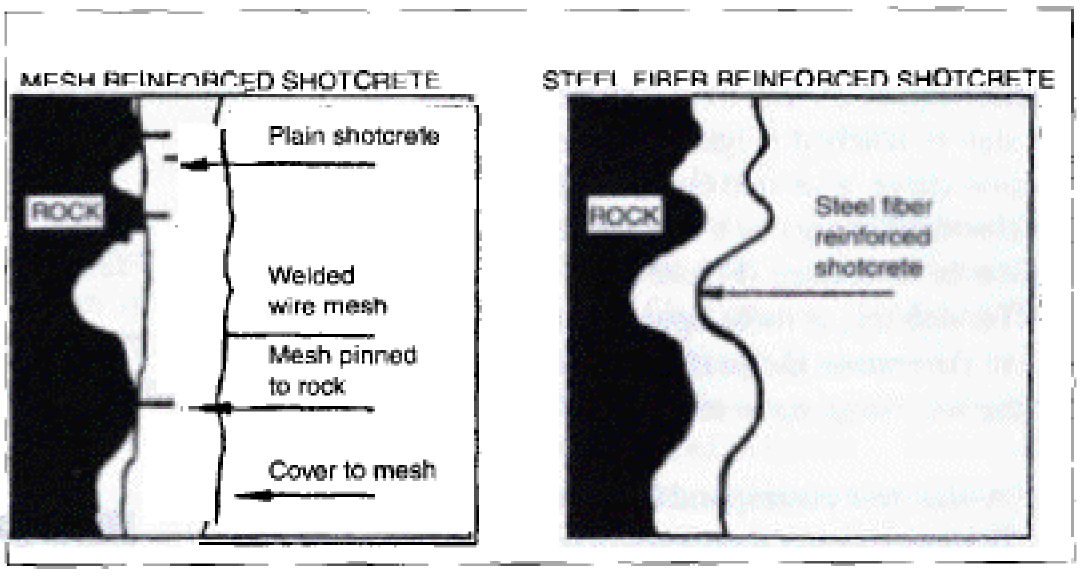

Figure 7. Comparison of a lining built up of mesh reinforced shotcrete vs SFRS.

hitting the wires make the mesh vibrate, which negatively affects the bond between the 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.

CONCLUSIONS

The normal approach to tunnel construction usually is:

- to produce a set of support designs covering the expected variation in rock mass quality;
- inside the tunnel, this support is to be installed according to the actual rock conditions;
- the installed support is monitored (observed) to check and verify that it behaves as presumed in the design;
- depending on the use of the tunnel and the requirements on the safety margins, sometimes an extra concrete shell is applied by spraying or pouring behind a formwork.

The support design, established before the start of the excavation, is principally a prognosis. All available tools can be used at that stage, depending on the complexity of the project. Analytical models are available for the first estimates. Actual tunnel lining design is commonly based on experience and empirical data.

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