# Shotcrete for Underground Support: a State-of-the-art Report with Focus on Steel-fibre Reinforcement

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***Abstract***—*This paper reviews current trends in shotcreting, primarily based on the Status Report of a Working Group of the International Tunnelling Association and the most recent U.S. Engineering Foundation conference on the theme (held in Uppsala, Sweden, in 1990). Of special interest is the increasing use of fibre reinforcement, which implies increased safety and substantial cost savings. The need for scientific collaboration and exchange of ideas between concrete and rock mechanics specialists is emphasized as a tool for a better understanding of the support behaviour of shotcrete linings.*

***Résumé***—*Ce rapport passe en revue les tendances actuelles des techniques de béton projeté, principalement fondées sur un rapport du Groupe de Travail de l'Association Internationale des Travaux en Souterrain et de la plus récente conférence de la Fondation Américaine d'Ingéniérie sur le thème (détenu en Upsalla, Suède, en 1990). Ce qui présente un intérêt particulier, est l'utilisation croissante du fibre renforcement, qui entraîne une meilleure sécurité et des économies en coût considérables. On insistera sur la nécessité d'une collaboration scientifique et d'un échange d'idées entre les spécialistes en béton et en mécanique des roches pour une meilleure compréhension des comportements en tant que support des revêtements en béton projeté.*

## 1. Introduction

Shotcrete for ground support is a very wide-ranging subject. Apart from typical questions related to general *concrete technology*, e.g., regarding mix design, the effects of additives, etc., it is also important to use *suitable equipment* for efficient and environmentally sound production of the lining. And, of course, *contractual arrangements* are essential to achieving a correct and economically justified use of this important element in rock tunnelling and mining. However, this paper deals primarily with the *structural behaviour* of shotcrete linings in different applications.

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### *1.1. ITA Working Group on Shotcrete*

The wide range of topics within the field of shotcrete was brought into discussion a few years ago at a meeting of the International Tunnelling Association (ITA), when it was proposed that a working group on shotcrete should be formed. Many countries showed a strong interest in the subject from various viewpoints and depending on their involvement in the technology. In 1988, the ITA established a Working Group on the Use of Shotcrete in Tunnelling.

Because active development of topics through international working groups is a difficult task, we started simply, with the compilation of some general information. The group has now published a Status Report on the use of shotcrete in tunnelling (Franzén 1991). The report includes national contributions in a comprehensible format, demonstrating today's technology in some fifteen countries and including references and abstracts of some important papers. The primary aim of the report was to review current activity in the field of shotcreting and to make it easy to find references and establish contacts with people or organizations active in this field.

The next task of the working group is to review guidelines or recommendations of various status that exist in some countries. A final draft report, (Malmberg 1992), which was discussed by the group in May 1992, may be used as a basis for some general and common guidelines. It is not altogether obvious, however, that such a document would serve totally beneficial purpose, as it might have a conservative effect on the development of the technology. In other words, the aim and format of such a document have to be thoroughly considered, at least before it is given any official status.

This report is largely based on the work of the ITA working group, as well as on information gained at the U.S. Engineering Foundation conference on shotcrete held in Uppsala, Sweden, in 1990 (Sharp 1992). In addition to these sources, several papers from journals and other conferences have been reviewed.

### *1.2. Few Scientific References on Shotcrete Support*

In trying to concentrate on the role of shotcrete as support, and more or less omitting other aspects (e.g., equipment and environmental issues), it is interesting to note that there is very little published in scientific journals on the real core of this problem, namely: *What is the actual supporting effect or behaviour of a shotcrete lining in cases where it is not evidently designed or functioning as an ordinary structural component, e.g., as an ideal arch or a beam with well-defined end supports and calculable loads?*

In the *International Journal of Rock Mechanics and Mining Sciences,* for example, only one article has been published during the last three years in which shotcrete is referred to in the title: "Support of weak rock with grouted bolts and shotcrete" (Stille et al. 1989). This article concentrates on bolts, but includes an analysis of the combined effects of bolts and shotcrete around a circular opening in a hydrostatic stress field. The results are compared and show good agreement with readings from instrumented bolts and extensometers in the Kielder experimental tunnel, which was excavated in mudstone. The analysis assumes a purely elastic behaviour of the shotcrete and takes into account the stiffness development at early stages, based on experimental results from Rokahr and Lux (1987), as shown in Table 1.

The importance of the early stage in supporting an advancing face is considered by Kielbassa and Duddeck (1991) in a paper in *Rock Mechanics and Rock Engineering,* in which the three-dimensional situation is analysed for determining realistic deformations of the ground and lining. An equivalent two-dimensional analysis is derived for technical applications and is given in diagrams. Hereby the effect of stress release is "at least approximately taken into account" and "the more relevant the stiffer the ground". The advancing face is also treated by Pöttler (1990) in *Computers and Geotechnics.* Still not published but underway at the Royal Institute of Technology, Stockholm, is work by Chang Yanting, who is performing laboratory investigations as well as further theoretical studies on the supporting effect of shotcrete at early age.

## 2. Ten Years of Important Development

Before we return to the key question of lining design, the general status of the technique and current trends over approximately the last ten years is briefly surveyed below.

### *2.1. Towards Wet Mix*

The 1980s witnessed very interesting and intense development and changes in the shotcreting technique in many countries. At the U.S. Engineering Foundation conference in Paipa, Colombia, in 1982, all of the papers were related to the traditional dry-mix technique, and just one paper dealt with fibre reinforcement (King 1985). However, at that time the wet-mix technique and steel-fibre-reinforced shotcrete (SFRS) were being introduced in some countries, and in Norway the wet-mix method already had achieved total dominance (Garshol 1992).

In Norway and Sweden, animated discussions took place concerning the quality aspects and environmental effects of the wet method in comparison with the dry-mix method. A great advantage of the wet-mix technique was the decrease in dust development; however, the final strength was less than that which could be obtained with the dry method. The counterargument was that the highest possible strength was not necessarily the ultimate goal, and other aspects became decisive in choosing the best method.

Though the issue remained unresolved through discussion, it ultimately was settled through experience. The Norwegians, who are active tunnellers (as evidenced by the fact that more than 100 km of tunnels are being built annually in a country of four million people) tend to take a pragmatic view of such matters. In short order, they switched over to the highly productive wet technique, which also provided a good basis for the development and use of fibre reinforcement.

*Table 1. Deformations at the rock surface according to Stille et al. (1989), analysis of results from the Kielder experimental tunnel, showing the influence of Young's modulus of shotcrete.*

| Type of Grouting (if any) | Measured | Calculated |
|---|---|---|
| Unsupported rock | 8 mm | 8.1 mm |
| Grouted rock bolt section | 4–5 mm | |
| Optimal action of the end plate | | 4.6 mm |
| Local deformation under the end plate | | 6.1 mm |
| Grouted rock bolt and shotcrete section | 2–3 mm | |
| Young's modulus applied to shotcrete, 20 GPa | | |
| Optimal action of the end plate | | 1.1 mm |
| Local deformations under the end plate | | 1.1 mm |
| Young's modulus applied to shotcrete, 2 GPa | | |
| Optimal action, end plate | | 2.6 mm |
| Local deformations under the end plate | | 2.7 mm |

### *2.2. Introduction of Steel Fibres*

As early as the 1970s, steel fibres were being proposed as a new technique for reinforcing shotcrete linings. The most obvious potential of this development was—and still is—to eliminate the heavy and time-consuming manual application of ordinary wire mesh, by replacing it with an immediate, mechanized and continuous production of reinforced shotcrete.

Pioneers to be mentioned in the development of this method are, in addition to Scandinavia, the Ruhr University at Bochum, Germany, where Professor B. Maidl early on encouraged research not only on "Stahlfaser Beton", i.e., steel-fibre-reinforced concrete, but also on shotcrete (see, e.g., Rapp 1979).

In Sweden, large-scale tests were performed in the late 1970s and included comparisons of steel fibres with mesh reinforcement, as shown in Figure 1 (Hahn and Holmgren 1979, Holmgren 1983).

Considerable research was conducted in the late 1970s in Canada, where dry-mix SFRS was used successfully in a large test chamber at the beginning of the 1980s (Morgan 1991).

As is typical when a new technique is introduced, the requirements for testing and verification of the features and capacity of the SFRS method were set much higher than for the established technique, which in this case was dry-mixed, conventional mesh-reinforced shotcrete. Authorities in Sweden and on the European continent demanded proofs of the function and quality of SFRS. Because there were few, if any, real specifications for the structural function of mesh-reinforced shotcrete, it was difficult to present relevant comparative tests or evaluations to convince clients and authorities that fibre reinforcement was an advantageous alternative (Bergfors et al. 1990).

Despite some resistance of this kind, as well as the naturally high costs in the initial stage, manufacturers of fibres and other enthusiasts persevered and soon had modified fibre types and shooting equipment for practical and efficient production. As a result, today the SFRS technique is accepted and used extensively in several countries.

### *2.3. Shotcrete Accepted as Final Lining*

Returning to the Paipa conference, it is also worth mentioning that the conference summary included the fol-

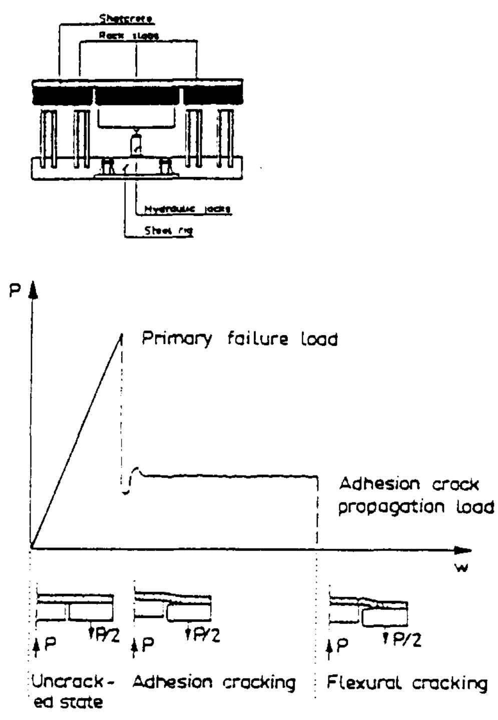


*Figure 1. Large-scale testing, simulating the load from a loose block, demonstrated the importance of adhesion between rock and shotcrete (Hahn and Holmgren 1979, Holmgren 1983).*

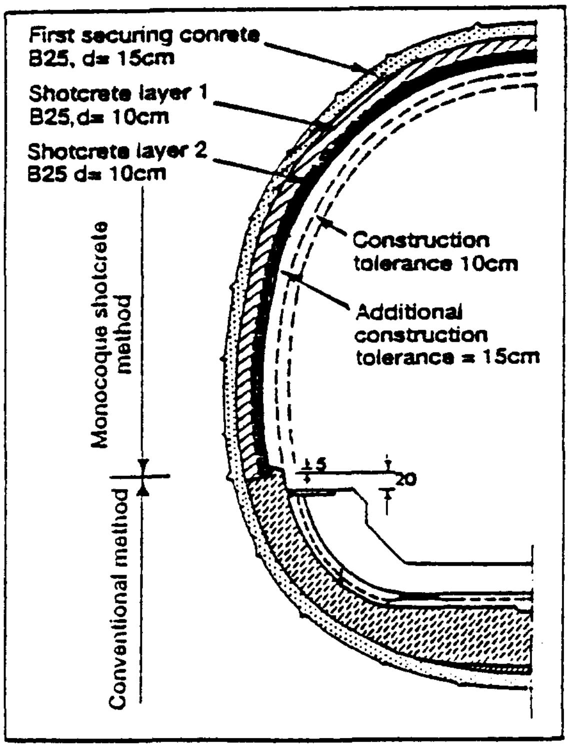


*Figure 2. Monocoque shotcrete lining for the Munich subway test line (Gebauer et al. 1991).*

lowing note: "The increasing use of shotcrete as a *final lining* for machine caverns, transportation tunnels and the lining of waterways, has been emphasized." (Sharp 1985).

Worldwide there have been, and still are, great differences in the local acceptance of shotcrete as a permanent lining for various applications. In Scandinavia, shotcrete has long been accepted, whereas the European continent has been more reluctant. However, it is interesting to note the extensive laboratory and field investigations now going on in Germany and Austria to test and evaluate single-shell shotcrete linings, as a technique to replace the conventional cast-in-place inner concrete ring (Haack 1989, Maidl 1991, Kusterle and Lukas 1990). A monocoque shotcrete lining for the Munich subway test line is shown in Figure 2.

## 3. Status of Shotcreting in Some Countries

As the Chairman of the ITA Working Group on Shotcrete Use, I would like to acknowledge all those who contributed to our Status Report. Some brief summarizing notes will serve to illustrate general trends today, as well as differences in practice throughout the world.

In 1985, the *Austrian* Concrete Society organised a working committee to compile their experience in shotcrete technology and to publish the results in the form of guidelines containing regulations for the planning and implementation of shotcrete work (Lindlbauer 1990). These guidelines were also published in English, which is of great value for the international exchange of ideas that may lead to improvements in techniques. A second part of the guidelines, on testing methods, is now being prepared.

In Austria at present, shotcrete is accepted and used as a permanent structural lining, e.g., in sewerage and district heating systems, as well as in diversion galleries and head race tunnels in hydro power plants. The choice between wet and dry mix is normally left to the contractor (Deix 1991).

In *Germany*, about 100,000 m$^3$ of shotcrete are produced per year, mostly by the dry method, which has been continuously developed to guarantee high quality (Hahlhege 1986). In connection with the expansion of the railway network, some investigations have compared the dry and wet methods (Maak 1986).

Special research programs have been performed regarding dust reduction; use of shotcrete under compressed air conditions (Schreyer 1982); effects of fires on permanent shotcrete linings; and, as mentioned above, steel-fibre reinforcement (Maidl and Koenning 1992, Ziegler 1991).

In *Switzerland* (Fechtig 1991), a series of research reports was published during the 1980s by the Institute for Planning and Construction Management-ETH, Zürich, regarding adhesion to rock; influence of low temperature; influence of aftertreatment; and the carbonisation of shotcrete, which is a complex and important question (Furrer 1990).

From *Italy*, it is reported that the wet process now dominates, representing 90% of a total volume of 160 000 m$^3$. A fair amount of this—some 25,000 m$^3$—is fibre-reinforced (and this percentage is forecasted to reach 60% within a couple of years). Silica fume has been introduced, and a working group on shotcrete has been established, with a wide representation from different parties involved in the technique (Tesio 1991/1 and /2).

In *France*, steel fibres have been used since about 1985, and were accepted for the final lining of a road tunnel in 1990 (Legrand 1991). A working group has been formed with the objective of updating a document published in 1974. To be included are recommendations on the use of fibre reinforcement, including a suggested test method explained in section 5.2, below.

From *Spain*, positive experience with SFRS is reported. In addition to the generally improved strength properties, an increased resistance against fatigue (on the order of 50–60 times!) has also been observed, which is of interest for long-term performance (Martinez 1991).

In *Belgium*, a research program is being performed at the Belgian Building Research Institute in cooperation with the N.V. Bekaert Company,a manufacturer of steel fibres. Special attention is being given to the influence of fibres (and silica) on the rebound (Dierckx 1991). Mention should be made of the book *Tunneling the World*, recently published by Vandewalle (1991), which contains a comprehensive survey of shotcreting technology, emphasizing the possibilities and advantages of steel-fibre reinforcement.

As noted above, the *Norwegians* use the wet-mix method predominantly, producing 30 000 $m^3$ to 40 000 $m^3$ of wet-mixed shotcrete annually. They have also carried out large-scale testing and have been involved in some of the Bekaert tests, which have been performed as a continuation of the original Swedish program (cf. Opsahl 1982, Skurdal and Opsahl 1985).

A new committee has been formed in Norway to update earlier recommendations, with special attention to the specification of SFRS.

Based on field and laboratory investigations, *Finnish* guidelines for shotcreting were published in 1988, and were summarized in English (Põllä 1991, 1992). The guidelines emphasize that they are not written with the intention of limiting further development of the technology. Rather, they are to be considered recommendations only, and have no "official" status, so that clients may feel free to use their own specifications for particular jobs.

The Finnish guidelines include recommendations regarding blasting near young shotcrete. They suggest that blasting not be allowed until 60% of final strength is obtained; and that peak particle velocities not exceed 10 mm/s within 3 days, 35 mm/s within 7 days, or 110 mm/s thereafter. However, these figures are more or less rules of thumb, and are not based on scientific evidence. For temporary support (provided that accelerators are used), the guidelines suggest no restrictions for 12 hours after shotcreting.

Finnish practice today includes wet mix and fibres, which have been accepted in civil engineering since the guidelines were published. However, when fibre reinforcement is used for structural support, e.g., for civil defence shelters, it is accepted only after governmental approval is given.

In mining, the wet-mix method has been used since the 1970s.

In *Sweden*, the annual production of shotcrete is estimated at 55 000 $m^3$, most of it wet mix today. Nearly half of the production is in the mining sector. Steel fibres are now used on many sites, and some studies have been performed to demonstrate its function (see below). In connection with the improvement of the railway network, (which will include a fair amount of tunnelling) and other infrastructure developments, increasing interest has been shown in developing accurate specifications for shotcrete.

In the *U.K.*, traditions for tunnelling in loose ground emanate from more than a century of continuous development of the underground railway network in London, tunnels for which normally were lined with steel or cast concrete segments. New experience has been gained in connection with the large-scale U.K. undersea crossover portion of the Channel Tunnel (Fugeman et al. 1991, Myers 1992). As a result of the successful completion of this work, shotcrete linings are being used and planned for several new rail and road tunnels in England (Watts 1991).

The report from *Japan* (Fukuchi 1991) includes an interesting overview of Japan's geological origins and relevant features that influence tunnelling in different regions of that country. Japan's annual production of shotcrete is estimated at 1–2 million $m^3$, 65% of which is wet mix. Fibre reinforcement still accounts for only a minor share of the shotcrete work (1987). Standard mix proportions are given and mechanization and automation are cited as important issues. A working group within the Japan Tunnelling Association is active in the field.

According to the ITA Status Report, *South African* practice differs from that of most other countries, primarily because of low labour costs and comparatively high prices on imported products such as steel fibres. Thus, the dominant practice involves hand-sprayed dry mix with weld mesh for reinforcement. There are specifications for training and testing of operators, who must meet certain required qualitative skill levels for hand-held spraying.

About 30 000 $m^3$ of shotcrete are produced annually in South African mining and civil projects. A working group has been established to develop national specifications, which today to a large extent follow U.S. and Canadian practices. Silica fume is currently specified in major civil works.

A special Steel Fibre Testing Program is being launched. The program will include long-term evaluation of fibre shotcrete in a water transfer tunnel (strength and corrosion), which thus far (after more than three years) has shown good performance (McKelvey 1991).

Experience from wet-mix shotcrete and fibre reinforcement in South African mines has been reported by Redford and Alexander (1992).

In the *U.S.*, there is still considerable use of traditional dry-mix shotcrete, but the trend is towards the wet method (Parker 1991). Steel fibres have been used successfully on some sites, although the use of fibres as a substitute for wire mesh is not universally accepted by clients and engineers. Shotcrete is sometimes accepted as final lining; however, it is used primarily for temporary support. There are exceptions: for example, SFRS was used for permanent support in a 10.4-m-wide flood control tunnel in Harland, Kentucky. Another application of shotcrete is in the rehabilitation of railroad tunnels throughout the western United States. Typically, such a wet mix design calls for 420–450 kg of cement per cubic meter, 47–60 kg 25-mm steel fibres, microsilica at 10% by weight of cement, superplastiziser and 2% silicate-based accelerator.

The ACI (American Concrete Institute) has a shotcrete committee, and a new subcommittee of the ASTM (Association for Testing Materials) has been established to develop test methods and standards for shotcrete.

*Canadian* practice is well described in the ITA Status Report and also in a paper presented at the Fifth U.S. Engineering Foundation Conference (Morgan 1991, 1992). In general, wet mix, silica fume and fibre reinforcement are well established methods and are widely used in most applications. Positive results from field and laboratory experiments have supported this development. Typical mix design for different application types is given in Table 2.

## 4. NATM

Any survey of shotcrete must make reference to the New Austrian Tunnelling Method, or the "NATM philosophy". Although there is some argument as to whether the method is truly Austrian and whether it it is truly New, the fact remains that it has achieved a worldwide reputation, primarily because of its undisputable merits. However, NATM has also been (ab-)used as a general, more or less unspecified name for "shotcreting in tunnelling". It is therefore often necessary to point out that the NATM is not merely a special shotcrete technology, but a high-standard tunnelling technology specially adapted for critical conditions.

The basic concept is based on the supporting effect of a lining which gradually deforms and balances the ground movements after a tunnel is excavated. The idea is best demonstrated by the Ground Reaction Curve Concept (Brown et al. 1983), which is also the core of the so-called NATM (see Fig. 3). It should be observed that the concept as such need not necessarily involve any shotcreting at all, even though it often does.

Whether this method is referred to as NATM or not, the fact is that this technique, which often includes shotcrete as an important support member (in combination with a rather so-

*Table 2. Characteristics of different mixes according to Morgan (1992).*

| | Dry-Mix Shotcrete | | | | | Wet-Mix Shotcrete | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Matrix Type | Plain | Silica Fume | | | | Plain | Silica Fume | | | |
| Fibre type | Nil | Nil | Hooked end | Corru-gated | Corru-gated | Nil | Nil | Hooked end | Corru-gated | Corru-gated |
| Fibre content, kg/$m^3$ | 0 | 0 | 60.0 | 60.0 | 75.0 | 0 | 0 | 60.0 | 60.0 | 75.0 |
| Compressive strength, MPa 7 days | 44.5 | 42.5 | 42.4 | 43.0 | 43.0 | 44.5 | 50.3 | 46.4 | 48.3 | 44.7 |
| 28 days | 49.6 | 51.9 | 55.9 | 60.0 | 58.0 | 55.8 | 65.7 | 65.0 | 66.6 | 66.1 |
| Flexural strength, MPa 7 days | — | — | 5.4 | 4.9 | 5.1 | 5.1 | 5.4 | 5.2 | 4.8 | 4.6 |
| 28 days | — | — | 7.9 | 8.0 | 7.4 | 6.0 | 6.9 | 6.6 | 6.7 | 5.9 |
| Toughness Index, 7 days: ASTM C1018 $I_5$ | — | — | 4.4 | 2.7 | 4.1 | — | — | 4.8 | 3.4 | 3.4 |
| $I_{10}$ | — | — | 6.2 | 3.6 | 6.7 | — | — | 7.2 | 5.2 | 5.2 |
| Toughness Index, 28 days: ASTM C1018 $I_5$ | — | — | 2.2 | 2.1 | 2.8 | — | — | 4.3 | 2.2 | 3.4 |
| $I_{10}$ | — | — | 3.1 | 2.3 | 4.0 | — | — | 6.4 | 3.2 | 4.6 |
| Boiled | — | 6.7 | 7.0 | 6.6 | 6.9 | 6.8 | 6.7 | 7.8 | 6.3 | 7.6 |
| Absorption: % | — | 14.8 | 15.6 | 14.7 | 15.4 | 14.8 | 14.7 | 17.3 | 14.1 | 17.2 |
| Rebound (&) Vertical | 35.0 | 21.6 | 22.1 | 24.5 | 26.7 | 3.4 | 5.4 | 6.0 | 6.0 | — |
| Overhead | 54.6 | 26.6 | 28.5 | 30.5 | 32.8 | 8.9 | 10.3 | 14.9 | 10.3 | — |

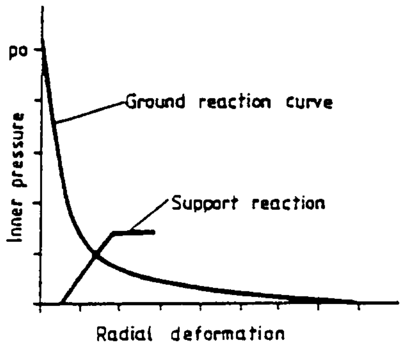


*Figure 3. The Ground Reaction Curve illustrates the inner support (p) needed to balance the ground pressure after excavation, when the tunnel contour is deforming.*

phisticated monitoring system) is gaining ground around the world. Examples of the method outside the European continent may be found in Japan and the U.S. (e.g., the Washington Metro). And following on its acceptance is an increasing amount of shotcrete being produced and a generally increasing interest in the whole "science" of shotcreting and the behaviour of such linings.

With reference to Austria, mention should be made of a publication (translated into English) describing experiences from the construction of the Vienna Metro system. Here, the traditional NATM philosophy was routinely used, but some "avant-garde experts' thoughts" are also included—for example, the idea of replacing the normally used light steel beams or lattice girders with SFRS (Braun 1991).

## 5. Steel-Fibre-Reinforced Shotcrete for Underground Support

The fibre shotcrete technique *per se* is well known. This method has many advantages in comparison to traditional mesh reinforcement. Production of this type of shotcrete is better accommodated in the tunnelling cycle because it eliminates the time-consuming application of wire mesh. It is also possible and easy to adapt the lining design to the actual conditions with regard to geometry and geology. This means that there will be little difficulty in

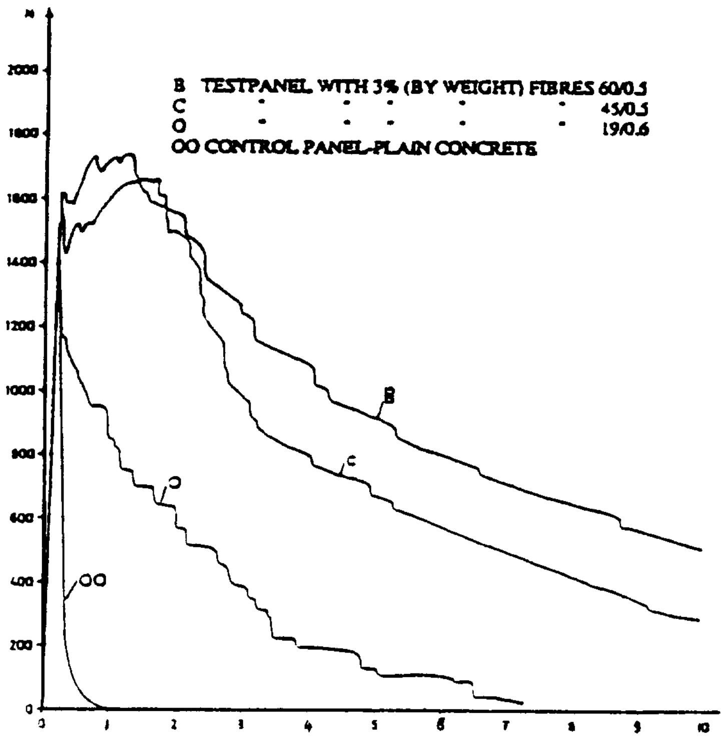


*Figure 4. Load-deflection curves of steel-fiber shotcrete with different lengths of fibers (Östfjord and Emt 1986).*

| Make | Shape | Type |
|---|---|---|
| Bekaert | | ZP 30/50 |
| Bekaert | | ZP 30/80 |
| ILM | | 25/60 |
| ILM | | 25/90 |
| Fibrocev | | 22 |
| Fibrocev | | 30 |
| Harex | | 1 - 32 |
| Draco | | 30/80 |
| Edilchem | | 20 |
| | | 30 |

*Figure 5. Examples of different fibre types that have been developed to achieve a good anchorage in the concrete matrix (from Tesio 1991/2).*

specifying, either before or during the operation, the composition and thickness of the lining and applying it at the right moment—provided that we know why and how to support a section of a tunnel or drift with fibre shotcrete. Thus, the major questions are: *Why do we support our tunnel? What characteristics or properties do we wish to obtain and include in the lining system?*

My goal is not to answer this question in any detail, but to point out some of the properties inherent in fibre-reinforced shotcrete that may be relevant in a design situation.

### 5.1. Fibres in the Matrix

Steel fibres, evenly distributed in the shotcrete matrix, result in a material that is ductile, tough and shock resistant—properties of clear importance for support applications (see Fig. 4).

To guarantee the anticipated quality at reasonable cost, it is important that the rebound not contain an overrepresentation of fibres. Although this has been a problem in the past, today's equipment and spraying technique are—within certain limits—capable of controlling the fibre content in the very lining. Of course, specific procedures are needed to check the obtained quality *in-situ*. This is a broad subject in itself, and will not be dealt with in this paper.

### 5.2. Testing of Toughness

Specifying requirements for the strength of fibre shotcrete is a delicate issue. The crucial questions are what kind of function is needed in terms of rock support, and what are the relevant test procedures. Toughness is of interest because it may prevent a progressive failure after initial fracturing in connection with deformation of the rock.

Toughness testing of steel-fibre-reinforced concrete has been specified according to ASTM, and is often referred to for steel-fibre-reinforced shotcrete as well (ASTM 1989). Briefly summarized, the test is carried out on beam samples sawed from a test panel using three-point loading. The method relates the post-failure energy to the elastic stadium before observation of the "first crack", according to a certain definition. Dimensionless toughness indices are then calculated and related to different deformation stages, as shown in Figure 6.

A similar evaluation of a test beam is specified in Japan, resulting in an "equivalent flexural strength" value. In France, a method has been proposed, based on testing of a 60-cm by 60-cm slab, which takes into account the two-dimensional effects of the fibres (Fig. 7).

It should be pointed out that these criteria need not necessarily be relevant, unless they are clearly related to some expected behaviour of the lining in its anticipated function as rock support. Discussions about the best criteria to use are now underway in different countries and committees, and it is hoped that these discussions will result in some consensus in the near future (Malmberg 1992, Kompen 1992).

### 5.3. Comparison with Mesh Reinforcement

As long as we lack complete or satisfactory knowledge, there is still a need to find some way of specifying fibre shotcrete. One possibility is to make simple and straightforward comparisons of mesh-reinforced linings, with an anticipated position of the mesh in the lining, e.g., in either an ideal or some typical or "average" position. The moment-bearing capacity can then be calculated theoretically.

This has been done by Vandewalle (1991), who presents tables to find the equivalent of a defined mesh-reinforced section, such as those as shown in Figure 8. He also has introduced an interesting way of comparing different fibre types and dosages, based on a reference test series that has measured the toughness properties and calculated the corresponding indices. The concept of "Identity Charts" seems useful and could be further developed as a guide for selecting from among different fibre types, etc.

Comparative calculations have also been done by Stille (1992), including evaluations of earlier large-scale test results, which show a good consistency with the calculations.

The criteria mentioned herein all assume that the mesh reinforcement used as reference is a relevant design. Normally the mesh ends up, somewhat randomly, in what will be the compressed, tensioned or neutral layer of the lining. We seldom know if there is

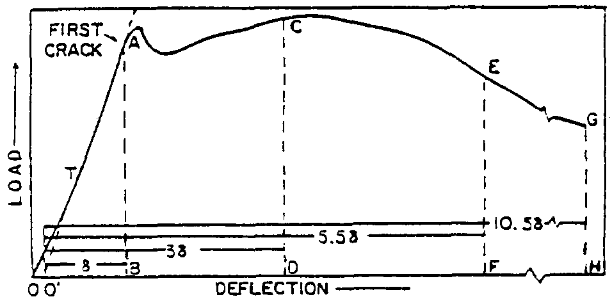


*Figure 6. Load-deflection curve according to ASTM (1989). Toughness index I is defined as the numbers obtained by dividing the area up to a specified deflection by the area up to first crack. ($I_5$ relates to $3\partial$ and $\partial$, $I_{10}$ to $5.5\partial$ and $\partial$, etc). Because the evaluation of the energy (equivalent area) up to first crack is very sensitive to the measurement of $\partial$, and, consequently, to the accuracy of the testing equipment, it has been suggested the use of an alternative index $R_{30/10} = 5(I_{30} - I_{10})$, which would be 100 for a perfect elasto-plastic material.*

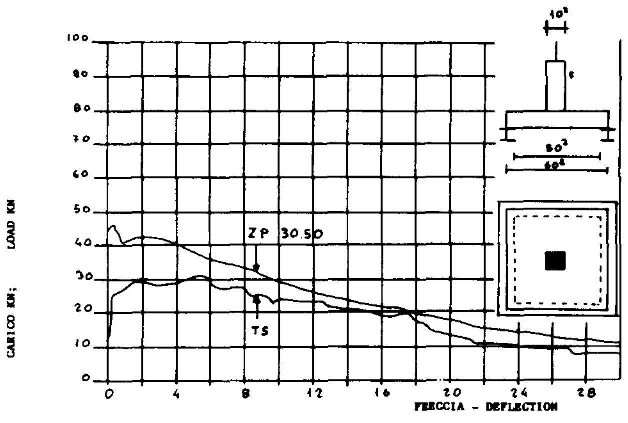


*Figure 7. The French testing method is based on centric loading of a square test specimen (Roux et al 1989).*

a positive or negative bending moment in a certain section of the lining. Therefore, the minimum bearing capacity of the mesh after first crack failure may be reduced to its membrane or suspension effect, as for various types of mesh often used in mining without any shotcrete and fixed with rock bolts. While this effect should not be neglected, it represents a minor secondary support after the first deformations have occurred. In addition, and as Holmgren (1985) has observed, the effect cannot even be fully utilized because remaining shotcrete on the mesh limits its free length of tension.

Accurately applied fibre reinforcement will provide continuous reinforcement over the whole cross-section of the layer. Thus, without any deeper analysis of the possible failure mechanisms, an even distribution of fibres in the matrix means a positive contribution to the strength, whether the requirement is bending, shear or shock resistance—provided, of course, that the amount and type of fibres are accurate.

Based on today's situation, a forecast could well be made that sooner or later, the old technique—i.e., utilizing conventional mesh reinforcement—will not be accepted in connection with support of irregular rock surfaces. This is not primarily because it represents a heavy and laborious technique; nor because it requires a skillful nozzleman to achieve a good quality application, without voids behind the bars; nor even because of the problems of dust and rebound associated with it. Rather, the main problem lies in its unsatisfactorily defined appearance. We continue to lack a firm and relevant basis for the design of mesh-reinforced shotcrete in the way it is conventionally used.

The situation can be further illustrated with reference again to the pioneering research accomplished by Hahn and Holmgren (1979) and later confirmed by others performing similar tests (Opsahl 1982). Their work demonstrated that the adhesion of shotcrete to the rock was a decisive parameter for the primary failure (in that specific loading case, as shown in Fig. 1). Designing for that stage means that reinforcement is not needed, or that it is put in as a safety margin for a secondary stage after bond failure. Hence, we must identify the next loading stage (or, rather, deformation stage) and find relevant design properties, safety margins, etc., for it (see Figs. 9 and 10).

### 5.4. Other Design Properties

Other design aspects, such as shrinkage cracking, are also influenced by fibres. Cracks will be evenly distributed and their widths small. This is beneficial for several reasons, not the least of which are increased water-tightness and less corrosion, as investigated e.g., by Hoff (1987), referred to in (Morgan 1992). Because they restrict early shrinking, fibres may also have a positive effect on the bond to the rock surface.

These characteristics are important, especially for the civil engineering sector using fibre shotcrete for permanent structures. Future case records regarding long-term performance will be of great interest for verification of what to date has been investigated mainly in laboratories. Many of these aspects fall primarily within the area of concrete technology. The same is true for the positive effects and widespread use of microsilica as an additive or substitute for some of the cement in shotcrete (see, e.g., Morgan 1992).

## 6. Conclusions

The increasing use of fibre-reinforced shotcrete, today often sprayed with wet-mix equipment, must be regarded as a welcome development. This very flexible composite material is most favourable because it adjusts easily to irregular rock surfaces, i.e., configurations where we will never be able to determine or control in any detail the actual loading case. Thus, it implies an *increased safety* (for example, when used in combination with rock bolting); and when used in place of cast concrete, it can result in substantial *cost savings*.

Research in this area will never come to an end, because an ultimate

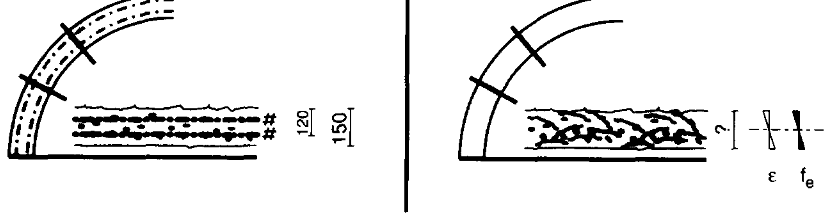


*Figure 8. Schemes for comparison of mesh reinforcement with fibres are presented in Vandewalle (1991), based on the Japanese "equivalent flexural strength" concept. Thus a corresponding thickness of SFRS can be calculated.*

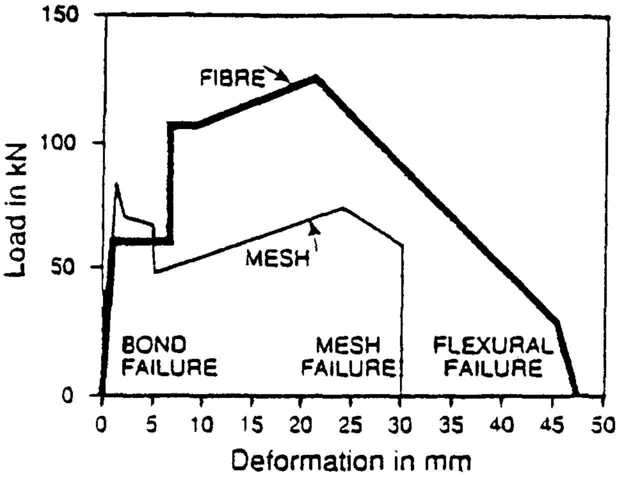


*Figure 9. Typical failure modes from large-scale laboratory testing, simulating the load of a loose block (Vandewalle 1991).*

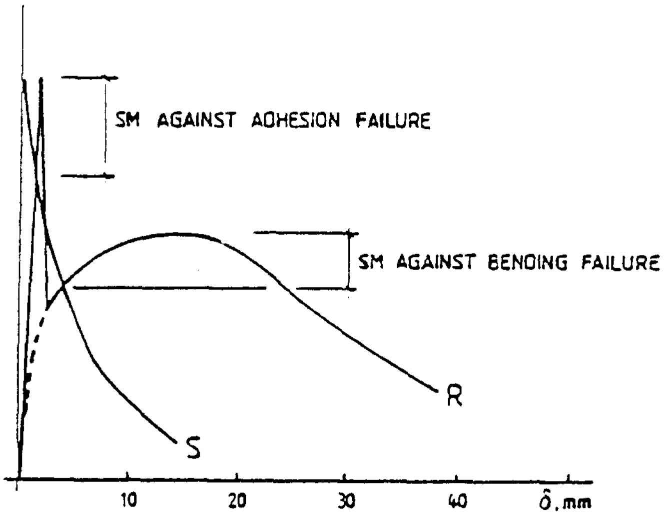


*Figure 10. A development towards relevant design criteria has been suggested by Stille and Franzén (1992), based on the Ground Reaction Curve philosophy and the resistance behaviour of different types of support.*

truth will never be found. Rather, further research will continue to improve our knowledge of this complex subject. Because the science of shotcrete involves many different aspects, it is suggested that research on "the concrete technology of shotcrete" be performed primarily by concrete specialists, and that the knowledge on supporting effects be furthered primarily through rock mechanics. It is most essential, however, to establish a forum for the exchange of knowledge and to find a "scientifical meeting point" between these two disciplines to enhance our mutual understanding.

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