ITA/AITES REPORT 2006 on

Shotcrete for rock support

A summary report on state-of-the-art

presented by ITA Working Group N°12 "Shotcrete Use"

PART B – CONTRIBUTIONS FROM NATIONAL GROUPS

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INTRODUCTION

The International Tunnelling Association (ITA) Working Group 12 on Shotcrete Use was formed in Toronto, Canada, in 1989. The Group's first task was to issue a status report on shotcrete technology in different countries. The report "Shotcrete in Tunnelling – Status Report 1991" [1] was published as a first result of this effort. The report contained a brief presentation of the status in some fifteen countries, including references to current developments, existing guidelines and local working groups. Bibliography and abstracts covering major papers were also included.

The next step was to compile a comprehensive report on national codes and standards and guidelines and recommendations in use. The Swedish national group of ITA took on the responsibility of compiling this report with Bo Malmberg, M.Sc., as the author. The report was ready end of 1992 and contains 83 pages covering contributions from 15 countries [2].

The compilation of guidelines and recommendations was also presented in a paper in Tunnelling and Underground Space Technology in 1993 [3].

What has happened within the shotcrete technology after 1993 is the focus of this new State of the Art Report. The further development of national codes and standards and guidelines and recommendations has not been specifically addressed this time. One reason being that documents with a wider basis are now available or under preparation. The already published EFNARC technical specifications and Guidelines is one example, but the new European Standards will also soon be ready. Two parts under prEN 14487, seven parts under prEN 14488 and prEN 934-5 are planned for publishing in 2004 and 2005. In North America the ACI Shotcrete Guidelines will soon be ready as well.

With this background the WG12 meeting held in Durban 14 and 15 May 2000, decided to produce a new State of the Art Report to supplement the now more than 10 years old first Reports. There has been a rapid development within several aspects of shotcrete for rock support and it was considered helpful for many interested parties in the industry to get information about the current status. The Report has been worked out by summarizing and referencing contributions submitted by ITA National Groups, members of the WG12 and by organizations and individuals submitting information of value for the task at hand.

The following key issues were highlighted in the invitation and request for input to WG12:

We want to document current usage of shotcrete in underground excavations and also as far as possible to show development trends within all sides of this technology.

The main aspects to cover under the above heading are:

- Temporary and permanent tunnel linings
- Method of reinforcement
- Method of application:
  Including type of equipment, manipulators, accelerator dosage systems, concrete batching and transport, accessories like nozzles, compressors, hoses etc.
- Materials technology:
  All concrete components including accelerators, admixtures, and additives with concrete property parameters achieved from batching through to hardened state. Information regarding shotcrete durability.

- Codes and standards:
  Which specification documents are being used, are there new under development, experiences made, comments about suitability and suggested improvements.
- Design; rock and shotcrete interaction, established limitations of usage

There are probably more issues that could be mentioned, but the above list is general enough to cover the most important ones and it is not meant to be excluding. Submittals are invited as National contributions as far as this is possible, but supplements in the form of selected and recommended papers and reports are also welcome. It is a priority to receive submittals providing a good geographical coverage and the form of submittal therefore has second priority. The final Report will be quality assured by review among WG12 members, before publication.

In total, 21 countries have contributed to this report. However, the received documents cover a very wide range, from a short note stating that the activity within underground rock support is very low, until 20 page documents and more.

Quite some effort has entered into getting a broader base of contributing countries, by repeated email, telefax and postings on the WG12 Private Forum (ITA web-site). This Report has about 40% more contributors than the first one, but many important countries and regions are still missing.

The Working Group 12 decided in its Amsterdam meeting in 2003 to integrate the Report on Sub-Task 3 (shotcrete and rock interaction, support mechanisms of shotcrete) into this State of the Art Summary Report. This has been done by appending the report named “Design of Shotcrete Support”, compiled by Japan. Also appended is the report submitted by France, “Design of Underground Support Systems made with Sprayed Concrete”.

OVERVIEW OF CONTRIBUTIONS RECEIVED

Twenty-one countries have sent information contributing to the Report. The content varies in length and scope between short notes and extensive detailed reports. In short, WG12 has received the following contributions:

- Australia: A two-page presentation given by the Australian Shotcrete Society [A1].
- Belgium: Three different papers have been received, primarily covering aspects of steel fibre reinforcement in shotcrete [B1, B2 and B3].
- Bulgaria: A very short information notice about low activity in the field of tunnelling and shotcrete for rock support in the country. No technical information provided.
- Brasil: A three-page presentation covering temporary and permanent tunnel linings, shotcrete materials, standardization and rock mass – shotcrete interaction [BR1].
- Canada: Four pages suggesting to clarify the distinction between placement of shotcrete and application of shotcrete. Furthermore, the contribution presents shotcrete usage in mining in Western Canada and in the Sudbury Basin. The use of boltless shotcrete in mining is described [C1].
- Czech Republic: Has delivered a six-page contribution describing general shotcrete usage, following the outline given by the WG12 for Task 1. Most of the suggested themes have been covered [CZ1].

- Denmark: A three-page presentation of the shotcreting works carried out in Copenhagen Metro [D1].
- Germany: A five-page paper covering developments in German tunnelling technology over the last 20 years was actually submitted by one of WG12's Swiss participants. However, the paper being about German tunnelling technology and written by a German author, the liberty has been taken to include it as a German contribution [G1].
- Greece: The country has submitted a paper titled "Comments on the draft National Specification for Sprayed Concrete and relevant proposals based on quality control data from the surveillance of Sprayed Concrete application in Athens". The paper is 6 pages and presents suggestions regarding how to take samples for quality control and testing [GR1].
- Italy: A SIG National Working Group Report with a good coverage of the most important issues of shotcrete usage in Italy. The contribution contains five pages following the outline given by WG12 [I1].
- Japan: A Japan Tunnelling Association Shotcrete Working Group contribution containing a comprehensive seventeen-page coverage of the Japanese shotcrete market. The special aspects of shotcrete methodology in Japan are well illustrated. Also the new airless spraying method is presented [J1].
- Korea: A three-page contribution has been received, giving an overview of the extensive tunnelling in South Korea and the development of shotcrete for rock support for this purpose [K1].
- Lesotho: A ten-page paper on the Matsoku Diversion tunnel has been submitted. The paper gives an in-depth presentation of the use of shotcrete at this 5.6 km tunnel project (part of Lesotho Highlands Water Project) [L1].
- Mexico: A two-page report presenting the current usage of shotcrete in Mexico with a focus on the need to bring more users up-to-date with modern shotcrete technology [M1].
- North America: "Guide Specification for Shotcrete for Underground Support" under preparation by the ACI 506 Shotcrete for Underground Support Committee. This is a comprehensive document covering all aspects of shotcrete usage of more than 100 pages in total. Because the document is the only all-inclusive comprehensive guide of this kind submitted to the WG12, it belongs in a different class than the other submittals and is therefore discussed under separate heading in this report [NA1].
- Norway: Contributions have been received in three steps. The final document contains seven pages, where the first two are summarizing the current status of shotcrete usage in tunnelling and the next 5 pages give highlights about eight different tunnel projects. One of them is the World's longest road tunnel [N1].
- Russia: A short two-page activity summary has been submitted with some comments on technical issues [R1].
- S. Africa: The twenty-page document gives a comprehensive presentation of shotcrete in deep level hard rock mining, rounding it off with three selected practical examples. The section about identified support mechanisms of shotcrete deserves special attention and credit, for being highly useful and educational [SA1].
- Sweden: Has submitted two papers on the Southern Link road tunnel project and the main document contains eight pages primarily about rock support and shotcrete. There is also a section about blast vibration effects on shotcrete and research on shotcrete durability and corrosion problems [S1].
- Switzerland: A set of five project-description papers has been submitted, covering a range of practical shotcrete application examples [CH1, CH2, CH3, CH4 and CH5].

- Turkey: A five-page paper describing the Bolu Tunnel project has been submitted. The paper compares wet mix shotcrete with two different types of accelerator and the influence on long term Young's modulus and compressive strength [T1].

1. GUIDELINES, SPECIFICATIONS, STANDARDS

1.1 Statements from the contributing countries

1.1.1 Australia

Australia has presented in their contribution one truly significant development in relation to testing and specifying the properties of fibre reinforcement in shotcrete. The statement reads: "Another significant Australian development related to shotcrete has been the development of the Round Determinate Panel (RDP) test in 1997. This test was developed as specification T373 by the RTA of NSW as their preferred method of post-crack performance assessment, and following its introduction and use during construction of the M5 East Motorway tunnel in Sydney it has become the pre-eminent means of assessing performance in Fibre Reinforced Shotcrete for both civil and mining projects. It is also used extensively for the development of new fibres and admixtures for shotcrete on account of the low within-batch variability typical of results using this test. The round panel test has been developed into a standard test method within the American Society for Testing and Materials (ASTM) and will be published in November 2002. Other testing standards used in Australia are the EFNARC panel and beam test, and the ASTM C-1018 beam test."

It is interesting to note that in Australia Quality Assurance systems previously typical for only civil construction projects have also been adopted by many mines after 1990. Since large rock deformations are common in many mines, the RDP test to check on post crack behaviour of the shotcrete layer was quickly accepted for performance assessments. Typical level of failure energy according to the RDP test has been 300 to 500 Joules (typically equal to 600 to above 1000 Joules in EFNARC panel tests).

1.1.2 Belgium

Belgium (like Australia) is making reference to the EFNARC panel test for ductility testing of fibre reinforced shotcrete. This test method was first developed and suggested by SNCF/Alpes Essais (France) and have received wide recognition world wide. The EFNARC organization has approved this method and included it in its Technical Specifications and Guidelines for Sprayed Concrete and it is also included in the new European Standard for Sprayed Concrete (as stated in the Belgian contribution). Normally, three different performance classes are recommended, depending on the quality of the ground: 500 – 700 or 1000 Joules.

A quick presentation of older testing methods that were based on different types of beam tests, conclude that these are less appropriate for simulation of the membrane action of thin layers of fibre reinforced shotcrete. The development the last few years seems to confirm this view (EFNARC test and RDP test, both based on panels and center point deflection). In support of this view the Belgian contribution states: "The slab test is much more appropriate than the beam test to determine the performance of a SFRS:

1. A slab corresponds much better than a beam with a real tunnel lining; the slab support on the 4 edges simulates the continuity of the shotcrete lining.

2. As in reality, steel fibres act in at least two directions and not just in one direction, which is the case in a beam test; the fibre reinforcing effect in a slab is very much similar to the real behaviour of a SFRS lining.
3. SFRS can be compared very easily with a mesh reinforced shotcrete to be tested in the same way."

1.1.3 Brazil

Brazil is in the final stages of publishing national recommendations for shotcrete: "ABNT – the Brazilian Association for Technical Norms – is responsible for the preparation of standards in the Country. In recent years, 9 standardizing texts have been produced about shotcrete, including guidelines, testing methods and procedures for placement. Feedback from construction works has shown the need to produce texts to spread the use of shotcrete.

For that purpose, the technical committee CT-306 was established 3 years ago by ABNT and IBRACON – the Brazilian Concrete Institute. A "Shotcrete Manual" is being prepared, including several aspects related to the material, such as: application, processes and equipment, component materials, mix design, properties and characteristics, quality, performance, health and safety.

After publication of the Manual, the committee will pursue the production of texts related to testing methods.

1.1.4 Czech Republic

The Czech Republic standards CSN 73 2430 (Construction and Inspection of Sprayed Concrete Structures) and CSN 73 2400 (Construction and Inspection of Concrete Structures) are currently in use and have not been revised in the past years. However, European standards are increasingly being used and the details will depend on the project requirements and the owner in question (rail or road authority etc.) along with the opinions of the consulting company being used.

1.1.5 Denmark

Denmark has given the complete list of codes and standards used at the Copenhagen Metro project, primarily German and European Codes:

"DIN 267 Fasteners and similar parts technical specifications generalities
DIN 488 Reinforcing steel, definitions, quality requirements, identification marks
DIN 1164 Portland -blast furnace -pozzolanic cement, definitions components, requirements, delivery
DIN 4100 Welded steel structure with predominantly static loads; proof of competence to weld structural steel work.
DIN 18200 Control (quality control) of construction materials, construction components, and construction designs, general principles.

DIN 18800 Steelworks.

DIN 1045/EVN 206 Structural concrete.
EC 2 Design of concrete structures.
EC 3 Design of steel structures.
EN 196 Methods of testing cement.
EVN 10080 Reinforcement Steel.

Guideline Shotcrete "Final Draft" Issue 20. February 1997, Austrian Concrete Society.

1.1.6 Greece

Greece has submitted a paper starting with the following Summary: “The present paper deals with factors affecting the performance and quality of spayed concrete based on the experience of sprayed concrete application in Construction Works, mainly tunnels, in Athens/Attika. The national Specification for sprayed concrete in Greece is still in draft form and it follows the philosophy of the Concrete technology Regulation (CTR-97). The authors propose changes with respect to quality control after the application of the sprayed concrete.”

The authors are pinpointing the fact that sprayed panels (that everybody knows will be tested) can be manipulated. Even if this is not happening, they still report a wide variation in quality parameters depending on the nozzleman and the equipment (using the same mix design). One of the most important influence factors reported is the variation in accelerator dosage.

It is concluded and suggested to only use conformity criteria based on cores drilled from the structure. One additional reason mentioned is the fact that curing conditions may vary and frequently no special efforts are made in this respect. This can cause another difference between the shotcrete in the tunnel and panels that are being treated with water for curing.

The final paragraph sums it up quite well:

“The results show that:

a) Accelerators affect seriously the 28 days strength by reducing it by 25 to 30 MPa.

b) The standard deviation of 28 days strength is related to the use of the accelerator by the nozzle-man.

The lack of adequate curing conditions in the tunnel reduces the 28 days strength by 5 MPa. The moisturizing methods inside the tunnels are not easy to apply. A solution would be the use of curing materials on the wet mix but it still is an expensive solution in Greece.”

1.1.7 Italy

Italy has its own official national shotcrete standard: “Owing to the lack of a standard specification, in 1989 SIG (Società Italiana Gallerie) issued a guideline for the production and control of shotcrete, which was similar, in its application method, to the relevant DIN norm and to the AFTES guideline, ten years later, prompted by SIG, it has been issued the official Italian standard: "**Calcestruzzo proiettato UNI 10834 -99**."

We want to draw attention to the praiseworthy initiative introduced by the **Italferr**, the consulting engineer of the Italian Railway (FS) which has inserted in its standard specification the control of the shotcrete production process, planning the various controls by means of a Quality Control programme.

This control programme includes the material qualification phases as well the study of the mixture, the application and the controls on strength development.

This production process control is included in the Quality Plan for tunnelling in compliance with Quality Assurance.”

1.1.8 Japan

Japan presents the following information about codes and standards:

"(1) JAPANESE STANDARD FOR MOUNTAIN TUNNELLING –The 5th Edition. This standard was published by (c) Japan Society of Civil Engineers in 1996, where standard mix proportion, recommended materials, suitable devices and so on are announced for tunnel constructions. There is also an English version.

(2) Guideline to execution of tunnel concrete (draft). This guideline was published by (c) Japan Society of Civil Engineers in 2000, which deals with not only shotcrete for tunnels but also tunnel lining concrete. In this guideline, especially focused on long-term durability.

(3) Guideline to design and execute high quality shotcrete (Shotcrete to be applied viscosity by mixing fine powder components). This guideline was published by Japan Railway Construction Public Corporation in 1996. In this guideline, low rebound shotcrete is interpreted, which is so called "high quality shotcrete". It is essential for high quality concrete to improve viscosity by mixing silica-fume and limestone powder. It can also improve strength of shotcrete.

(4) A guideline on countermeasures to dust in tunnelling. This guideline was published by the Ministry of Health, Labour and Welfare, in 2000. The guideline recommends the maximum dust concentration value should be less than 3.0 mg/m^3 in order to prevent pneumoconiosis."

1.1.9 Norway

Norway has had national Guidelines for shotcrete application dating back to the 1970s. The current status is: "The guidelines "Sprayed Concrete for Rock Support" were reviewed in 1993, revised in 1999 and are under revising in 2003."

2. DESIGN

The subject of tunnel support design is a complicated one and the subject is treated more in depth in Appendices 1 and 2 to this Report. There are still some relevant comments in the received submittals that are directly linked to shotcrete design considerations that we therefore include.

1.2 Statements from the contributing countries

1.2.1 Belgium

"One of the main breakthroughs was the change in mentality when designing a tunnel. Observational methods, such as NATM (New Austrian Tunnelling Method) and NMT (Norwegian Tunnelling Method), are <u>strengthening</u> the underground to become self supporting instead of <u>supporting</u> the rock mass above the tunnel opening.

This of course made it possible to build underground constructions in a much more economical way and much faster than what was done in the past.

Shotcrete has become a standard technique and is used as a major tool to stabilize the rock in the early stage of the tunnel construction.

Shotcrete has a double effect; it glues the loose pieces of rock together forming a continuous outer shell and it develops strength in order to control and support the rock in it's early movements. Both effects contribute to create a new equilibrium and to help the rock to become again self supporting."

1.2.2 Brazil

Brazil seems to support the ideas presented above, but is also showing that there are diverging opinions:

"There has been a wide variety of assumptions regarding the role of the rock mass when designing permanent lining, as already mentioned in item 2. However, it is worth mentioning that some agencies and engineering companies have developed designs based on assumptions that have led to very economic linings.

These assumptions not only have taken into considerations the proper interaction with the rock mass, but also the role of the primary lining in the evaluation of the long term safety.

A recent comparison of single-shell tunnels constructed in the 80's in Brazil and in Germany (Franzén & Celestino, 2002) showed much more economic designs in Brazil. However, as mentioned before, this is not a generally accepted rule and the design criteria of the forthcoming Line 4 of she São Paulo Subway disregards the role of the primary lining for long term purpose."

At this point it seems appropriate to diverge from the alphabetic listing and insert a statement found in the Norwegian submittal (since it also specifically links design and economy, involving shotcrete for rock support):

"In the context of road and rail tunnels, the Norwegian Method of Tunnelling, NMT is a collection of practices that produce dry, drained, permanently supported and "lined " (fully cladded) tunnels for approximately USD 4,000 to USD 8,000 per meter (1996). These low-cost, high-tech Norwegian tunnels may range in cross-section from about 45 m^2 to 110 m^2 for two-lane roads and three-lane motorways. The Q-system is the most commonly used design method. The updated Q-system of rock mass classification (revised 1994 and 2001) and use of seismic investigations, is used in NMT, consisting of high quality robotically applied steel fibre reinforced sprayed concrete and corrosion protected rock bolts. Cast concrete linings are not used unless rock conditions are exceptionally poor and concrete is needed locally for stability against squeezing or swelling rock. (Gol, 1996)."

1.2.3 Czech Republic

Czech Republic highlights the importance of proper geological conditions knowledge, which is combined with FEM calculations to determine allowable deformations. The design will then specify lining convergence over time and this is combined with models for the strength and stiffness increase of the applied shotcrete layer. Also normal NATM approach is sometimes used and these tunnelling methods are prevailing over the use of TBM for design and excavation.

1.2.4 South Africa

South Africa has included an excellent presentation with good illustrations of supporting effects arising from the placement of shotcrete in underground excavations. A proper understanding of these basic mechanisms is the very foundation of any design work and is included in full below:

"At deep level, the rock surrounding any opening is almost certainly fractured immediately upon excavation, due to the high stress levels. In many mining situations, these stress levels will change over time as a consequence of changing mining geometry. In addition, rock surface temperatures at these depths are high. Therefore, any shotcrete used will be applied to a hot surface of fractured, possibly broken rock, and it will often be subjected to increasing levels of stress after application. Further, the shotcrete may be subjected to dynamic loads due to seismicity, and also to mechanical damage caused by machinery and equipment. This paints an extremely severe picture (which is not unrealistic), and it is therefore of value to consider the requirements that might be demanded of such support. It can be envisaged that the shotcrete support will be subjected to a variety of different types of loading and deformation, and will have to withstand these with a variety of behaviour mechanisms.

It is considered worthwhile for this report to summarise mechanisms of behaviour of shotcrete support, and mechanisms of loading of this support (Stacey, 2001a). These mechanisms might occur individually and in combination. The identified mechanisms of support behaviour, which are illustrated in Figure 2-1, are:

- Promotion of block interlock: the effect of this mechanism is the preservation of the rock mass in a substantially unloosened condition. There are several sub-mechanisms involved in the promotion of block interlock: the interlock that is promoted by the bonding of the shotcrete to the rock, and the tensile strength of the shotcrete, preventing shear on the interface and restricting block rotation (a); the development of shear strength on the interface between the shotcrete and the rock as a result of irregularity of the interface surface (b); the penetration of shotcrete material into joints and cracks (c), which will inhibit movement of blocks, which is particularly relevant in very high stress situations in which some loosening and stress fracturing will have taken place (d); prevention of block displacement by two mechanisms – the shear strength of the shotcrete (e), and the tensile strength of the shotcrete (f).
- Air tightness: for a rock mass to fail, dilation must take place, with opening up occurring on joints and fractures. If such dilation can be prevented, failure will be inhibited (g). Coates (1970) suggested that, if the applied surface support is airtight, entry of air will be prevented or limited, and hence dilation will be restricted. This mechanism is identified as a contributory support mechanism by Finn et al (1999). Although this is unlikely in a static loading environment, in dynamic loading situations, in which rapid entry of air into the rock mass will be restricted, it is possible that air tight shotcrete might promote stability.
- Structural arch: deformation of the rock mass induces stresses in the support, which then resists further deformation of the rock mass (h). Important in this structural mechanism is the strength of the shotcrete and its flexural rigidity.
- Basket mechanism: when the surface support develops the form of a basket, which then contains the failed rock, it will be acting mainly in tension. In this situation there are three considerations: firstly, the flexural rigidity or ductility, which will serve to resist the deflection of the liner to form a basket; secondly, the tensile strength of the shotcrete itself; and thirdly, in the case in which there are two constituents, such as mesh or fibre reinforcing in shotcrete, both the tensile strength of the matrix material and the tensile strength of the cracked matrix. In this case, the behaviour of the reinforcement is

particularly important - it may undergo material yield or, more importantly, the liner may yield by progressive pull out of the reinforcement elements from the matrix material.

- Slab enhancement: slabs or incipient rock slabs, formed under high stress conditions, may fail due to buckling. The application of shotcrete support effectively decreases the slenderness of the slab and increases its buckling resistance (j).
- Beam enhancement: this is similar to slab enhancement – shotcrete support on the underside of a roof beam may enhance the bending performance, and hence stability, of a roof beam.
- Extended "faceplate": shotcrete support will extend the area of influence of rockbolt and cable faceplates (k).
- Durability enhancement: some rock types deteriorate on exposure and when subjected to wetting and drying, and the mechanism of the shotcrete support is to seal the rock to prevent exposure and hence preserve the inherent strength of the rock.
- Mechanical protection: this is an extremely important mechanism, since mechanical damage will quickly destroy the effectiveness of shotcrete support.

The most common mechanisms of surface support loading, which are illustrated in Figure 2-2, are:

- Wedge and block loading: when a block or wedge of rock is defined by fracture or joint planes, it may displace and load the liner locally. With "rigid" and bonded liners, shear stresses will be induced in the shotcrete along the perimeter of the block (a). If breakdown of the bond occurs, the mechanism will tend towards a localized or point load acting on a "basket" (b). These loading mechanisms can be both static and dynamic.
- Distributed surface loading: shotcrete support is subjected to a distributed load imposed by the rock. The retention of the shotcrete will generally be by point supports provided by rockbolts and face plates. The distributed load may be due to several alternative situations: failed rock, under the action of gravity (static); squeezing rock conditions, due to high stresses or swelling (static); rockburst loading - about a 1m thickness of fragmented rock is often ejected at high velocity during rockburst events (Ortlepp and Stacey, 1993). Distributed loading causes the shotcrete to provide support with a basket mechanism. Localised deformation may occur at locations of fractures and rock joints, which will particularly be the case when the shotcrete is well bonded to the rock surface, and when the roughness of the rock surface prevents shear on the interface. In such cases the value of high quality bonding between shotcrete and rock is questionable. A lower quality bond, which allows yield and shear displacement on the interface, may be preferable.
- Stress induced loading: well bonded shotcrete will be subjected to the same deformations as the rock. It may be stiffer, or more brittle, than the jointed, fractured rock mass, and therefore may fail prematurely under the imposed deformations. Shear (c), bending (d), buckling (e) or tension, or more complicated failure mechanisms, such as combinations of these, and possibly others, may also occur. The result could be stress induced spalling of the shotcrete (f).
- Water pressure loading: water pressures will be distributed pressures which may be sufficient to fail undrained shotcrete support.
- Bending loading: in mining excavations it is very rare that support is installed in the floor, with the implication that support tends to be installed in the roof and sidewalls only. The result is that, although deformation may be contained in these three areas, the floor may deform freely. The consequence could be greater convergence at floor level than roof level, and hence bending loading on the shotcrete, particularly in the haunch areas (g).

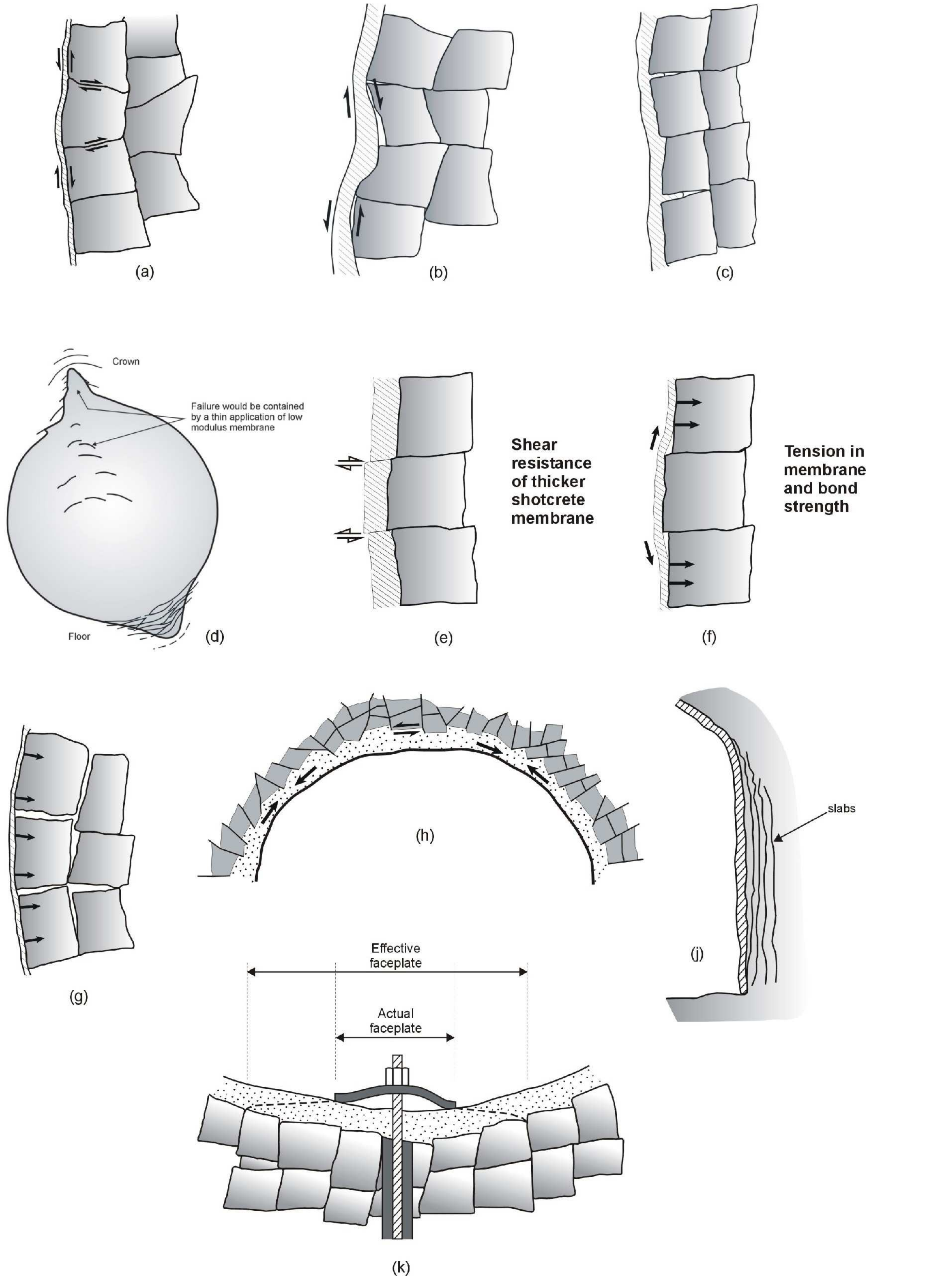


Figure 2-1: Mechanisms of shotcrete support behaviour

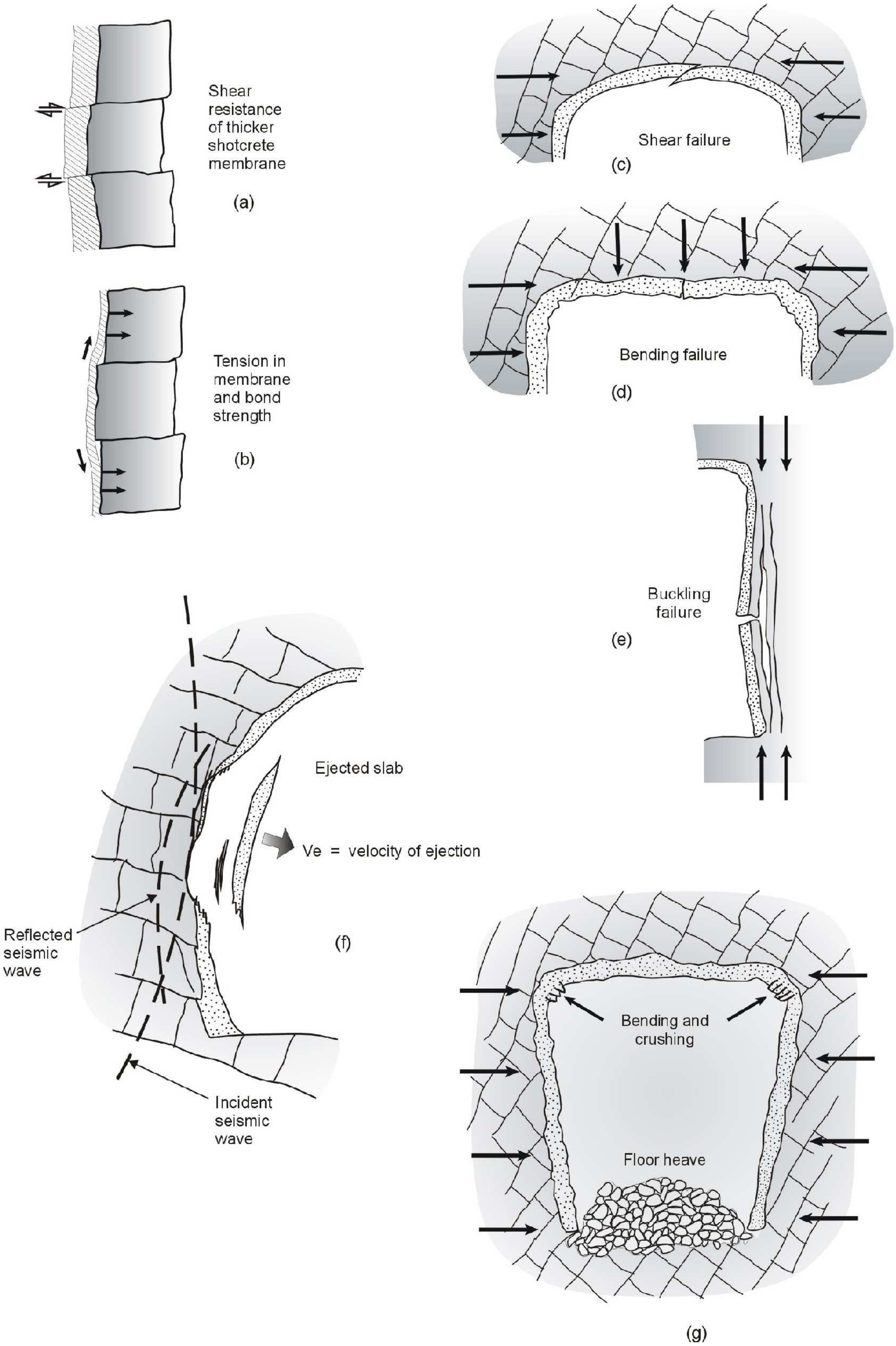


Figure 2-2: Shotcrete support loading mechanisms

It is important to highlight several effects of the above loading mechanisms:

- Localized deformation of shotcrete support may lead to localized failure. The localization of deformation of well bonded shotcrete may result in failure after very small local "opening";
- The shotcrete is one component of the support system, which usually also includes rockbolts. The interaction between the shotcrete and the rockbolts is extremely important. The behaviour of the rockbolts influences the behaviour of the shotcrete and may dictate the characteristics desired of this support.

It is probable that all of the above mechanisms of behaviour and of loading are applicable in a hostile mining environment, the implication being that very severe requirements will be demanded of shotcrete support, and it will be subjected to very severe loading."

1.2.5 Sweden

Sweden presents the following about design issues: "There are still no specific national standards for sprayed concrete, but authorities and clients make their own specifications, and again the Southern Link where the National Road Administration is the Client, is a good illustration of today's normal practice. The criteria for strength and stability are still much based on experience and rock classification, but extended with design considerations for certain loading cases and assumptions.

The interaction between rock and sprayed concrete in supporting a deforming rock mass is a very complex system, which is governed by the magnitude of displacements, the strength and elasticity properties of both rock and concrete, and their interaction. Many researchers have been trying to learn more about this and to describe the mechanisms, to arrive at a better basis for the design. There is still a lot to do as we probably over-reinforce parts of our tunnels today. The complexity of the system and the variations of rock conditions make it very difficult to come up with any simple design rules. Either we have to accept the uncertainties and apply reasonable safety factors, or we have to use more sophisticated design criteria based for instance on probabilistic considerations. Awaiting any major steps in that direction, it is most valuable to learn more about single components of the supporting system.

That is why large scale laboratory tests were done in Sweden already in the 1970-80s, which demonstrated the importance of bond between rock and shotcrete for the support of possible loose blocks in a hard rock mass. These findings resulted in requirements on adhesion strength and a general concern about cleaning rock surfaces before spraying, to achieve as high bond as possible. Recently, high-pressure water jet cleaning, up to 22 MPa, has been tested with positive results at the LKAB iron ore mine in northern Sweden.

Further considerations about the support system and the interacting mechanisms under different geological conditions, have been presented e g by Stille 1992. Some theoretical studies have also been performed to investigate whether the use of partial coefficient methods could be a feasible way to treat the stochastic character of many of the governing parameters.

In parallel with trying to understand the behaviour of the system as a whole, we are now performing further laboratory tests in a doctorate project at the Royal Institute of Technology. Here the bearing capacity of fibre reinforced shotcrete as one component of the system is being tested and the results are compared with a proposed calculation model. Preliminary results from this project were presented in Hobart, Australia, last year (Nilsson, Holmgren

2001). The tests were performed on circular fibre reinforced shotcrete panels (actually cast concrete in the first test series). The aim was to test a proposed calculation model, base on yield line theory.

The main conclusion was that the calculation model had to be considerably modified to take into account the actual boundary conditions of the tested slabs, which were arranged to simulate the real situation. The first calculations showed to highly underestimate the bearing capacity, because the fixed support of the slabs meant that a "compressive arch action", even for these fairly thin slabs, had a dominating effect, which had to be taken into account. Thus, the tests revealed factors of great importance that had not been fully realised when the calculation model was first proposed. Later calculations, where the "dome effect" was included, have now demonstrated good agreement with the test results."

3. CONCRETE TECHNOLOGY

1.3 Statements from the contributing countries

1.3.1 Australia

"Accelerated wet mix shotcrete is increasingly the preferred choice for ground support in mining and civil construction work in Australia. In the majority of civil sites and mines, alkali free accelerators are used due to the stringent Occupational Health and Safety practices typical of the Australian workplace.

These accelerators can be divided into the two groups, 2nd generation or normal performance alkali-free, and third generation high performance alkali free accelerators. Three international admixture producers support these markets. There is also a very small residual amount of alkali and sodium silicate accelerators being used, on a dwindling number of project sites. The reasons appear to be tradition more than performance, with the contractors preferring to use what they are used to, what they have had no problems with, and from a cost perspective.

Among batch plant (pre – mix) admixtures there is work going on to reduce expensive Silica Fume from the mix and to utilize man made or manufactured sands and aggregates for cost and environmental reasons. Pumping aids, are not new and are used in some instances, though a properly designed mix is the first priority. Non ideal mixes can be assisted with these aids, but these are predominantly used in lower specification work where durability is not a major concern.

Almost all shotcrete produced for mining and civil construction industries contains some form of set stabilizer / hydration control admixture for up to 4 hours control in normal applications. Along with this they would use a high range water reducer /superplasticiser to control water demand, as most contractors prefer reasonable slump, low water cement ratio shotcrete to control the dose rates of accelerators to the minimum."

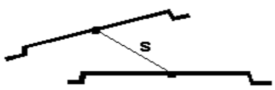
1.3.2 Belgium

Belgium has included some details regarding the link between concrete technology and the use of fibres. It is clear from the documents that the bond between fibres and the shotcrete matrix should be as good as possible, provided the fibre tensile strength is high enough to avoid breaking the fibres under load (they should be pulled out). The shotcrete mix design as such is not discussed, but it is well known that the higher concrete qualities (high compressive strength) tend to improve the fibre/matrix bond.

It is stated that: “The steel fibre length has to be in the range of 3 times the maximum aggregate size in order to bridge the gap between two aggregate particles, where a crack uses to start. The fibre length also has to be sufficient to provide enough bond to the matrix in order to avoid too easy pull out. Taking into account that shotcrete mixes usually have coarse aggregate of maximum 10 to 12 mm, steel fibres need to be 30 to 35 mm long.

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.

In order to achieve a homogeneous reinforcement, the spacing (s) between fibres calculated as:



$$s = \sqrt[3]{\frac{\pi d^2 l}{4 e}}$$

Example

s = distance between 2 fibres	
d = fibre diameter	**0.50 mm**
l = fibre length	**30 mm**
e = fibre dosage	**40 kg/m3 = 0.5% = 0.005**

Input in the formula: **s = 10.56 mm**

must be smaller than 0.45* l.
The minimum dosage required to meet the spacing limit for different fibre types (length and diameter) is indicated below:”

Table 3-1

d	l = 25 mm s = 11.25	l = 30 mm s = 13.5	l = 35 mm s = 15.75
0.45	22	20	20
0.50	27	20	20
0.55	33	23	20
0.60	39	27	20
0.80	69	48	35

1.3.3 Czech Republic

Czech Republic submittal outlines the aspects of concrete technology as follows:

“Aggregate containing two fractions, i.e. 0-4 and 4-8mm, which are available at concrete batching plants for production of cast-in-situ concrete, are used for sprayed concrete.

As to the Mrazovka tunnel and some other construction sites in Prague, single-fraction aggregate from the Uhy locality is used, which is specified as an atypical fraction 0-11.2 mm (to achieve a reduction of material costs). Because of its mineralogical origin, about 1,700kg of the aggregate is needed for $1m^3$ of shotcrete. The grading curve is compared with grain size limits recommended by CSN standards or the Austrian guidelines for sprayed concrete.

If the detailed design does not specify differently, domestic portland cements grade 42.5 and 52.5 are used. If the higher grade sprayed concrete B25 after 28 days is required and all effects potentially reducing the shotcrete strength are taken into consideration, the concrete mix (without other improving admixtures) usually contains 400kg of cement per $1m^3$ of shotcrete as a minimum.

To achieve the required development of shotcrete setting and hardening in the course of initial minutes after application, domestic liquid alkali-free additives are used. The speed of the green concrete hardening process is assessed in compliance with the Austrian Guidelines, according to the range J_2. Strength values are examined by means of calibrated penetration needle and by Hilti DX 450 cartridge hammer and Tester 4. Special attention was paid to monitoring of shotcrete temperature under different conditions of its application and its age in the course of monthly carried out check testing at the Mrazovka tunnel. The method of the shotcrete testing by means of the MEYCO KAINDL extraction method was refined in the Klokner's Institute of the Czech Technical University. The height of the truncated cone was introduced into the assessment diagram (MEYCO KAINDL's nomogram contains the truncated cone height of 50mm only). It was determined that the measurement results exhibit a large scattering, therefore 5 measurements had to be carried out as a minimum for each age of concrete.

Durability of sprayed concrete, being an aggregate of properties, has not been described for sprayed concrete applied in the Czech Republic. For that reason, particular measurable properties (e.g. strength, watertightness, sulphate resistance, frost resistance etc.) are specified by the design of a final lining individually, from case to case."

1.3.4 Denmark

Denmark presents the requirements for the Copenhagen Metro project under the heading Materials Technology:

"The temporary shotcrete used on the Copenhagen Metro was classified as shotcrete Class T and was not designed to carry permanent loads.

The cement content conformed to the following requirements:

- Chrome content (Cr^{6+}): Not more than 2mg/kg
- Fineness: Not less than $340m^2/kg$
- Bleeding: Not more than $20cm^3$
- Comp strength after 3 days (of cubes): Not less than $18N/mm^2$

Aggregates were a nominal 10mm in size, were clean, were not frozen and it was stipulated to the batcher that the size of particles under 7,5 mm should not exceed 3%.

The shotcrete characteristic strengths were as follows:

After 24 hours: 6N/mm^2
After 28 days: 22N/mm^2

1.3.5 Italy

Italy gives this account of current concrete technology for shotcrete:

"As mentioned earlier, 98% of shotcrete in Italy is produced by the wet process, and 95% of it is put in place by using Na Si O_2 "waterglass", its low cost and its easy availability has favoured the spread of its use.

In order to maintain this supremacy, waterglass producers, to respect the new Italian standard specification are looking for new formulas which will maintain this substance comparable with the new products that have been introduced on the Italian market.

These new products can be subdivided into:

- alkaline accelerators, such as sodium and potassium aluminates,
- alkali free and non-caustic accelerators
- thixotropic agents, which cause an almost immediate hardening of concrete

Superfluidizers are used to reduce the W/C ratio.

New technologies for the application of shotcrete and the control of its characteristics are now developed in research centres established in Italy.

The salient technologies worth mentioning are:

1. Delvo Crete system for a total control of workability
2. Sika Tard system for a total control of workability
3. SGI system of Sika Italia
4. MAPEI HWPS 2000 (High- workability and Performance shotcrete) Technologies

The *first* system, which permits to stop the hydration in cement up to a maximum of 72 hours, is now being applied in particularly demanding works.

The *second* system, which is known as the slump killing system, is appreciated owing to the high reduction of rebound under any conditions, to the possibility of preparing shotcrete mixtures with a low W/C ratio, and the possibility of finishing the surface.

The *third* system allows to adapt shotcrete to the client's needs, by using colloidal and or alcali free accelerators, to the high reduction of rebound under conditions and to the possibility of finishing the surface.

The *fourth* system, which includes superplasticizer and last generation accelerators, allow to manufacture shotcrete with a high fluidity for a very long time: These products reduce rebound to a percentage less than 10% and allow to use low dosages and accelerators which have a very short setting time and a high mechanical strength. This system is recommended, above all, in presence of water.

However, research in Italy has mainly developed in relation to the production of special cements, which permit to reduce the quantity of additives, or even to do without them.

In this connection, it can be mentioned that "Cementi Buzzi" company produces a special cement for shotcrete, in which hardening has been regulated in such way as to allow adhesion and to limit rebound.

The said cement can be classified as IV/A Pozzolanic 42.5, with a low hydration heat and a high degree of resistance to chemical attacks.

As regards admixtures, this is quite another question, with respect to both the flying ashes and the more effective silica fume. These products are used only in the construction of few tunnels. The reason why their use is so limited are their high cost.”

1.3.6 Japan

Japan is presenting an overview of the normally applied concrete technology approach for recent projects, starting with what is termed “Standard Shotcrete”:

“The standard mix proportion of shotcrete in Japan is shown in Table 3-2. The compressive strength of the standard shotcrete is more than 18 N/mm^2 at the age of 28 days.

Table 3-2: Standard mix proportions of shotcrete in Japan

Maximum size of coarse aggregate (mm)	Slump (cm)	Water-cement ratio (W/C) (%)	Sand-total aggregate ratio (S/a) (%)	Unit cement weight (C) (kg)	Accelerator (C x %)
10-15	8-12	55-60	60-65	360	5.5-7.0

Silica fume and/or Lime stone powder is begun to use because of reducing rebound and dust emission. The shotcrete admixed with both silica fume and limestone powder is adopted in the Shinkansen tunnels.

Recently, it is reported shotcrete mixes with fly ash because of recycling.

Setting and hardening time modifier can control the setting and hardening time of the base concrete of shotcrete, is begun to use. When the setting and hardening time modifier is admixed, the concrete consistency can keep fresh about 24 hours after mixing.

The base concrete of shotcrete with silica fume or lime stone powder stiffens. To improve the pump-ability of the concrete, high range water reducing agent admixture is admixed into the shotcrete.

Powder type accelerator is generally adopted in Japan. The annual use of the powder type accelerator is about 60,000 ton. In recent years, some kind of alkali free liquid type accelerators are begun to use.”

The contribution continues by presenting what is termed “high strength shotcrete and fibre reinforced shotcrete”:

“The cross-section area of the tunnels of the 2nd Tomei- Meishin expressway is about 200 m^2. In the tunnels, high strength shotcrete and/or fibre-reinforced shotcrete are adopted. The mix proportions of the shotcrete are shown in Table 3-3.

Table 3-3: Examples of mix proportions of shotcrete adopted in the expressway tunnels

Mix proportion	σ_{28} (MPa)	C (kg/m^3)	W (kg/m^3)	S (kg/m^3)	G (kg/m^3)	Admixture (%)	Accelerator (kg/m^3)	Steel fibre (kg/m^3)
Standard	18	360	194	1161	624	-	25.2	-
High strength	36	450	202.5	1052	567	1.6	45	-
Steel fibre reinforced*	36	450	202.5	1114	478	1.76	45	78.5

*: Case of Shimizu third tunnel

Japan Railway Construction Public Corporation has developed high quality shotcrete to improve concrete quality and workability, and to reduce rebound and dust emission. As for the concrete, the target slump for air-conveyance (rotary type) system is 8 cm and that for pump-conveyance system is 14 cm. The mix proportion of high quality shotcrete is shown in Table 3-4.

Table 3-4: Mix proportion of High quality shotcrete adopted in the Shinkansen tunnels

G_{max} (mm)	Slump (cm)	Air (%)	Binder-water ratio (%)	S/a (%)	Unit content (kg/m^3)						
					W	C	S.F.	S	L.S.P*	G	Admixture
10	8+2	-	57.8	64	208	342	18	1039	98	644	1.8

1.3.7 Lesotho

The described **Lesotho** project had the following shotcrete specification:

“The specification for both plain and SFRS contained many requirements that were designed to ensure a quality end product. These were in addition to the usual acceptance, routine and operator testing; equipment; batching; surface preparation; placing generally in accordance with good practice as detailed in ACI-506-R ‘Guide to Shotcrete’; checking applied thickness and remedial work to areas of failed shotcrete.

The wet mix process was mandatory. Surfaces were not to be trowelled, touched up or smoothed off unless instructed otherwise by the Engineer’s staff. As usual, the Engineer’s staff retained the right to have shotcrete applied as soon as an excavated surface was barred down. Between 30 and 50 kg m^{-3} Silica Fume was required in the shotcrete mix with a total cementitious content of 430 to 480 kg m^{-3} whilst water/cement ratios were to lie between 0,35 to 0,45 primarily to achieve the specified characteristic strength of 40 Mpa at 28 days.

Aggregates with gradings falling outside the specified grading envelopes were permitted provided that satisfactory results were obtained from full scale site trials. Nevertheless an aggregate/cement ratio of 3 to 5 was specified. Steel fibres had to comply with Type

1 deformed, exhibit an equivalent diameter of 0,5 mm and an aspect ratio between 40 and 80. A steel fibre content between 30 kg m^{-3} and 60 kg m^{-3} was also specified. Accelerators had to be non-caustic and non-corrosive with dosing limited to 3% of cementitious material, all backed up by manufacturers proof of satisfactory long term performance. A 3 day curing period during which time the shotcrete surface had to be kept damp was also specified.

Performance requirements are summarized in Table 3-5.

Notes:

1) The values are all "minimum" acceptable limits, except for boiled absorption and volume of permeable voids, which are "maximum" acceptable limits.

2) N/A indicates "not applicable".

Table 3-5: Shotcrete performance requirements

Sprayed Concrete Class		**A**	**B**	**C**	**D**
Mix Description	Test Method	Plain	Steel Fibre Reinforcement	Steel Fibre Reinforcement + Accelerator	Plain + Accelerator
Cube Strength	**ASTM C42**				
MPa at 8 hours		N/A	N/A	5	5
MPa at 24 hours		N/A	N/A	9	9
MPa at 28 days	(BS 1881)	35	40	40	40
Peak Flexural Strength	**ASTM C1018**				
MPa at 28 days		N/A	3.2	3.2	N/A
Toughness Indices	**ASTM C1018**				
I_{20} at 28 days		N/A	16	16	N/A
I_{30} at 28 days		N/A	22	22	N/A
I_{50} at 28 days		N/A	30	30	N/A
Boiled Absorption %	**ASTM C642**	8	8	9	9
Volume of Permeable Voids, % at 7 days		17	17	19	19
Setting Time	**ASTM C403 (BS EN 1963)**				
Initial Set, mins.		N/A	N/A	3	3
Final Set, mins.		N/A	N/A	9	9

1.3.8 Norway

Norway started using wet mix shotcrete already in the early 1970s. Development and updating of the technology has been an ongoing effort as illustrated in the following:

"The Norwegian Wet Spray Method was modernized completely in 1996/97 by means of a new generation of alkali-free liquid accelerators, polymer based non-retarding superplasticizers, and special set-retarding agents. Especially in bad rock conditions, with water ingress, it is of great importance to obtain safe conditions for the workers at the tunnel front. Using sprayed concrete with traditional water-glass accelerator, it takes usually up to 3 hours to obtain early strength for adequate rock-stability. It has been shown through recent studies, that high early strength of sprayed concrete with these new liquid alkali-free accelerator and admixtures could imply safer working conditions almost immediately after finishing the spraying process. In 1998 a project on Health and Safety during spraying was initiated. The Health tests performed showed less personal dust exposure by the use of alkali-free accelerators compared to silicate based accelerator. The durability tests performed indicate a good, homogeneous and durable material for all alkali-free accelerators investigated, better early strength developments for all the alkali-free accelerator compared to water-glass, but wet conditions delayed the early hydration reaction, and the early strength development depended strongly on the alkali free accelerator type chosen.

Use of recycled aggregates in fibre-reinforced sprayed concrete was demonstrated in a project in Oslo 1999. The project was a full-scale on-site and laboratory test of sprayed concrete containing up to 20 % recycled aggregate. On-Site documentation showed that sprayed concrete with recycled aggregate obtained excellent spraying and compacting properties, and adheres to the substrate very well, no spraying difficulties occurred due to the use of recycled aggregates and the need for accelerator decreased for all sprayed concrete -mixes with recycled aggregates. The compressive strength of sprayed concrete with recycled aggregate was reduced compared to a reference mix without recycled aggregates, but the strength obtained still exceeded 45 MPa at 28 days."

1.3.9 South Africa

South Africa has submitted a mining related account and regarding actual concrete technology there are descriptions of three different cases. The shotcrete used was quite similar in all three, so the South Deep shaft development has been selected:

"The specification called for a shotcrete strength of 60 MPa, with an energy absorption of 1000 J in an Efnarc test, and a life expectancy exceeding the projected 60 year life of the mine. After a test programme, the mix finally adopted included the following main components (Erasmus et al, 2001): cement, superfine fly ash (Superpoz), quartzitic aggregates complying with a defined grading envelope, 40mm long stainless steel fibres (Bekaert) as the main reinforcing elements, and microfilament polypropylene fibres (Fibrin 23) in small quantities. Additives were Delvocrete (MBT), which was used to extend workable life and assist in dispersion of fibres, and Meyco TCC 735, an internal curing agent and concrete improver. The accelerator used was Meyco SA 160. The rock surface was subject to running water and the mix was designed to prevent washout. Spraying was carried out in very wet conditions. In all, about 7500 m^3 of shotcrete were sprayed during the project."

1.3.10Sweden

Sweden presents the concrete technology issues for the Southern Link highway tunnels, starting with pre-construction trials:

"The designers and contractors had no prior experience of any project where the shotcrete properties were as stringent as for these tunnels. For example, frost-durability has usually not been specified in other tunnelling projects in Sweden. It was therefore necessary to conduct pre-construction trials under site conditions to demonstrate that the required FRS properties could be achieved.

An initial mix-design was determined from available literature on materials. See Table 3-6.

Table 3-6: Initial mix-design for shotcrete.

Ingredient	Quantity (kg/m^3)
Aggregate (0-8 mm)	1600
Portland Cement (SR)	480
Silica Fume	5
Water/cement ratio	0.45

It was also decided that Dramix RC 65/35 hooked-end steel fibres would be used at a dosage rate of 55 kg/m^3. Superplasticizer and alkali-free accelerators from Rescon, Sika, and Master Builders were tried. Test spraying was performed in a tunnel under construction in Stockholm. The pre-construction trials started in 1997 and were completed in 1998."

The results of pre-construction trials and construction period follow-up were presented as follows:

"Vattenfall Utveckling AB, Älvkarleby, undertook laboratory testing of shotcrete properties. All the requirements were fulfilled after only two rounds of trials. It was especially satisfying that freeze-thaw tests showed acceptable results. The final mix included Rescon Superflow 2000 as superplasticizer and Rescon AF 2000 as accelerator. The results from laboratory-tests for this mix-design are shown in Table 3-7.

Table 3-7: Test results for trial-mix shotcrete.

Property	Method	Specified	Result
Compressive strength (MPa)	SS 13 72 20	40	60
Post-crack flexural strength $f_{5.10}$ (MPa)	ASTM C1018	4.0	4.5
Post-crack flexural strength $f_{10.30}$ (MPa)	ASTM C1018	3.0	4.0
Frost resistance (kg/m^3)	SS 13 72 44	0.5	0.15

A number of tests were required to be carried out on the in-place shotcrete for Quality Assurance during construction. These were all required in the project specifications. The tests included:

- Fibre content
- Thickness, measured in 25 mm diameter drilled holes
- Compressive strength, based on cubes sawed from panels sprayed during construction
- Flexural strength of beams sawed from panels sprayed during construction
- Adhesion, based on cores drilled and pulled off in-situ
- Freeze-thaw resistance

Frequency of testing depended on risk estimations and geological conditions. The compressive strength-tests were normally carried out once per 1000 m^2 of in-place shotcrete, and flexural tests once per 2000 m^2. Adhesion tests were done once per 1000 m^2. Freeze-thaw tests were only necessary in zones where frost was expected.

To date, more than 95 % of the contract has been completed, which is equivalent to about 26000 m^3 shotcrete. Some changes in the mix-design were necessary during construction, the most important involved changing the superplasticizer to Master Builders Glenium 51. This was done because of some unexpected variations in viscosity in the concrete that influenced pumpability. More than 200 strength tests, including both compressive and flexural strength, have been completed during construction to date, and all show satisfactory and uniform results."

1.3.11 Turkey

Turkey is presenting a very interesting comparison of shotcrete mixes based on use of alkali free accelerator and silicate accelerator, as shown in the following tables 3-8 and 3-9:

Table 3-8: Shotcrete mix design

Component/ Property		Alkali-Free Shotcrete Kg/m^3	Sodium Silicate Shotcrete Kg/m^3
Portland Cement 42.5		500	500
Water		215	205
Water-cement ration		0.43	0.41
Water cement ratio including Microsilica		0.41	Not used
Slump (mm)		180	180
Aggregates	Sand 0-1mm (13%)	211[a]-215[b]	211
	Sand 0-5mm (57%)	878[a] -892[b]	878
	Gravel 5-12mm (30%)	474[a] -482[b]	474
Admixtures	Rheobuild 716 (2% of cement wt)	10	Not used
	CV-1 (1.2% of cement wt)	Not used	6
	MEYCO MS 610 Microsilica (5% of cement wt)	25	Not used
	Steel fibre	50	50
Accelerators	MEYCO SA 160 (7% of cement wt)	35	Not used
	Sodium silicate (15% of cement wt)	Not used	75

a MBT Mix 34 (original mix) applied between 17-02-99 to 21-04-99
b MBT Mix 34A (revised mix) applied after 21-4-99

Table 3-9: Strength properties summarized

	MBT Mix 34		MBT Mix 34A		Sodium silicate s/c	
	Age	**strength**	**Age**	**strength**	**Age**	**strength**
Penetrometer testing[1]	2 min	189N	2 min	152-267 N	2min	276-314N
	5min	237N	5 min	203-347 N	5min	402-455N
	10min	307N	10 min	305-417 N	10min	529-534N
Lab cubes (15xx15x15cm)[2]	3 days	33.6MPa	NA	NA	NA	NA
	7 days	61.1MPa	7 days	55.7	NA	NA
	28days	75.0MPa	27 days	67.3	NA	NA
	56days	79.6MPa	NA	NA	NA	NA
In-situ cores (10x10cm)[3]	1day	17.8MPa	1 day	12.5	NA	NA
	3days	29.5MPa	NA	NA	NA	NA
	7days	41.6MPa	7 days	32.2	7 days	14.8-21.6MPa
	28days	55.7MPa	27 days	37.6	28 days	20.0-22.2MPa
	56days	56.8MPa	58 days	42.3	56 days	18.1-23.9MPa
Masterkure In-situ cores (10x10cm)[4]	7days	44.7MPa	NA	NA	NA	NA
	28days	49.9MPa	NA	NA	NA	NA
	56days	50.6MPa	NA	NA	NA	NA

1 Proctor penetrometer CN 419, with 9mm plunger pushed 15mm into shotcrete (average of 8 readings taken within 60secs given)
2 reference mix, without accelerator
3 Cores taken from in-situ tunnel lining after one day, then cured in water at 20°C for 10 days, then cured in air at 20°C till crushing age – as recommended in clause 12.4.1 Shotcrete Guidelines "final draft".
4 Cores taken from lining at crushing age and tested., but cured prior to this by applying "Masterkure 112" material to the lining

A diagram showing tests made on sodium silicate accelerated shotcrete illustrates quite negative long term developments. Measured Young's modulus at 28 days gives 20 GPa and a normal projection until 1000 days would give 22 GPa. However, at 1000 days it has dropped to a mean value of about 9 GPa. Also the compressive strength shows a reduction from 28 days to 1000 days.

4. EQUIPMENT AND APPLICATION METHODS

As could be expected in this investigation, equipment usage is covering a variety of different set-ups. The small jobs are often executed by low output dry mix machines with hand-held nozzle, sometimes even manually mixing the concrete on the tunnel invert. At the other end of the scale there are the integrated complete robotic systems mounted on different types of 4-wheel carriers.

Materials transport in the delivery hose is either thin stream (with compressed air, or dense stream by positive displacement). The first system is mostly used for dry mix (adding the water in the nozzle), while the dense stream can only be used on wet (pumpable) material. However, wet mix is sometimes placed using thin stream and in Japan they frequently use dense stream from the pump about 50% of the way to the nozzle, injecting compressed air for thin stream transport the last part of the way to the nozzle.

Adding to the complexity on the equipment side is the fact that even though most users use liquid accelerators, there are also powder products on the market. Depending on the choice of accelerator type, this may have a significant effect on the overall equipment solution.

1.4 Statements from the contributing countries

1.4.1 Australia

"Practically all major wet shotcrete that is applied in Australia in the mines and in civil tunnelling projects is done by robotic shotcrete equipment. The equipment complexity varies depending on the specific projects, with the high specification civil tunnelling projects often requiring more state of the art equipment for quality control. Integrated dosing of accelerator with shotcrete output is seen as a major issue in the high specification tunnel projects.

Most robotic shotcrete equipment have facilities to monitor the dose rate of accelerator that is being applied. This would be seen as a minimum requirement."

1.4.2 Canada

"Other developments in shotcrete usage for mining in Canada include a shift from dry mix materials and shooting methods towards wet mix with many operators using dry mix material supply with wet mix shooting in what is referred to as 'hybrid' shotcreting. There have also been successes in the use of shotcrete for shaft lining. Recent results include a completely robotic, continuous placement of 75 mm of shotcrete in a 415 metre deep, 2.4 metre diameter shaft using wet mix materials and placement. As this technology is developing, so are the applications using robotic placement for primary rock mass support."

The submittal is not describing the equipment involved in the presented development into wet mix fibre reinforced boltless shotcrete, especially within INCO in the Sudbury Basin. However, as a matter of fact there has been a rapid increase in the use of robotic shotcrete application and even computer controlled or computer assisted placement of shotcrete. The majority of the shotcrete is still being placed by dry mix equipment.

1.4.3 Czech Republic

"Considering the short-term stability of an excavation and the extent of water saturation of grounds encountered mainly at excavation of galleries and tunnels, there prevails a dry process of shotcrete application in the Czech Republic.

Using of the wet process of shotcrete application has been introduced recently thanks to larger extent of contracts for construction of transport-related tunnels. Those projects are associated with upgrading of traffic networks for which longer tunnels with higher overburden, driven in more stable geological conditions, are designed. As a consequence, big volumes of shotcrete require deployment of highly productive mechanical plant and availability of certified production plants with a sufficient capacity, capable of ensuring production and transport of specialist wet mixes. It is possible to state that this way of shotcrete application is, at its very beginning, considering the rather slow start-up of the above referred to projects funding.

Similarly as in other European states, products of Aliva and Meyco companies are used for application of shotcrete. This applies to concrete sprayers, shotcrete pumps, hose-type accelerator additive dosage units and manipulators. Cheaper and less efficient domestic shotcrete sprayers and domestic plunger dosing pumps for liquid accelerator additives are used for smaller structures, which are built by smaller companies."

1.4.4 Denmark

"The shotcrete spraying equipment used was the ALIVA 260 shotcreting unit applied by a super silenced compressor capable of delivering 2 x 24m^3/min and thus supplying two shotcreting units at one time. The shotcrete units were each capable of delivering 5m3/ hour. The shotcrete itself was delivered as a premixed dry type in 10 ton kiln dry silos from an external, local supplier (GH Beton). The silos were transported by road on the suppliers own specialist vehicles."

1.4.5 Germany

The summary of tunnelling works in Germany during the last 20 years [G1] also gives some insight into the use of shotcrete. What is called the shotcreting construction method accounts for a high percentage of the tunnelling undertaken in Germany. For years, it has been used for 65 to 70% of all long distance road and rail tunnelling.

The advantage of flexible primary linings placed by shotcreting, allowing controlled deformation concentrated to open convergence slots, was highlighted as an innovative solution for heavily squeezing ground conditions.

The paper also describes the change from dry mix into mechanized wet mix shotcrete application, specifically mentioning the output increase from typically 8 m^3/h to 20 m^3/h and the reduction of dust and eluates (which was previously a problem).

The use of specially developed cements for shotcrete application, used as dried and pre-mixed silo material is also described. This system allows dry mix method spraying of shotcrete without accelerator or admixtures.

1.4.6 Italy

"Most of shotcrete produced in Italy, 98%, is produced by "wet process". There are many reasons for the choice of this process instead of the dry process, we want to mention them according to the preference given by the Italian building companies and designers:

- the composition of the mixture can be controlled with certainty, if it is entirely prepared in one installation and the relationship between components remains the same as fixed during the design stage;
- the wet process produces less rebound, particularly because the shooting pressure can be easily regulated;
- the pumps used for the wet process give a higher output (cm/h);
- the wet process produces a very small quantity of dust which is harmful to the human body;
- it is more and more difficult to find nozzlemann who are able to operate a nozzle in the case of a dry process;
- the machinery manufactured in Italy for pumping and spraying of shotcrete is exclusively designed for the wet process;
- industrial-safety norms are very strict in Italy, and in the safety plans **the use of manipulators is imposed**. These manipulators are at present only produced for the wet process. (Emphasis added).

Today, 35 years after the first Italian manufactures of such equipment made their appearance, 90% of the Shotcreting machinery is produced by Italian companies.

The most widespread pumping system uses the wet process, about 98%.

After opening the way to the setting accelerators "wasserglass" prevailed for years in all tunnel site in Italy. Today, new solutions are imposing themselves, which allow to obtain better strengths and structural qualities in the work achieved. Moreover, they cause no environment pollution problems. With the use of the new fluid products, the high quantities of waterglass needed may be replaced by definitely smaller quantities of additives, which require a higher proportion accuracy and higher pumping pressures for a better spreading in the projected concrete.

The pneumatic pumps, or fluid pumps of independent type, were discarded and pistons pumps, peristaltic or diaphragm pumps, directly connected with the hydraulic circuit of the shotcrete pump, began to be used.

At the same type, some products in powder form have been put on the market, which are to combine with the liquid ones and with require special proportioning and pumping units that are still at setting up stage.

As regards manipulators they are always used as required by the severe Italian rules about safety."

1.4.7 Japan

Japan has a special situation on the equipment side that should be kept in mind when reading the presentation about equipment and methods. Almost all the huge quantity of more than 2 mio m^3 of shotcrete per year is placed by the wet mix method. What is special, is the extensive use of thin stream concrete conveyance for the last 10 to 15 m up to the nozzle. This technique is frequently combined with the addition of powder accelerator also transported by compressed air. The Japanese focus on dust may be partly linked to this special situation.

"Spraying manner:

The ratio of Wet process and dry process in executed volume are 99% and 1% respectively. Wet process is easy to obtain stable quality of shotcrete. Dry process is mainly adopted with small diameter tunnel of long range, because the devices are compact and has long-range conveyance ability.

Conveyance system:

Pump (+air) conveyance system and air conveyance system are adopted by spraying manner. Table 4-1 shows kinds of shotcrete machine by conveyance system. Percentages of materials conveyance devices are piston 69 %, rotary 27 % and the other 3 %.

Table 4-1: Types of shotcrete machines

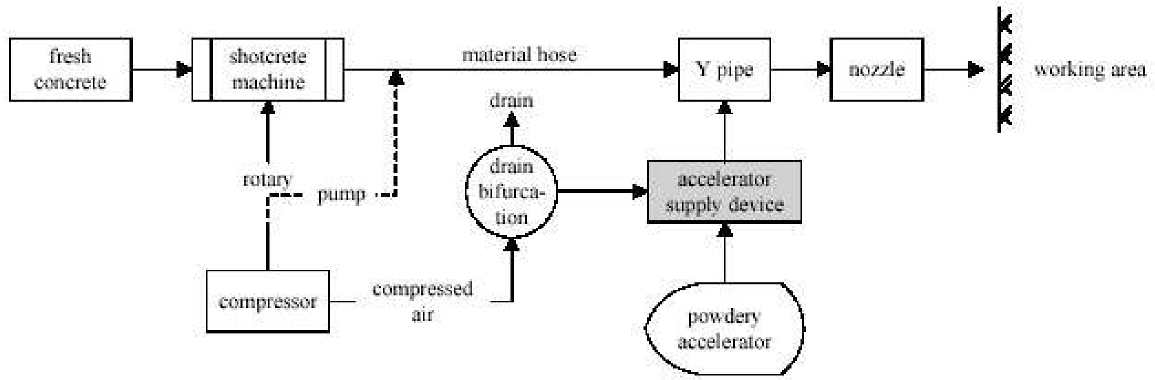
process	Conveyance	discharge	
dry	Air	feeder pocket	SBS TS
		rotary	Aliva280, 285 Need Gun 400, 2000
wet	Pump	squeeze	Squeeze-crete
		piston	Putzmeister Schwing Techman Symtec MKW-25SNT
	air	rotary	Aliva 280, 285 Need Gun 400, 2000

Feeder pocket type is used in small diameter tunnel, because the machine is compact. It has discharge ability of 10 m^3/h and materials conveyance ability of maximum 1,000 m with horizontal distance.

Accelerator supply device:

Both powder and liquid type accelerator are used. Figure 4-1 shows an example of powder accelerator supply device. Figure 4-2 shows system flow of both wet and dry spraying system using powder accelerator. In case of wet process, powder accelerator is conveyed with air, and is mixed with concrete at the point of Y-shape pipe forward to nozzle by 2 to 3 m.

Figure 4-1: Powder accelerator supply device



(a) System of wet process

(b) System of dry process Shotcrete machine

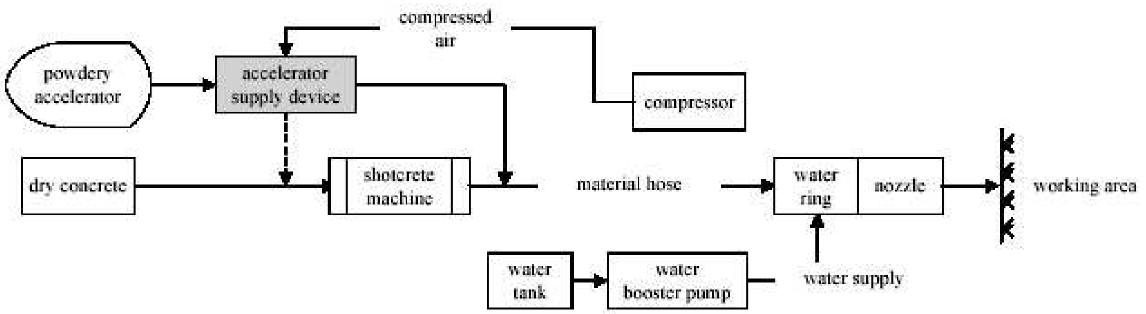


Figure 4-2: System flow of shotcrete (a and b)

Generally, shotcrete machines of one body type with compressor deployment are used. Shotcrete machine with discharge ability of over $20m^3/h$ is adopted for spraying in the tunnels with large cross section.

Air-less spraying device:

Air-less spraying devices which compressed air is not used for have been developed in order to reduce rebound and dust emission. In the Air-less spraying devices, concrete is conveyed from the pomp to the head of material hose by pumping pressure and throw out by the rotation force of impeller blade shown in Figure 4-3. The discharge abilities of the spraying devices are as same as usual pomp type devices. It is reported that dust concentration is reduced into 1/2-1/4 by changing spraying device from usual one to these ones. On the other hand, they have problems of their operation and impeller exhaustion.

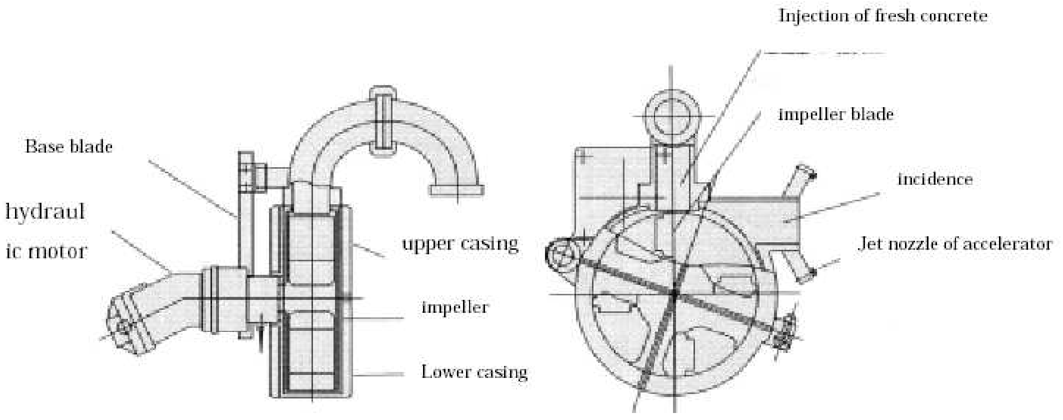


Figure 4-3: Example of airless spraying device

1.4.8 Korea

"Since 1995 design of rock support in road tunnels has changed to wet shotcreting with steel fibre using robot."

1.4.9 Lesotho

Lesotho water transfer project: "The shotcrete was hand sprayed by a trained nozzleman using Aliva Duplo wet/dry shotcrete machine rated up to 20 m^3/hour, to the satisfaction of the Engineer. It is worldwide experience that manual spraying of shotcrete has many disadvantages. Such disadvantages include dust emissions that may impair the nozzleman's vision, increased chances of more rebound than with robotic application and increased health hazards to workers due to close proximity of the application. Rebound for both plain and steel fibre reinforced shotcrete were not materially different. The measured rebound constituted an average of 8 %. The problem of ventilation was ongoing arising from the time when the tunnel heading exceeded 1 km. There was no potential threat to workers health as confirmed by measurements of oxygen content, dust and noxious fumes, which were carried out regularly. The poor quality of ventilation adversely affected the overall quality of applied shotcrete simply because it was difficult to see what was on the rock."

1.4.10Mexico

"The use of dry mix shotcrete is the main application method. The equipment used dry mix shotcrete is essentially the same as use in other countries, compressor, drum mixer, cement gun (continuous feed type), nozzles, houses and in some cases water pressure pump.

The wet mix process utilizes positive displacement equipment (concrete pump) with the continuous load characteristics, air compressor, nozzles and pressure hoses.

The main application method is by hand. There are very few robotic equipment units for shotcrete applications.

In most of the cases the mix is made on the job site. Some field mixes are well formulated and applied properly obtaining a very good shotcrete, but unfortunately this is not always the case.

For wet mix the use of ready mix concrete from a local concrete plant is very common, with better quality control of the mix."

1.4.11 Norway

Norway is reporting that wet mix robotic spraying with the use of steel fibres and silica fume was introduced in the late 1970s. As a matter of fact, robotic equipment was in use even from the beginning of the 1970s. From about 1980 practically all shotcrete has been placed by the wet mix method using robotic equipment of the last generation all the time.

1.4.12 Russia

"In general shotcreting is performed with domestic equipment, machines of rotor type and with output 4 – 6.5 m3/h." (It is assumed that this means dry mix machines)."

1.4.13 South Africa

South Africa is not specifically describing the equipment usage (since the focus is on other aspects in the submitted document). Regarding the described modern wet mix example projects, the two shafts were both sprayed with hand-held nozzle and small piston pumps. Also in many other applications in SA mining, small piston pumps are being used, partly in combination with robotic equipment.

In the described kimberlite case the following interesting observation was made: "It was subsequently found that shotcrete thicknesses were not to the required standard and it was concluded that hand held application should not be undertaken. From testing carried out on the four shotcretes, a recommended wet shotcrete design for Premier Mine was chosen."

About the general situation in SA: "Although the cases described represent the state-of-the-art in shotcreting in South African mines, the sophisticated techniques used will not be applicable in all situations. It is likely that the dry mix process will continue to be used in many applications. This technology has also been developed, and, as a result of significant improvements made during the programme of research carried out by the Shotcrete Working Group, many of the disadvantages of the method compared with the wet mix method have been removed (Snashall, 1998). It is expected that, in many of the "conventional" and smaller mining operations in which small quantities of shotcrete may be required, dry mix will continue to be used on a significant scale."

1.4.14 Sweden

"In parallel with the pre-construction trials to develop the shotcrete mix for this project, machines were developed to suit the conditions existent in this project. Aliva AG, Switzerland, was contracted to supply concrete pumps, robotic arms, and the additive pump for shotcreting. AB Besab, Sweden, completed the carrier, compressor, and electrical equipment.

The maximum capacity of the concrete pump was 20 m^3 per hour. However, this was reduced to 10-15 m^3/h during practical spraying. The total vertical reach of the robot arm was 15 metres, and the unit could move five metres along the tunnel during spraying before re-location of the equipment was necessary."

1.4.15 Switzerland

The 6 different project descriptions submitted by Switzerland are confirming that the main volume of shotcrete under ground is now executed by robotic equipment and by the wet mix method. Switzerland has also more or less completely switched to alkali free accelerators and fibres are used a lot for reinforcement.

As an example, the description covering the new CERN particle accelerator project, reads as follows on shotcrete:

“At the planning stage, the following requirements were made on the shotcrete:

- Non-alkaline setting accelerator
- Automatic dosing of the accelerator
- 10 mm maximum aggregate
- Minimum drill core compressive strength:
  - 1 day: 8 MPa
  - 7 days: 23 MPa
  - 28 days: 28 MPa

The mix design contained 40 kg steel fibres per m3 of shotcrete.

The description of the Thalwil TBM tunnel enlargement, states as follows:

“Immediate support comprises rockbolts, wiremesh and layers of wet mix shotcrete applied using 4 Aliva AL-500 mobile wet mix shotcreting rigs. In the headings of the single track spur tunnels, instead of wire mesh, the wet mix shotcrete is reinforced with 40 kg/m^3 of Dramix steel fibres.

Liquid alkali-free accelerator is dosed automatically into the moving stream of shotcrete from the nozzle by the Aliva AL-404 dosing unit and from the on-board liquid container.

Tests regularly achieve results of up to 20 to 25 N/mm^2 after 24 hours, with 30 to 35 N/mm^2 after 7 days and 40 to 50 N/mm^2 after 28 days. The minimum design specification is shotcrete of B30 average quality with a minimum 20 N/mm^2 at 28 days.”

1.4.16 Turkey

Turkey presents the Bolu tunnel project equipment in table 4-2.

Table 4-2: Wet mix shotcrete plant and equipment

WET SHOTCRETE ROBOTS:	4 No. SCAMAC SC271/160 Chassis & Robot Arm	Max. Pump Capacity 20 m3/hr. SCAMAC Doseage System (for use with Sodium Silicate Accelerators)
	2 No.SCAMAC SC271/160	Chassis & Robot arm fitted with MEYCO Suprema CPL Pump Max. Pump Capacity 3 - 14 m3/hr. MEYCO TDC Doseage System (for use with MBT SA 160 Accelerators)
CONCRETE BATCHER:	2 x CIFA PD5 Batching Plant Max. Batching Capacity: 90m3/hr.	
TRANSMIXERS:	8 No. ASTRA TRUCKMIXERS Capacity: 9m3	
COMPRESSORS:	4 No. ATLAS COPCO GA 1407(Electric) Normal Working Pressure: 100 psi/7 Bar Max. Air Delivery: 750 cfm/355 l/s	
NOZZLES:	MEYCO NW80 Diameter: 3"/80cm	

5. METHOD OF REINFORCEMENT

Reinforcement of shotcrete has been a subject of discussion for decades. More than 20 years back it was a question about which kind of steel mesh to use, how to combine with bolts, steel beams or reinforcement ribs, shadow effects when spraying the concrete and a number of other details.

These questions are still there (with no resolution regarding shadow problems and poor compaction locally), but now there is much more focus on fibre reinforcement. This development started already in the 1970s and it is fair to say that practical experience and conclusive research documenting the properties and advantages of fibre reinforcement became available during the 1980s.

Pioneers in the research and development as well as high volume practical use of steel fibre reinforced shotcrete (SFRS) were Scandinavia, Germany and Canada. Certainly there were also countries and people with special interest from other regions involved in this field and in the 1990s this technology was extensively accepted and used. The previous Animateur of WG12, Tomas Franzen, has described this development in more detail [3].

There is still discussion about fibre reinforcement of shotcrete for rock support and there are still defenders of the traditional mesh reinforcement. The arguments are sometimes technical (e.g. what happens at large deformations, how to ensure reinforcement continuity through construction joints) and there are various economic views as well. Today, the plastic fibres are also on the market (primarily polypropylene) and this is further complicating the picture as well as adding new possibilities.

One of the possible problems of using fibres for reinforcement has been the question mark on reinforcement continuity through construction joints. In many tunnelling projects using shotcrete for primary (and partly final) support, excavation and support takes place in steps (e.g. two top headings and a bench) and this question therefore becomes very important. A substantial contribution to remove the question mark was presented at the Fourth International Symposium on Sprayed Concrete in Davos, Switzerland, September 2002 by J-F Trottier [4]. The conclusions given are far reaching and deserve to be copied in full:

Based on the results generated by this testing program on large jointed and un-jointed South African Water Bed panels, the following conclusion can be made:

- *The presence of construction joints did not have any detrimental effect on the cracking behaviour of plain, monofilament fibrillating synthetic and hooked-end steel fibre reinforced shotcrete panels. It is anticipated that similar trends will be observed in the field. It is therefore concluded that when steel or synthetic fibres are used in the field, no particular precaution, other than the proper fabrication and preparation of the joint itself, is required at the construction joint locations.*

- *The presence of a construction joint on a mesh reinforced shotcrete panel, in which the mesh has been overlapped at the joint location, appears to have a detrimental impact on the initial cracking load and behaviour at small deflections of the panels. It is possible that the mesh may cause voiding during the shooting process and create a weakness at the construction joint location. Based on the results obtained with the plain jointed shotcrete panels, the authors conclude that the overlapping of the mesh at the construction joint is not required. The reduced amount of mesh at the joint location should also reduce the potential of voiding behind the mesh.*

- *The performance of both fibre types investigated in this program offered similar or superior performance, as measured with the South African Water Bed Test method, to the performance of the 102mm x 102 mm 4.1 mm / 4.1 mm gauge welded wire mesh.*

1.5 Statements from the contributing countries

1.5.1 Australia

Australia has in many ways been in the front of the new developments the last few years, especially regarding plastic fibres. From the contribution: “A number of developments have taken place within the shotcrete industry in Australia between the late 1990’s and 2002. These changes have occurred both within the mining and civil underground construction industries, and to a lesser extent in pool construction.

One of the most significant developments to occur over the last 2 years has been the rapid increase in usage of structural synthetic fibres compared to steel fibres and mesh. Australia witnessed the widespread adoption of steel fibres for the reinforcement of shotcrete during the 1990’s, especially within the civil construction industry; the rate of acceptance was somewhat slower in the mining industry. However, the emergence of high performance structural synthetic fibres that have proved an effective form of reinforcement for shotcrete at the high levels of deflection typical of mine roadway development has promoted acceptance of this type of fibre within the mining industry. This type of fibre has only seen sporadic use within the civil construction industry because crack containment with this type of fibre is not as good as for steel fibres at present.”

We may also add what was written under the heading Large Civil Tunnel Projects: “Although experiencing a low level of activity, the Australian underground construction industry was very busy in the late 1990’s through to 2001, and will soon see the start of several major underground infra-structure projects, particularly in Sydney. Almost every project recently designed or commenced has included the use of FRS as a major or principal form of ground support. The advantages of using FRS in combination with rock bolts in the jointed sandstone underlying the Sydney basin have become obvious to all observers familiar with the industry within Australia. As a result of this, the level of expertise among contractors has risen and an awareness of the benefits and economies available with FRS has increased markedly among consulting designers. The activities of AUCTA and the Australian Shotcrete Society have also assisted in educating the industry to these benefits.”

Since it is not quite clear from the text of the last quote, SFRS has actually been used for permanent support. The Eastern Distributor and the M5 East tunnels in Sydney were all permanently lined by SFRS.

1.5.2 Brazil

“Fibre reinforced shotcrete has been widely used recently. This is a new trend, as mesh has been almost the only reinforcing element until recent years.

For the tunnels of a sample of 5 hydroelectric schemes under constructions (Itapebi, Campos Novos, Barra Grande, Sonora and Corumbá IV) steel fibre reinforced wet mix shotcrete is being used in 4 (tunnel spans ranging from 15 to 17 m), and mesh is being used in one case (8-m tunnel span).”

1.5.3 Belgium

Belgium has submitted three different papers [B1, B2 and B3] on the subject of steel fibre reinforced shotcrete (SFRS). As is generally accepted, un-reinforced shotcrete is a brittle material and there are many rock support situations where this needs to be overcome by the use of reinforcement. One statement from reference [B1] illustrates why the use of fibres is increasing:

”Traditional wire mesh is difficult to fix to the irregular substrate of the blasted or excavated cross section. Also this meshing operation takes a lot of time. Job data have shown that installing the mesh lasts 3 times more than shotcreting the same surface. The continuously changing position of the reinforcement within the shotcrete lining does not guarantee at all a uniform bearing capacity.”

Reference [B1] describes the development of standardized testing of ductility of SFRS in Europe, expressed as energy absorption during test sample deformation. The square slab test originally suggested by SNCF/Alpes Essais (France) was adopted by EFNARC and has also been included in the new European Standard on Sprayed Concrete. Typically, test results are classified as follows:

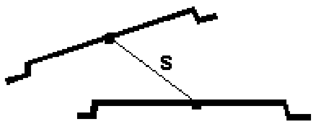
500 Joules failure energy	for sound ground conditions
700 Joules failure energy	for medium ground conditions
1000 Joules failure energy	for difficult ground conditions

The third paper submitted by Belgium discusses the properties of steel fibres in shotcrete in more detail [B3]. Ductility testing methods like the ASTM C1018 (USA), the JSCE SF4 (Japan) and the French/EFNARC tests are shortly discussed. One conclusion given is that beam tests are less representative of the real case situations than slabs. The paper also highlights that specifications for SFRS should focus on basic quality parameters and required performance of the shotcrete layer:

- minimum fibre length (3 times maximum coarse aggregate size)
- aspect ratio (range 45 – 80)
- minimum fibre tensile strength (minimum 800 MPa)

- required ductility (500 – 700 – 1000 Joules, EFNARC)

Another important factor discussed is the need to achieve a homogeneous reinforcement effect by limiting the spacing of fibres. The spacing (s) can be calculated according to the following formula (by MacKee) and example:



$$s = \sqrt[3]{\frac{\pi d^2 l}{4 e}}$$

	Example
s = distance between 2 fibres	
d = fibre diameter	0.50 mm
l = fibre length	30 mm
e = fibre dosage	40 kg/m3 = 0.5% = 0.005

Input in the formula: s = 10.56 mm

The requirement is that steel fibres are dosed at more than 20 kg/m^3 and that the distance between fibres (s) must be smaller than 0.45 times the fibre length. In the above example all requirements are fulfilled.

1.5.4 Canada

”Over the years, ground control strategies have moved from timber sets in the 1950s, to rock bolts in the 1970s, to an increased use of shotcrete through the 1990s. By the mid-1980s, the standard support for a new development heading comprised a 1.2 metre x 1.2 metre staggered pattern of 1.8 metre long, mechanically anchored 19 mm diameter rock bolts, together with #6 gauge welded wire mesh with 100 mm x 100 mm openings, commonly referred to as screen.

As the acceptance of shotcrete improved, some mines started looking at extending the applications past a replacement for screen and into new areas. At deep levels within some Sudbury mines the rock mass stresses are equivalent to rock mass strength. Under these conditions rock mass failure is occurring on a continual basis and readjustments of stresses lead to localized dynamic failure known as ‘rock bursts’. It has been found that this is an excellent application for shotcrete, especially when reinforced with mesh that has the capacity for high levels of energy absorption and residual load bearing even after it has been “hit” by a rock burst event.”

And regarding INCO and the Sudbury area: “INCO estimates that 65% of the 8,650 cubic metres of wet mix shotcrete for the Stobie/Frood ramp area is supplied with steel fibres (50 kg/cu metre of Dramix ZC 30/.50) for the purposes of boltless shotcreting. This amounts to some 5,622 cubic metres of steel fibre reinforced, silica fume wet mix shotcrete or just less than 8% of the total usage by INCO.

Results of the trials in boltless shotcrete at INCO's Stobie Mine are making ripples across the mining industry. It has been reported that INCO, Manitoba Division in Thompson is reviewing the results with a view to initiating trials at the new 777 Orebody. Other mines in Eastern Canada have also been keeping a close eye on the trials to evaluate the potential for similar applications in other mines."

1.5.5 Czech Republic

"A method of reinforcing shotcrete primary lining by means of steel mesh and lattice girders prevails. The use of steel rolled sections decreases. Shotcrete final lining is reinforced by steel mesh and additional distance or reinforcing steel bars or prefabricated reinforcement cages. Application of steel fibre reinforced shotcrete has not been utilized for lining structures in the Czech Republic yet. Steel fibre reinforced concrete is used as a reinforcing layer at refurbishment to existing rail tunnels and on special occasions where special requirements on tightness and prevention of concrete shrinkage during the process of hydration exist (e.g. at sealing plugs of an underground gas storage construction)."

1.5.6 Denmark

Denmark's contribution presents the usage of shotcrete for the Copenhagen Metro. Shotcrete was used for primary lining and regarding reinforcement the following was stated:

"Reinforcement	Wire mesh and connection steel bars Steel grade : 460N/mm^2 Longitudinal and cross pitch : 150mm Diameter for longitudinal and cross wires : 6 mm Wire mesh and connection steel bars consisted of high tensile steel complying to EVN 10080. The mesh was applied with a minimum spacing to the excavated ground of 100mm with a mesh overlap minimum of two pitches (or 300mm)."

1.5.7 Italy

"About 30 % of the shotcrete produced in Italy is fibre reinforced (out of 115'000 m^3 shotcrete in 2000). The first fibre type to be used was metallic fibres, because these were well-tested. Many tests have been carried out on the use of synthetic fibres in shotcrete and some very interesting results have been obtained.

For a better understanding of how technology has spread, it is worth mentioning that, even before the improvement of the mechanical characteristics of shotcrete, the reasons that drew the designer to introduce and to accept the fibre reinforced shotcrete were the following:

- labour saving in comparison to laying the welded mesh
- less rebound
- a reduction of the thickness of the applied shotcrete

The lack of an official methodology for determination of the characteristics of fibre reinforced shotcrete has been the cause of an insufficient appreciation of the advantages produced by the use of fibres. In addition, the price of good quality fibres was too high in comparison with the price of conventional electrowelded mesh. The concept of fibre reinforced shotcrete evaluated according to mechanical shotcrete has been introduced into technical specifications only few years ago.

According to the newly issued technical specifications, the fibre qualification tests foreseen and the determination of the optimum quantity to be used are now carried out following the plate test described in the Italian standard (Calcestruzzo proiettato UNI 10834 -99).

The required compressive strength value is 25 MPa at 28 days. The absorbed energy till a deflection must be > 500 Joules."

1.5.8 Japan

Japan produces an amazing about 2'100'000 m^3 of shotcrete per year. About 2.4% or 50'000 m^3 is currently executed as fibre reinforced shotcrete.

1.5.9 Korea

Korea has rapidly accepted fibre reinforcement in shotcrete. This is illustrated by the following statements: "Since 1995 design of rock support in road tunnels has changed to wet shotcreting with steel fibre using robot."

The reasons were to improve the quality of shotcrete linings and for cost saving. Decreasing rebound and improving workmanship were confirmed as additional effects. Even large cross sections in subway projects have been supported with steel fibre shotcrete since then. The same applies to high speed and conventional railway tunnels.

Now wet shotcrete with steel fibres are more common than dry shotcrete in Korea and improving compressive strength of wet shotcreting is the main subject for Researchers. Steel sets are also being replaced by lattice girders to improve the quality of rock support and to improve economy."

Korea is also already trying out synthetic fibres in shotcrete.

1.5.10Lesotho

Lesotho submitted a paper about a 5.6 km water diversion tunnel. Steel fibres were used for reinforcement: "The sidewalls of the tunnel are entirely lined with a 75 mm thick steel fibre reinforced shotcrete to the height of maximum calculated water flow levels. The SFRS for lining was applied in parallel to excavation activities so as to recover some of the time lost due to slower than expected excavation rates. The Contractor applied SFRS lining on the sidewalls during a window when the excavation team was drilling the face, a period of 2 hours when there was not much traffic required in the tunnel. During this period approximately 10 linear tunnel metres was lined."

1.5.11Mexico

Mexico is stating the following regarding reinforcement: "One of the biggest problems is the use of steel fibres in dry mix shotcrete. Here in Mexico this is a common practice. The problems are the low dosage of fibres per m^3, less than 5 cm thickness of the shotcrete layer with fibres and the very high rebound of fibres. This leads to layers of shotcrete with lower fibre content than required. The shotcrete technology has arrived to Mexico with the use of new admixtures, silica fume and alkali free accelerators. Synthetic fibres and steel fibres have been use for a few years and is now more often specified."

1.5.12Norway

Norway has been using steel fibre reinforcement in shotcrete since the early 1980s. Where heavier reinforcement was necessary, shotcrete ribs with 4 to 6 rebars of typically 12 mm diameter would be installed. The rebars would be installed in two layers. All kinds of steel mesh are practically excluded from shotcrete for rock support. The following statement illustrates the extensive use of this reinforcement approach (and in this case for permanent linings): "In the context of road and rail tunnels, the Norwegian Method of Tunnelling, NMT is a collection of practices that produce dry, drained, permanently supported and "lined " (fully cladded) tunnels for approximately USD 4,000 to USD 8,000 per meter (1996). These low-cost, high-tech Norwegian tunnels may range in cross-section from about 45 m^2 to 110 m^2 for two-lane roads and three-lane motorways. The Q-system is the most commonly used design method. The updated Q-system of rock mass classification (revised 1994 and 2001) and use of seismic investigations, is used in NMT, consisting of high quality robotically applied steel fibre reinforced shotcrete and corrosion protected rock bolts. Cast concrete linings are not used unless rock conditions are exceptionally poor and concrete is needed locally for stability against squeezing or swelling rock. (Gol, 1996)."

1.5.13Russia

Russia is mentioning the use of lattice girders and steel mesh for reinforcement in shotcrete.

1.5.14South Africa

South Africa has submitted an extensive and excellent report on shotcrete in deep level mining. With the high loads and rock burst situations encountered in these mines it is no surprise that fibre reinforcement has been seriously investigate in research and also used in practical cases under ground. Research on fibre reinforced shotcrete has been executed both for static loading and for the rock burst situation, starting in 1994 and ongoing for more than 5 years. Excerpts from the received submittal illustrate the very advanced level of fibre knowledge in SA:

"Under the auspices of the "Shotcrete Working Group", extensive testing of shotcrete beams, Efnarc panels and large panels reinforced with various types of reinforcing fibres was carried out. The ductility criterion established early in the research programme related directly to the large panel test method. The criterion was that, under the uniformly distributed loading applied to the $1m^2$ central area of the 1.6m x 1.6m panel supported by rockbolts on a 1m spacing, the load capacity of the panel up to a central deflection of 150mm should not be less than 50% of the peak load capacity of the panel.

In the early testing carried out, panels reinforced with various types of steel and polypropylene fibres tested. These tests showed that Dramix steel fibres performed better than other steel fibres as far as ductility was concerned. Similarly, monofilament polypropylene fibres performed better than fibrillated fibres. The test method and results of these tests have been included in several publications (for example, Kirsten et al, 1997), and the summary results are given in Figure 5-1.

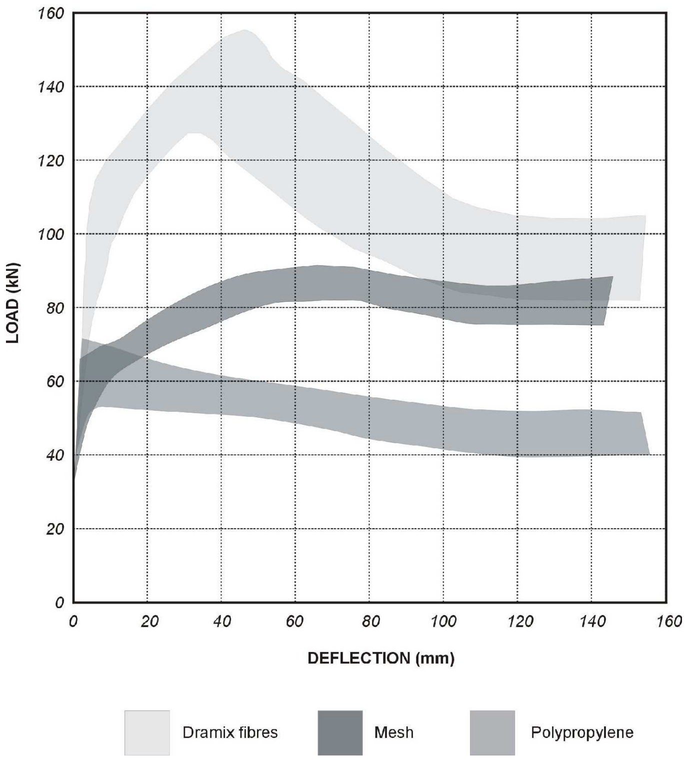


Figure 5-1: Summary panel deformation test results

Recent testing concentrated on the two fibre types which demonstrated the more successful performance. Monofilament fibres with a star shaped cross section, developed to provide greater fibre surface/matrix contact area, were also tested as a variation. The results of these tests showed that Dramix fibres performed best, followed by the star shaped polypropylene fibres. Comparative results are shown in Figure 5-2. In this figure, the pressure is normalized - the applied test pressure divided by the square of the average depth of the panel and multiplied by the square of a normalized depth of the panel (taken as 75mm in this case). These results also show clearly that the panels retain substantial load carrying capacity after 150mm of deflection, demonstrating the ductility of the fibre reinforced shotcrete.

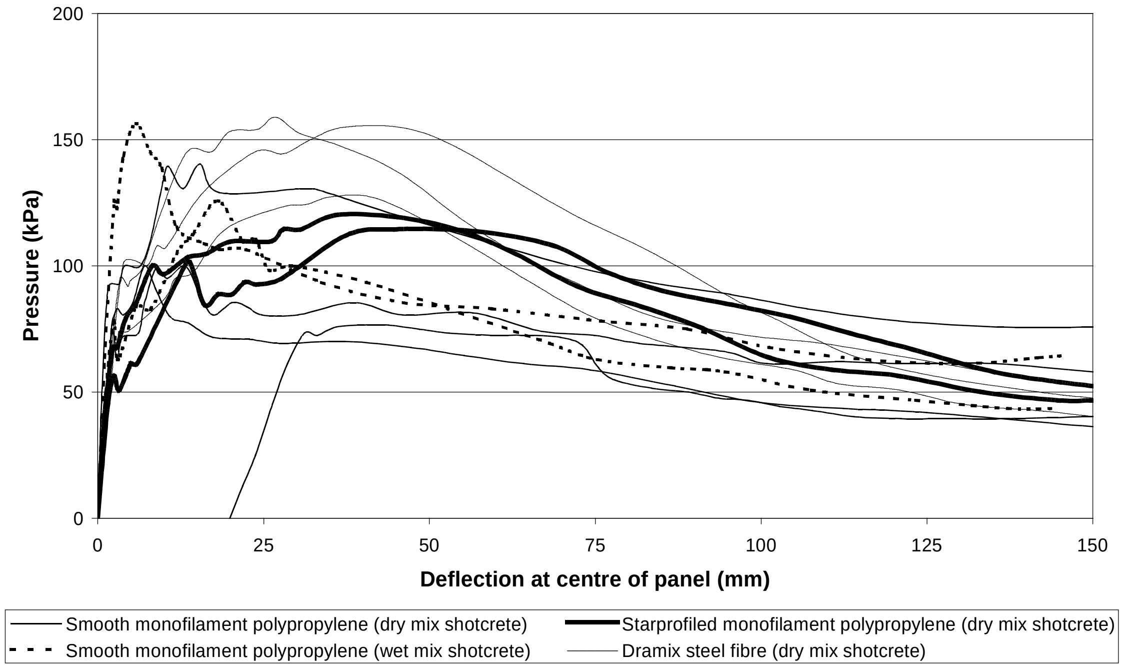


Figure 5-2: Comparative performance of different fibres

The results in Figure 5-2 are for the following fibre contents in the mix before spraying:

- Polypropylene: 0.5% by dry mass (12 kg/dry m^3);
- Dramix: 2.0% by dry mass (48 kg/dry m^3).

The actual polypropylene fibre contents in these results for the sprayed panels varied from 0.25% to 0.4%. The actual fibre content was determined for only one of the three results in Figure 5-2, and this was 1.21%.

Two panels were also sprayed with a mix containing 0.3% of polypropylene fibres and an actual content of 0.12% was measured for one panel. These panels (not included on Figure 5-2) gave a lower initial capacity, and neither panel survived to a central deflection of 150mm. These results, and the results presented in Figure 5-2 indicate, logically, that there is a significant increase in support capacity with increase in fibre content.

Early tests showed that the longer the fibre the better the performance from a ductility point of view (Stacey et al, 1998). This is directly relevant to the basket mechanism of behaviour, since longer fibres can pull out of the matrix to a greater extent across a crack, whilst still bridging the crack. As long as they are bridging a crack, they are providing support. Results for Dramix reinforced shotcrete panels are shown in Figure 5-3. The results in this graph illustrate the effects of both fibre length and fibre content.

In the more recent testing, fibre length has not been varied, and 40 mm long fibres were used in all of the tests whose results are shown in Figure 5-2.

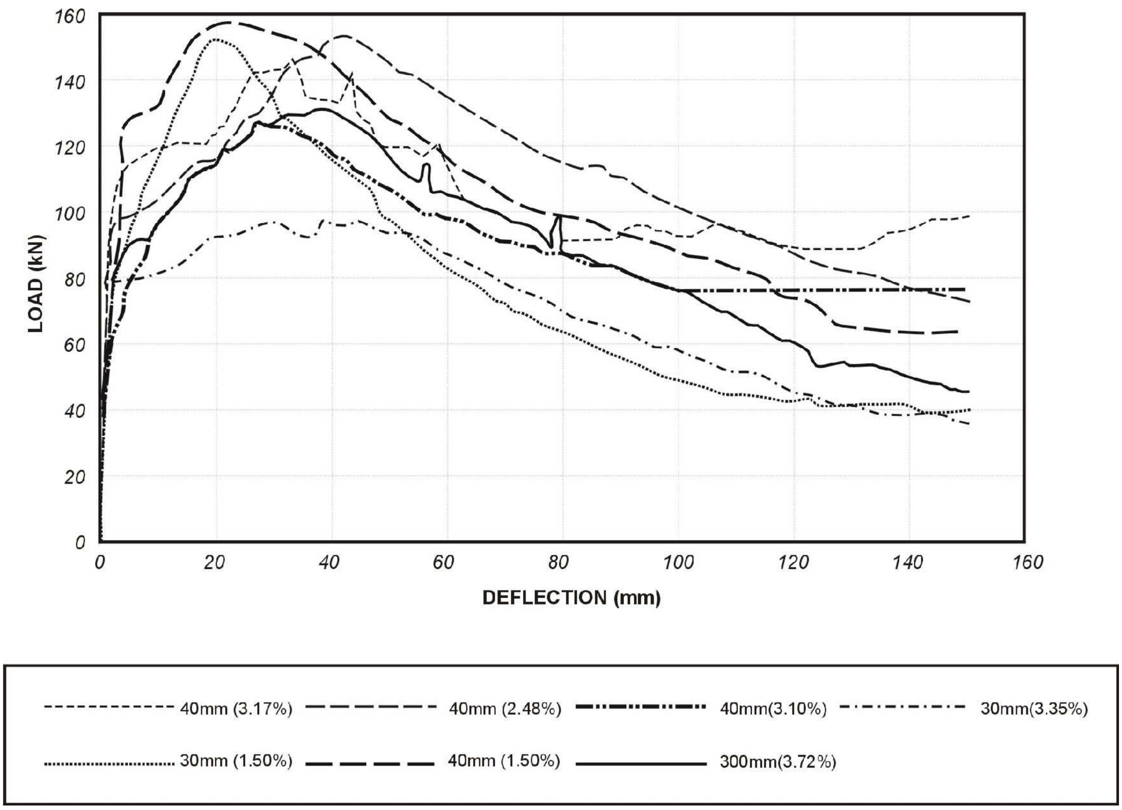


Figure 5-3: Panel deformation tests illustrating effects of fibre length and fibre content

Research into the performance of large shotcrete panels under simulated rockburst conditions has been carried out over a period of about 5 years. These tests have been carried out on plain shotcrete, mesh reinforced shotcrete, fibre reinforced shotcrete, and fibre reinforced shotcrete enhanced with wire rope lacing. The same sized panels of shotcrete as described above for the static testing were used for the dynamic tests. The panels were suspended by means of four rockbolts spaced 1m apart, and an artificial rock mass and pyramid of steel clad concrete blocks distributed the impact load onto the panel. A drop weight provided the energy input, and impact velocities of up to about 8 m/s were achievable. The maximum energy input was 70 kJ/m^2. This testing method has been described by Ortlepp and Stacey (1996). In this method, determination of the total input energy is simple, but it was not possible to determine the energy actually imposed on the panels themselves. The aim of the testing was to allow comparative results to be obtained for different surface support systems.

The results of the tests have been described by Ortlepp and Stacey (1999) and are summarized in Figure 5-4 in terms of centre deflection of the test panel against the total energy input. The results of tests on other surface support liners are also shown for comparison. The unreinforced shotcrete has the poorest performance as might be expected. Dramix fibre (30mm long) shotcrete was stiffer than monofilament polypropylene shotcrete, and performed slightly better in terms of energy absorption. It is probable that, with longer Dramix fibres, the performance would have been even better. The performance of these fibre reinforced shotcretes was approximately equivalent to that of diamond (chain link) mesh and to shotcrete reinforced with weld mesh.

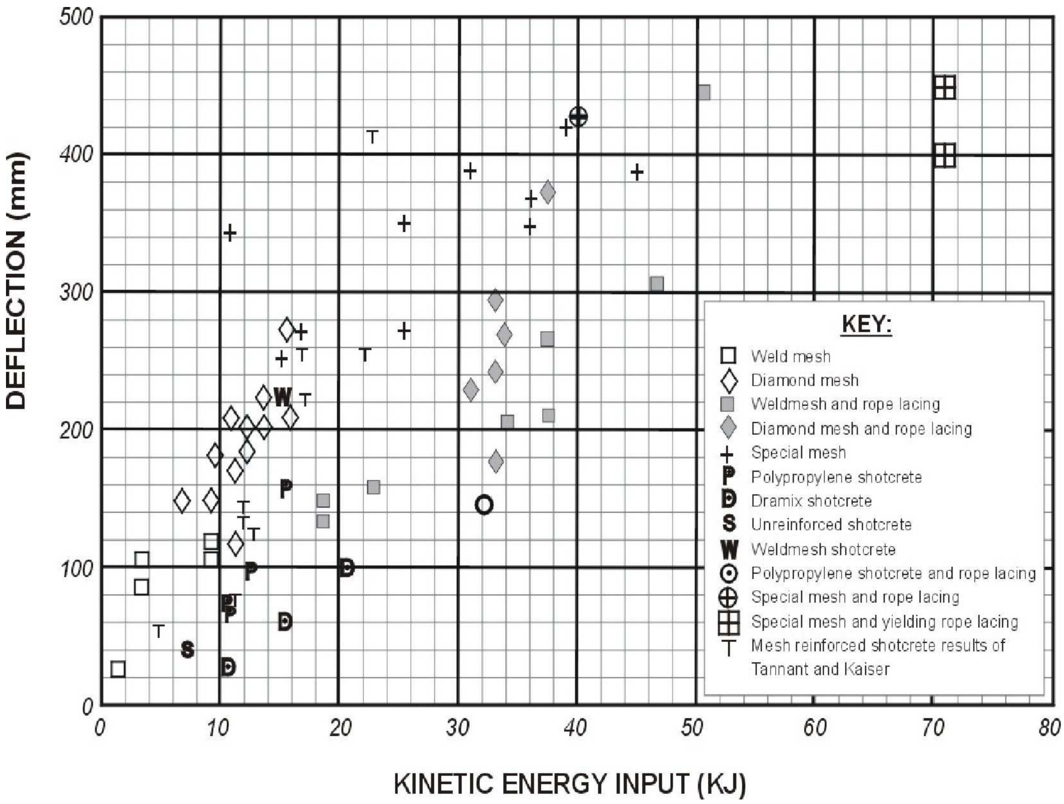


Figure 5-4: Behaviour of shotcrete under dynamic loading conditions

A concern from observations of the testing was that, after the first impact on the panel, in which the impact energy was absorbed and the panel cracked, a second impact destroyed the panel. The implication is that the effectiveness of fibre reinforced shotcrete as a surface support on its own in dynamic conditions is questionable, in particular if it is subjected to repeated dynamic loading, or to dynamic loading after it has been cracked by static deformation.

The addition of wire rope lacing more than doubles the capacity of the panel. The result plotted in Figure 5-4 does not represent complete failure of this support, and the capacity indicated is therefore conservatively low.

More recent testing has been carried out to determine the effects of different rockbolt spacing, and different shotcrete panel thicknesses, on the capacities of the panels. The results showed that the performance was very sensitive to both factors, and that, for rockburst conditions, a rockbolt spacing of greater than 1.2m, and a shotcrete thickness of less than a nominal 75mm, would not be acceptable."

The submittal also contains detailed descriptions of very successful applications of wet mix SFRS in two deep shafts and in a very demanding kimberlite environment.

1.5.15Sweden

Sweden has submitted an account of the Southern Link Road tunnel project and SFRS was used as stated: "Steel Fibre Reinforced Shotcrete (SFRS) and bolts were used as primary rock support. The rock support mainly consisted of un-tensioned rock-bolts and shotcrete. The crown of all tunnels was supported with fibre-reinforced shotcrete, while most of the tunnel walls were sprayed with plain shotcrete. The fibre-reinforced shotcrete was covered with a 20 mm thick unreinforced shotcrete-layer. In frozen areas, temporary support was provided by shotcreting, and the final support consists of a pre-cast lining with a thickness of 0.8 m.

1.5.16Switzerland

The different papers submitted by Switzerland mostly include the use of steel fibres in wet mix shotcrete for reinforcement. The one from the Berg Bock tunnel is describing this choice as follows:

"Advantages relating to working safety were the determining factor for applying steel fibre shotcrete. The construction site was particularly convinced by the fact that it was not necessary to attach the mesh reinforcement over-head in a still unsecured working area. A further governing aspect was that there was no need for drilling operations, which would have possibly resulted in additional disaggregations.

A reduction in working stages furthermore promised that time and cost could be saved.
Instead of:

- Drilling
- Installing the mesh
- Attaching the mesh
- Placing the shotcrete

Only a single stage was required:

- Installing the steel fibre shotcrete

In this way it was possible to reduce the time needed for installing the support by around 30%."

1.5.17Turkey

Turkey has submitted a paper presenting the very demanding Bolu highway tunnel excavation comprising twin tunnels of 18 m excavated diameter. Regarding the primary shotcrete lining and its reinforcement, the following has been stated: "The original lining design was based on the New Austrian Tunnelling Method (NATM), with a shotcrete primary lining augmented with rock bolts and light steel ribs. The shotcrete is reinforced with wire mesh (8mm dia, 150mm x 150mm square mesh), or with steel fibre (typically 50kg/m^3 utilizing 30 mm long Fibrocev Fibra Due). Ductility of steel fibre reinforced shotcrete is being assessed from plate tests. Beam tests are considered unrepresentative of the 3D fibre distribution in the tunnel lining."

6. SHOTCRETE FOR PERMANENT LININGS

Permanent lining of tunnels and other underground excavations was for many years not an alternative at all in many countries. Shotcrete was used for primary and temporary support, a sort of first aid only, and then some sort of in-situ concrete lining would follow.

As the cost of shotcrete in place has dropped over the years and the concrete quality and its uniformity has improved, there has been a clear increase in the use of shotcrete permanent linings. Already in 1985 John Sharp wrote the following in the conference summary note for Shotcrete for Underground Support V – Uppsala, Sweden [1]: "The increasing use of shotcrete as a final lining for machine caverns, transportation tunnels and the lining of waterways, has been emphasized."

There is still quite a spread in the view about shotcrete for final linings and therefore also in its use. The development has still continued and it accelerated during the last 10 years. Working Group 12 of ITA (Shotcrete Use) has compiled a reference list of projects where permanent lining shotcrete has been used. The list is far from complete, but it is still covering 610 km of tunnels at this stage (compiled by WG12 Japanese members).

1.6 Statements from the contributing countries

1.6.1 Belgium

Belgium has not given any specific examples of permanent tunnel linings, but the following general statement connected to the use of steel fibres is relevant: "Steel fibres are being used both in the first and the final shotcrete layer, be it for different purposes. Ductility is required in the first stabilizing layer, while in the final layer crack control improves the durability of the lining.

The single shell method offers the advantage of being able to apply the final layer shortly after the first layer. This allows to shorten drastically the total construction time. In the double shell method very often the final cast lining only can be applied after the breakthrough as the mold obstructs the normal traffic in the tunnel."

1.6.2 Brazil

"Shotcrete permanent tunnel linings have already been adopted in Brazil since decades ago. Such decisions depend on both the characteristics of materials available, and on design assumptions.

It is interesting to note, however, that such decisions have depended very much on different attitudes adopted by different agencies responsible for tunnel construction, and engineering companies responsible for design. For example, in the mid 70´s the important decision was taken for substituting the permanent lining of the 26-m span Paulo Afonso IV Underground Powerplant for shotcrete, at the same time that railway tunnels were being constructed with 40-cm cast in place concrete lining, some of which with geology similar that of the powerplant. For the powerplant, the original design called for a 1.50 m heavily reinforced cast concrete. Substantial economy was achieved when 15-cm shotcrete was adopted instead.

In the early 80's the first NATM tunnels were constructed for the São Paulo Subway, with shotcrete as permanent lining. Specifications were written at the time with tight criteria for porosity, permeability and electrical resistivity, with the purpose to reach durability. Recent inspections of those tunnels have shown that the shotcrete is in good shape. Leakage is within standards (Celestino et al, 2001). Ground water level was up to 20 m above tunnel crown. During the 90's, other subway tunnels were constructed also adopting shotcrete for final lining. Some of those tunnels were excavated in pervious ground masses with severe water pressure. No water proofing measures were taken other than tight shotcrete specifications. Water leakage in some of these tunnels is above acceptable limits. This fact led the São Paulo

Subway Company to a decision contrary to the use of shotcrete as permanent lining. All the tunnels of the forthcoming Line 4 are designed to have cast concrete for final lining and sealing membrane.
On the other hand, the recently completed West section of the São Paulo ring road includes 3 twin tunnels with large cross-sections (200 m² for four lanes in each direction). Permanent shotcrete linings were adopted. This decision was taken during construction due to predictable problems of meeting the schedule, in case cast concrete had been adopted. Localized grouting of the rock mass has been adopted, as well as spot drainage between the two linings. Leakage is negligible, if any."

1.6.3 Czech Republic

"Shotcrete as a final structural layer sprayed on primary lining or intermediate insulation has been applied namely at construction of urban utility tunnels till now. For road and metro tunnels, it was used as an optional technique on shorter sections."

1.6.4 Lesotho

"Shotcrete was used extensively for support, protection of degradable basalt rock and as the permanent lining in this 5.6 km long raw water transfer tunnel. Shotcrete once again proved to be a flexible solution that could be used to provide immediate support to the tunnel, prevent ongoing deterioration of degradable basalt, arrest minor stress related spalling of brittle NAB and provide a hydraulically smoother surface to tunnel sidewalls. In addition, when the Contractor's rate of tunnel excavation became a concern with a real possibility of time overrun, it was possible to start the SFRS lining operation in parallel with the tunnel excavation. Practical constraints determined that the lining had to be placed during a 2 hour window whilst the face was being drilled. This action helped to mitigate delays."

1.6.5 Norway

"The Norwegian Public Roads Administration (NPRA) initiated in 1995, due to the dramatic increase and the systematic use of sprayed concrete as (permanent) rock support, a comprehensive project to broaden our knowledge on durability aspects. The project "Proper use of sprayed concrete in tunnels" was managed by The Public Roads Administration and the work is performed in co-operation with The Public Railroads. The investigations in Norwegian road tunnels clearly conclude that the condition of sprayed concrete is generally good. At some spots with thin layers (less than 3 cm) deterioration and delamination has nevertheless taken place."

1.6.6 Russia

Russia is highlighting the interest in questions related to durability and reliability of permanent shotcrete structures. It is also reported about shotcrete for temporary and permanent support between the Kievskaya and Park Pobedy stations in the Moscow Metro. Totally 1300 m running tunnel and access tunnel was treated this way. In Dagestan a 63 m^2 road tunnel has been permanently lined by 15 cm mesh reinforced shotcrete and rockbolts over a length of 2000 m.

7. HEALTH AND SAFETY

1.7 Statements from the contributing countries

1.7.1 Canada

Canada is using a large volume of shotcrete in the underground mines, with the primary purpose of improving safety for the miners. This paragraph from the submittal gives the background: “Although ground control strategies are included within the mandate of the Mines Act, many of the day-to-day activities of individual mines already exceed minimum legislated requirements. For example, it is not permitted to allow workers to enter an “unsupported” heading in an underground mine. The definition of “unsupported” is somewhat vague and allows for a high degree of variation in the conditioning of the opening. If a particular mining company wishes to reduce the amount of installed ground support (rockbolts and welded wire mesh, for instance) then a detailed review could be carried out and signed off by a professional engineer to attest that the conditions did not warrant the normally installed support. When a rockfall event takes place, and especially if the event leads to injury, an enquiry takes place from which recommendations are commonly made to ensure that a similar event is prevented in the future. It is this process that has led to the installation of a “standard” support in the mines of the Sudbury Basin in Ontario.”

1.7.2 Italy

Italy has also presented a very clear account of the situation in this important field: “Subsurface work in Italy is regulated by precise and strict norms which are constantly updated and which are today in compliance with the last EEC Directives.

Before starting any excavation work, a building company must prepare and submit to the Client the following documents:

- A safety handbook
- Safety plans for each type of processing.

Besides, an employer must take the necessary measures for worker's safety and the protection of their health, including the prevention of occupational hazards, as well as information and training activities. He must put into action measures to be foreseen on the basis of the following main principles and facts:

- struggling against hazards at source;
- adapting work to man as regards the conception of work places and the choice of work and production equipment, taking into account the progress of technology;
- planning prevention;
- giving adequate instructions to workers;
- considering the specificity of the process, in the case of shotcrete;
- fall of rock pieces moved by shotcrete
- being hit by the rebound of the nozzle which can be wrongly diverted;
- reduction of the noise produced by the machinery and the nozzle;

These assumptions have brought to the manufacturing and the spreading, in Italy, of modern machinery complying the said principles.

As regards environmental protection, this is held in great consideration, and for some, in all technical specifications, insistence has been placed on the fact that the choice of the products to compound mixtures must comply with the limits that are now prescribed by the European norms.

Manufactures of additives and cements have therefore modified the composition of materials, in order that they are not harmful to worker's health and to the environment."

1.7.3 Japan

Japan Ministry of Health Labour and Welfare established new regulations for acceptable dust limits during shotcrete application in 2000. The criterion is maximum 3.0 mg/m^3 air measured 50 m behind the tunnel face (except for small cross section tunnels). Persons working in the tunnel must wear a dust-tight mask and the submitted document shows such a mask equipped with a filter, battery pack and an electric fan for supply of clean air.

8. OTHER ITEMS

1.8 Shotcrete Terminology

Canada has suggested that WG12 should try to promote a more uniform use of two specific terms:

"Over the last few years considerable effort has been made to ensure that terminology in various fields of engineering is clear, precise, and unambiguous. Within shotcrete technology, however, there is one term that is used rather indiscriminately and that is the expression shotcrete "application". In order to resolve some of the communications difficulties that arise from the use of this word the following proposal is made. Two distinct and separate terms should be used in shotcrete technology to refer to two discrete components of this wonderful material.

Shotcrete 'placement' should refer to the act of placing shotcrete. This includes various components of mixing, pumping and spraying both wet- and dry mix products. It is suggested that the term 'applying' shotcrete should be dropped completely in favour of the term 'placing'. For example:

"Typical placement strategies for the XYZ Tunnel used steel fibre reinforced, silica fume wet mix shotcrete with a maximum 9 mm diameter aggregate." "The shotcrete was placed at an average rate of 12 cubic metres per hour." "The crew was able to place shotcrete at a uniform thickness of 75 mm using the laser profiling system on the robotic nozzle."

Shotcrete 'application' should refer to the engineering use to which shotcrete is put, the role it is intended to play, or the conditions in which it is used. Examples of this include:

"Improvement in ground control stability is one of the main applications of shotcrete." "It has been found that highly stressed ground is an application in which shotcrete provides significant benefit."

1.9 Selected recommendations from Czech Republic

Regarding temperature conditions, the following is suggested:

- Sprayed concrete can be applied up to the ambient temperature of –5°C, under the condition that concrete mix is used with a temperature above 10°C, measured just before spraying. At the same time, accelerated process of the setting build-up according to the range J_2 has to be ensured for a period of 3 hours after the spraying at least (even for thin layers of sprayed concrete).
- Temperature ranging from 15 to 25°C can be considered as an optimal temperature of concrete mix in the hopper of a concrete sprayer or a shotcrete pump. Should the concrete temperature be lower and also the background temperature and ambient temperature lower, it is necessary to count with an increased dosing of accelerator additive and higher volume of rebound.

1.10 Activity of the Italian Tunnelling Society Working Group Shotcrete

The Italian contribution outlines the last 15 years as follows:

“The SIG (Italian Tunnelling Society) constituted the WG "Use of shotcrete" in 1988, after the ITA meeting in Toronto. On that occasion, the aims of its activity were defined, following the programme of the parallel ITA WG.

Our activity has always been directed towards the spreading of research of Italian and foreign products, also through articles published in the SIG magazine "Gallerie"

At present, the WG programme includes a collaboration with UNI (the Italian organization for standardization) which is revising the European standard on shotcrete.

In November 1994, the working group, in the context of its information work and to conclude a cycle of activity, organized a meeting on Shotcrete (Utilization technologies and new products) in Milan.

We can say with pride that this meeting, which was the first of its kind in Italy, marked the beginning of a new interest in shotcrete, which was shown by building firms as well by designers and owners in relation to subsurface works.

In these fifteen years of activity, Italian building companies, additives and cement producers, as well as equipment manufactures have continued to improve their products, also availing themselves of the experiences of their foreign colleagues, and the result of their work can be seen in the number of tunnels and subsurface works which we have been able to carry out in Italy and all over the world.”

1.11 Dynamic effects on shotcrete linings

Sweden reported very interesting research results about this frequently discussed subject. The whole section from the contribution reads as follows:

“As mentioned above shotcrete is used also in our mines. Even if design requirements may be somewhat different in a mine, where some of the openings are more or less temporary, the general concerns are basically the same. Thus some investigations and tests have been done in the LKAB mine in Kiruna and at the Technical University of Luleå, in northern Sweden. Plate tests have been performed by Malmgren, 2001, e.g. to study fibres in comparison with mesh reinforcement. He also looked upon the dynamic effects from blasting. This is important because the mining method, which is used in Kiruna - i.e. sublevel caving - involves huge blasting rounds with heavy dynamic effects.

Particle velocities of up to 1100 mm/s were measured at 4.5 m distance from the blast holes in the production blasting. Calculations showed that plain, unreinforced shotcrete would be too brittle to support loose blocks, whereas fibre reinforced layers would have the strengthening capacity.

The dynamic effects were also tested in a field experiment, set up in a drift in the mine, to see what vibration levels that young shotcrete could withstand, Ansell 2000, Ansell & Holmgren 2001. This test was part of SveBeFo's research programme and was related to the restrictions referred to earlier in this paper, and thus a background to the tests later carried out in the Southern Link tunnels. Shotcreting was done at different times so that the blasting affected the young shotcrete at different ages, 1 to 25 hours. All tests resulted in ejection of large volumes of rock, creating 600 - 1000 mm deep craters in the rock wall, c.f. figure 8-1. Acceleration measurements showed that the shotcrete in general withstood high particle velocities without being seriously damaged. However, drumminess over certain areas indicated that adhesion failure could occur at vibration levels above 500 mm/s. Numerical simulations of the behaviour showed that thin linings might be less sensitive to vibrations than thicker layers. It could also be concluded that the curing of shotcrete goes through different stages, where it is most vulnerable to vibrations between 2 to 12 hours of age, whereas it is less sensitive when very young or fully mature. After 24 hours of curing, the shotcrete was resistant to vibrations up to 500 mm/s. These results should be compared with the findings in the tests done in the Southern Link, where vibrations were less than 80 mm/s, as close as 5 m from full blasting rounds at the tunnel face.

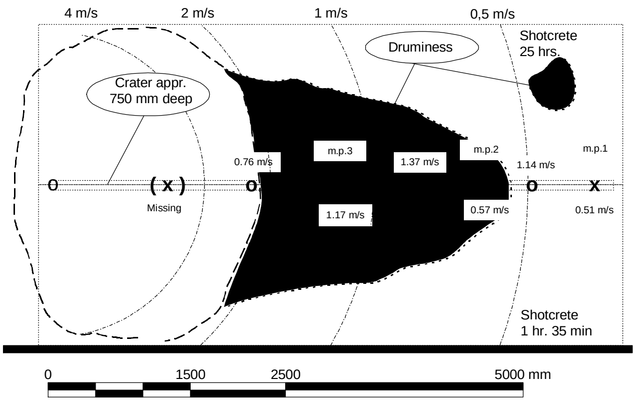


Figure 8-1: Dynamic effects on young shotcrete from tests in Kiruna, Anders Ansell.

9. ACI-506.XR GUIDELINES FOR UNDERGROUND SHOTCRETE

WG12 has received a Preliminary Draft of this document as an input to the Report. This version already consists of more than 100 pages of general and specific guidelines for shotcrete for underground support.

The document is covering e.g. wet mix and dry mix, all sorts of accelerators and admixtures, plain shotcrete and fibre reinforced, along with mesh and other reinforcing elements. Under requirements and testing of fibre concrete ASTM 1018, EFNARC and Round Determinate Panels are covered, with the choice left to the specifiers. This is the nature of such guidelines, that all alternatives are described, but there are no recommendation about the choices that must be made.

It is beyond the scope of this Report to go through these Guidelines in any detail and it is recommended to rather read the document in its complete form. Bits and pieces will not show the real value of the Guidelines and many chapters are so closely linked that they should not be separated. However, to give an indication of the scope of the Guidelines, the 24 Chapters are headed as follows:

1. OVERVIEW
2. SCOPE
3. DEFINITIONS
4. SUBMITTALS
5. MATERIALS
6. ANCHORAGE AND REINFORCING
7. MATERIALS HANDLING AND STORAGE
8. SHOTCRETE PROPORTIONING
9. PERFORMANCE REQUIREMENTS
10. QUALITY ASSURANCE AND QUALITY CONTROL
11. PRE-CONSTRUCTION TRIALS AND TESTING
12. CONSTRUCTION ACCEPTANCE INSPECTION
13. BATCHING, MIXING, AND SUPPLY
14. PLACING EQUIPMENT
15. AUXILLIARY EQUIPMENT
16. SAFETY
17. PREPARATION FOR SHOTCRETING AND GROUND WATER CONTROL
18. REINFORCEMENT INSTALLATION
19. SHOTCRETE APPLICATION
20. CURING AND PROTECTION
21. SHOTCRETE ACCEPTANCE/REJECTION
22. SHOTCRETE FOR THE REPAIR AND REHABILITATION OF UNDERGROUND STRUCTURES
23. MEASUREMENT AND PAYMENT
24. REFERENCES

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