Shotcrete use in the Southern Link and some current shotcrete research in Sweden

SPRITZBETON IN DEN TUNNELS DER STOCKHOLMER SÜDUMFAHRUNG UND DIE AKTUELLE SPRITZBETONFORSCHUNG IN SCHWEDEN

TOMMY ELLISON, TOMAS FRANZÉN, BO I. KARLSSON

Die Südumfahrung ist ein herausragendes Straßentunnelprojekt in Stockholm. Das Projekt umfasst 17 km konventionell aufgefahrener Tunnel. Stahlfaserpritzbeton und Felsanker sind die hauptsächlich eingesetzten Sicherungselemente. Hohe Anforderungen zur Erzielung einer 120jährigen Nutzungsdauer und bestens abgesicherter Frostbeständigkeit stellen eine große Herausforderung für die Material- und Verfahrenswahl bei diesem Projekt dar.

Ein laufendes Forschungsprojekt befasst sie mit der Dauerhaftigkeit von Stahlfaserspritzbeton. Dazu sind Testplatten in verschieden aggressiver, natürlicher Umgebung ausgelagert.

In anderen Versuchsserien wird das Tragvermögen von Stahlfaserspritzbeton in Laborgroßversuchen untersucht. Dabei wird besonderes Augenmerk auf die Einleitung der Ankerkräfte- als Teil der Interaktion zwischen Fels, Anker und Spritzbetonauskleidung, gelegt.

The Southern Link is a major road tunnel project in the southern part of Stockholm. The project includes 17 km tunnels produced by drilling and blasting. The support mainly consists of steel fiber reinforced shotcrete and rock bolts. Tough specifications in order to achieve 120 years durability and highly secured frost resistance mean a great challenge to develop materials and methods in the project.

Ongoing research is focusing the durability of fibre reinforced shotcrete, by tests on panels, exposed in different environments. The bearing capacity of fibre reinforced shotcrete is also tested in large scale laboratory experiments, where especially the anchorage of bolts is studied as part of the interaction between rock, bolts and shotcrete linings.

1. Introduction

The Southern Link (Södra Länken) is a road tunnel project to the south of Stockholm city. The primary aim of the project is to improve the urban environment for the city's inhabitants by freeing the central urban area of through-traffic. The project will solve a major traffic congestion problem by diverting over 100000 cars daily from the area. According to the plans the project will be completed in 2004.

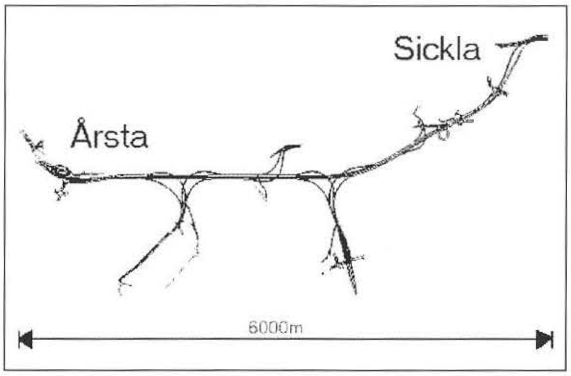

Fig. 1: Map of Southern Link route

1.1 Geology

The rock tunnels in the project are located in the Precambrian Scandinavian gneiss formation. Rock quality is fairly good, typical Q-values (Barton et al. 1974) are between 1-100. Some fractured zones occur, and cracks are more intense in some areas. Rock support requirements in this project were governed by maintenance considerations rather than geological factors.

1.2 Design

The Southern Link consists of a 6 km road of motorway standard. There are several underground grade separated junctions, installation-rooms, shafts, and emergency exits. The total length of rock-tunnel is about 17 kilometers, and the rock volume to be excavated is well over 2 million cubic metres.

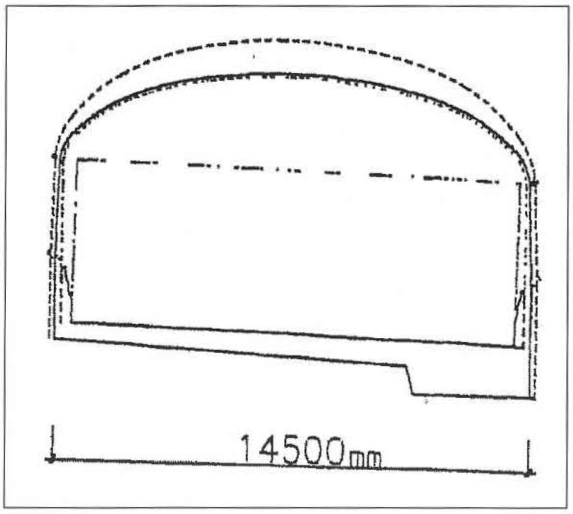

Fig. 2: Main tunnel section

Most of the tunnels are located quite close to the ground surface. Soil depth varies from 0 to 20 m, and the groundwater level is near the ground surface. The dimensions of the rock-tunnels are quite imposing with spans up to 32 metres.

The project includes 12 tunnel portals, and due to the rock topography there are underground connections between rock tunnels and concrete-lined tunnels.

One of the tunnel portals has a span of 32 meters and an over burden of less than 5 m. This section has been excavated very carefully by two pilot-tunnels and 28 stope-rounds (*see Figures 3 and 4*). Longitudinal rock-bolts with a length of up to 10 m were installed outside the tunnel profile, and the rock mass excluding tunnel-face were shotcreted before excavation started. Shotcreting and bolting were carried out after each blasting round. The required shotcrete thickness was 0.5 m, and cavities were also filled in places behind the lining. In extreme cases the total thickness of lining was up to roughly one metre. Approximately 500 rock-bolts with a length of 2-4 m were installed over this 20-metre length of tunnel. This method places high demands on the shotcreting process, especially in order to satisfy the requirement for spraying layers up to 200 mm thick that remain in place. This was possible due to the use of alkali-free accelerators. The excavation and rock support in this section took six months to complete. Deformations were checked during the whole operation, and so far no alarming settlements have occurred.

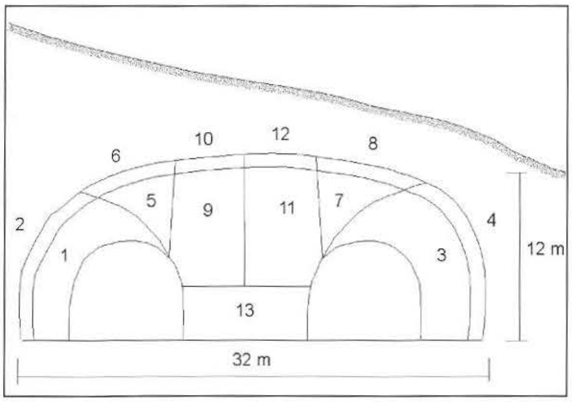

Fig. 3: Blasting sequence, cross-sectional view

1.3 Environment

It was required that the groundwater level should not be affected during construction or after the tunnel was completed. This was due to the presence of sensitive structures, streets, railways, pipes, and buildings founded on wooden piles above the tunnels. Considerable efforts were made to limit noise, vibration, and traffic congestion associated with construction. All buildings in the area were inspected before excavation started, and on-line vibration recorders were used during excavation. Drilling and blasting were not permitted between 10 pm and 7 am.

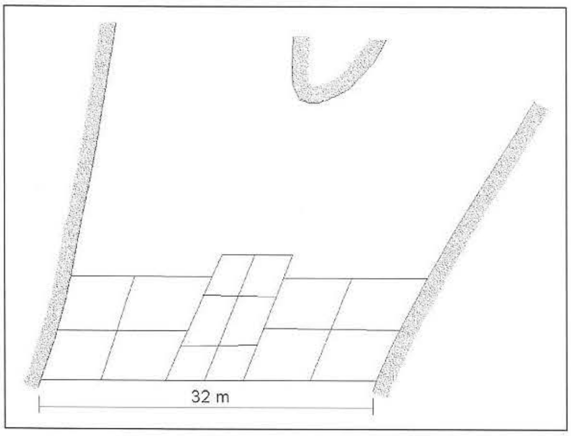

Fig. 4: Blasting sequence, plan view

Providing information about construction activities is an important way to make the people living in the area less concerned about the consequences of construction. Two public relation officers have been employed basically full time for this purpose. Information has been dispersed through notices in local newspapers, flyers, brochures, open house evenings, etc. A bus has been specially fitted and designed as a mobile exhibition, travelling around to the various residential areas affected by the works. Tours down into the tunnels have also been arranged for the general public, and have proved very popular.

1.4 Tunnelling

The excavation method used was traditional drill and blast. All the tunnels were pre-grouted, and some post-grouting is being done in places as well. In some areas with no or very little rock-overburden, the ground was frozen before excavation. To prevent frost problems associated with ingressing water in the tunnels, isolated wall drains were used. The drains were covered with fibre-reinforced shotcrete.

1.5 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 precast lining with a thickness of 0.8 m.

2. Development of materials and equipment

2.1 Requirements

There were several clauses within the specifications affecting shotcrete properties, and these stipulated the following requirements:

- The tunnels were constructed to last at least 120 years.
- For environmental reasons, use of admixtures that could pollute the ground water was not permitted.
- Adhesion between rock and shotcrete was not to be affected by admixtures.
- The concrete must be resistant to freeze-thaw cycling.
- Strength requirements were considerably higher than normal, both with regard to Modulus of Rupture and post-cracking toughness.

  Apart from these specifications, there were additional issues to consider:
- Regard was to be paid to the health and well being of those working in the tunnels.
- It was considered beneficial to be able to place thick layers of shotcrete in one pass.
- Rebound must be low.
- Pumpability and sprayability must be good.
- The shotcrete mix must be cost-competitive to be acceptable.

2.2 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 (*Table 1*).

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

Tab. 1: Initial mix-design for shotcrete

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. Betongindustri AB, Stockholm, who were later contracted to deliver ready-mix concrete for shotcrete use during construction, supplied the concrete. The pre-construction trials started in 1997 and were completed in 1998.

2.3 Pre-construction trial results

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 2*.

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	04.Mai
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

Tab. 2: Test results for trial-mix shotcrete

2.4 Quality control

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:

1. Fibre content
2. Thickness, measured in 25 mm diameter drilled holes.
3. Compressive strength, based on cubes sawed from panels sprayed during construction.
4. Flexural strength of beams sawed from panels sprayed during construction.
5. Adhesion, based on cores drilled and pulled off in-situ.
6. 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.

2.5 Machine development

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.

2.6 Construction

To date, more than 95 % of the contract has been completed, which is equivalent to about 26 000 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.

2.7 Cracking

In some areas a sharp, dark pattern has been observed on the shotcrete surface. Investigations have been carried out in order to find an explanation to this problem. Cores have been drilled over such "cracks" and investigated by concrete specialists. Results show that the patterns consist of minor cracks, generally less than 0.2 mm wide. In some places no cracks could be found although the dark patterns are visible in the tunnel.

No explanation is verified by the investigations so far, but some facts and theories that can be part of the explanation have been discussed:

- Alkali-free accelerators have been used in this project
- Curing is being carried out as intermittent water spraying
- The phenomenon occurs after 1-2 months

- The patterns are mainly visible in rainy periods
- The patterns are more common in upper walls and lower roof
- The phenomenon was less frequent when the shotcrete thickness was over 40 mm
- The visible patterns seem to consist of water from natural cracks in the rock
- Large wet areas on the shotcrete surface are not as common here as in other tunnels in the same area

3. Vibration tests on applied shotcrete

3.1 Background

Technical specifications for this project required that the shotcrete should reach a compressive strength of 6 MPa before loading, and the maximum allowable Peak Particle Velocity (PPV) arising from blasting-induced vibrations had to be less than 150 mm/s up to 24 hours from shotcreting. It was therefore necessary that spraying not be allowed closer than 50 metres from the blasting face. These restrictions tended to interfere the construction cycle during this project. Similar projects have been successfully completed without such restrictions, e.g. the Arlanda Express railway tunnel north of Stockholm, where shotcreting was carried out much closer to the blasting face.

It was therefore desirable to determine how blasting vibrations affected the shotcrete. Ansell (2000) has studied how blasting-induced vibrations affect young shotcrete, and in particular determined the maximum allowable PPV's associated with stress waves close to the location of a blast. It was therefore necessary to determine how far from a blast the Peak Particle Velocity decreases to the critical level. Swedish Rock Engineering Research (SveBeFo), the Swedish National Road Administration, and the contractors Selmer/Besab have assessed the last issue in the Southern Link project.

3.2 Blasting tests

The blast-holes were charged with Site Sensitised Emulsion (SSE) explosives. The whole length was 5.2 metres, and each hole was charged with approximately 7 kilograms of explosive. All tests were performed without shotcrete on the tunnel-walls.

Accelerometers were installed in boreholes of 0.30 m depth in the tunnel walls between 5 and 50 m from the blasting face. Each installation included two accelerometers, one parallel with the tunnel axis and one perpendicular to the tunnel wall. The accelerometers were grouted into the boreholes and were connected to a measuring unit with one channel dedicated to each accelerometer. Seven blasting rounds were recorded, each involving 14 devices.

3.3 Data analysis

Peak Particle Velocity (PPV) data from four rounds were used for the final analysis (Reidarman & Nyberg 2000). The measured vibration directions at each station were both parallel and perpendicular to the tunnel axis. All together 69 values across and 98 values along the tunnel axis were analysed from the four rounds. For construction work it is necessary to know the maximum vibration level and the most interesting may be to determine a level that no vibrations may exceed.

3.4 Results

The tests showed that the first arrival Peak Particle Velocities (PPV's) were usually moderate in magnitude, even as close as five metres from the blasting location. This was particularly true for the registrations from those accelerometers located perpendicular to the tunnel wall. Recorded peak particle velocities (PPV's) for the tests are shown in *Figures 5 and 6*. It is apparent that peak vibration levels parallel to the walls are higher than the values perpendicular to the surfaces. For simplicity, a borderline representing the maximum vibration intensities was used for both directions (PPV=80-1.5 R).

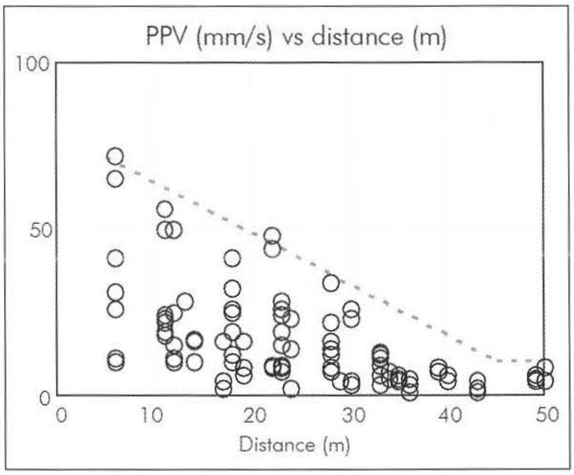

Fig. 5: Measured Peak Particle Velocity (PPV) parallel to tunnel axis, as a function of distance from blasting face

Based on the report by Nyberg & Reidarman (2000) it was concluded that the measured vibration levels were far below the maximum permitted 150 mm/s required by the client. Comparing this study with Ansell (2000) also indicates that shotcreting might be performed close to the blasting face without causing damage to the concrete. However, more studies are needed to confirm this. Such a study can provide important input to future tunnelling projects.

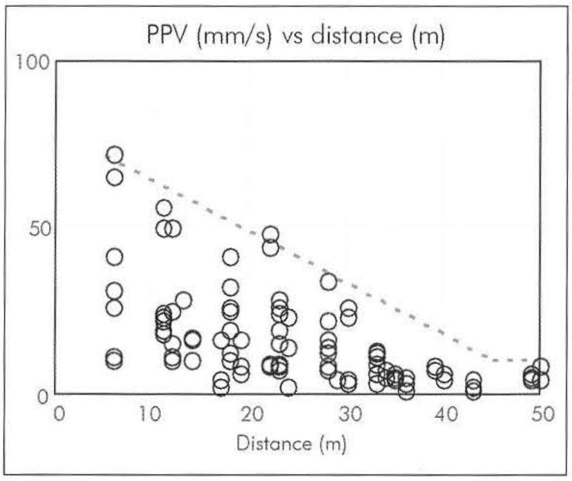

Fig. 6: Measured Peak Particle Velocity, PPV, perpendicular to the tunnel axis

4. Trends in R&D and some current research projects

Fibre reinforced shotcrete in combination with rock bolts is normal practice for most tunnels in hard rock in Sweden, and the technology used in the Southern Link, as presented above, illustrates some typical solutions of today. In the mining sector, unreinforced shotcrete and mesh reinforcement is still used, but even there, fibre reinforcement is gaining terrain.

4.1 Basis for design

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 basic philosophies and the general background for such requirements were presented here in Austria at the "Spritzbetontechnologie '99" (Malmberg 1999).

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.

4.2 Laboratory tests on fibre reinforced slabs

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). Figure 7 shows the general principles of the tests, which 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.

A second part of this project is now going on with the aim to investigate failure patterns and the bearing capacity when a bolt including a steel washer is punched trough a fibre reinforced shotcrete panel (in this case shotcreted panels are used, actually manufactured at the Southern Link tunnel site). It is still too early to present any results from this series, but we believe that it is important to further improve our understanding of this part of support system.

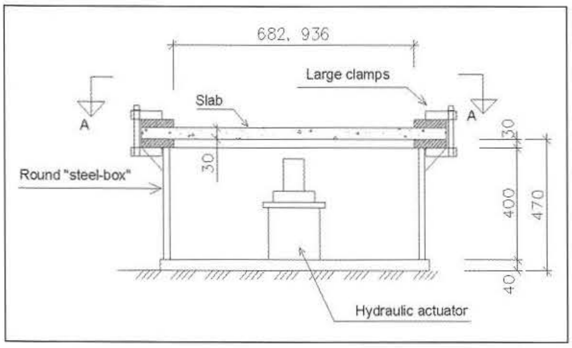

Fig. 7: *Test rig for bearing capacity of circular fibre reinforced shotcrete (concrete) slabs, from Nilsson & Holmgren, 2001*

4.3 Dynamic effects on shotcrete linings

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 necessary strengthening capacity.

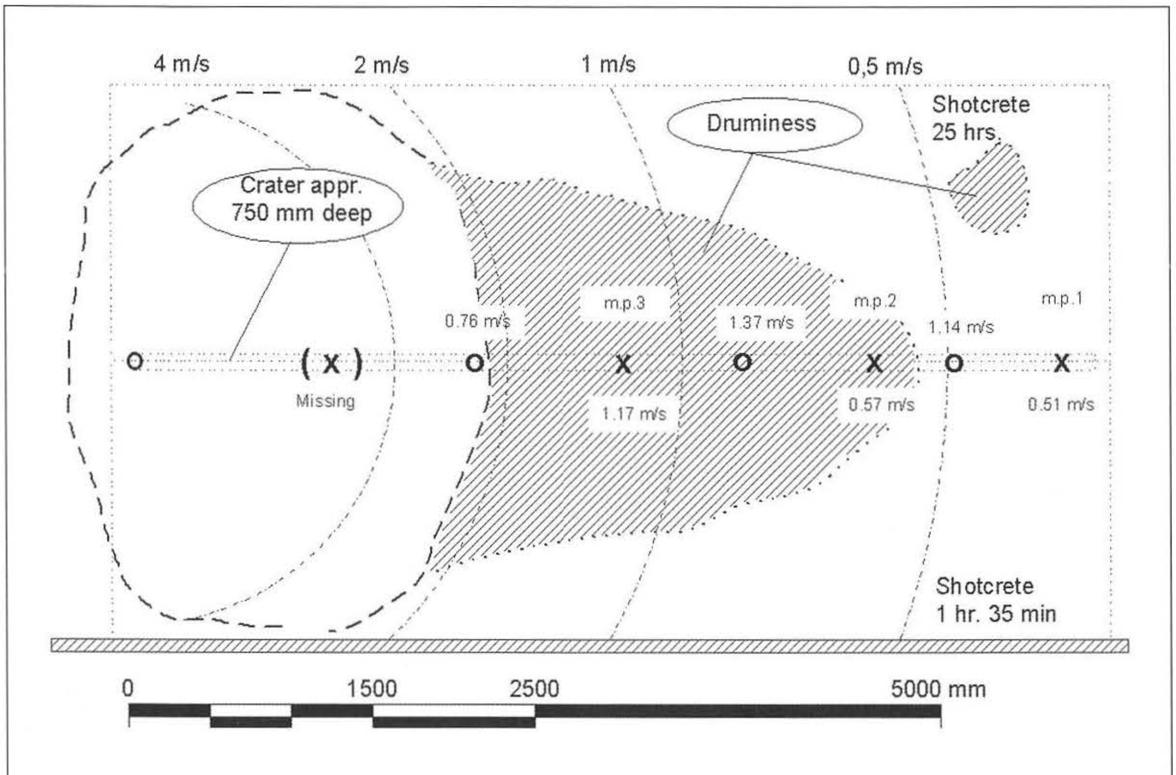

Fig. 8: *Dynamic effects on young shotcrete from tests in Kiruna, Anders Ansell*

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. 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.

4.4 Long time durability of sprayed concrete

Another field of interest is today's concern about sustainability of facilities and their different components, like support systems etc. For this purpose, long time exposition of fibre reinforced shotcrete panels have been started some years ago. The aim is to investigate the effect on fibres, which are exposed in cracks of different widths after different time periods up to at least five years, which we will reach late this year. The panels are placed in three different environments: (1) in a road tunnel in Stockholm, (2) close to a road in the open air, in both cases exposed to de-icing agents used on the roads in wintertime, and (3) in surface water in a river to be affected by different temperatures and water and ice conditions over different seasons. Samples have been taken out with regular intervals and tested, both strength and corrosion of fibres exposed in fractures. The investigations have been done as part of SveBeFo's research programme in collaboration with Vattenfall Utveckling and the Swedish National Road Administration, Nordström 2001.

The test specimens were sawn from large shotcrete slabs including 65-70 kg/m^3 of fibres, with 30 or 40 mm length. The test beams were then pre-fractured by flexural loading in accordance with standard testing of residual strength capacity (ASTM C1018). Crack widths were 0.1, 0.5 and 1.0 mm. At certain time intervals specimens from the test sites have been taken out for laboratory testing of corrosion and residual strength, which could be compared with the original capacity before exposure. In parallel, laboratory tests were done on samples with accelerated exposure of chlorides and changing temperatures.

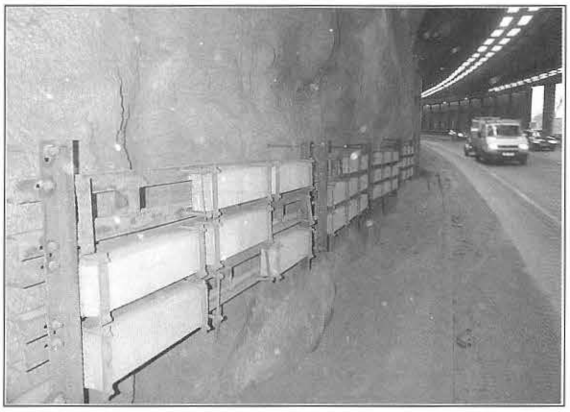

Fig. 9: Field exposure of shotcreted test specimens in the Eugenia road tunnel in Stockholm, photo Erik Nordström

After one year it was stated that the residual strength actually had increased somewhat for most of the samples. The explanation is probably that the hydration was still developing positively and any corrosion effects were limited. After 2.5 years, the strength still increased for samples with 0.1mm cracks, but decreased slightly for samples with 0.5 and 1.0 mm cracks.

To be able to examine the corrosion of fibres, the samples had to be broken in some way that would not damage the fibres. This was done by freezing the samples after vacuum treatment and then full saturation. Freeze-thaw cycles over three weeks, with temperatures swinging between +20 °C and -25 °C and back to +20 °C over 24 hours, resulted in fully degraded concrete, and free fibres were then available for examination.

The corrosion was reported in terms of diameter loss and ranged after 2.5 years exposure between 5 and 15 percent. One observation was that 30-mm fibres were more resistant to corrosion than 40-mm fibres, probably due to galvanic effects. Since corrosion has been initiated already after 2.5 years, the performance over 100 years or more must be questioned. Results from 5 years exposure will be reported in the beginning of 2003. But already now, we can state that the service life of this kind of linings must be taken into account when planning maintenance programmes. The status of cracking must be investigated and repair of cracks or an addition of an extra layer of shotcrete may be required. Still, narrow cracks, up to a critical width, seem to have a limited effect on the residual strength and the service life of the product.

5. Final remarks

Shotcrete - or sprayed concrete - is routinely used in Sweden in most tunnels and also to a large extent in mining. Wet spraying and fibre reinforcement are the standard procedures since long. We can foresee a continued development of equipment and materials, including additives and additions to enhance the performance at spraying and in its final function. Large infrastructure investments are planned for the next decades in Sweden, especially for development of roads and railways. These will include a large amount of tunnelling, often because of environmental considerations, when roads and railways will be crossing urban areas as well as sensitive areas in the countryside. There is much to gain economically by further development of all components for tunnel construction, which means that we will see continued efforts in R&D related to the enhancement of the shotcrete technology.

6. References

[1] **Ansell, A.:**
Dynamically loaded rock reinforcement. Doctoral Thesis, Bulletin 52, Dept. of Structural Engineering, Royal Institute of Technology, Stockholm. Also in SveBeFo Report 47, 2000.

[2] **Ansell, A.; Holmgren, J.:**
Dynamically loaded young shotcrete linings, Proc. Shotcrete: engineering developments, Hobart, Australia, Balkema, 2001.

[3] **Malmberg, B.:**
Spritzbeton in Schweden - Stand der Technik, In Spritzbetontechnologie, 6. Int. Fachtagung, Innsbruck-Igls, 1999.

[4] **Malmgren, L.:**
Shotcrete rock support exposed to varying load conditions, Lic Thesis 2001:64, Dep of Civil and Mining Engineering, Luleå University of Technology, Sweden, 2001.

[5] **Nilsson, U.; Holmgren, J.:**
Load bearing capacity of steel fibre reinforced shotcrete linings, Proc. Shotcrete: engineering developments, Hobart, Australia, Balkema, 2001.

[6] **Nordström, E.:**
Durability of steel fibre reinforced shotcrete with regard to corrosion, Proc. Shotcrete: engineering developments, Hobart, Australia, Balkema, 2001.

[7] **Reidarman, L.; Nyberg, U.:**
Vibrationer bakom front vid tunneldrivning, SveBeFo Report 51, Stockholm, Sweden (Swedish with English summary), 1999.

[8] **Stille, H.:**
Keynote lecture: Rock support in theory and practice. Proc Int Symp Rock Support in Mining and Underground Construction. Sudbury, Canada, Balkema, 1992.