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Shotcrete research and practice in Sweden—development over 35 years

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ABSTRACT: In 1973 a large research project on shotcrete in hard rock tunneling was started by the Royal Swedish Fortifications Administration (FortF) and the Swedish Rock Mechanics Research Foundation (BeFo). That project was also the starting point for me on a long journey through a totally new landscape—the underground. In this paper the development of shotcrete practice in Sweden and its connection to research will be described. In 1973 neither bond testing, rock anchored reinforced shotcrete, fibre reinforced shotcrete or modern accelerators were known. Nor were high speed trains creating considerable loads from under- and overpressure on tunnel linings. The mode of action of shotcrete drains was not explored either. Today there is an increased need for better methods of crack prevention and improved knowledge regarding shotcrete subjected to blasting vibrations and the time-dependent development of material properties in shotcrete.

1 AUTHOR'S STATEMENT

1.1 *General*

I have been involved in shotcrete research since 1973. This has led me to believe that a general review paper is of interest to the shotcrete community. It is based on my experiences connected with shotcrete in hard rock, but it is not the complete history of shotcrete in Sweden.

1.2 *References*

In this paper some facts cannot be supported by references since they are based on my own experiences or on personal information. I also believe that too many references in this type of text would make it difficult to read. Important scientific reports and papers have, however, been referenced.

2 THE SIXTIES

2.1 *Design*

In the nineteen sixties shotcrete linings were not designed in the manner that they are today, but of course there were many ideas about the mode of action of shotcrete in hard rock. It was intended that shotcrete penetrate cracks and keep smaller or larger keystones in place thus helping the rock mass to stabilize itself. The pyramidal block, which punches through the lining, was early introduced as a model for the mode of action of shotcrete. The shotcrete lining was normally designed on the basis of experience and the thickness of the shotcrete was normally in inverse proportion to the quality of the rock. For the worse rock conditions reinforcing mesh was introduced together with increased thickness of the shotcrete or sometimes instead of increased thickness. Rock bolts were normally not designed for interaction with the shotcrete, which seems reasonable in the cases when the shotcrete was unreinforced, but that was also the case when the shotcrete was reinforced.

2.2 *Practice*

All spraying was by the dry mix process. Where water ingress was observed mineral wool drains covered with plastic sheets were used. They were then covered with steel mesh and sprayed. In some cases the shotcrete was accelerated with extremely high dosages of a powder accelerator dosed with a shovel! Such shotcrete could stop the water inflow but the material soon broke down chemically. If the accelerated shotcrete was covered with shotcrete without accelerator a dangerous situation could be created in which the lining could look satisfactory from the outside although it did not bond to the rock surface.

3 THE SEVENTIES

3.1 *Research*

At the University of Illinois at Champaign-Urbana a comprehensive research program on shotcrete commenced. That inspired the Swedish Rock Mechanics Research Foundation (BeFo) and the Royal Swedish Fortifications Administration (FortF) to start discussions about a Swedish research project on the interaction between shotcrete and hard rock. I was asked to be the leader of that project. After some initial discussions it was decided that a series of well controlled tests on a simple block model should be performed at full scale. The reason for this decision, among other things, was that the pyramid-shaped block model commonly in use assumed a punching shear failure of the shotcrete at the boundary of the block, but it was doubted to some extent whether this mode actually occurred in reality. The reason why full scale testing was chosen was primarily pedagogical: it was believed that practitioners would be easier to convince about the relevance of the testing if it was conducted at full scale.

A large steel stand with three granite blocks totalling 5 tonnes was constructed, Figure 1. It was possible to tilt it so that the top surface of the granite blocks could be sprayed in a vertical position. Before testing it was tilted back so that the shotcrete was on top and the middle block was pressed upwards during testing. The test rig was used over several years. Tests on unreinforced, mesh reinforced, bar reinforced and fibre reinforced plane and arch shaped shotcrete layers were performed (Holmgren, 1979, 1985a). Many of the test specimens were also rock anchored. The most important findings were that the bond between shotcrete and rock constitutes a very strong connection between the two materials and that there is a weak correlation between the thickness of the layer and its load transferring capacity over a crack. This subject is still under discussion and not everyone agrees with my finding. The tests also clearly showed that rock-anchored reinforced shotcrete has a beneficial effect both when bond is unreliable and when a plastic behaviour is required.

The findings of this project put a focus on the bond between shotcrete and rock. Hahn performed

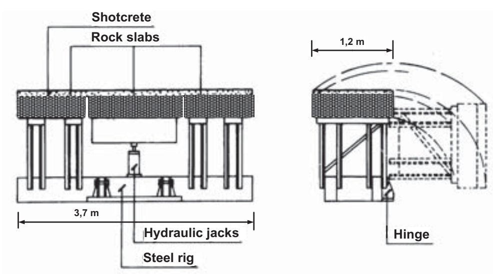

Figure 1. Large scale test rig for experimental investigation of the mode of action of shotcrete bonded to hard rock.

a thorough laboratory investigation on bond between shotcrete and different rock types. His report was published in Swedish, but an English, shorter version is to be found in (Hahn & Holmgren, 1979). This study showed that very good bond (above 1 MPa) is to be expected against most of the normal rock types in Sweden except for mica schist and, of course, also excessively weak rock types.

3.2 *Design*

Some consultants realized the importance of bond and put requirements on bond into contracts. That caused some confusion in the beginning, but when rules had been established how to assess the test results and how the test equipment should be designed, the requirement for 0,5 MPa bond strength was accepted and it is still in force today. The value 0,5 MPa was intentionally chosen because it is a low value compared to what is practically reachable. The idea is that every contractor who does a good job shall not fail in this respect. On the other hand contractors who do not clean the rock surface or do not inform the owner about bad rock conditions should be punished by this rule. This background is important to know because today some people want to divide this value with safety coefficients of different kinds, something that is already built-in to this rather low value.

The Swedish Fortifications Administration (FortF), which had special types of caverns designed for explosive loading, decided that only "simple" linings were allowed to be sprayed without supporting design calculations. More advanced types of lining should be designed using models where the lining was supposed to carry a certain "rock load". That forced design engineers to go through all details of the linings and show by calculation that they could carry the assumed load. Thus the load carrying capacities of the rock bolts, the plates or washers on them, the reinforcement in the shotcrete between the bolts, and the shotcrete itself became balanced against each other. If the required capacity of any part of the system was found not to be inadequate then a re-design could easily be performed.

3.3 *Practice*

During this decade the wet mix method became more and more used. Experiments with steel fibre reinforced shotcrete were also performed. At first short fibres of cold drawn wire were used. The method of adding the fibres was also subjected to a lot of experimentation. Cold drawn fibres with wave form added with a vibrating table gave an acceptable quality of the shotcrete. One contactor replaced such fibres with ones cut from a steel band in a contract with the Swedish Road Administration. That produced an extremely brittle shotcrete and made the Administration ban steel fibres in their contracts for nearly ten years.

4 THE EIGHTIES

4.1 *Research*

Tests on steel fibre reinforced shotcrete in the large test rig described above indicated that such a shotcrete might exhibit a plastic behaviour in shear in the cracked stage. Small scale shear tests were performed and they showed that steel fibre reinforced shotcrete displays very good deformation capacity in shear and that it exhibits plastic characteristics with a load-deformation curve that does not end until most fibres are torn out (Holmgren, 1985a).

Questions about the design of shelters and military caverns situated in rock near the surface were raised regularly—especially since steel fibres had become the dominant reinforcement method for shotcrete. A research project was undertaken in order to find out the optimum design of such facilities. In this project a large test series on dynamically loaded unreinforced and reinforced shotcreted specimens was performed (Holmgren, 1985b, Holmgren & Ansell, 2006). The project resulted in some important principles for the design of dynamically loaded shotcrete linings. Dynamic loading from rock blocks excited by bomb detonations, etc., causes primarily a bond failure at the interface between the rock and the shotcrete. The loosened shotcrete itself has a low energy absorbing capacity, so the momentum from the rock blocks must be absorbed by rock bolts with sufficient deformation capacity. The reinforced shotcrete layer shall thus be designed for a distributed load which corresponds to the yield load of the bolts. That load shall be transferred to the rock bolts by a device that has a larger load capacity than the bolt in order to avoid a localized, brittle failure. The shotcrete layer can be designed using yield line calculations where the residual bending strength is used as the yield capacity.

4.2 *Design*

Steel fibre reinforced concrete was developed by materials researchers who were not focused on the need of the structural engineer to have a strength estimate for determining the dimensions of a structure. For steel fibre reinforced shotcrete in actual applications where yield line calculations were performed, knowledge about the yield strength of the fibre concrete was needed. It was also quite clear that steel fibre reinforced concrete could not be defined in contracts by type and amount of fibres, but a requirement should be based on the capacity demanded by the structure. For Swedish contracts a requirement was formulated based on the load-deflection curve for a notched beam (the JH method), (Holmgren, 1985c). The requirement was very simple to use for the assessment of the actual material. The beam curve should pass over a certain minimum level and fall down beyond a certain level of deformation. The level was chosen so that shotcrete with inferior tensile bending strength was excluded and the position of the point was chosen so that a shotcrete with inferior residual strength was excluded. See Figure 2.

This concept is very similar to the one now introduced in Eurocodes.

4.3 *Practice*

The wet mix method had now become the dominating spraying method in Sweden. On the fibre market the Bekaert zl-fibres and the EE fibres were the most widely used. The contracting company Besab experimented with fibre addition using a specially designed fibre feeder that was able to keep the fibres apart and deliver them to a specially designed nozzle, where concrete and compressed air were added. The fibre feeder required one extra operator and became thus too expensive.

Another contractor, Ekebro, experimented with a device that cut fibres from a cold drawn wire during the spraying process. The fibres had to be delivered with a very high speed to the nozzle, which caused unwanted stops too often. This equipment was used in a factory where balcony facades

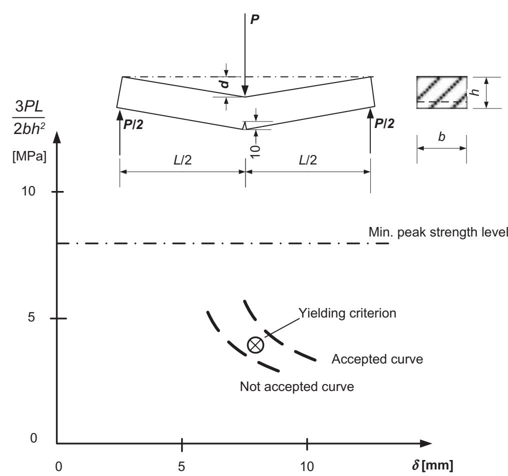

Figure 2. Early Swedish method for defining requirements for steel fibre reinforced shotcrete (the JH method).

were produced, but it was never introduced into production underground. The Bekaert fibres and the EE fibres could easily be added to the mixed concrete, which gave them a market advantage.

The need for a handbook for testing of shotcrete properties was strongly felt during this decade and one was written that contained advice concerning the spraying of test boxes, wash out testing for the determination of fibre content and performance of beam tests (Alemo et al, 1986). Beam tests according to ASTM C-1018 and the determination of toughness indices were described as well as the JH method.

5 THE NINETIES

5.1 *Research*

This decade was dominated by problems connected with shotcrete drains. The old types based on mineral wool and plastic sheets did not perform well. Since large infrastructure projects were planned in Sweden an improved shotcrete drain was absolutely necessary to develop. In a large R&D project the Swedish Road Administration investigated and evaluated a number of designs with reference to constructability, behaviour at freezing, fatigue and possibility to flush them clean inside, (Fredriksson et al, 1996). The basic design consisted of an insulation sheet with closed pores which is covered with steel fibre reinforced shotcrete fixed to the rock surface on both sides of the insulation sheet by bond only. See Figure 3.

This drain concept was used in a Swedish railroad tunnel project before the final report by Fredriksson et al was published and it was subjected to measurements of air pressure variations and accelerations, (Holmgren, 1994) and (Bäck & Oscarsson, 1995). In 1996 I got the chair of Concrete Structures which gave me a possibility to employ PhD students and focus a little more on shotcrete problems.

One important issue in all tunneling projects is the influence of vibrations from blasting on fresh shotcrete. This was studied in one part of a thesis from the division of Concrete Structures by (Ansell, 1999). One interesting result was that thicker linings are more sensitive to vibrations than thinner ones. This research is still going on with a PhD student under supervision by Ansell.

In 1998 I got a Swedish patent on a yielding rock bolt which was intended to be used as the energy absorbing element in a dynamically loaded shotcrete lining. The bolt was thoroughly studied both experimentally and theoretically by Ansell in one part of his doctoral thesis. The rock bolt is used by the Swedish Defense in some caverns together with steel fibre reinforced shotcrete.

5.2 *Design*

The ASTM C-1018 standard for requirements on shotcrete was adopted. It could not be applied on our contracts in Sweden since it did not make it possible to define design strength of the steel fibre reinforced shotcrete from the toughness parameters I_n. After some communication between Colin Johnston, Åke Skarendahl and me the residual strength parameters $R_{m,n}$ were introduced. By multiplying this parameter by the strength at first crack it was possible to determine a residual strength, which could be used for yield line calculations.

In 1992 a handbook on the design of shotcrete linings in hard rock was published by the Swedish State Power Board, (Holmgren, 1992). It was also accepted as a design guide by the Swedish Road Administration and the Swedish Railroad Administration for several years before they had written their own codes for tunneling. The handbook contained recommendations regarding the design of shotcrete linings for different types of cracked rock and diagrams for the calculation of the dimensions of the lining and rock bolting for both static and dynamic loading. A special chapter was written about the handling of errors. I had observed many times that owners often were badly prepared when requirements were not met. In such situations it is very important to act in a rational way, so that the required actions are regarded as logical in relationship to the original requirements. Otherwise there will be an unnecessary debate with the contractor and perhaps even suspicions that the owner wants to punish the contractor. According to my experience there is seldom a problem in convincing the contractor that he has to take the responsibility for his mistakes if you can explain why the original requirements are in place and why additional actions are necessary to restore the functionality of the lining.

During the nineties a more or less standardized design for traffic tunnels developed. Those tunnels are always fully sprayed with bonding, steel fibre reinforced shotcrete in the lowest reinforcement class. No unreinforced shotcrete or unlined walls were permitted anymore! In the next class the shotcrete is a bit thicker and is combined with rock bolts with washers outside the shotcrete layer. The third class is similar to the second class but the shotcrete layer is thicker and the bolts more closely spaced. A fourth class often consists of an arch solution to be applied where rock anchors cannot be used, e.g. where the overburden is small.

5.3 *Practice*

The handbook on testing and assessment of steel fibre reinforced shotcrete was revised and rewritten, (Holmgren et al, 1997). This edition was more directed towards rock reinforcement than the previous one. References to actual standards were introduced as well as the modified ASTM C-1018. The JH method was now abandoned since the modified ASTM method allowed the determination of a residual strength value, which could be used in yield line calculations.

The contractors had by now understood that the owners do not accept mistakes in the control procedures. Bond testing as well as sawing out test cubes and beams and testing them are now performed by specialist companies. The most problematic requirement is the one on residual strength. Because of the large scatter in this parameter one beam test often falls well below the requirement. Other requirements are normally met.

6 YEAR 2000 AND FORWARD

6.1 *Research*

In a PhD project which was started before 2000, the mode of action of bolt anchored steel fibre reinforced shotcrete was studied, (Nilsson, 2000 & 2003). Nilsson showed both experimentally and by FEM calculations how the punching failure in steel fibre reinforced shotcrete in the vicinity of a washer develops. He also explained why the increase in load carrying capacity because of dome action from restrained horizontal deformation of a shotcrete slab was much larger than was expected from theories and experience from testing of conventionally reinforced concrete slabs.

This period was otherwise dominated by shrinkage and cracking. When the large traffic tunnel system Södra Länken south of Stockholm was constructed there were many complaints about extensive cracking in the bonding shotcrete. It was assumed that the water curing was not well performed. The cracking also seemed to decrease when special teams were set up to implement water curing.

When the tunnels were finished it was discovered that a large number of drains, especially the continuous ones were heavily cracked. Also in the large railway project in northern Sweden, Botniabanan, it was felt that the cracking problems were more serious than normally occurs. Suspicions soon were directed towards the alkali free accelerators that were introduced approximately at the same time as the increased frequency of cracking was observed. Everybody knows that water curing of shotcrete seldom is performed sufficiently, but this was different from ordinary experiences. Perhaps shotcrete with alkali free accelerators was more water demanding and more prone to shrinkage.

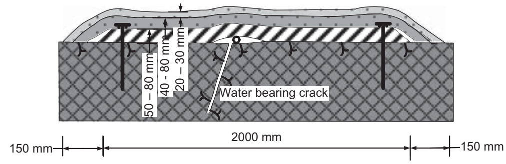

Figure 3. The Swedish drain consists of a perforated plastic tube at the water bearing crack, which is covered by an insulating sheet with closed pores. The sheet is fixed to the rock by short bolts and reinforcement bars. The sheet is covered with steel fibre reinforced shotcrete which bonds to the rock surface at the edges. Finally the steel fibre reinforced shotcrete is covered by unreinforced shotcrete.

A project was started where the structure and shrinkage of differently accelerated shotcretes were studied by Prof. Björn Lagerblad and his team at the Swedish Cement and Concrete Institute and the shrinkage cracking problem was studied by Dr Ansell and me.

The first project showed that ettringite crystals that are created by the alkali free accelerators form an open structure that gives a larger water loss than in ordinary concrete. It was also shown that its shrinkage was larger than experienced by ordinary shotcrete.

With the commonly used cement for shotcrete in Sweden (CEM I, MH, LA, SR) and normal rock temperature it will take more than 24 hours before the shotcrete will get any significant strength. In normal concrete the cement reactions occur in a plastic structure which means that the chemical shrinkage can take place without causing any problems. In accelerated shotcrete they occur in an already existing, "stiff" structure consisting of ettringite crystals why the chemical shrinkage will affect micro cracking. An effect of this is an autogeneous shrinkage of around 0.5 mm/m. Thus water added from the start is needed. Moreover, the hardened shotcrete will get a coarser pore structure, which will increase the drying shrinkage by between 15 and 20%. Together this produces shrinkage levels that can explain the increased cracking observed in the field.

The amount of shrinkage is dependent on the amount of cement paste in the mix. Normally shotcrete contains more cement (and water) than ordinary concrete. By careful proportioning with increased amounts of filler it is possible to reduce the amount of cement by around 20%, but one will get problems at low w/c ratios. One effective method is, however, to add substantial amount of air to the mix, air that disappears during the shooting operation. Another effective method is to add shrinkage reducers to the mix (Lagerblad et al, 2007).

In the shrinkage cracking project some preliminary tests with shrinkage rings were performed. The concrete used was a shotcrete mixture which was cast instead of sprayed. The tests showed that normal amounts of steel fibres cannot prevent cracking but if glass fibres are added the combination of fibres efficiently prevents the formation of micro cracks so that larger cracks never form. The explanation is probably that shrinkage stresses successively relax while the glass fibres keep the micro cracks together since shrinkage is a slow process. When beam specimens with steel fibres and glass fibres were loaded under short term conditions they all cracked in a way that is typical for a strain softening material and it did not appear as if the glass fibres made any difference at all, (Ansell & Holmgren, 2007a; Holmgren & Ansell, 2008).

The research by Ansell on young shotcrete subjected to vibrations from blasting is continuing (Ansell, 2004, 2007b). A FE-model has been developed and is now being refined. A PhD student is also working in this project since 2008.

6.2 *Design*

The introduction of high-speed trains focused attention on the design of shotcrete drains. The Swedish Railroad administration increased the design loads for those structures on at least two occasions, so now shotcrete drains have to be designed for an air pressure ranging from ±3 kPa at single track tunnels and speeds 170–219 km/h up to ±5 kPa at double track tunnels and speeds 220–270 km/h. The design shall also take fatigue into consideration.

In the standard design the drain is fixed to the rock by bond only, but also other concepts exist where anchoring devices are sprayed in.

The drain must either be designed assuming that a shrinkage crack has formed at an unfavourable position or a crack control device shall be installed so the position of a shrinkage crack is known in advance.

6.3 *Practice*

Shotcrete drains have continuously caused practical problems during this decade. The first problem has been related to shrinkage cracking. Such cracks have of course raised the question whether the cracks have decreased the load carrying capacity or not. A tremendous amount of work has been performed mapping cracks in drains. Many of the cracks are parallel to the direction of the tunnel and thus more or less harmless. Others are perpendicular to the tunnel direction but very limited in length and thus considered harmless. Some are both directed perpendicularly to the tunnel direction and of several meters length and thus regarded to be a potential danger.

In the last case the drain capacity was recalculated taking the crack into consideration and if the thickness was at least equal to the nominal amount some of them were accepted because the shotcrete strength increased considerably by that time. In the opposite case the drain has been made thicker by additional spraying.

The second problem is connected to the first one and that has to do with the spraying technique. Nozzlemen have not been made aware that there is a difference between shotcrete on the rock surface and shotcrete on a drain. In the latter case the shotcrete is designed to carry a comparatively large load and thus the thickness is of great importance.

Traditionally the thickness of shotcrete is measured according to a standardized pattern. That pattern does not take the function of a drain into consideration. In a drain the thickness is most important where the bending moments are largest but it has also to be considered that the thickness shall be constant over the drain in order to minimize the risk that shrinkage cracks are concentrated at the weak parts.

7 CONCLUSIONS

It has been demanding and challenging to work with problems connected with shotcrete in tunnels. The demands come from the fact that tunneling people are very pragmatic and that many of them are very experienced. The research must therefore give answers to questions that are regarded as realistic by people involved in shotcreting practice.

The challenge comes from the fact that rock problems are so complex that they seldom can be described with any accuracy. Yet the solutions must be possible to adopt in varying practical situations. It is also to be remembered that the conditions in a tunnel are such that actions which seem to be simple and clear on a drawing or in a description, might not even be possible to perform.

I am very happy that chance once lead me into this field of technology and that I have been allowed not only to contribute to the development of engineering technology but also to solutions to practical problems.

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