EXAMPLES OF THE BEHAVIOUR OF SHOTCRETE LININGS UNDERGROUND.
By Rolf Selmer-Olsen

Introduction.

The following examples of the use of shotcrete are taken from a number of different tunnels and permanent underground openings in Norway. Roughly calculated only 1.5 percent of our total tunnel length is lined with shotcrete. This 1.5 percent, however, is equivalent of more than 15 miles of tunnel length. Shotcrete linings of varying lengths are to be found in railway, highway, water supply and sewage tunnels, but first of all in hydro power tunnels. Shotcrete is also used in a number of different underground rooms for lining and supporting. Compared with this, concrete linings cast in place make about 3 percent of the total tunnel length.

Without exception all these tunnels and underground openings are situated in bedrock of Paleozoic or Precambrian age. Sandstones, limestones, shales, mica schists, marbles, greenstones, different intrusive rocks and gneisses, granites, amphibolites and quartzites are the most common rocks types encountered.

Shotcrete linings are often regarded as an alternative to concrete linings cast in place. Hence these two types of support have to be carefully compared in cost, quality and flexibility. This will often set a limitation on the use of shotcrete.

For instance, in Norway a 20 cm thick reinforced shotcrete is more expensive than a concrete lining of 30 cm minimum thickness, unreinforced and cast in place, and the time it takes to produce it is longer. When supporting close to the face, the shotcrete, however, involves, in general, less delay in the advance of the tunnel if thin linings are used. It also allows a greater flexibility when the unstable area has irregular boundaries. This makes shotcrete favourable as a temporary support after each or after every second round.

x) Professor of Engineering Geology, The University of Trondheim, The Norwegian Institute of Technology.
When determining the permanent support of a tunnel one has not only to consider the cost and the type of stability problem, but also different circumstances concerning the prospective use of the tunnel. For instance the degree of safety against outfall of small chips with time and accessibility for later supplementary works. The low total percent of linings in tunnels in Norway is due to such assessments and to the fact that more than 90 percent of our tunnels are made for hydro-electric power schemes.

Furthermore, the physical and mechanical conditions for a tunnel often change after taken it into use. For instance it could be exposed to freezing and thawing or it could be used for conveying water, perhaps under high pressure. The choice of type of linings depends also on behaviour fixed by the utilization of the tunnel. Not all stability problems that arise during use express themselves equal clearly during the period of excavation.

Experiences of different methods of tunnel linings in relation to the type of stability problems and the use of the tunnel have been valuable for the design of tunnel support in Norway. Some of these experiences concerning the use of shotcrete linings will be described in this paper.

Underground openings with dry conditions and temperature above 0°C.

The first shotcrete linings used in tunnels and underground openings in Norway date back to 1952. In the early years their use was restricted to rock masses of good or very good quality. Shotcrete was used in underground petrol storage excavations to prevent sparks caused by falling rocks, or to avoid repeated scaling control every second or third year in tunnels where people worked daily. Before shotcreting the rock was scaled down and unstable areas were supported by rock bolts. Complicated stability problems were solved by concrete linings cast in place.

What was called 6 cm shotcrete was generally used, only in a few cases 10 cm. We have no information about the
dosage of accelerators used in these old shotcrete linings and what strength they intended to gain. But we know that admixtures, if used, were treated with great caution at that time in Norway.

An inspection a month ago of some of the 10 - 25 years old shotcrete linings confirmed that they had served their purpose perfectly. In general their strength and adhesion to the rock seemed to be very good. A few small areas with no adhesion were of course observed, but such occur also in newer linings, and are the results of unsatisfactory cleaning of the rock. This was probably partly due to oil coatings from the drilling equipment and contaminants from the explosives, and partly a result of the problem of keeping clean upward-facing rock surfaces which easily collected dust. A careful cleaning of the rock surface is essential for the strength of the lining.

We also experienced early that adhesion was not obtained on surfaces formed by joint planes coated with clay. Further, that the adhesion to surface areas parallel to the foliation in mica schist, phyllite or the like, and bedding planes in certain types of shale, was often very low and considerably less than the minimum tensile strength of the rock. This is likely due to a finely splintered rock surface having microscopic cracks parallel to the surface which result from the splitting of the rock. The minerals on schistosity planes that we regard as the most dangerous are mica, chlorite, talc, graphite, hematite and clay minerals.

Rock bolts and reinforcement nets were gradually taken into use at places where such minerals occurred, in particular at protruding parts of the tunnel surface. This strengthened the shotcrete, increased the interaction and helped to build bridges to areas which gave good adhesion.

At protruding corners of edges the extending plane is often a joint or a schistosity plane with the mineral coating already mentioned. In such a case, the shear strength along the very thin shotcrete cover at the jutting edge and
the very low adhesion to the joint plane reduces the strength of the construction. The use of a reinforcement net and rock bolts at the joint plane allows the possibility of increasing the thickness along the edges and the total strength of the lining.

Another thing that was tried in the early sixties was to use shotcrete linings with reinforcement net and rock bolts as permanent support in openings with high anisotropic stresses and rock burst phenomena. Briefly described the method used was expansion rock bolts in the roof, if needed close up to the face after each round. Behind the drilling rig, supplementary bolts were installed and in some cases also a temporary net. Later on, loosened slabs were carefully taken down, the rock bolts replaced one by one with grouted dowels and the temporary net replaced by a reinforcement net. Finally 10 - 20 cm shotcrete was applied. This supporting method has proved to be a success and is now frequently used.

Also when benching 20 m down in a underground opening in rock of good quality, but with high stresses, a shotcrete lining seems to take up the small, unavoidable deformations of the crown in a very satisfactory way. A single tension crack in the reinforced shotcrete is, in this case, generally of no consequence for the stability.

As mentioned, however, the changes of physical conditions in a tunnel after the time of completion have given serious failures of shotcrete linings. I would like to comment on some of these types of situations that have led to great disappointment in Norway.

**Underground openings exposed to freezing and thawing.**

In Norway frost may in some cases be active in railway and highway tunnels over stretches of up to 1.5 km. It often takes, however, some years before shotcrete used in such tunnels loosens, cracks and falls out due to the freezing process. The destruction process starts in humid places and places with low adhesion to the rock.
The areas with low adhesion are, as earlier mentioned, schistosity planes, bedding planes and joint planes with mica, chlorite, talc, graphite, hematite and clay minerals, as well as areas coated with oil, dust and contaminants from explosives. Some highway tunnels, railway tunnels and metro tunnels have had great maintenance costs.

Figure 1 shows a rather small failure due to a joint plane and frost action in a railway tunnel near Oslo. A temporary reinforcement with bolts was carried out.

![Failure due to joint plane and frost action in a tunnel.](image)

**Figure 1.**

Failure due to joint plane and frost action in a tunnel.

Due to shotcreting, the seepage water will be held back in joints, pores and the large number of microscopic cracks in the splintered rock surface and cause frost burst phenomena. Draining by means of drillholes has only a limited effect. A much more effective drainage or an insulation against frost is needed to prevent failure. Rock bolts also have a limited effect. A reinforcement net, however, often prevents larger loosened slabs of shotcrete from falling out.

The shotcrete seems to resist the frost action better on dry fracture planes in crystalline rocks that do not follow the foliation or joints. But in tunnels one seldom get such idealized conditions on all parts of the surface.
It should be unnecessary to mention that also in open cuttings shotcrete exposed to frost action has, in general, been a failure. Figure 2 shows such an open cutting in shales coated with shotcrete. The picture is from Oslo.

![Shotcrete failure in an open cutting due to frost burst.](image)

**Figure 2.**

Shotcrete failure in an open cutting due to frost burst.

It is obvious that instead of solving a problem, shotcrete lining on surfaces exposed to frost action very often leads to new stability problems of considerable extent.

**Water tunnels with gouges containing swelling clay.**

Gouges containing swelling clay occur frequently in Norway. Often they are heavy consolidated and individually several meters, in some cases more than ten meters, wide. They have developed along joint planes or fault planes. Often the feldspar in the wall rock is altered to montmorillonite. In other cases a secondary schistosity, defined by thousands of microscopic fillings of montmorillonite, characterises the wall rocks of the clay gouges.

Often the only thing that could be observed in the tunnel surface is a change in colour, and the softer nature of the rock. In such cases the water percolation through the
rock is often less than the evaporation so that the swelling process does not start and the real stability problem does not become apparent. Nearly nothing may happen to the gouge during the time of construction. Only in the ditch and partly in the invert the water has softened the clay material by soaking and made it swell. The situation, however, still seems harmless to the miner.

If the tunnel is taken into use as a water tunnel, the altered rock swells and breaks down part by part and fills up the tunnel. Several thousand m$^3$ could fall out during a month or two if the water is flowing. If the water is not flowing, more or less watertight plugs may be built up. Shotcrete linings often seem in these cases to be of no help even if the shotcrete is 25 cm thick, reinforced and bolted. It makes no difference if the shotcrete is inserted by the wet or the dry method.

Figure 3 and 4 show situations in a pressure tunnel for water supply from the south of Norway a few months after the water was introduced in the tunnel. Shotcrete linings of different design and up to 25 cm thick and reinforced with net were cracked or broken down in about 30 places and the gouge material had completely plugged the tunnel in three places.

The rock mass was intersected by gouges up to 5 m wide containing a very active swelling clay in form of altered amphibolites and gneisses. Only a few of the gouges caused difficulties during the advance of the tunnel due to seepages and a relative low degree of consolidation. They had been temporarily supported with shotcrete.

The permanent support was done by shotcrete adapted to the size of the zones. The strength was tested during the construction by spraying in pans. A uniaxial compressive strength of more than 30 MPa was claimed.

In the approximately fifteen years' older water supply tunnel running parallel to the one in question, the linings were cast in place and no failure had occurred. Linings cast in place have also been the usual means of supporting the very many tunnel areas with gouges containing swelling clay.
SHOTCRETE LININGS

Figure 3.
Failure due to swelling clay in water supply tunnel.

Figure 4.
A total break down of a shotcrete lining in a water supply tunnel due to a gouge with swelling clay.
This is, however, not the first time that shotcrete linings have failed in water conveying tunnels. Since 1960 we have had four different tunnels with more or less the same case history as the one mentioned.

From experience it is known that all damage to shotcrete linings of thicknesses between 10 and 25 cm, occurring before or after the tunnel is taken into use, have happened when the swellability is greater than 0.25 MPa after Brekke's swelling test. Furthermore, we know that the clay content in average for the total affected area of larger zones has been more than 5 percent, but chiefly concentrated in one or more gouges. In smaller single gouges with thicknesses down to 20 cm, it seems that both the concentration and the swellability has always been somewhat higher in cases of failure.

An interesting and favourable experience with shotcrete is the sealing method used to support small clay gouges where the wall rock is of good quality. It has been used with success on clay zones of widths up to one meter when supporting inactive clays. The arching effect that can be obtained with the good, clean and bolted siderock as abutments, and the eventual swelling or squeezing effects that may occur, should be carefully evaluated in each case. The method has also been successfully used on single zones with active swelling clay when the width of the zone is less than 20 cm. The sealing method is, however, a typical piece of craftsmanship, both the blasting of the wedge along the gouge as well as the bolting and spraying of the zone. On the other hand concrete is saved and the profile of the tunnel is not reduced.

In some cases reinforced shotcrete linings have been used in combination with rock bolts where small veins of swelling clay occur in different directions. To attain a satisfactory result, however, a sufficient number of big blocks are needed between the veins to facilitate effective bolting. Furthermore, the total content of clay in the whole rock mass should be less than one percent, no larger concentrations should occur, and the
direction of the veins should not be too unfavourable in relation to the tunnel axis. In certain types of rock the method should not be used, for instance: dunite, serpentine and soapstone.

It is obvious from the examples that shotcrete linings in general must be able to withstand higher stresses from the swelling clay than do cast linings. If the rock pressure is not so high in relation to the strength of the consolidated clay, such that a squeezing effect arises, the clay in a gouge will build up a silo effect or arching effect after a very limited and tolerable expansion. This is the explanation of the relatively small expansion which is needed to reduce the mobilized stresses on a lining to an acceptable level. This also explains the different behaviour of the two types of linings.

The required expansion seems to be a function of the level of consolidation, the swellability, the amount of clay and the width of the zone. This expansion varies from case to case; usually it is less than one inch, but under certain conditions it can be considerably more.

Because of the cracks formed by the blasting and the destressing of the periphery, the exact consolidation is in general of minor interest. However, a cast lining in place close to the face gives a larger possibility for expansion of the clay than a shotcrete lining, due to; less scaling and cleaning, less concrete penetration in cracks, more time for swelling, lower adhesion to the surrounding rock, larger shrinking (which depends on the total geometry of the concrete construction) and, in addition to this the incomplete filling against the crown.

In extreme situations where very active clay in wide gouges have had small possibilities to expand due to dry conditions we have also observed cracks and deformations in the walls of cast linings. However, a total collapse caused solely by the swelling process has never occurred in Norway. In some serious cases we have successfully allowed the clay possibility for expansion behind the walls by special techniques.
In cases where very active swelling clay in larger gouges has swelled sufficiently without falling out before the shotcrete is inserted, the result in tunnels carrying water has been somewhat more encouraging. However, to insert the shotcrete on the very fissured and soft clay material is difficult, and the penetration of the shotcrete in the fissures reduces the free volume needed for the swelling process. Also the low adhesion and the irregular shape of the lining do not provide reassuring conditions for the support. A critical attitude to the use of shotcrete is well founded in these cases, too.

Water tunnels with squeezing phenomenon in crushed zones.

Very fine crushed dikes of altered diabase rich in chlorite have turned into squeezing rock after having been saturated with the water that penetrated the shotcrete in a tunnel carrying water under pressure at 500 m depth. Fall-out of several thousand m$^3$ from the crushed zone into the tunnel was the result. Also in this case of squeezing induced in fine crushed and dry chloritic material by saturation in few meters wide zones, a lining cast in place served the purpose perfectly.

Similar observations have been made in the case of crushed soapstone, serpentine and dunite, as well as in schists containing talc in addition to a very high content of chlorite or mica. Whatever else the cases may have in common, they all show a number of slickensided fissures. The water saturation gives the rock mass a very low internal friction. A small expansion seems needed also in these cases to reduce the stresses on the lining as much as in case of swelling clay.

Conclusion.

As a conclusion, I will draw attention to the fact that a proper use of shotcrete is a demanding art both for the nozzelman and for the geologist. It is an excellent method for permanent support and lining when used in the right way and in the right place. In areas exposed to freezing and thawing and against active swelling clay deposits in
water tunnels, however, shotcrete linings are often unsatisfactory. This is also the case in instances of squeezing in crushed zones. Furthermore shotcrete is often effective as a temporary support to increase the stand up time in cases of swelling clay, too. But used close to the face during the advance of the tunnel it often covers the problems without solving them, and one has to make decisions about the permanent support blindly if such decisions were not made before shotcreting.

Selected references.


