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Performance of shotcrete linings in road tunnels

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Sammendrag

Lining with shotcrete was tested in road tunnels in the early 1960's. The experience gained was so unsatisfactory that the support method was hardly used in road tunnels for almost 15 years. The main reasons for this were problems with delamination, water leakage, frost damage as well as difficulties in assessing safety and the demand for maintenance.

To evaluate the performance of different support methods, 140 road tunnels have been studied, of which 32 had shotcrete linings. The linings amount totally to an area of 186'274 m^2. Half of this, 90'862 m^2, was so penetrated by water leaks that water and frost protective panels were, or should have been installed. The total shotcreted area penetrated by water is probably much higher since large areas were already covered by panels when mapped.

Increasing the tunnelling speed and savings in rock bolting was the motive for reintroducing shotcrete, now mainly supplied with steel fibers. Studies of the excavation procedcure at Heggura tunnel in 1980 demonstrated that shotcreting hardly increased tunnelling speed and did not reduce the demand for bolting support.

Shotcrete, combined with rock bolting, has its main advantage as a heading support in poor, highly fissured rock. However, the study demonstrated that the linings, in particular leaking ones, are subjected to degradation with time, reducing strength at the very cracks where it may be needed most. It is therefore evident that a shotcrete lining cannot be considered as a permanent support in road tunnels sections which are prone to water leakage.

Shotcreted sections have generally to be proided with protective panels against water leaks and, where necessary, frost damage. Where panels are installed in leaking and poor rock sections, the rock support is normally hidden for future inspection. Very careful mapping prior to shotcreting is therefore required to achive a rock support of a satisfactory safety level.

Emneord: *Shotcrete, concrete deterioration, shotcrete delamination, water leaks, maintenance, rock stress, tunnel convergence*

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Contents

BACKGROUND

History

Shotcrete has been applied for rock support in Norwegian road tunnels since the beginning of the 1960's. The first tunnels to apply shotcrete were the Mosseporten tunnel, Moss, and the Høgenhei tunnel, Brevik.

In 1962, the crown of the Høgenhei tunnel was sprayed with concrete after the dry-mix method. After some time, shotcrete slabs began to fall down, creating a hazard for the traffic. A prefabricated concrete lining was then installed in the tunnel crown to solve this stability problem.

In 1963, about 300 m of the Mosseporten tunnel was sprayed with concrete. The tunnel was mapped in 1981 to survey the need for restoration and improvement of the tunnels safety standard. This survey disclosed widespread water leakages and that 30-50% of the sprayed area was delaminated.

After the poor performance of the shotcrete experienced, the use of shotcrete as a general method for rock support came to an end in road tunnels for many years. From the 1990's on, the use of shotcrete as a heading support has dramatically increased. To reach a conclusion as to the consequences of this new support strategy, performance studies of in service road tunnels with shotcrete have been initiated.

The scope of the study

In the years 1987 to 1990, the NRRL made a study of the state of safety in 140 tunnels that had been in service for some time. The mapping included inventory of the state of rock support, the state of linings for water and frost protection, and the distribution of the water leakages. Available information on the extent and type of maintenance was also collected.

The scope of the study was to achieve an outline of the total costs and the technical/ economic lifetime of the different support and lining designs used. Evaluation of support and lining design was made by visual inspection only, sampling for laboratory testing was not carried out. The results of the study were presented in 22 reports.(Table 1)

DESCRIPTIONS

Shotcrete in three of the tunnels

The tunnels described below are dealt with because they are representing types of tunnels of special interest to the study. The Heggura shotcrete lining is subjected to rock stresses, and was the first shotcrete lining in Norway to contain steel fibers. The Flekkerøy tunnel represents the new generation of shotcrete used for subsea tunnels subjected to salt water. The Mosseporten tunnel has the longest shotcrete record in the study, it represents the initial type of shotcrete applied in Norway and has documentation of some of its rehabilitation works.

Experiences from the Heggura road tunnel, Tafjord

The Heggura tunnel was opened in 1982 after two years of construction time. It is 5280 m long with a cross-sectional area of 40 m^2. The tunnel was the first one to be sprayed with steel fiber concrete according to the wet-mix method.

The tunnel was also the first one to be mapped, in fact before the study even started, and the only one in this study to be remapped some years later. The geological investigations indicated that problems with rock burst and spalling were to be expected. (Fig 1)

Just before its construction, severe rock burst problems had been successfully handled during the excavation of the 7600 m long Høyanger road tunnel. The heading support used at Høyanger was rock bolts connected with steel nets. For permanent support, additional rock bolts were installed, and this has performed well ever since.

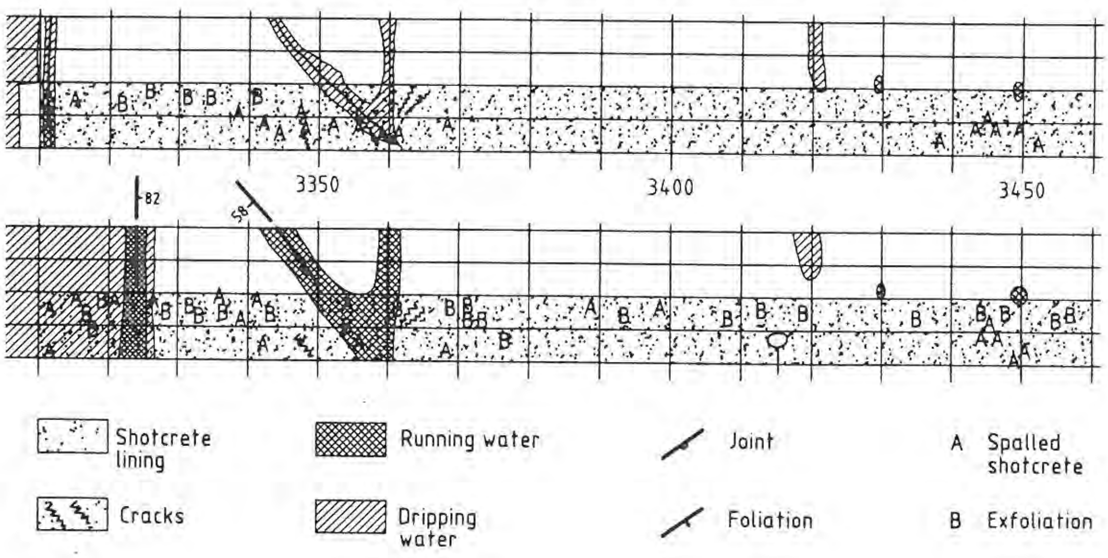

Fig. 1 Surveys of 1982 and 1989 show propagation of shotcrete spalling off in the Heggura tunnel

The motive for reintroducing shotcrete was the contractor's conviction that it would increase tunnelling speed and make savings in rock bolting possible. Contributing to this view was the belief in the superiour properties of the steel fiber shotcrete that was appearing on the market. It was claimed that these avantages would more than outweigh the considerably higher costs involved in the use of shotcrete.

The importance of evaluating the two designs led to the decision to make studies at the Heggura construction site.

The 1982 study
The survey of the tunnel and collection of tunnelling data took place in October 1982. Concrete had been sprayed from 1.5 m above the road surface on the western wall to the middle of the tunnel crown. The sprayed area was 26500 m^2 over a length of 3800 m, in all 2650 m^3.

This gives an average thickness of 100 mm, but in reality the thickness varied considerably, from a few mm to about 150 mm. The concrete mix was 1600 kg aggregate, 450 kg cement, 36 kg silica, 3 l Rescon"P", Rescon accelerator" Sprut", 75 kg 14.5 mm EE steel fiber C, and 243 l water. Schmidt-hammer tests gave 23 N/mm^2.

The excavation procedure was the ordinary drill and blast, followed by rock scaling. The normal heading support was rock bolting, as was the case in the Høyanger tunnelling, except that steel nets were not used. Generally, the shotcreting operation took place 2 to 5 blasting rounds behind the face.

Normally, the time from when the mucking out is finished to when the drilling operation can start is the one for deciding the excavation speed. The less time to be used for heading support, the higher the speed. In this case the shotcrete was not used for heading support. It may therefore be concluded that the claim of shotcreting increasing excavation speed is not documented by the tunnelling at Heggura.

Sections subjected to the most intense stress activities were supported on average by 7.7 rock bolts pr m length of the tunnel, while low to no activity sections were supplied with a bolt frequency of 2.6 pr m. It may be concluded that the site personnel considered the bolting as the most reliable type of heading support. Again, as compared to the Høyanger tunnelling scheme, it may be concluded that no saving in bolting support was achieved.

Delamination and spalling
The survey disclosed many local areas of delamination in the shotcrete layer, however, only a moderate number of spalled-off areas were found. This improved stability is considered due to the high rock bolting density in these areas. These phenomena were found at locations subjected to moderate to low stress activity. The spalled-off areas were found mainly at locations having thin shotcrete layers. However, examples of spalled-off shotcrete or shotcrete/rock slabs up to 120 mm thickness were also recorded. (Fig 2) Core drilling presented evidence of poor bond between rock and shotcrete. Measurements disclosed that no stresses existed in the shotcrete layer. It may therefore be concluded that

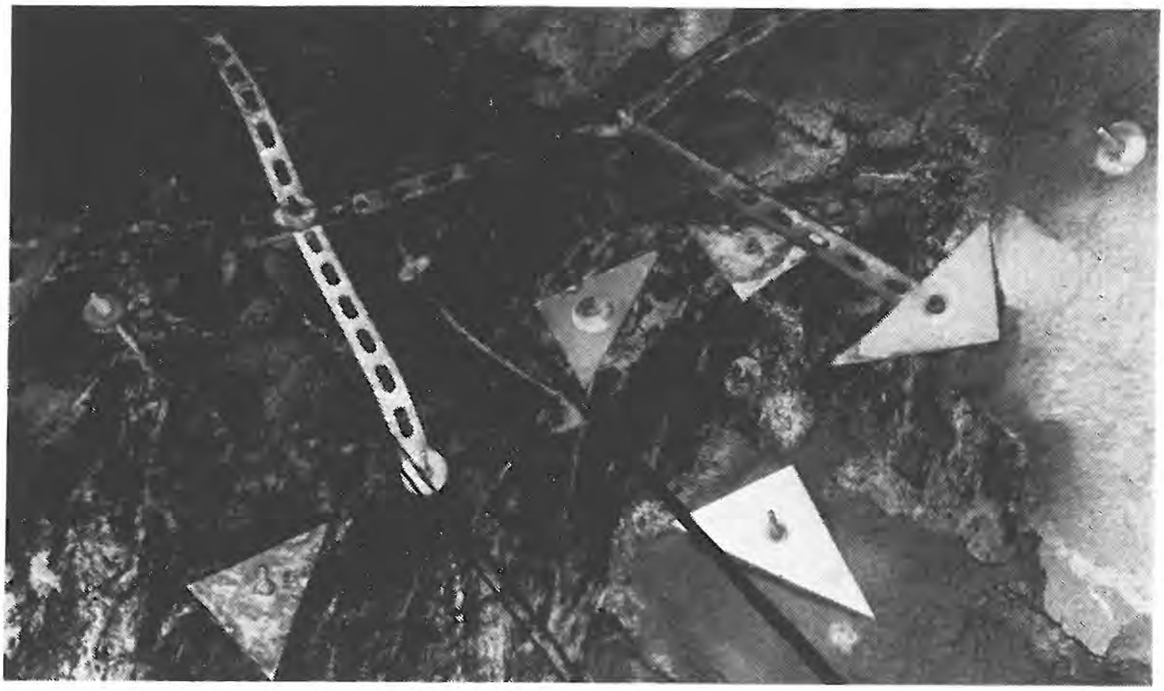

Fig. 2 Delamination and spalling of the shotcrete lining

the shotcrete support only provided insignificant protection against the spalling process in the rock.

Permanent support
No shotcrete, but a total number of 5246 rock bolts were added for permanent support after the excavation was finished. Of these, 2422 were installed in the area already lined with shotcrete. It was concluded that the shotcrete was neither sufficient nor reliable enough for permanent support of the tunnel. Water and frost protection was provided by installing PE-foam mats in 1.7% of the tunnel area, however another 3% was considered necessary by the study.

The survey disclosed leakages and calc-sinter deposits on the concrete surface, indicating widespread leaching and deterioration of the shotcrete.

Conclusions
1. Rock bolting was used for heading support
2. The spalling pattern indicates that it is the bolts that carry the rock loads
3. The shotcreting contributed to a small degree in reducing the use of bolts.
4. Core samples gave evidence of poor bond between the rock and the shotcrete.
5. Only rock bolting was considered reliable as final supplement for permanent support.
6. It is highly probable that the extensive deterioration of the shotcrete shall require significant surveillance and repair in the future.

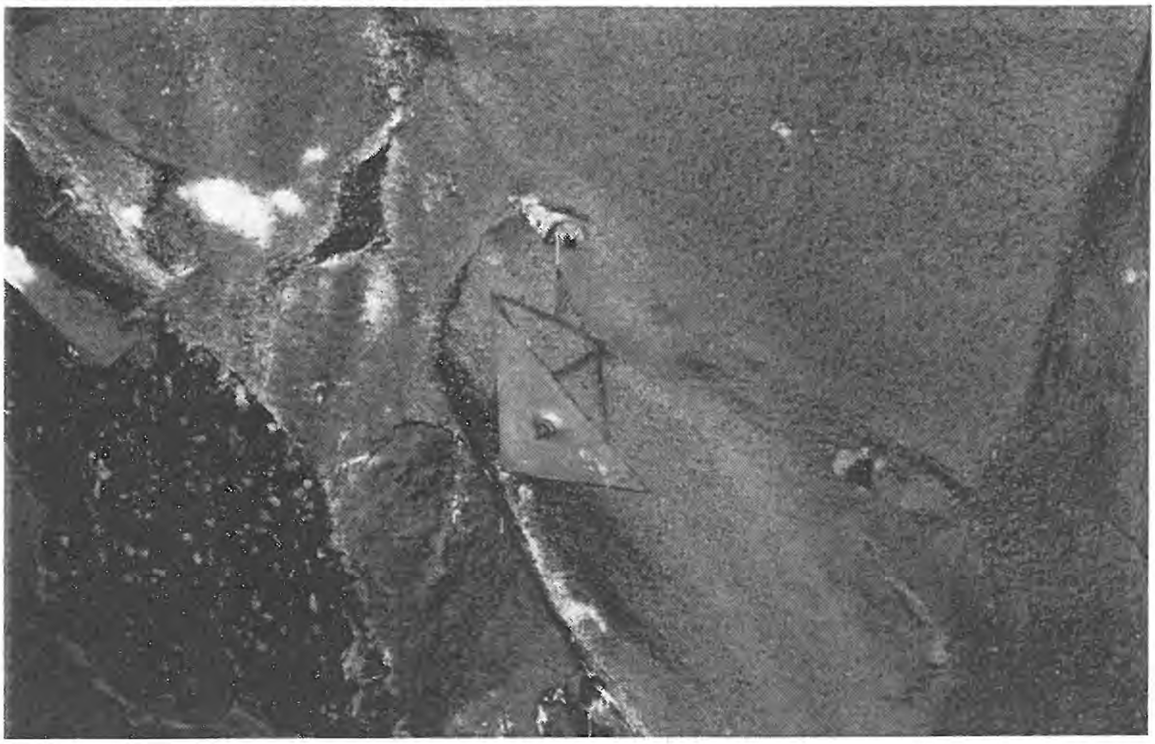

Fig. 3 Stalactites demonstrating leaching of the concrete

The study in 1989

The Heggura tunnel was remapped in August 1989, as a part of the project. In the intermediate period, in 1983/84, water and frost protective PE-foam mats had been extended to cover 2.5% of the tunnel area.

The condition of the shotcrete

The condition of the shotcrete in the tunnel was described as follows (Fig 3):
Water leaks are found in 6350 m^2 of the shotcreted area. Of this, 2050 m^2 are wet areas, 2500 m^2 have dripping and 1800 m^2 running water. Also found were large areas of shotcrete leached by water and dry areas containing calc-sinter deposits and stalactites

Mapping of the shotcrete condition also disclosed extensive delamination throughout the tunnel, except for a section from P1950 m to P2600 m where the tunnel was generally dry. This observation represented a dramatic change since the initial survey in 1982. The recorded number of delaminated locations had increased from 50 to 350, while the number of spalled-off locations had increased from 150 to 183. In addition, a number of rock bolts and steel nets had been installed for immediate support requirements by the maintenance division.
The condition of the tunnel is characterised by the following quote (translated):
"Scaling and fall-down of shotcrete is ocurring and represents a hazard for the traffic".

Conclusions

1. There has been a moderate increase in the spalling process
2. Delamination has increased by a factor of 7 in 7 years
3. There is a continuing tendency for the leaking areas to spread

4. Extensive increase in the number of calc-sinter deposits demonstrates that the shotcrete continues to deteriorate

Shotcrete in the Flekkerøy tunnel

This road tunnel is a subsea crossing from Kristiansand on the mainland to the island of Flekkerøy. The tunnel was opened for traffic in 1989, is 2348 m long and is at its deepest 101 m below sea level. The tunnel has been sprayed with steel fiber concrete, according to the wet-mix method. A length of 963 m in the tunnel crown, or an area of 23070 m^2 has been sprayed. The extent of deterioration of a large shotcreted area that is covered behind the 310 m long PE-foam lining has not been recorded. Of the area exposed, 36% is leaking, most of it shielded in the crown by a sheet metal lining.

Shotcrete in the Mosseporten tunnel

The tunnel is called "The Moss gate" because it provides the road entrance to the city of Moss. When opened in 1963, permanent support was supplemented by rock scaling, rock bolting and installation of steel nets. Because it was decided to spray concrete in almost the whole tunnel length, 300 m, the tunnel was carefully cleaned beforehand. The concrete was sprayed using the dry-mix method on an area of 5400 m^2 with an average thickness of 50 mm.

In 1981, after a rockfall in the western part of the tunnel, NRRL was asked to evaluate the support and to make a rehabilitation scheme to reduce the maintenance problems in the tunnel. A survey was undertaken and a proposal for improving the tunnel standard was presented. The survey disclosed that delaminations were widespread throughout the tunnel, between 30 and 50%. The reason for the delamination process was attributed to insufficient thickness of the shotcrete, slippery joint surfaces and poorly cleaned rock surfaces.

Some 5-6 leakage areas were recorded. At two of these, the water was originally collected by means of frost isolated plastic drainage pipes suspended by rock bolts and imbedded in shotcrete. This method has appeared to be a minor success also elsewhere. In addition, smaller leakages were widespread in the whole tunnel.

According to the proposal, the tunnel was scaled and the dry areas sprayed with concrete. Additional support was provided by rock bolts and steel nets. The leaking areas were provided with PE-foam mats for water and frost protection.

In 1986, NRRL was consulted again concerning the further spreading of water leaks in the tunnel. The financial situation did not allow for a total rehabilitation of the tunnel. A minimum solution was adopted, repair of the PE-foam, scaling of the delaminated or deteriorated shotcrete and installation of some rock bolts and nets. Since that time, protective maintenance is executed continuously.

Review of the tunnel studies

The study includes 32 tunnels containing shotcrete linings in various quantities summing up to 186'274 m^2. Of this, 90'862 m^2, or 49% is so penetrated by water leakages that water and frost protective linings are, or should have been installed. The mapping collected does also disclose that a considerable part of the shotcreted areas was covered by linings and unaccessible for study at the time of inspection.

Consequently, the proportion of shotcreted area penetrated by water leaks is significantly higher than 50%. It is probable than this proportion only reflects the leakages in the rock itself, and that the dry parts of the shotcreted areas correspond to sections of rock without leakages.

This study contains unfortunately insufficient information on the condition of the shotcrete material itself. It is based on visual recording of water leakages, calc-sinter, spalled-off and disintegrated material. The information is based on the tunnel maps and comments in the reports. However, the material presented strongly supports the record of the spreading water leaks, leaching, delamination and spalling-off process made in the three tunnels described above (table 1).

EVALUATIONS OF SHOTCRETE LININGS

On the background of this study and experiences from consulting, evaluation of the performance of shotcrete linings may be summarized as follows.

Evaluation of the water sealing properties of shotcrete

From time to time it is maintained that lining with shotcrete is useful for water sealing of tunnels (for example; see Astad et al). And on other occasions, it is maintained that lining with shotcrete reduces the area of the water leakage by moving the water leaks to locations where they may be handled in easier ways.

Documentation of the claims have not been found in the literature, and a closer study will probably meet with difficulties in the evaluation of the data. Statistical treatment of the presented observations might give some indication. It may not be rejected that some concentration of the leakage may occur, but not to a degree that has significant influence on the demand for water and frost protective linings. On the contrary, the overall impression obtained from this study is that shotcrete has no water sealing effect.

This idea is supported by the observations described. Firstly, where the unlined tunnel sections leaks, the adjoining shotcreted sections also leaks. Secondly, where the unlined tunnel sections are dry, adjoining concrete sprayed sections are also dry.

And thirdly, it appears that the linings cover areas of shotcrete not accessible for observation at the time of survey. Since the linings are installed for water protection, large areas of leaking shotcrete that is not recorded in the study, are found. Including these areas, the ratio of leaking shotcrete areas shall substatial increase.

Consequently, these factors are adding up to an increased ratio of leaking/dry shotcrete linings. It is therefore concluded that the shotcrete has little, if any influence on the requirement for water protective linings in road tunnels.

Evaluation on the durability of shotcrete

The main part of the Norwegian tunnels are situated in acid rocks of igneous or methamorphic origin. The calc-sinter deposits on concrete lining surfaces therefore originates from the lime in the concrete itself. This statement is also supported by the observation that calc-sinter is not found outside the concreted areas, except for tunnels situated in limestone.

The widespread water leaks in the sprayed tunnel areas expose the shotcrete linings to substantial leaching. The occurrence of calc-sinter deposits on apparent dry surfaces demonstrates that shotcrete areas containing small, otherwise undetectable, or occasional leaks that are also substantially affected. Where the water is running or dripping the leaching process goes even faster. Water leaks therefore are an important agent in deteriorating the concrete lining.

Evaluation of shotcrete used as heading support

The application of shotcrete for heading support has shown a dramatic increase in the 1990's. It has by the present use become to a large degree a substitute for rock scaling. This procedure is considered advantageous for the excavation speed, but it ignores the drawbacks of the method outlined above. In addition to the problems presented for the maintenance operation, some other arguments shall be put forward.

Tunnel sections lined with shotcrete have in many cases failed, leading to rocksfalls, and even in some cases to rockslides.The collection of information of such events was outside the scope of the original study. Evaluation of the present use of shotcrete is required, and has to be based on relevant information concerning failures.

Shotcrete as heading support requires surveying for safety evaluation
During tunnel excavation, a rockfall development may be halted or stopped by shotcreting if the convergence is stepwise or below a certain creep velocity.This type of deformation may allow the shotcrete to be applied and harden to the required strength before failure.

Evaluation of the rock support for permanent stabilization is, however, very difficult, because slow deformations in the shotcrete are difficult to detect visually. This statement applies to fiber reinforced shotcrete in an even higher degree than the normal type, because it takes more deformation without cracking or failing. Sections prone to rockslides therefore have to be surveyed by means of detailed studies.

One approach to such an evaluation is to adopt the NATM convergence recording procedure. With the large extent of shotcreting now applied for tunnelling, it will be difficult to sort out the locations in need of instrumentation. To survey all the shotcreted areas would be too ambitious and expensive. A second approach used in some projects, is to have the tunnel carefully mapped geologically before shotcreting. On this background, the support is designed without having the information observation of the rock stability (i.e. convergence and rock loosening) over some time may provide.

The third, and best approach is to restrict the use of shotcrete to locations where it has its real advantage. That is to heading support in poor rock sections, where it is of importance to halt the rockfall development until stronger support can be installed. This situation, which will not happen very often, gives opportunity to employ the NATM procedure to control the stability development.

For the normal tunnelling operation, the third aproach involves returning to the old, resonably cheaper support method, rock scaling, rock bolting with steel straps and nets. It is also more surveyable, because rock-fall material collected in the net present an easy visible detection of locations where support should be strengthened.

Shotcrete as support against rock bursting
Rock bursts and spalling caused by natural anisotropic stresses in the bedrock occur occasionally in the high mountain and valley regions of Norway. Such conditions may become a problem for the heading support, because rock discs may loosen and even suddenly being ejected into the tunnel.

The belief that shotcrete is an efficient support against rock spalling and bursting was introduced early in the history of shotcrete in Norway. Various experiences made by different people at different tunneling sites have put this concept forward. However, no studies as to the valitity of the claim have been found in the literature, except for references to the Heggura tunnel. As described above, this provides no satisfactory documentation. Detailed information from other sites has to be collected for an eventual verification.

Evaluation of the shotcrete as permanent support

It has been stated that tunnels normally have to be provided with water and frost protective linings in the sections lined with shotcrete. Thus the rock and shotcrete is made unaccessible for inspection. This presents a serious problem and increases the importance of the final survey of rock and shotcrete stability that has to be made prior to the installation of the linings.

Deterioration of the shotcrete by water leaching
It is maintained that the water passes through the concrete in narrow cracks at joints dissecting the tunnel. So, the argument goes, even if the concrete is wet, the main part of the concrete is unaffected by the water leaks. This claim may be true, the greater part of the shotcrete may be in good shape. However, it may be shown that, even in this case, it is the supporting ability of the shotcrete that may be fundamentally affected (fig 4)

The water is conducted to the tunnel through the joints in the rock. Blasting tends to open additional cracks, causing the leaks to spread and reducing the stability of the rock. Except for some sections of poor rock quality, most of the unstable rock originates from

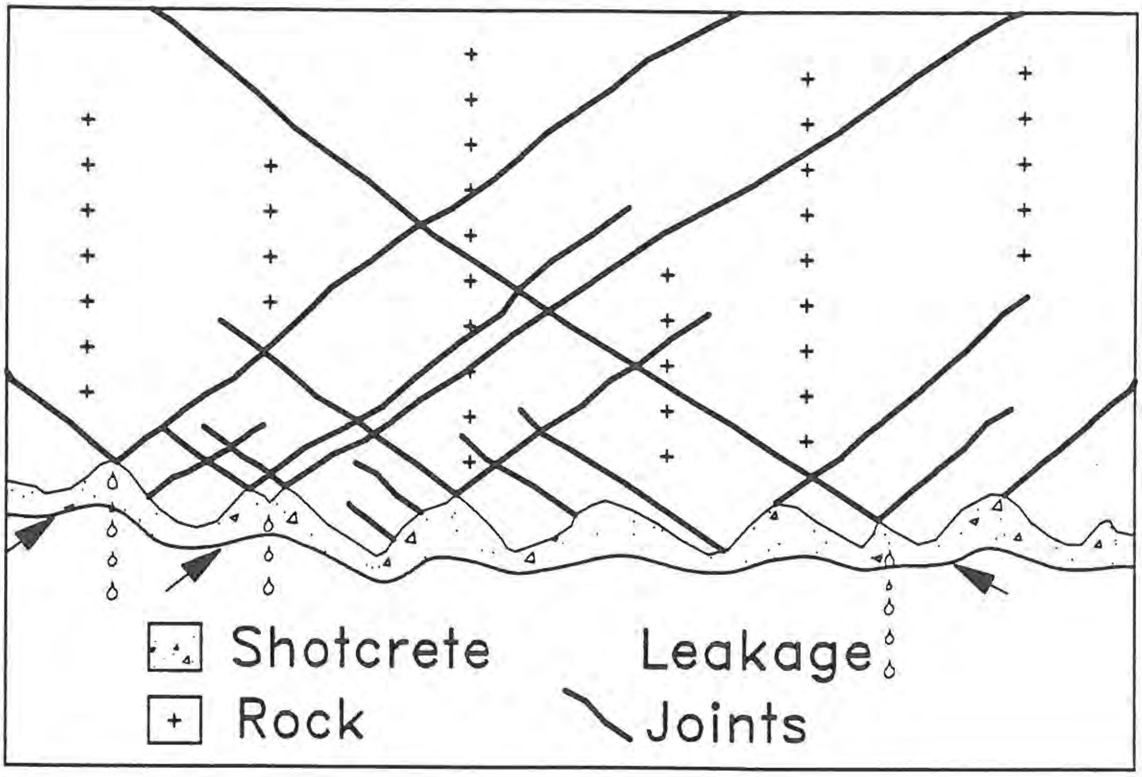

Fig. 4 Deterioriation of a limited area of shotcrete may cause large volumes of instability joints of unfavourable direction and location around the tunnel periphery.

From the moment concrete is sprayed onto the leaking joints, a contact between the water phase in the concrete and the leakage water in the surrounding rock is established. Regardless of the quality of the concrete mix or the spraying procedure, leaching of the concrete is going to start. This leaching takes place at the leakage joints where stability failures is prone to occur. (Fig 4) The concrete is therefore deteriorating along the very lines or ribbons where its strength is required. The fact that the main part of the shotcrete is not affected, does not assist in preventing rockslide failures.

Maintenance of the shotcrete in road tunnels required
Rockslide events may be caused by the deterioration of the shotcrete due to long-term rock convergence or leaching . In wet areas, frost action also may be an important agent. To prevent the rockslide hazard, surveillance is necessary. If the rock surface is geologically mapped prior to shotcreting, the area that needs surveillance may be limited. Otherwise, the evaluation of the state of safety against rock slides is difficult.

FURTHER WORK

The use of shotcrete has dramatically increased during recent years. This change in support strategy has been introduced without studying the concequences for safety, economy and maintenance. The presented material makes relevant the question of whether the support design now adopted is suitable for road tunnels. Some of the questions that have to be answered are:

For tunnel operation
1) How far should the shotcrete be relied upon for support?
2) How should the surveillance of the shotcrete support be done?
3) How should the quality of the shotcrete be recorded?
4) Which alternatives for support may be relevant?

For tunnelling
1) What tecnical/economic advantages does the shotcreting offer?
2) How should the shotcrete be dimensioned?
3) What support does the shotcrete offer?
4) What relevant alternatives for heading support are found at present?

To arrive at reliable conclusions to these questions, more extensive and careful studies of the shotcreted areas as well as other support methods used, have to be conducted.
In addition, information of rockslide events have to be collected and studied. And finally, the material has to be carefully evaluated.

TABLE 1

SHOTCRETE SURVEYS IN ROAD TUNNELS. PROJECTS P 364/461								
Name of Tunnel	**Opened Year**	**Road no.**	**County**	**Length m**	**Surveyed time**	**Shotcrete length and area lm/m²**	**Leakage area m² leak./ tot.**	**% leak. area**
Mosseporten	1963	Rv19	Østfold	392	mai 81	392/5400	1000/5400	19
Porsgrunn	1989	Rv356	Telemark	877	88	60/1000	1000/1000	100
Gåsehelleren	1989	Rv 9	V-Agder	1351	okt 89	167/3150	400/3150	13
Flekkerøy	aug 89	Fv 457	"	2348	"	950/23700	12000/23700))	50
Lavoll	1970	E18	"	378	nov 88	50/762	532/762	
Gaupås		"	"	316	"	16/235	0/235	0
Fosseland		"	"	619	"	21/420	0/420	0
Lervik	1960	"	"	798	"	5/75	0/75	0
Kleven		"	"	209	"	27/270	270/270	100
Åtland	1970	"	"	362	"	25/272	210/272	77
Lovraeidet I		Rv 13	Rogaland	216	sept 89	46/580	(180/580)	31
Velaskaret		"	"	298	"	41/820	(700/820)	85
Varstad		"	"	901	"	19/380	(180/380)	47
Gya	1989	Rv42	"	508	s/o 89	77/1540	600/1540	39
Røyrdalen		Rv45	"	723	"	10/200	0/200	0
Lauåsen		Rv502	"	226	"	82/1640	400/1640	24
Eidsvåg I		Rv14	Hordaland	846	des 88	35/265	265/265	100
Flåten		E16	"	1756	nov 88	48/960	180/960	19
Horda	1988	Rv11	"	465	nov 89	70/1400*	1200/1400	85
Austmannali	1982	"	"	910	"	66/1000*	850/1000	85
Haukeli	1967	"	"	5686	"	586/11430	På PE	10
Haga		Rv50	Sogn &Fj	680	juni 89	140/2650	¤0/2650	0
Stonndal	1972	"	"	2230	"	50/1000	20/1000	2
Berdal	1972	"	"	4250	"	100/2000	300/2000	15
Nesbø	1973	"	"	2488	"	55/1000	350/1000	35
Botna	1973	"	"	905	"	13/250		
Heggura	1982		M & R	5280	okt 82	3800/38000		
Heggura	1982	"	"	"	aug 88	3860/38600	8000/38600	21
Skafonna		Rv9	"	945	okt 89	260/1565*	3400/6700	51
Runehammar		"	"	1535	"	970/18000*	4000/25600	16
Fonnafonna		Rv16	"	629	"	525/10410	9900/10410	94
Valderøy	1987	Rv658	"	4177	1987	2365/47300	34800/47300	74
Ellingsøy	1987	"	"	3483	1987	700/14000	11100/14000	76

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