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**Tunneling Asia '97
Optimization of Linings
in Road Tunnels**

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Abstract

Up to present, 800 road tunnels have been built to overcome communication difficulties in the Norwegian landscape of mountains and fjords. Half of these tunnels have a traffic volume less than 1000 AADT, as they are primarily links to scattered settlements.

To be able to proceed the ambitious road construction programme, development of low traffic tunnel design has been going on since 1965. Rock stabilization by means of costefficient methods like careful blasting, rock scaling and extensive bolting is normally adequate, poor rock conditions are delt with by special methods. This concept leaves the problems associated with water leaks, ice-up and frost action to be solved.

Panels made of frost insulated, aluminium corrugated shee and PE-foam linings have been in extensive use. Recently, shotcrete/PE foam linings, PVC-coated polyester fabric linings and prefabricated concrete elements of special designs have been introduced.

Applying separate methods to accomplish the rock support and the water/frost protection is one of the basic principles of the Norwegian road tunnel design. It has been found that this yields an optimum between performance and economy.

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TUNNELLING ASIA '97

OPTIMIZATION OF LININGS IN ROAD TUNNELS

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ABSTRACT

Up to present, 800 road tunnels have been built to overcome communication difficulties in the Norwegian landscape of mountains and fjords. Half of these tunnels have a traffic volume less than 1000 AADT, as they are primarily links to scattered settlements.

To be able to proceed the ambitious road construction programme, development of low traffic tunnel design has been going on since 1965. Rock stabilization by means of cost-efficient methods like careful blasting, rock scaling and extensive bolting is normally adequate, poor rock conditions are dealt with by special methods. This concept leaves the problems associated with water leaks, ice-up and frost action to be solved.

Panels made of frost insulated, aluminium corrugated sheet and PE-foam linings have been in extensive use. Recently, shotcrete/PE foam linings, PVC-coated polyester fabric linings and prefabricated concrete elements of special designs have been introduced.

Applying separate methods to accomplish the rock support and the water/frost protection is one of the basic principles of the Norwegian road tunnel design. It has been found that this yields an optimum between performance and economy.

1. A HIGH VOLUME OF ROAD TUNNEL EXCAVATION

The development of road connections between the scattered settlements in the Norwegian fjord and mountain regions is to a large degree dependent on tunnels. From an annual output of 15 km excavated per year in the 60's, tunnelling had increased to almost 50 km/yr at the beginning of the 90's. Up to present, 800 tunnels have been excavated, with a total length of 600 km.

In the last 15 years, undersea tunnels are even made an alternative to bridges for island connections or crossing fjords. At present, a number of 17 with a total length of 55 km are in operation, another 5 is going to be added in the coming years (Fig 1).

A most remarkable feature is the proportion of low traffic road tunnels. About 50% of the tunnels have a traffic volume less than 1000 AADT, and 20% even less than 500. About

20 % have AADT above 5000, and the tunnels in the urban areas have a traffic volume up to 60 000. (Fig 2).

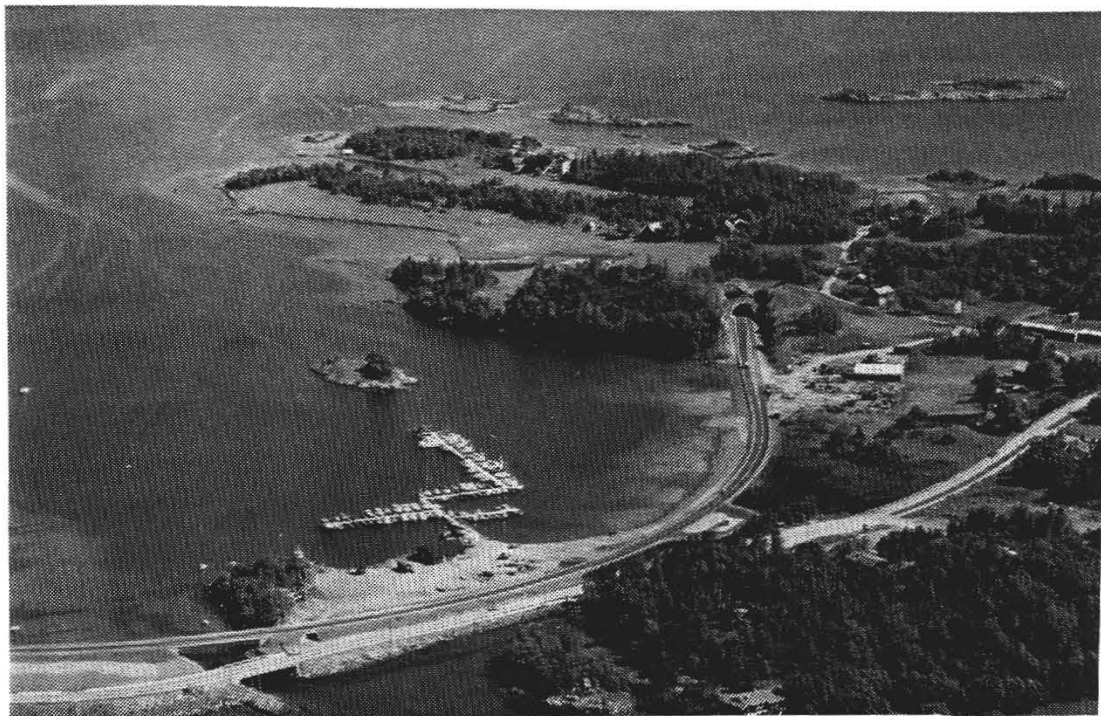


Fig. 1 Subsea tunnels are introduced as an alternative to bridges

2. PRINCIPLES OF NORWEGIAN ROAD TUNNEL DESIGN

If Norway is to be able to continue its ambitious road tunnelling programme, optimizing is vital. One of the main ways to achieve this is to avoid using expensive cast in situ concrete linings for rock support and water protection. Efforts have been going on since the 60's to optimize lining alternatives.

The principles arrived at were presented at THE INTERNATIONAL SYMPOSIUM ON LOW COST ROAD TUNNELS, OSLO 1984. The principles may be summarized in 13 items:

1. All phases from planning, construction and not least to operation and maintenance should be considered for achieving an optimal design
2. Careful geological studies should be made for construction planning
3. The tunnel should be located in the best possible ground
4. Circular cross sections should be adopted or approached
5. Standardized cross sections/widenings (curves/linings etc) should be adopted
6. A smallest possible number of support methods should be adopted
7. Careful blasting procedures be adopted to conserve the stability of the rock
8. Rock support should exploit the inherent, self-supporting capacity of the rock,
9. Rock support at lowest possible cost, ie. rock bolting
10. Heading support should not obstruct the installation of the permanent support
11. The heading support should be made a part of the permanent support
12. Rock support and water/frost protection should be dealt with separately
13. Water and frost protection is achieved by special designs

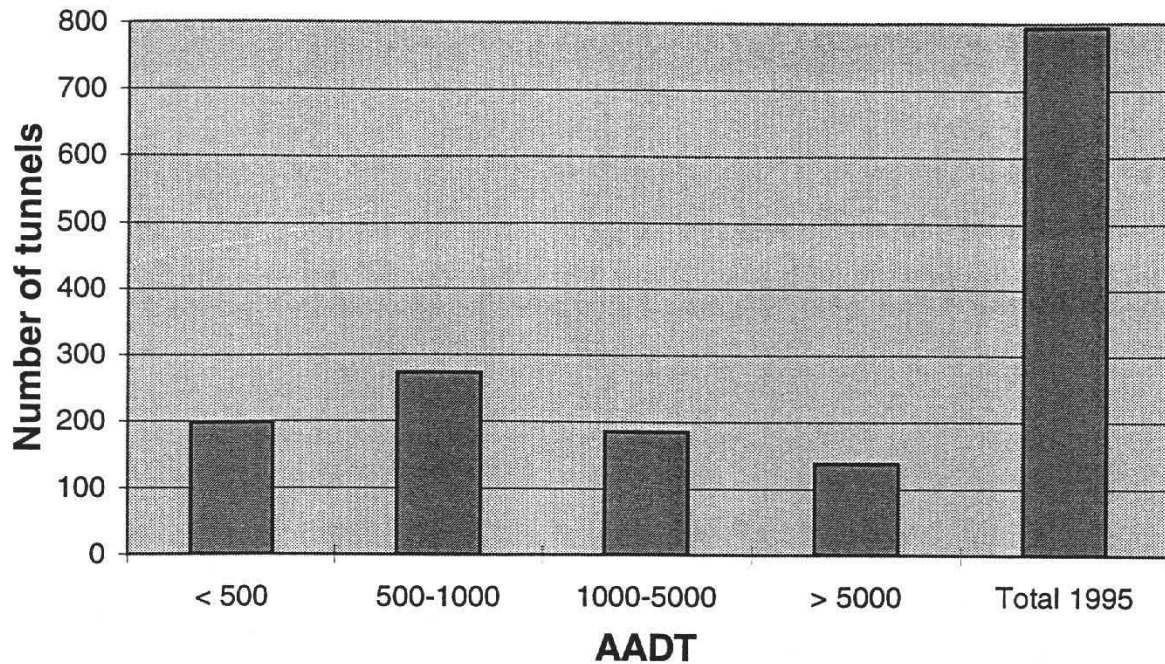


Fig 2. A large part of the tunnels on the Norwegian road network serves a very low traffic volume

3. ROCK SUPPORT METHODS

A rock mass has an inherent self-supporting potential that may be exploited by supplying it by means of cost efficient support methods. Rock bolting is a method which combines this goal with good performance and flexibility [1]. It has been shown that this method of support can stabilize even loose sand [5].

Rock bolting was introduced for rock support in the late 1950's, and has later on, in combination with rock straps and nets been made the general method for both preliminary and permanent rock support. In situ load tests and sampling made by core drilling of in situ rock bolts have been adopted for studies of the condition of the bolts. The studies prove that the condition of fully grouted rock bolts are satisfactory. Even 20 years old bolts anchored by polyester glue cartridges performed well, provided the bolts were coated by a satisfactory protection against corrosion.

Poor rock conditions have to be handled by special methods. Shotcrete combined with rock bolting has its main advantage as a heading support in poor, highly fissured rock. Sections containing clayey rock are dealt with by the use of one or a combination of the methods; careful blasting, shortening the round length, pilot tunnelling, shotcreting, forepoling and eventually in situ concreting by means of steel shuttering.

However, the shotcreted sections have generally to be provided 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 achieve a rock support of a satisfactory safety level.

4. SEPARATE DESIGNS FOR ROCK SUPPORT AND WATER/FROST PROTECTION

Support to a high degree based on rock bolting leaves the problems associated with water leaks, ice-up and frost action to be solved. Where it is not required to maintain the ground water level constant, the development of special designs for water protection has proved to be of vital importance.

Construction according to the principles of Norwegian road tunnel design has major consequences for the economy of tunnel projects. Only because of the austerity of this protective design has the extensive road development over the past 30 years in Norway been possible. Experience to date shows that with good planning and careful implementation, it is possible to combine austerity with a high safety level.

In the 1960's, when rock bolting came into extensive use, unlined tunnels were subjected to water and ice problems that became one of the chief safety and maintenance problems. At the time, the only thoroughly tested method for providing full water protection employed membrane-insulated linings which were an extremely costly design for water/frost protection. In order to optimize water-protection methods suitable for ordinary Norwegian road tunnels, the NRRL has been involved with development work in this area since the 1960's [3].

A number of systems for protecting road tunnels against water and frost have been tested and implemented. There has been a particularly rapid development of new methods over the past few years. This is due to the increase in the building of road tunnels which has taken place. The following provides an overview of the tested methods and methods still being developed.

5. GROUTING TO PROVIDE WATER-PROOFING

Grouting technology was the first method tested. It was not found to have the quality necessary for permanent water-proofing of road tunnels, and it is therefore not included in the development programme.

6. LIGHTWEIGHT STRUCTURES

A concept which involves deflecting water leakage all the way down to the trench was considered early on. The problem was finding materials and designs with adequate stability, strength and durability that made rational installation possible at an acceptable price. The designs embarked upon included panels made of aluminium, steel, sandwich elements, PE-foam/shotcrete and PVC fabric.

Lightweight linings cannot withstand rockfall, vehicle impacts or ice loads. The designs must therefore encompass full protection against rockfall and impacts and, where harmful frost quantities occur, full frost insulation. Air pressure pulses generated by high-speed heavy traffic also impose a significant stress on the lightweight structures. This is an aspect that must be encountered in evaluating the different designs. Specifications now require designs dimensioned for air pressure loads of 400 N/m².

6.1 Metal sheet linings

From the start, a lining structure consisting of corrugated aluminium sheets was chosen. The sheets are continued below the road surface to the trench, to protect the road surface from water inflow and ice-up. It has a smooth, easily cleaned surface, which can be coloured according to choice.

Single sheet lining can only be used in road tunnels that are subject to small amounts of frost, i.e. frost index up to 3000 h°C. *Crown lining* is sheet-metal lining which is mounted only above the road itself, and equipped with gutters and drainpipes in the walls. It can be used in places with minor frost loads, or where frost penetration can be checked by means of thermal doors or retarded by means of ventilation fans. The advantage is a durable structure for a low price.

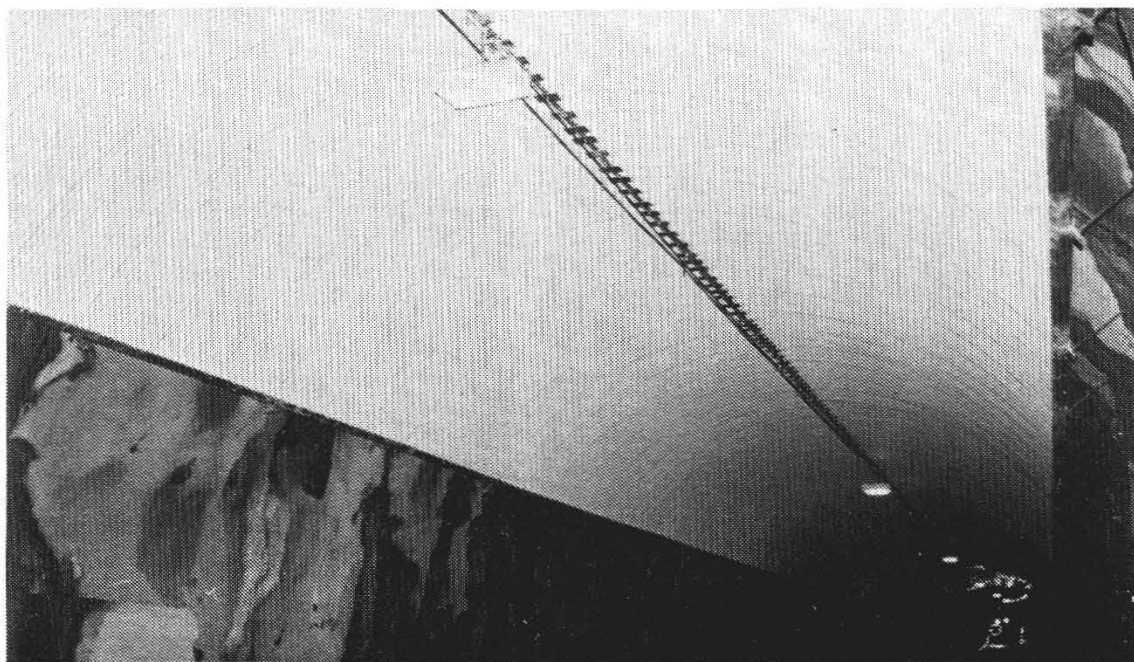


Fig 3 Crown shielding made by corrugated aluminium sheet

Frost-insulated sheet-metal lining consists of two aluminium sheets enclosing a layer of mineral wool mats. The lining layer facing the road is self-bearing, but also stabilized by means of rigid pipe arches. A circular cross section is required for maximum stability. The mineral wool mats can be delivered in various thicknesses and 10 cm provides insulation for frost quantities up to 40 000 h°C. The lining has a more flexible structure than the uninsulated type, so that traffic induced air pressure impacts are absorbed better.

New designs of frost-insulated sheet-metal lining are now offered. The frost-insulated sheet-metal lining consist of a single sheet of aluminium and mineral wool mats with an overlay of high-quality foil. Initial linings have been of varying quality and enforced stricter specifications [4].

6.2 PUR/PETP sandwich linings

Sandwich linings were developed to bring about more rational production, to simplify replacement and erection, and make installation faster than with insulated aluminium linings. Sandwich lining is relatively expensive.

The most commonly used lining is shaped as half-arches and produced in forms by application of glue to the foam mats. It consists of 50 mm polyurethane (PUR) foam enclosed in hard-wearing, diffusion-proof glass-fibre-reinforced polyester (PETP) with a thickness of about 1 mm. The insulation thickness can be varied, but this is adequate for frost quantities of up to 20 000 h°C.

The half-arches are fixed to a rail running along the centre of the crown and founded on compressed frost-free sub-base, which give a waterproof structure. The arches are joined along the length of the tunnel in such a way that the lining can be adjusted to curves with a radius down to 300 m. If sheet-metal lining is damaged by vehicle impacts, at least half an arch must be replaced. To encounter this drawback, linings made from sandwich boards have been designed and installed.

The initial design is no longer approved because of its combustibility. Noncombustible sandwich linings (for instance made from phenol foam) was expected to be soon on hand, but further developments are delayed.



Fig 4 PE foam lining fire protected by lightweight shotcrete

6.3 Water and frost protection with PE foam mats

The PE foam lining consists of mats of extruded polyethylene foam glued together in strips of the appropriate size. The strips are suspended by means of bolts and arch-shaped steel straps mounted along the tunnel cross section.

Experiments involving insulating road tunnels against frost with mats of PE foam were started in road tunnels in about 1980. Because of their flexibility and ease of erection, their use has been increasing rapidly. Initially developed for locally sealing point leaks and water curtains, now taken into use for lining the entire tunnel profile. The normal thickness 45 mm is sufficient for insulation in the presence of up to 15 000 h°C of frost. With greater frost quantities it is found most advisable to install two layers of mats.

The mats are elastic, flexible and combine low weight and low heat conductivity with high vapour diffusion resistance that will keep the material dry and conserve its

properties. PE foam lining is simple to erect and easy to adapt to different rock contours and transitions between different tunnel profiles. The surface of the lining follows rock contour, and its appearance reflects this.

PE foam is highly combustible, and if PE-foam lining is to be used, fire protection is required from 1994 onwards. Full-scale tests show that the linings have to be fire protected by shotcrete or fireproof fabric. The ordinary lining, steel fiber reinforced shotcrete is applied on the foam surface in a layer 60 mm thick. More heat-insulating types of lightweight concrete, can reduce the thickness necessary to 30 or even 20 mm.

The Ekeberg lining design recently introduced has the potential of producing absolute water-proof linings, provided correctly installed. At the Ekeberg tunnel project, Oslo, a new concept for PE foam/shotcrete lining was introduced. The major difference compared with earlier methods, is that the PE foam mats are completely without penetrating bolts and overlaps. The PE foam is mounted on water-proofed steel arches, bolted to the tunnel profile. Reinforcing nets are used and a 60 mm shotcrete layer was sprayed on the foam surface. In the Ekeberg tunnel project, this lining was installed in the crown and combined with concrete wall elements insulated with XPS foam and PVC foil.

6.4 Tunnel fabric

Tunnel fabric consists of high quality PVC-coated 9x9 polyester fabric with a weight of 700 g/m² (Protan quality 55401). It is erected by clamping it between backing pipes, bolted to the tunnel periphery and pipe bands. The fabric is clamped against the backing pipes by means of erect pipe straps. All bolts are passed through at mat junctures.

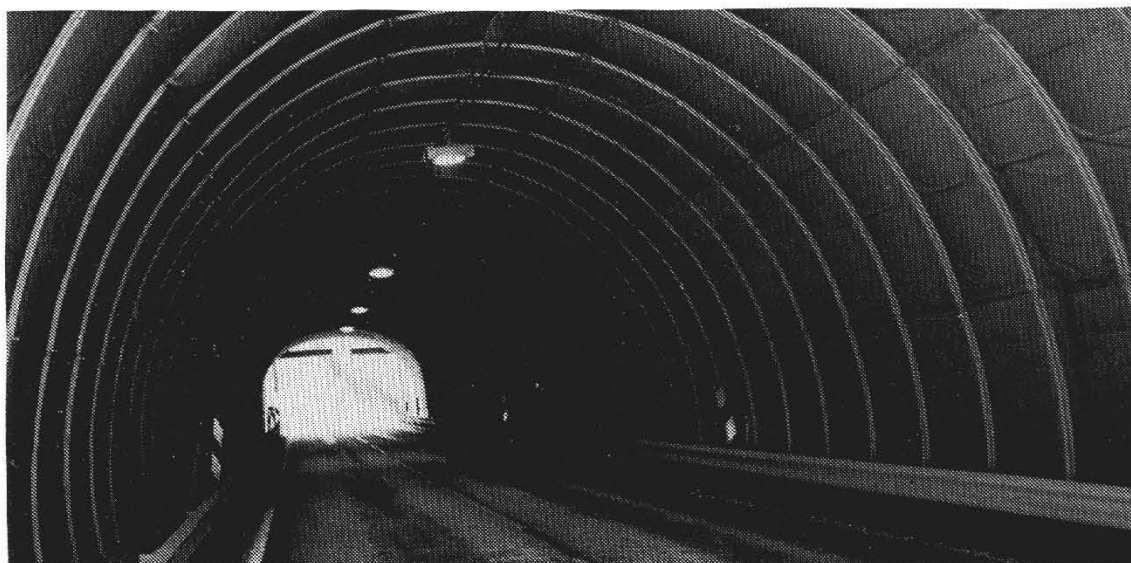


Figure 4. Lining made by PVC/polyester tunnel fabric

The holes are water-proofed with a double set of rubber washer. The lining is hot-air welded and the structure produced is claimed to be just as waterproof as the rest of the fabric mats. Double sets of rubber washers, metal disks and nuts are used to make the bolt holes tight.

The tunnel fabric lining marketed under the name of WG tunnel sealing, has been made so durable, air- and waterproof that stringent requirements regarding long term protection against humidity in storage halls are satisfied. Tents and stores made of fabric are finding

a growing number of applications and fabric has also started to be used for water-proofing of stores in rock caverns. A subterranean coffee storehouse in Bergen has controlled humidity since 1982 by means of this lining supplemented by a small dehydration plant.

The drawback of using tunnel fabric for moisture insulation in road tunnels lies largely in the structure's lack of stiffness. It can be subjected to vandalism, is easily damaged by fire and wears against the rock due to vibrations caused by traffic. Test sections installed in high traffic sections will provide more information about traffic-induced wear.

The tunnel fabric lining has a low price, can be delivered in many weave and thickness grades with strength made up to specifications. It is resistant to wear due to dripping water, chemicals and oil resulting from normal use of the tunnel. However, it has to be given selective additives to prevent various microbial attacks.

The erection time is short and the tunnel fabric is simple to repair. It requires little space, and correctly tautened, gives a fine optical alignment. The linings have a smooth, easily cleaned surface which can be coloured according to choice. It has been classified as fire-proof because its fire load and fire spreading ability is very low. The fabric can stand moderate rockfalls and ice loads har up to present not produced any problems.

7. CONCRETE ELEMENT LININGS

Concrete elements have been used by the Public Roads Administration in the Fosskollen Tunnel on the E18 at Drammen in 1970. To provide space for installation, inspection and repairs of the waterproof membrane, the tunnel cross section was expanded by 1.5 m. The membrane consisted of glass-fibre reinforced asphalt mats welded onto the concrete elements from trench to trench.

The advantage of this method is the resulting high quality, which has resulted in maintenance savings for water and frost items. The drawbacks were the high costs of the design the, weight of the elements and that the installation and maintenance of the membrane structure requires so much space.

7.1 Concrete element linings

In order to meet requirements to more cost-effective designs, concrete elements have been developed. These developments relate to frost insulation, easier handling, transportation and reduced space requirements. Designs introduced in 1989 have been undergoing continuous development as new experience is acquired.

One important principle includes the installation and stabilization of the elements by means of through-going bolts. The linings have consisted of 4-segment, 3-segment and 2-segment arches with or without cast in place walls. The elements are cast in factories that have been specially developed for high production and stringent quality assurance.

The elements are erected rapidly and simply by means of special equipment. The wall elements are erected first and anchored to the rock wall by means of rockbolts. The roof elements are then set up on top of the wall elements and anchored to the rock through a pre-made hole in the element. To achieve maximum stability, particularly during

erection, the roofing elements are displaced 1.25 m in relation to one another. In order to reduce breakage, increase precision and production, rational erection machines with hydraulically controlled vacuum plates have been developed

The membrane foil rolls are placed on the lining, welded and rolled stepwise out as the elements are erected. The bolt holes are moisture-proofed by means of a double set of metal disks, rubber washers and nuts clamping the whole in place.

The concrete element method is complicated for tunnels that have frequent changes in the tunnel cross section. The concrete lining is resistant to the loads that may occur, which makes it justified to reduce the rock support.

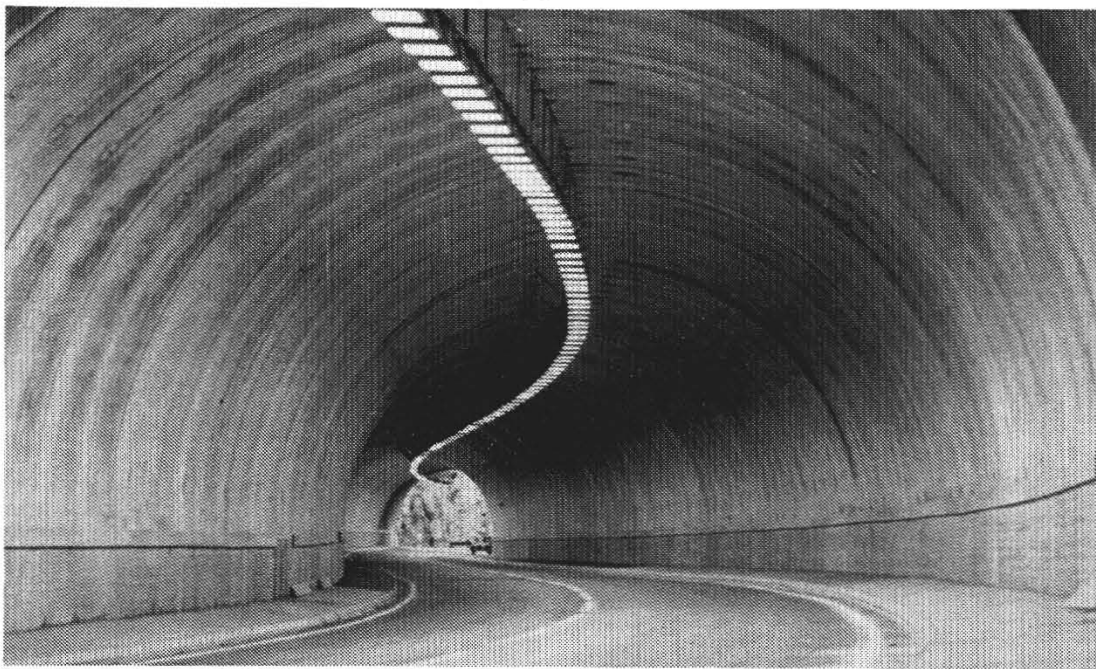


Fig. 5 Light-weight concrete lining

7.2 Lightweight-concrete element lining

The leight-weight lining was introduced for easier handling and achieving frost insulation. Other advantages include that screws and nails can be used on lightweight concrete just as they are in wood. The elements show good resistance to fire, but the frost insulation is normally insufficient in Norway. The elements are prone to breakage during transport and installation.

7.3 Concrete sandwich elements

The frost insulated elements are composed of extruded polystyrene (XPS) foam mats sandwiched between concrete layers. The first lining used was in the Nordby tunnel south of Oslo, where a total of 7.5 km was installed. The lining is tripartite, with roof elements 2.5 m and wall elements 5 m wide.

8. COMBINATION SOLUTIONS

A number of facilities are being put up today with water and frost-proof linings which are a combination of two methods. The new Granfoss tunnels in Oslo has been lined with light steel ("Environmental") lining on the roof and concrete on the walls. Other designs

have the combination PE foam/shotcrete on the roof and concrete elements on the walls. The competition situation in the market changes from one project to the next and it is difficult to say which systems will dominate. Quality requirements are growing more stringent, and the struggle is going to be between qualitatively equivalent products.

9. FURTHER WORK

Due to the escalating rate of road-tunnel construction in recent years, an increasing number of designs have been developed. New guidelines for fundamental requirements and design have been prepared by the Norwegian Public Roads Administration (NPRA). Intensive work is in progress by the industry, as well as the NPRA, to achieve realistic adjustment to the market. Additionally, the NPRA has launched a programme designed to rapidly produce means to simplify evaluation and tendering work by an approval arrangement for lining designs.

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