Repair of Chloride-Contaminated Concrete Walls in a Tunnel

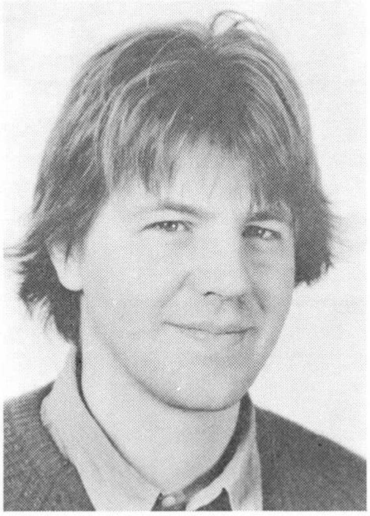
Réparation de murs en béton de tunnels endommagés par des chlorides

Sanierung von chlorid-geschädigten Betonwänden in einem Strassentunnel

Ole Viggo ANDERSEN
Civil Engineer
Technological Institute
Copenhagen, Denmark

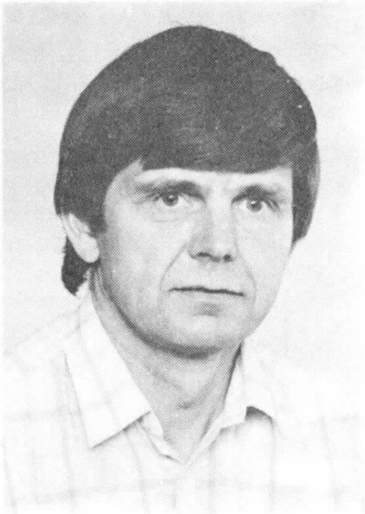
Jens Vejlby THOMSEN
Civil Engineer
Danish Road Directorate
Copenhagen, Denmark

Egon A. SØRENSEN
Senior Design Engineer
COMAR Engineers A/S
Copenhagen, Denmark



Ole Viggo Andersen, born 1958, obtained his civil engineering degree at the Danish Engineering Academy. For three years he was involved in the design of structures for a Danish contractor. For five years he has been responsible for condition surveys on concrete structures and development of new techniques to maintain and repair concrete structures.

Jens Vejlby Thomsen, born 1940, graduated from the Danish Engineering Academy in 1968 as a civil engineer. Experience as site engineer and project leader for construction companies. Since 1980, senior engineer in the Bridge Department of the Danish Road Directorate, responsible for operation, maintenance and repair of tunnels and major bridges.



Egon A. Sørensen, born 1946, graduated from the Technical University of Denmark in 1970 as a civil engineer. From 1971 to 1987 he worked for Christiani & Nielsen A/S and since 1987 he has been working for COMAR Engineers A/S. His main tasks have been design of bridges and tunnels and the maintenance of tunnels.

SUMMARY

Many concrete structures, especially in countries where de-icing salts are used, are suffering from chloride contamination. The consequences are durability problems and increasing maintenance and repair costs. In order to solve some of these problems the Danish Road Directorate is testing remedial measures on concrete walls in a road tunnel. The measures include replacement of deteriorated concrete by new concrete, cathodic protection by a conducting coating and chloride extraction. The object of the tests is to help in choosing the most suitable time and the most appropriate method for carrying out repair work, as well as to determine the required extent of such repairs.

RÉSUMÉ

Beaucoup de structures en béton subissent des dommages dûs à des chlorides, plus particulièrement dans les pays où sont utilisés les sels de déverglaçage. Les conséquences en sont des problèmes de durabilité et des coûts croissants d'entretien et de réparation. Afin de résoudre ces problèmes, différentes méthodes d'assainissement des murs en béton de tunnels routiers sont examinées. Ceci comprend le remplacement du béton endommagé, une protection cathodique par une surface conductrice et l'extraction des chlorides. Ces recherches permettent de fixer le meilleur moment, la méthode adéquate et l'envergure des travaux d'entretien.

ZUSAMMENFASSUNG

In Ländern mit Tausalzverwendung erleiden viele Betonbauwerke Chlorid-Schäden. Die Folge davon sind Probleme mit der Gebrauchstauglichkeit sowie Unterhaltungs- und Sanierungskosten. Zur Lösung dieser Probleme wurden Methoden zur Sanierung von Betonwänden in Strassentunnels untersucht. Dies beinhaltet den Ersatz des geschädigten Betons, kathodischen Schutz mittels einer leitenden Oberfläche und Chloridextraktion. Die Versuche sollen den zuständigen Behörden ermöglichen, den geeigneten Zeitpunkt, die beste Methode und den Umfang von Sanierungsarbeiten festzulegen.

1. INTRODUCTION

The tunnel is situated in the northern suburbs of Copenhagen, and leads the southbound road traffic on Bernstorffsvej under and into Lyngbyvej - the motorway which is the main road link between Copenhagen and Elsinore.

The traffic is heavy during the morning rush-hours, and in winter de-icing salts are often used. The winter climate in Denmark is characterized by repeated frost and thaw periods.

The tunnel was built in 1969 and is about 180 m long and 11 m wide, including two 1.75 m wide emergency and service footways and a 7.5 m wide dual traffic lane for one-way traffic. The reinforced concrete cast-in-situ walls are 0.5 m thick, shown in Fig. 1.

The tunnel is administered by the Road Directorate and during periodic inspections it was found that the lower parts of the walls showed signs of reinforcement corrosion.

Therefore COMAR Engineers A/S as general technical consultants on maintenance of structures and the Technological Institute as special consultants for investigation and testing of concrete were asked to make an investigation of the state of the concrete and the reinforcement in the spring of 1988.

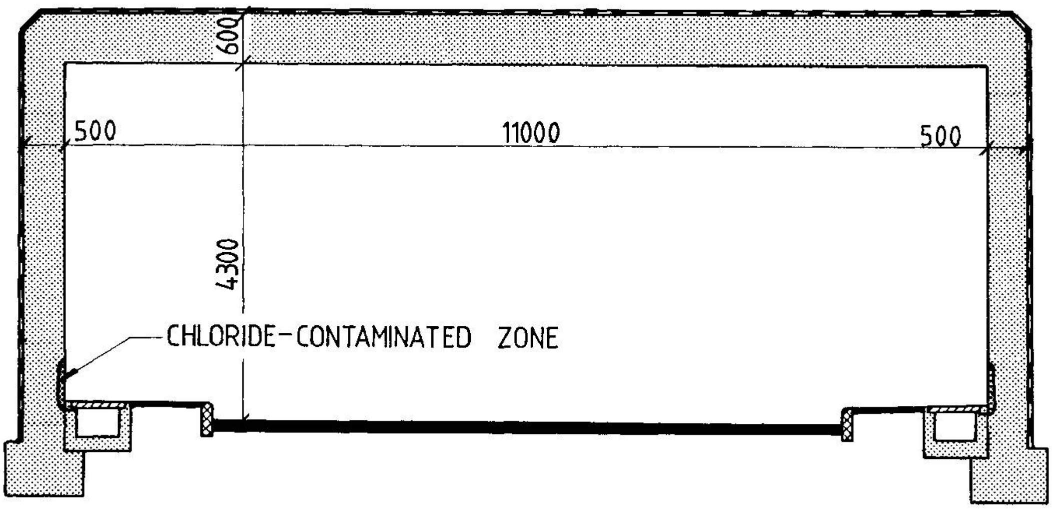


Fig. 1 Cross Section of Tunnel

2. RESULTS OF CONDITION SURVEY

The condition survey is an attempt to combine a visual assessment with appropriate on-site measurements and laboratory tests.

The visual assessment of the walls indicated cracking of medium width in approximately 25% of the tunnel in the lower parts of the walls. Distinct rust stains were visible on the concrete surface in approximately 40% of the lower parts of the walls.

On-site measurements were limited to a half-cell potential survey of the lower parts of the walls. The concrete cover was measured and parts of the reinforcement were exposed to visual examination. The half-cell potentials measured with a copper-coppersulphate electrode indicate a high risk of corrosion of the reinforcement, limited to the lower parts of the wall. Visual examinations of exposed reinforcement at these locations revealed severe pittings, while there were found no signs of corrosion on reinforcement located higher than 0.5 m above ground level in the tunnel. The concrete cover is 25-30 mm. The variation of the chloride content was measured on powder samples from more than 100 locations.

Ten concrete cores were sampled for laboratory tests. The locations of the cores were determined by the analysis of the half-cell potential survey. Tests of the cores included visual examination, petrographic analysis on thin sections, determination of the chloride and moisture contents and distribution: The concrete is mixed with a water-cement ratio between 0.45 and 0.50. Carbonation depth is approximately 15 mm (half the depth of the concrete cover). The sand fraction contains alkali-silica reactive aggregates. Severe alkali-silica reactions were observed locally in the lower parts of the wall, where the chloride content is very high throughout the length of the tunnel. Typical chloride profiles are shown in Figs. 2 and 3. The distribution of chloride content indicates that the chloride is permeating from outside sources - probably from de-icing salts. The moisture content is medium - but high enough to generate corrosion and alkali-silica reactions.

On the basis of these observations it was concluded that severe corrosion of the reinforcement located in the walls 0 to 0.5 m above ground level is caused by an excess of chloride in the concrete.

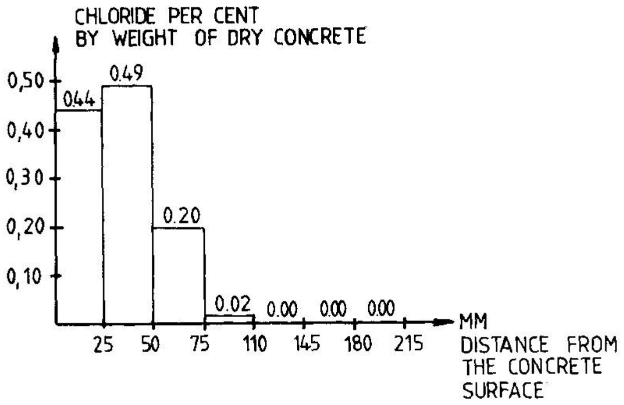


Fig. 2 Typical Chloride Profile at Ground Level

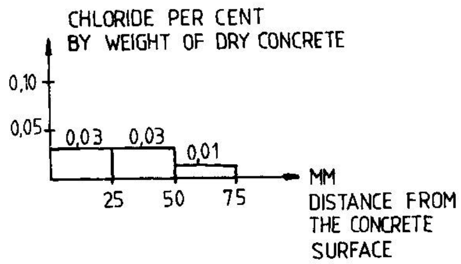


Fig. 3 Typical Chloride Profile approx. 0.7 m above Ground Level

3. SELECTION OF REPAIR METHOD

Before repair work commenced, possible alternative methods were considered. These were:

- Replacing of deteriorated concrete by new concrete
- Cathodic protection
- Chloride extraction

The traditional method involves removal of chloride-contaminated concrete, cleaning of reinforcement bars and, finally, placing of fresh chloride-free concrete. The disadvantage of this method is that the original homogeneity of the structure will not be fully re-established. Further, if all chloride-contaminated concrete has not been removed there is a risk that new corrosion of the reinforcement will start at the casting joint between new and old concrete.

Cathodic protection systems for reinforced concrete have been developed during the past 30 years. Today several systems are available, including:

- Mesh anodes placed in protective concrete layer
- Conductive coating anode systems

The mesh anodes system was left out of consideration for architectural reasons as the mesh should be protected by a 30-50 mm thick layer of concrete.

For the actual job, the conductive coating anode system seemed to be the most attractive. It is easy to apply and there are no dimensional limitations.

For the successful use of a cathodic protection system several conditions have to be fulfilled:

- Corrosion of the reinforcement should not be so advanced that the strength of the structure is reduced to an unacceptable level
- Concrete deterioration, such as spalling, coarse cracks and lamination should not be more advanced than could be repaired prior to installation of the cathodic protection system
- All reinforcement should be in mutual electrical connection

These conditions were fulfilled in the actual case.

The disadvantages of cathodic protection systems are their maintenance requirements and the limited lifetime.

The method of chloride extraction is fairly new and only little experience is available. The system consists of a steel mesh embedded in a fibre mass with an electrolyte. The system is connected to a rectifier, positive to the mesh and negative to the reinforcement. By applying a sufficient DC current the chloride ions should migrate from the concrete into the fibre electrolyte.

Chloride extraction systems should only be used if the above-mentioned conditions for the use of cathodic protection are fulfilled.

On the basis of these considerations, it was decided to make a trial installation of both cathodic protection and chloride extraction systems, while traditional replacing of chloride-contaminated concrete was used for the major part of the tunnel walls. A short section was left untreated as a control.

After the repair work had been carried out the walls were coated with paint to avoid new chloride contamination of the concrete.

4. EXECUTION OF THE REPAIR WORK

4.1 Replacement of Chloride-Contaminated Concrete

The criterion chosen for the repair work was that all concrete with a chloride content of more than 0.05% by weight of dry concrete should be replaced by new concrete. Based upon half-cell potential survey and chloride test results the extent of repair was determined. Typically, the concrete was removed up to 0.4-0.7 m above the road surface. In depth a minimum of approx. 100 mm concrete was removed in order to expose the reinforcement. At that depth the chloride content was well below the 0.05% level.

Most of the concrete was removed by a pneumatic machine hammer and only the last part was removed by hand tools.

Cleaning of the reinforcement was mainly done by sand blasting but, as expected, it was found to be very difficult to remove all chlorides from grooves in the reinforcement. Normally the sand blasting was done twice and the last traces of chlorides were removed by grinding. Supplementary reinforcement was placed near bars which had been unacceptably reduced by corrosion or by the grinding. In order not to overstress the wall it was also necessary to do the repair work in two steps.

After cleaning of the reinforcement, formwork was installed and new concrete cast. Alternatively, the Contractor could have placed new concrete by guniting.

4.2 Cathodic Protection

A cathodic protection system was installed on the lowest 1.0 m of the wall on a 50 m long section. The system consists of a platinum metal anode wire placed along the wall in the lower zone, where the highest chloride content was measured. The wire was embedded in a conductive paste and a conductive coating was then applied to the wall. The conductive coating (black) was overcoated with a white decorative topcoat. The cathodic protection system is powered by a computer-controlled rectifier. The purpose of the conductive paste is to provide a more uniform current distribution from the anode into the conductive coating. The conductive paste and coating are carbon filled waterbased polymer products.

Prior to the installation of the cathodic protection system the tunnel wall was cleaned by sand blasting to remove existing paint, dirt, etc. Then all metallic projections were treated so that they would be electrically isolated from the conductive coating and all major cracks in the concrete were sealed to prevent a short circuit between the reinforcement and the conductive coating through the crack.

In order to ensure the best possible results the work was performed under close quality control. This involved checking of preparation of the wall and temperature and humidity monitoring. Adhesion and conductivity of the coating was measured and finally a thermographic survey was performed to locate possible shorts which had not been discovered during work execution.

After starting operation of the system a new half-cell potential survey was carried out in order to adjust the current density so that on the one hand sufficient protection is obtained and on the other hand overprotection is avoided.

In order to permit continuous monitoring of the cathodic protection system and ambient conditions, reference electrodes and humidity and temperature sensors were installed in the tunnel wall.

4.3 Chloride Extraction

A system for chloride extraction was installed on the lowest 1.0 m of the wall on a 50 m long section.

The system consists of a 100 mm mesh of 5 mm dia. wire which is fixed at a distance of 20 mm from the wall by means of insulated inserts.

The mesh is then embedded in an approx. 50 mm thick layer of fibre mass with a $Ca(OH)_2$ electrolyte. The wire mesh is connected to the positive pole of a rectifier and the reinforcement in the wall to the negative pole.

Before installation of the system, the wall was cleaned of existing paint, dirt etc. by water jetting. In order to avoid short circuits major cracks were sealed and projecting steel parts were insulated.

The current is adjusted to a density of max. 1 A/m^2 concrete surface. The fibre mass is kept wet by daily spraying with water. When a decrease of current density is observed the spraying is done by $Ca(OH)_2$ to maintain the electrolyte. After a period of 8 weeks, the mesh and the electrolyte were removed and the wall was cleaned by water jetting.
It was specified that the chloride content should be reduced to a max. of 0.03% by weight of dry concrete. This was achieved for the major part of the wall, but at some locations no reduction at all was measured, probably because of lamination of the concrete, not discovered during the preliminary investigations.

4.4 Untreated Control Area

In order to be able to evaluate the three different repair methods described above, a 10 m long section was left untreated apart from the fact that it received the same final coating as the remaining parts of the walls.

5. EVALUATION

5.1 Problems for future Investigations

Replacement of chloride-contaminated concrete involves two major problems: Is the corrosion of the reinforcement stopped and what is the quality of the casting joint? The quality of the casting joints was analysed on cores and no entrapped air, cracks or lack of adhesion were found. The corrosion activity in the reinforcement will be monitored by half-cell potential measurements and visual evaluation of corrosion on the reinforcement.

The cathodic protection system is continuously supervised and maintained. The maintenance programme includes:

- Observations with permanent probes measuring temperature, humidity and half-cell potentials
- Observations with external probes: temperature and half-cell potentials
- Visual observations on the installations and anode

A test programme is planned to supplement the maintenance program with this information:

- Chemical reactions
- Visual evaluation of corrosion on the reinforcement
- Moisture movements
- Adhesion strength and durability of the paint and
- Variations of the concrete properties

to be measured after three years.

Chloride has been extracted with a high current density for a period of 2 months. Migration speed of the chloride ions towards the anode will vary with concrete properties, cracks, porosities, etc. The chloride content and distribution will be measured in concrete cores. The high current density may accelerate alkali-silica reactions. Petrographical analyses on thin sections from concrete cores will reveal such reactions. The long-time effect on the corrosion activity on the reinforcement is monitored by half-cell potential measurements.

A detailed condition survey of the untreated control area after three years will enable the effect of the three methods described above and the speed of the deterioration of the concrete and reinforcement to be evaluated.

5.2 Economic Aspects

As the actual costs for the repair work previously described include expenses for both development and investigations, they do not represent the real costs for the execution of similar works in the future.

To obtain a realistic cost comparison we have estimated the costs of repairing 350 m^2 of tunnel wall by each of the three methods.

- Traditional replacing of chloride-contaminated concrete incl. subsequent coating:	3400 DKK/m^2
- Cathodic protection:	700 DKK/m^2
- Chloride extraction incl. subsequent coating:	900 DKK/m^2

In addition to the above-mentioned costs, approx. 20,000 DKK/year must be added for operation and maintenance of the cathodic protection system.