Experience and tests of the fire-resistant plaster coating in bored tunnels

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ABSTRACT: CBBN Fireproofing Int., in which Vogel B.V. and BAM Betontechnieken are partners, has employed an innovative approach to apply a fire-resistant plaster to the two largest bored tunnels and a city tunnel in The Netherlands. The three main components of the method are a scientific test method, an optimized plaster and a robotized application technique. The method’s success has been demonstrated in the Westerschelde Tunnel, the Groene Hart Tunnel and the Hubertus Tunnel. The method guarantees that the underlying concrete will not be damaged in the event of an extreme load such as a tunnel fire. With the right fire protection plaster the concrete has full protection and it is not spalling. The quality of the concrete has much influence on the design of the fire protection. Therefore the fire protection plaster is tested by Efectis. This paper describes the influence of the concrete on the fire-resistant material and will discuss test results and application of the fire-resistant plaster Fendolite MII.

1 INTRODUCTION

Exactly 30 years ago a serious accident in combination with fire took place in the Velser Tunnel, 6 people were killed. This event was one of the main reasons for the introduction of legal rules and a revision of the guidelines for the interior equipment of road tunnels.

The most important destroying mechanism by unprotected concrete is when the inherent moisture becomes to steam up quickly, depending on the permeability of the concrete for water vapour, high pressure stresses are developing in the pores of the concrete, with tensile strength as result. By exceeding tensile strength cracks are coming up and the concrete starts spalling, in the worst case the reinforcement starts yielding.

In The Netherlands in case of road tunnels an accident with a petrol tank truck has taken into account. These trucks are able to transport about 45000 litres of petrol and can cause an average fire load of 200 MW (with a maximum of 300 MW). This fire which can hold on for about 2 hours, has led to the definition of the so called RWS fire-curve (Figure 1). The structural integrity of the tunnel must be guaranteed during this fire for 120 minutes. Rijkswaterstaat (RWS) and Efectis (former TNO Centre for Fire Research) developed a procedure for testing the fire-protecting.

For other types of tunnels than road tunnels another fire-curve might be relevant. In those tunnels the temperature of the fire rises not so fast and the maximum temperature might be lower. For example the train tunnel in the High Speed Line has its own fire-curve.

Starting in the early 80’s all tunnels in The Netherlands were renovated and, among others, provided with a fire-protection. All these tunnels were all immersed road tunnels with a concrete quality of B35, fire tests were executed by Efectis and it came out that a layer
of 30 mm of fire-protecting plaster or 27 mm of fire-protecting plates was sufficient. However, this turned out not to be enough for bored tunnels with quite a different type of concrete, like the Westerschelde Tunnel.

2 THE WESTERSCHELDE TUNNEL

2.1 Design

The Westerschelde Tunnel in The Netherlands is a 6.6 km long road tunnel crossing the Westerschelde river. The outer diameter of 11.3 metres in combination with large hydrostatic pressures and difficult ground conditions made this project one of the greatest challenges in the field of large tunnelling projects in Western-Europe. After a design, bidding and optimization period of several years, contracts were signed in 1996 and the works started by the end of 1997. In spite of huge design and technical problems during execution of this project, it was realized within schedule. A lifespan of one hundred years was required for the concrete and this had to be proven by the contractor. A special probabilistic method was introduced, based on the existing European DuraCrete project. Some significant parameters in the model for material resistance are the concrete cover, the diffusion coefficient and the exposure period. The result was a B55 with a very high density and a large percentage of fly-ash.

During this design period the world was shocked by two serious fire incidents in bored tunnels; 1994 a fire in the tunnel boring machine of the Great Belt Tunnel in Denmark and the fire in the Channel Tunnel in 1996. In both cases the tunnel lining was seriously damaged, spalling of the concrete occurred and at some places only 20 mm of lining thickness was left! Although the consequences (in time and money) were extremely high, one was also very lucky because the tunnels did not collapse. Why spalling of concrete happens now and why was this not recognized before?

The mechanism of spalling is very complex. But the big difference in concrete quality in case of immersed tunnels compared to the bored tunnels is not only a higher concrete strength by the bored tunnels (B55 or B65) but also:

- greater density of the concrete, more sensitive for spalling;
- the existence of pressure stresses which increases the danger of spalling;
- the moisture percentage in the concrete.

Until this moment it is not possible to predict the phenomenon of spalling of the concrete in an accurate way. We are completely depending on test results, tests which have to be done under comparable circumstances as in the as built situation. The first lining segments were produced and fire tests on these segments could start up.

2.2 Full-scale fire tests

The first full-scale tests took place in Braunschweig University of Technology (Germany). The lining segments were specially fabricated with channels for the tension ropes to simulate the high ground pressure around the lining when they are embedded in the ground. The fire protection on the tunnel segments was the same as used on a lot of the immersed tunnels; 27 mm thick plates.

The results were amazing in a negative way, spalling of the concrete happened and even the reinforcement started yielding (Figure 2). This big surprise shocked the designers and investigations were set up, the conclusion was that the behaviour of the lining concrete (B55 or B65) was much different than the concrete (B35) in case of immersed tunnels. It was decided to continue full-scale tests by Efectis. Lots of tests were necessary because there wasn’t an accurate calculation program to predict the required thickness of a fire-resistant layer. At the end the conclusion was 45 mm (average thickness) layer of plaster Fendolite MII with a minimum of 42 mm. In total 240.000 m² of a fire-resistant material had to be applied in the tunnel.

2.3 System description

The fact that the Westerschelde Tunnel was the first large bored road tunnel in The Netherlands in soft soil did the designers decide to provide the plaster layer with a wire mesh. There were two main reasons for using a wire mesh:

- The different geological conditions might cause uneven settlements of the lining rings, with cracking of the plaster as a result.
- The behaviour of the bond strength over a long period of time was unknown.

The wire mesh of stainless steel quality AISI 316, consisting of wires of Ø 1.5 mm at centre-to-centre distance of 50 mm each way, was fixed to the concrete lining using stainless steel anchors Ø 6 mm, embedded.
depth 40 mm in 45 mm deep holes drilled in the concrete lining. A minimum number of 6 anchors per m² was applied. The wire nets are 1.4 × 2.4 m² in size and were installed with a minimum lap length of one mesh width of 50 mm.

2.4 Application of the fire resistant plaster

The application of the fire resistant plaster Fendolite MII by CBBN consisted of four main activities:

- covering of the recesses in the lining segments;
- installation of the wire mesh reinforcement;
- cleaning of the concrete lining surface;
- spraying of the fire-resistant plaster Fendolite MII.

To cover the recesses in the lining segments promotec plates were glued over the holes and after that the wire mesh was connected. Nearly 1.4 million anchor holes had to be bored by hand!

Cleaning of the lining surface was executed by means of water of ±70°C at ±180 bar at the nozzle for “steam cleaning”.

Depending on the large scale of the project (240,000 m²) CBBN decided to develop two robots. That wasn’t easy because the robots at that time (1999/2000) were able to spray concrete, none of them could spray mortars in mm’s thickness. At last there were two robots at the working site and they worked perfect (Figure 3). Spraying of the plaster started already during the tunnel boring process and other activities, such as making cross-passages, barriers etc. So logistics were extremely difficult and also the working circumstances for a large number of people working in the tunnel. During the application lot of tests were done. The most important tests are:

- plaster thickness
- bond strength
- mortar control

The progress the robots made was very good, an average of 45 à 50 m² per hour per robot was normal, this resulted in weekly productions of 5000 m². The robots did their work in an extreme short time, one of the main reasons the Westerschelde Tunnel was finished on schedule.

3 THE GROENE HART TUNNEL

3.1 Design

The Groene Hart Tunnel in The Netherlands is a 7 km long high speed railway tunnel with an outer diameter of 14.5 meters. A separation wall divides the tunnel into two single compartments. High speed trains will pass the tunnel at speeds of more than 300 km/h. Inside the tunnel 200,000 m² fire-resistant plaster Fendolite MII with wire mesh reinforcement was applied in a very short period of time. A testing program and a risk analysis were carried out to verify the compliance of the fire resistant plaster with the safety requirements of the tunnel. The fire-resistant plaster suggested by the contractor turned out not to comply with the clients requirements.

With the experience of the Westerschelde Tunnel full scale fire tests on another material (Fendolite MII) could start up very quickly, extensive tests and risk analysis of the system by Efectis proved that this sprayed plaster meets all the requirements in relation to the prescribed fire-curve, the structural safety and durability.

3.2 System description

The fire resistant plaster Fendolite MII was applied in an average layer thickness of 42 mm, with a minimum of 35 mm. The plaster is reinforced by a wire mesh of stainless steel quality AISI 316, consisting of wires Ø 1.5 mm at centre-to-centre distance of 50 mm each way. The wire mesh was anchored to the concrete lining using stainless steel quality A4 anchors. The anchors are fixed to the wire mesh with specially bend washers.

The loads on the fire resistant plaster due to passing high speed trains were specified as follows:

- A maximum pressure of 4 kPa and a suction of 2 kPa in addition to the atmospheric pressure;
- A pressure drop of 3 kPa in 0.01 second;
- The anchor fixation of the wire mesh to the concrete lining should be able to resist a quasi static suction load of 12 kN/m². This value includes the partial load factor as well as dynamic and fatigue effects.

The main requirements applicable to the system are related to the fire safety and to safety in use.

Fire safety
- A period of 170 minutes should be taken as a guideline for the fire load, according to the HSL30MW fire curve (Figure 4);
– The protected concrete lining should not be damaged or break down during the full period of the prescribed fire load.

Safety in use
– The plaster should not significantly contribute to the risk of failure accepted for a structure complying to the Dutch Building Decree during a reference period of 100 years;
– The plaster should be able to resist the mechanical loads due to normal day-to-day use of the tunnel for high speed trains and the accompanying climatological circumstances.

3.3 Application of the fire resistant plaster; logistics

The application of the fire resistant plaster Fendolite MII by CBBN consisted of four main activities exactly in the same way as the Westerschelde Tunnel was done. Depending on the concrete separation wall in the tunnel the work space was limited to 3.2 meters width only. During the application of the plaster it was not possible for others to carry out work at the same location. The work plan for the application was determined by CBBN’s own logistics. The experience gained with the installation of the fire-resistant plaster in the Westerschelde Tunnel appeared to be very helpful in this respect.

It was necessary to use two work fronts and two work shifts in one compartment. A work front consisted of (one work shift):
– 1 team with cleaning robot (3 people)
– 7 teams for covering the recesses and installation of the wire mesh (18 people)
– 1 team with the spraying robot to spray the plaster (5 people)

For the logistics (transportation of the wire mesh, mortar and disposal of rebound) a team of 8 people on average was available. All transport and lifting installations were executed using 1.40 m wide equipment.

3.4 Covering of the recesses in the lining segments and installation of the wire mesh reinforcement

The recesses in the lining were covered by small promatex plates (thickness 8 mm) en connected on the concrete with anchors. The wire mesh of stainless steel A316 was fixed to the concrete lining using anchors Ø 6 mm, embedment depth 25 mm, in 30 mm deep holes drilled in the concrete lining. A minimum of 8 anchors per m2 was applied.

3.5 Cleaning of the concrete surface

In the Groene Hart Tunnel the cleaning system was robotised to ensure that every spot on the lining was cleared properly.

3.6 Spraying of the fire resistant plaster and production achieved

Spraying went just the same as the Westerschelde Tunnel, as described before, but the execution time of the 200,000 m² fire-resistant plaster was only 6 months including preparation time such as adjusting robots and setting up a project organisation. On average ±160 people worked on this project. The daily production was 700 m² per robot per shift. CBBN made the almost impossible time schedule come true, a remarkable success which the project needed very much in order to achieve the time of delivery.

3.7 Quality control activities

The quality control activities which carried out have been listed in Table 1.

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<td>visual inspection</td>
<td>clean surface</td>
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<tr>
<td>Fixation of wire mesh</td>
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</table>
4 THE HUBERTUS TUNNEL

4.1 Design

The Hubertus Tunnel is a 1.5 km long bored road tunnel in the city of The Hague, consisting of two tubes with an outer diameter of 10.5 metres. It is the first tunnel in The Netherlands passing under buildings, so during the boring process an advanced monitoring system was used in order to control settlements of buildings and roads above the tunnel under construction. The tunnel is designed for a speed of 50 km/h, this is one of the reasons there is more attention for the finishing of the inner part, for instance the fire resistant layer must be covered by a coating over a height of 4 metres. The tunnel is at this moment still under construction and is planned to be opened for traffic September this year.

4.2 System description

Contractually (UAVGC-2000) the contractor was allowed to initialize optimizations. So the contractor HTC has chosen a Fendolite MII fire-resistant plaster without a wire mesh. Two main reasons to design without a wire mesh:

- No uneven settlements between lining rings expected, due to the geological conditions;
- Bond strength increases over the years, as learned before in the Westerschelde Tunnel.

By the two tunnels as described before the recesses in the lining segments were covered by using promatect plates, this solution turned out not be sufficient by the type of concrete used for the Hubertus Tunnel. The promatect plates were replaced by finned metal plates in order to let steam to escape. Full scale tests by Efectis learned this was a right solution (Figure 5). In total 55,000 m² Fendolite MII must be applied.

4.3 Ceramic coating

Traffic in a city tunnel is passing not so fast (maximum 50 km/h) compared to other road tunnels, so the client required a coating of a light coloured and good maintainable material. HTC decided to use a Ceramic coating, well known from other tunnels in Europe. The finishing of the plaster direct after application became an important point in order to apply the coating in the correct way.

4.4 Application of the fire resistant plaster and ceramic coating

The works started with fastening of the finned metal plates by means of stainless steel anchors. Before that the plates are covered with a very thin layer of Fendolite by hand, in order to prevent the sprayed Fendolite to go through the small openings of the metal plates.

Cleaning of the lining surface went the same way as the other tunnels but now there was an extra handling because a kind of soap had to be sprayed on the concrete surface first to clean it in the correct way.

Spraying of the Fendolite has become a routine process with all the experience of other tunnels done before. By the end of January 2008 in about 1 km of the first tube Fendolite was applied. The ceramic coating consisting of two layers will be sprayed on primer layer which is applied on the Fendolite.

5 EVALUATION OF THE FIRE RESISTANT PLASTER

5.1 Introduction

In case of the Groene Hart Tunnel an extensive test program was carried out by TNO Built Environment and Geosciences. The evaluation program consisted of the following research activities:

- testing of fire resistant properties;
- testing of material properties of Fendolite MII;
- testing of bond between Fendolite MII;
- testing of back up fixation system with wire mesh and anchors;
- risk analysis of the total system.

5.2 Fire resistant properties

Two full scale segments with 35 mm fire-resistant plaster including wire mesh were tested by Efectis. Important by testing was the moisture content of the plaster of ±9% (m/m) which is comparable with the moisture content in the tunnel during operation. The tests results were positive, no spalling of the concrete lining occurred.
5.3 **Material properties of Fendolite MII**

Large investigations took place, also on older tunnels with a comparable material as the Fendolite MII. The final conclusion of these investigations was that, as the composition and the chemical properties of Fendolite MII remain stable in time, the material properties (physical, mechanical and fire resistant properties) will not decrease during the service life of the tunnel.

5.4 **Bond between Fendolite MII and concrete lining**

Bond tensile tests were carried out in the Groene Hart Tunnel and the Westerschelde Tunnel at different ages of plaster. The results learned that in time an increase of bond tensile strength takes place by the increasing degree of hydration. The bond tensile strength is significant higher than the suction load of 2 kPa on the system caused by the passing of high speed trains.

5.5 **Back up fixation system**

The wire mesh fixed to the concrete lining with anchors acts like a back up fixation system, because no guarantee can be given that unbonded areas of limited size will not occur during the service life of the tunnel. This back up fixation system has been tested in the Efectis laboratory, both static and fatigue tests were carried out.

The static strength was in all cases about 1.5 kN per anchor, with a value of 3 kN the static requirement is fulfilled.

The fatigue tests on the back up fixation system were done at different load interval levels, namely at 200 N, 350 N and 500 N. The actual failure mode observed was in all cases rupture of the wire mesh around the anchor due to fatigue. The maximum anchor loads vary from 150 N to 200 N. This level of anchor loads may lead to fatigue failure after 2 million load cycles or more.

5.6 **Risk analysis of total system**

Finally a risk analysis of the total system was made, different failure mechanisms have been analysed and the failure probabilities were quantified. The conclusion was drawn that in case of unbonded areas are present, the failure probability may exceed the safety requirement after a period of time which is related to the number of train passages. On this basis requirements were established for an inspection and monitoring regime, which is expected these activities will be limited and fall within the definition of low maintenance.

6 **CONCLUSIONS**

- Full scale tests on lining segments with exactly the same concrete composition as the building segments for the tunnel are most important and always required;
- By all three bored tunnels the fire safety requirements are fulfilled;
- As the composition and the chemical properties of the Fendolite MI plaster remain stable in time, the material properties (physical, mechanical and fire resistant properties) will not decrease during the service life of the tunnels, hence the durability requirements are fulfilled;
- The bond tensile strength between the fire resistant plaster and the concrete lining increases in time and is, in case of the Groene Hart Tunnel, significantly higher than the suction loads on the system caused by passing trains;
- Covering of the recesses in the lining segments by means of an stiff, open (breathing) material;
- In case of difficult geological conditions and or expected settlements of segment lining rings with failure of the bond between the plaster and the concrete as result, the back up fixation system of the wire mesh with anchors will take over this function;
- In case of unbonded areas are present, with or without a back up fixation system, the failure probability in connection with the fatigue failure can be kept within the safety requirement by inspection and monitoring of the system during the service life, followed by repair of the system if necessary;
- Robotic cleaning of the concrete surface and robotic application of the Fendolite MII guarantees the quality of the fire resistant layer.

**REFERENCES**


