Fire behaviour of large scale loaded tunnel segment tests for project Rotterdamsebaan, the Netherlands

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Abstract

Assessing the performance of tunnels in fire is becoming increasingly crucial for the overall usability and durability of the structure. One of the most reliable methods for evaluating the presentation of the concrete during fire in tunnels is by testing. In this work, the fire tests performed on the Victory Boogie Woogietunnel, project Rotterdamsebaan (The Hague, the Netherlands) are discussed. The study aims to assess the fire performance of the cut and cover concrete section when subjected to a tunnel fire curve. A series of 6 fire tests were performed on concrete slabs of the size 5,0 m x 2,4 m x 0,4 m when exposed to Rijkswaterstaat (RWS) fire curve for 120 minutes. Based on the work, one of the main conclusions drawn were that it is necessary to test a large-scale specimen to judge the performance of a protection system accurately. Another important conclusion is that the test specimen should have the concrete mixture which accurately represents the tunnel concrete to avoid uncertainty in the fire induced spalling behaviour of concrete.

Keywords: fire; fire protection; Rijkswaterstaat fire curve; fire induced spalling; tunnel.

1 Introduction

Over the last few decades, it has become quite apparent that the impact of fire in a road tunnel should be taken into account during the design phase. This learning has been due to a combination of lessons learnt from past accidents and the stricter safety measures placed by the various authorities [1]. One of the phenomena which governs the behavioural response of concrete tunnels in fire, is spalling. A number of factors govern the phenomena of spalling, such as the strength of concrete, moisture content, type of cement used, size of aggregate, the compressive stress in the concrete cross-section, among others. However, it is not possible to state with certainty which factors will be governing for a particular tunnel concrete [2]. Another challenge is to determine the extent and intensity of spalling that might occur in a specimen [3]. In the absence of any theoretical model that is validated with fire tests for a diverse data set, it is impossible to determine the nature of spalling and apply to a tunnel project. Hence, fire testing is the more viable and sufficiently conservative method to ascertain the tunnel fire behaviour.

The Victory Boogie Woogietunnel is part of the new road connection called the Rotterdamsebaan between the highways A4 & A13 and ring road of The Hague (the Netherlands). The tunnel comprises of both cut and cover tunnel sections (at both ends of the tunnel) and a bored tunnel section. The (cast in-situ) cut and cover part of the tunnel is 220 m in length and the bored tunnel part is 1640 m in length. The tunnel is constructed under typical Dutch soil conditions with sand, clay and peat layers in combination with a high groundwater table. Furthermore, the tunnel is located in a densely populated area and passes several residential and commercial buildings.

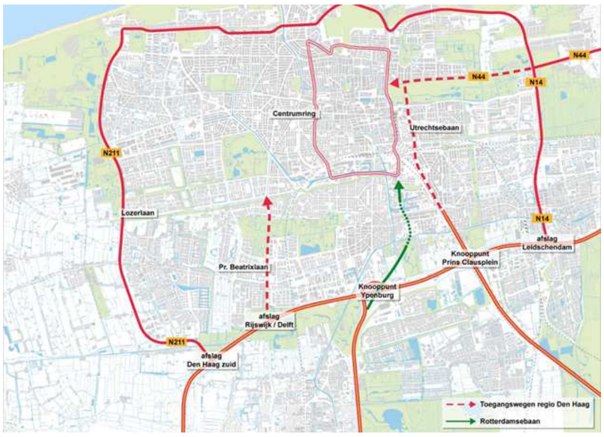

Figure 1. Rotterdamsebaan, The Hague

The current work focusses on the fire performance of the cut and cover tunnel section when subjected to a tunnel fire curve and the series of fire tests executed to arrive at the final protection system.

The concrete used in the cast in situ tunnel section has been designed according to the specifications defined by Rijkswaterstaat, The Dutch Ministry of Infrastructure and Water Management in the *Richtlijnen Ontwerpen Kunstwerken (Guidelines for the design of Civil Engineering Works),* ROK 1.2 [4]. Until recently, the ROK defined concrete mix was assumed to be 'spalling free' which meant that no external protection system or integrated protection (such as the addition of polypropylene fibers to the concrete mixture) had to be provided to the tunnel elements. In 2015, a research study conducted by Efectis concluded that the ROK 1.2 defined concrete mix may not necessarily prevent the occurrence of spalling of concrete when subject to a RWS fire curve [5]. In this study, both specimens cast according to the guidelines provided in the ROK 1.2 showed severe progressive spalling.

Owing to the findings, it is necessary to review the fire performance of a tunnel which has been made according to the ROK 1.2 specified concrete mix. Hence, the decision by the project team Rotterdamsebaan to assess the fire performance of the tunnel with large scale fire tests.

1.1 Procedure

The jointly written RWS/Efectis testing procedure, 2008-Efectis-R0695, 'Fire testing procedure for concrete tunnel linings' is followed for performing the fire tests [6]. The test procedure requires that for determining the spalling behaviour of a concrete specimen, a fire test should be repeated at least twice. Thereby reducing the uncertainty in the test results.

Since it is unknown how the concrete itself will perform during a fire, a first test is performed with bare concrete. Once it is established that the intensity of spalling of bare concrete is unacceptably high, it is decided to protect the concrete with a board protection system. The next set of tests are performed with a single layer board protection system. It is however noted that during the testing of the single layer board protection system, the gaps at the board joints are susceptible to a sudden temperature rise, which in some cases resulted in spalling of the specimen near the board joints. To avoid the negative effect of the joints, it is decided to test with a double layer board protection system. Thereby, finally arriving at the protection system which is applied to the tunnel.

The observations during the full test series are discussed further and recommendations for future tunnel tests are provided.

2 Background

A realistic behaviour of the concrete performance in a tunnel fire is achieved in this work by testing of large concrete slabs of the size 5,0 m x 2,4 m x 0,4 m. The choice of these dimensions is a reflection of the test procedure [6] which defines that the thickness of the specimen shall be as in practice. In case the thickness is higher than 0,4 m, it may be limited to 0,4 m for the test. The width of the specimen is 6-8 times the thickness, and hence the 2,4 m width of the specimen. The length of 5 m is

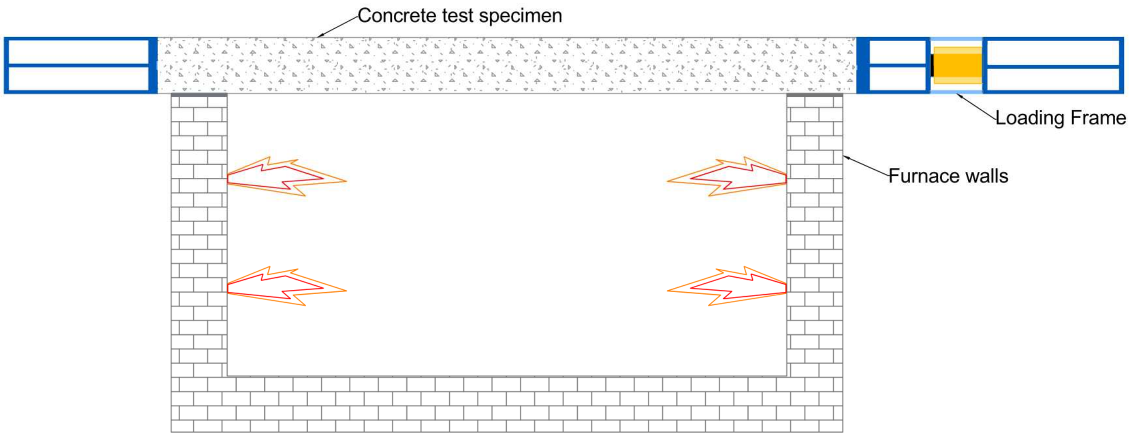

Figure 2 . Scheme of the experimental setup

chosen as it is ideal for loading with the available loading frame.

The reason behind the large dimension is to simulate a full mechanical behaviour of the system (concrete + protection) where expansion of the concrete aggregate, the shrinkage of the cement paste, shrinkage of the board system is realistically replicated. Another reason is to avoid edge effects in the system.

The reinforcement in the concrete slab is also representative of the real tunnel situation. The depth of the first layer of reinforcement is 100 mm and the diameter of the reinforcement bars is 16 mm with a centre to centre distance of 125 mm in both directions.

The slabs were cast and thereafter cured for a period of minimum three months. The required compressive stress in the concrete slab was applied using the Efectis loading frame. The test specimens are subjected to RWS tunnel fire curve for a period of 120 minutes.

The test specimens were cast in two batches and the fire tests were performed in two batches as well. The first four tests in the period of March 2018 and the next two tests in the period of October 2018.

The concrete mix used has been described in table 1.

Table 1. Concrete Mix properties

Description	**Properties**
Strength class	C25/30
Cement	CEM III/B (320 kg/m^3)
Aggregate	4-32 mm
Sand	0-4 mm
Water cement factor (wcf)	0,5
Slump	170 mm
Density	2370 kg/m^3
Superplasticizer	0,2% of cement weight

3 Experimental setup

As already explained in the previous chapter, it is important to test a scenario that as closely as possible reflects the situation on-site. The test specimens are placed horizontally on the furnace. The exposed surface of the specimen is 4 m x 2.4 m. The specimen was supported on two sides and had two free edges. In Figure 2, the scheme is shown, the test specimen is loaded horizontally with the loading frame. The loading frame is described in Figure 3 and an overview of the resulting compressive stress in the concrete slab (on the exposed surface) is given in Table 2. The weight of the concrete test specimen is ignored while calculating the load to be applied laterally. It is expected that the effect of the self-weight is limited in the global behavior of concrete.

The requirement criteria for the acceptance of a test result is defined by the Rotterdamsebaan project team as 'no spalling'.

Additionally, for the tests with fire protection boards, it was required that the temperatures on the surface of the concrete shall not exceed 380 °C.

Figure 3. Loading frame

3.1 Fire curve and furnace pressure

The RWS fire curve, as shown in Figure 4, was used for all the fire tests. The temperatures in the furnace are measured with special temperature sensors, in this case mineral insulated sheathed thermocouples. The furnace pressure is maintained at a positive pressure difference of around 20 pascal with respect to the ambient pressure for all the fire tests.

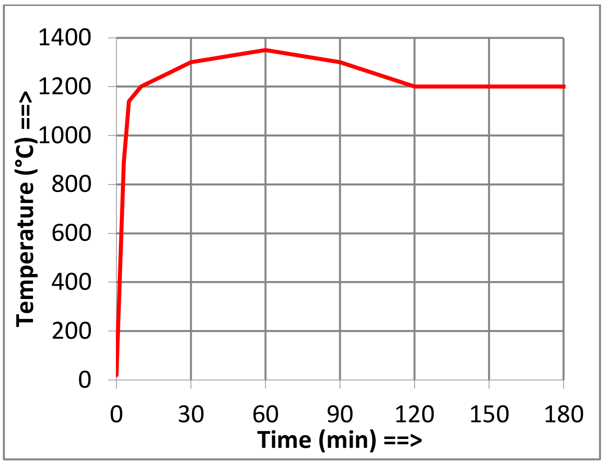

Figure 4. RWS fire curve

4 Test series

A total number of 6 fire tests were performed to obtain information about the spalling behavior of the concrete and to determine the design and the amount of protection required. The fire tests in ascending order of date of testing have been described below and the results have been discussed in Table 2.

Fire test 1 - unprotected concrete
Fire test 2 - concrete protected with boards - single layer - 25 mm
Fire test 3 - concrete protected with boards – single layer - 30 mm
Fire test 4 - concrete protected with boards – single layer - 30 mm
Fire test 5 - concrete protected with boards - two layers - 15 + 25 mm
Fire test 6 - concrete protected with boards - two layers - 15 + 25 mm

The type of joints between the boards were simple butt joints for both single- and double-layer protection and no additional insulation was applied between the joints.

The first four concrete slabs were cast in the first batch and the last two concrete slabs were cast in the second batch. During the casting of unprotected concrete specimen, temperature sensors/ thermocouples were applied at different depths in the concrete. In this work, only the temperatures at a depth of 100 mm are discussed which corresponds to the location of the reinforcement.

For both the batches of concrete slabs with board protection applied to the concrete, thermocouples were installed at the interface between concrete and the boards (on the surface of concrete). The conductivity of the board material is approximately 0.17-0.18 W/mK at 20 °C. A brief summary of the recorded concrete surface temperatures is shown in Table 2 and due to confidentiality reasons not all recorded values (i.e. the temperature time graphs) are provided in this paper.

Table 2. Description of the fire tests

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Thickness of applied protection [mm]	no	25	30	30	15 + 25	15 + 25
Compressive stress in the concrete slab (exposed surface) [MPa]	10	15	10	10	10	10
Time to first spalling (t1)	2 min	74 min	128 min	94 min	No spalling observed (test till 180 min)	No spalling observed (test till 180 min)
Number of thermocouples applied at the concrete surface (or the interface between boards and concrete)	6	19	19	19	17	17
Average temperature on the concrete surface at time t1	96 °C (based on the thermocouples applied before concrete casting) 1140 °C (at t = 29 minutes)	231 °C	254 °C	186 °C	225 °C (at 180 min)	229 °C (at 180 min)
95% characteristic temperature at time t1	109 °C 1211 °C (at t = 29 minutes)	428 °C	405 °C	296 °C	241 °C	249 °C
Average temperature at the location of reinforcement (100 mm) in concrete (if measured) at time t1	13 °C 355 °C (at t = 29 minutes)	-	-	-	-	-
Average temperature measured behind the joints at time t1 (8 thermocouples)	-	318 °C	312 °C	251 °C	-	-
Average temperature measured in locations other than behind joints at time t1 (11 thermocouples)	-	169 °C	208 °C	155 °C	-	-
Time to the end of the test [min]	29	78	133	102	180	180

4.1 Observations and discussion of test 1

In the first test the bare concrete was directly subjected to the RWS fire curve. The test specimen started to spall almost immediately after the start of the test. The test was continued further irrespective of the intensity of spalling. Once the reinforcement was visible from the furnace camera (after 29 minutes), it was decided to stop the test for safety reasons. The temperatures on the concrete surface after a few minutes of spalling were almost following the furnace temperature, as can be seen in the final values of Table 2. In Figure 5, the test specimen after the fire test is shown.

Based on the results, it was decided to perform the next tests with concrete protected with passive fire protection boards.

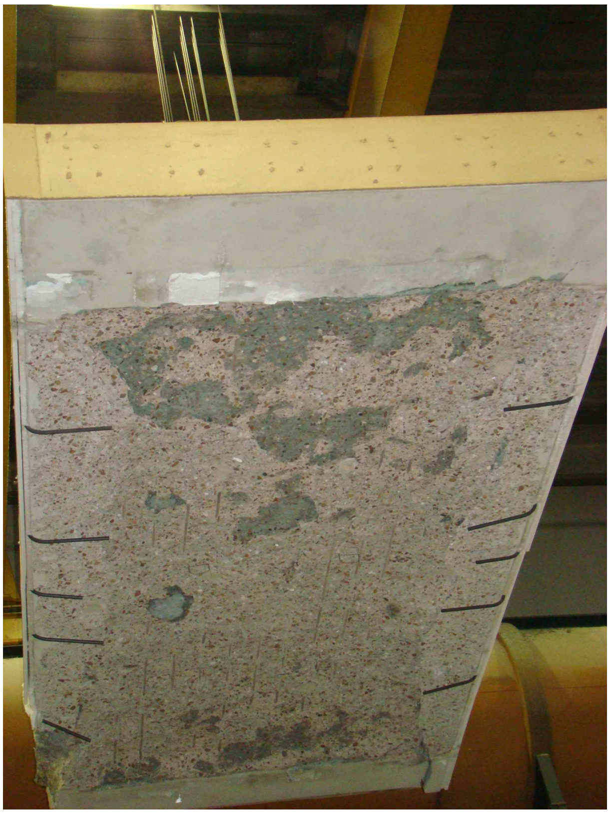

Figure 5. Test specimen 1 after the fire test

4.2 Observations and discussion of test 2, 3 and 4

Passive fire protection boards which are fit for the tunnel hydrocarbon fire curve (RWS fire curve in this case) are used. The boards are post-fixed onto the concrete with the help of anchors, which makes them easy to install. A typical board protection system is shown in Figure 6.

A board thickness of 25 mm is first chosen for the fire test. Around 74 minutes into the fire test, a part of the board comes off and spalling is observed. Due to the failure of the test earlier than the set requirement of 120 minutes, it is decided to increase the board protection thickness to 30 mm.

It is noted that, with the new board protection thickness, there is no spalling observed for a period of 120 minutes. The fire test was continued, as it was interesting to know the margin in the fire test. Spalling was observed around 128 minutes.

As the test procedure [6] requires that a fire test should be successful twice to avoid the uncertainty in the outcome, the same system with boards is tested again. The repeat fire test fails at 94 minutes where part of the board falls off and spalling is observed.

In this test series it is observed that a single layer of boards can be quite susceptible at the joints. At all three tests the spalling started near the board joints. When a passive board protection system is exposed to fire, the boards might shrink leading to slight gaps in the protection system. Also the deformation of the tunnel structure due to the increase of the concrete temperature can contribute to the gap formation. During a fire test, the temperature in these gaps may rise sharply compared to the rest of the concrete surface.

For test 2, 3 and 4, the thermocouples were installed across the concrete test specimen in locations which were behind the joint and locations away from the joints. It was noted that the temperatures behind the joints were significantly higher compared to other measurement locations as shown in Table 2.

The tests show that the performance of a single layer of fire protection boards may depend on the temperature development near the joints. Since the temperature development in the joints depends on many factors (application tolerances, shrinkage of the boards, deformation of the test specimen, etc.), the outcome of similar fire tests may show a divergence. Therefore, the performance of such a fire protection system during a fire (test) may not be predictable, as observed between test 3 and test 4. Also, the tests show that the behaviour of the board joints can only be accurately tested in a large scale fire test in which full size boards and joints are applied.

The unpredictable behaviour at the board joints can be resolved in two ways in practice, one is using backer strips, where behind all the joints of the boards, a thin board material is applied minimizing the effect of the gaps that may be present between the boards. Another way is to opt for double layer board protection material with a sufficient offset between the joints in the boards in the first layer and in the second layer, thereby making the effect of joints insignificant. The later method is chosen by the project team.

Figure 6. Test specimen 3 before the fire test

4.3 Observations and discussion of test 5, 6

For test 5, passive fire protection boards are applied to the concrete specimen in two layers. The 15 mm layer is applied close to the concrete surface and a 25 mm layer is applied on the exposed side. The boards of the second layer have an offset of 200 mm in longitudinal and transverse direction compared to the boards of the first layer.

No spalling was observed for the entire duration of the test. The test was extended beyond the necessary requirement of 120 minutes to 180 minutes to determine the safety margin present in the system. The exact test was repeated, and also during the second test no spalling was observed till the end of the heating period of 180 minutes.

As can be seen in in Table 2 the temperature range on the concrete surface in test 5 and 6 is much smaller (about 20 °C difference between average and 95% characteristic value) compared to the single layer tests 2, 3 and 4 (up to 200 °C between average and 95% characteristic value). This proves that with two layers of fire protection boards the negative influence of the joints is reduced to a minimum. It was concluded with these tests, that a double layer of fire protection boards is (more than) sufficient to protect the tunnel structure against a severe tunnel fire.

4.4 Conclusions and additional discussion

It has been noted during the test series that the final answer to the fire safety design lies in a combination of sufficiently largescale testing, representative materials (e.g. concrete mixture) and representative details (e.g. full size board with joints) such that all possible limitations of a fire protection system/ concrete are tested. In this manner all possible mechanical behaviour of the system can be investigated along with the thermal behaviour.
In addition to the above discussed test series, two more tests were performed with specimens consisting of concrete in which polypropylene (pp) fibres were included. The pp-fibres are considered as a possible integral fire protection measure as they are part of the concrete mix and can offer, if properly designed and validated, a solution without the need for external measures, if there is no criteria for the concrete temperatures. These tests were considered beyond the scope of the current paper and hence no further details are provided.

5 Conclusions

The final outcome of the work resulted in a robust fire protection system for the cut and cover part of the Victory Boogie Woogietunnel. Based on the work, four main conclusions can be drawn

a. It is necessary to test a large scale specimen to accurately judge the performance of a fire protection system, in case of fire protection boards (in this case) that would mean testing of at-least 1 full size board including all joints.
b. The test specimen should have the concrete mixture which accurately represents the tunnel concrete and a realistic compressive stress

should be applied to the specimen during the fire test.

c. In case of a fire protection system with boards the joint between the boards requires specific attention in the design and fire tests.
d. At least two tests must be performed with any concrete specimen in order to limit the uncertainly in the spalling behavior.

6 References

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