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Ministry of Infrastructure and Water Management

Fire testing procedure for concrete tunnel linings and other tunnel components

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This report is the result of a joint effort between Rijkswaterstaat and Efectis Nederland

PREFACE

Rijkswaterstaat, the executive body of the Dutch Ministry of Infrastructure and Water Management (hereafter denoted as “RWS”), has laid down specific requirements with regard to the fire resistance of road tunnels in the Netherlands[1]. A substantial part of these requirements refers to a test procedure described in the document “2008-Efectis-R0695 Fire testing procedure for concrete tunnel linings”.

A fire testing procedure has been available since 1986, when TNO published the report “BI-86-69 – Tunnel Protection Fire Test Procedure”. This report described a test on a concrete slab with fire protection, which was exposed to a hydrocarbon-fire according to a newly introduced RWS fire curve. In 1998, RWS and TNO Centre for Fire Research (now known as Efectis Nederland) jointly produced the more detailed document “1998-CVB-R1161 (rev.1) - Fire Protection for Tunnels - Part 1: Fire Test Procedure”. The document described a more detailed procedure for testing fire protection systems on concrete slabs, and also introduced a test procedure for the evaluation of the spalling behaviour of concrete tunnel structures when exposed to fire.

In 2008, RWS and Efectis Nederland issued an update of the test procedure presented in “1998-CVB-R1161 (rev.1)” to reflect the state of the art at that moment, and to make the procedure suitable for a wider, practical range of tunnel construction types and fire protection systems. This update was the most recent version of the test procedure and was laid down in the document “2008-Efectis-R0695 Fire testing procedure for concrete tunnel linings”.

Over the last decade, with growing experience in fire tests, spalling behaviour of concrete and the presence of new fire protection materials and systems, RWS and Efectis Nederland have taken the initiative to develop an updated fire testing procedure.

As the spalling behaviour of concrete is largely dependent on the composition of the concrete, stricter standards have been introduced to assess the concrete mix in the new procedure.

In order to extend the suitability of the test procedure, this update also includes fire resistance testing of other tunnel components, such as tunnel doors, penetrations, cable ducts and tunnel joints.

On top of the above-mentioned extensions, the update also contains several other modifications to reflect the current state of the art, including the addition of a cooling phase to the fire curve and more specific furnace pressure conditions during testing.

Over the last few years, an increasing number of authorities have made it obligatory for tunnel owners to demonstrate the fire safety of existing tunnels. Due to this, the need arose to perform fire tests on-site with a mobile furnace instead of in the laboratory. The updated 2020 test procedure therefore also contains a procedure for this testing option.

In this document, “Efectis-R0695:2020 Fire testing procedure for concrete tunnel linings and other tunnel components”, the updated 2020 test procedure is presented. The document has been jointly produced by RWS and Efectis Nederland.

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[1] See the Dutch document “Richtlijn Ontwerp Kunstwerken (ROK) 1.4” (Guidelines Design Infrastructure Works 1.4). ROK 1.4 will be replaced by ROK 2.0 shortly.

CONTENTS

1. INTRODUCTION

Unprotected or insufficiently protected concrete tunnel linings can undergo serious damage during a fire in a tunnel. Many real tunnel fires over the last decade have shown that such damage is likely to result in repair works that are very costly and take the tunnel out of service for a long time. Also, such damage may jeopardise (infra-)structures or buildings erected above the tunnel.

To prevent or at least mitigate such damage during and after a fire, measures can be taken to protect the tunnel. Measures may aim to:

- avoid or limit spalling of concrete;
- limit temperature or the heating rate of the concrete;
- limit temperature of the reinforcement;
- limit temperature of the concrete around the reinforcement;
- limit temperature at the unexposed side; and
- limit propagation of cracking into the cold zone.

Depending on the situation, different fire protection measures may be chosen. These measures can be divided into two categories:

1. measures inside the concrete (concrete mix, additives, polypropylene fibres, etc.); and
2. measures outside the concrete (external fire protection systems).

Obviously, for refurbishment of existing tunnels 1 is not an option. For new tunnels, either 1 or 2, or a combination of both, could be chosen.

A large scale fire test is the best possible way to simulate the conditions that occur during a real fire. In some cases, a medium scale fire test will also provide sufficient information. When testing in the laboratory is not possible, it is possible to perform tests on-site.

Nevertheless, every fire test remains a simulation and can never fully replicate all of the conditions that will occur in the event of fire. Therefore, it is important to consider the conditions under which the tests are performed and whether a single test setup is sufficient, or whether multiple test setups are necessary in order to confirm that the tunnel is able to withstand a real fire. The fire testing procedure presented in this document will describe the different tests that are available to confirm that a tunnel is well protected in case of fire.

Two key tests are defined, aiming to provide information on:

- spalling behaviour of the concrete structure (“Spalling Test”); and
- temperatures of the concrete surface, reinforcement and other critical locations inside the concrete (“Thermal Insulation Test”).

Generally, in a spalling test, temperatures will also be measured. In that case, the spalling test gives information on spalling behaviour as well as concrete temperatures, i.e. thermal penetration.

The “Spalling Test” is described in Chapter 4 and the “Thermal Insulation Test” is described in Chapter 5.

The test procedure also includes fire resistance testing of other tunnel components, such as tunnel doors, penetrations, cable ducts and tunnel joints. The procedure for these tests is described in Chapter 6.

Finally, the procedure to perform fire tests on-site with a mobile furnace instead of in the laboratory is given in Chapter 7.

Besides carrying out a fire test, it may be required to demonstrate the resistance of a fire protection system to other influences such as air pressure waves, frost-thaw cycles, chemically aggressive environments, etc. Such tests are not described in this document.

Caution

All persons concerned in managing and carrying out fire testing shall be aware of the risks related to the testing activity. Such risks involve, but are not limited to:

- high temperatures and flames;
- harmful smoke and gases;
- falling and hot debris;
- lifting and transportation of (heavy) equipment and test samples; and
- mechanical failure of the test sample during the construction.

For both laboratory tests, as well as in situ tests, an assessment of the potential risks is required. Instructions tailored to the purpose, use of equipment and location of the test shall be given to personnel and other persons involved.

2. NORMATIVE AND OTHER REFERENCES

The following documents are referred to in the text:

ROK 1.4[2], *Richtlijn Ontwerp Kunstwerken,* April 2017, RTD 1001:2017, Rijkswaterstaat

EN 1363-1, *Fire resistance tests – Part 1: General Requirements*

EN 1366-3, *Fire resistance tests for service installations – Part 3: Penetration seals*

EN 1366-11, *Fire resistance tests for service installations – Part 11: Fire protection systems for cable systems and associated components*

EN 1634-1, *Fire resistance and smoke control tests for door and shutter assemblies, openable windows and elements of building hardware – Part 1: Fire resistance test for door and shutter assemblies and openable windows*

EN 1634-3, *Fire resistance tests for door and shutter assemblies – Part 3: Smoke control doors and shutters*

EN 1992-1-2, *Eurocode 2: Design of concrete structures – Part 1.2: General rules – Structural fire design*

EN 206*, Concrete – Specification, performance, production and conformity*

3. TERMS AND DEFINITIONS

For the purposes of this document the following terms and definitions apply:

3.1
fire-induced spalling
Fire-induced spalling is a phenomenon that occurs during exposure of concrete to fire, whereby spalling of concrete spontaneously occurs at the heated side of a concrete structure. In the remainder of this document fire-induced spalling is simply referred to as spalling.

3.2
fire protection material
Material, or a combination of materials, that is able to protect tunnel structures and components from a fire. Examples of fire protection material are fire protection boards and spray mortar.

[2] ROK 1.4 will be replaced by ROK 2.0 shortly. The most recent version of ROK shall be used.

3.3
fire protection system
System consisting of a fire protection material and fixing system for the purpose of increasing the fire resistance of a concrete structure.

3.4
fixing system
System for fixing fire protection materials to concrete structures. For a board system, an example of a fixing system is a combination of anchors, washers, anchor pattern and joint pattern. For a spray system, an example is a combination of mesh, anchors, mesh/anchor pattern and application procedure.

3.5
furnace camera
A special type of video camera system that can withstand the high temperatures of a fire test and is able to give a real-time view of the test specimen during testing.

3.6
mobile furnace test
On-site (medium scale) fire test with a mobile furnace. The mobile furnace is transportable and is able to assess the fire resistance performance of existing tunnel structures.

3.7
RWS
RWS stands for Rijkswaterstaat. Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management and is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands.

3.8
shall/should
For the purposes of this document *shall* denotes a requirement that is mandatory whereas *should* denotes a recommendation (i.e. non-compliance is permitted).

3.9
spalling depth
Depth over which concrete has spalled after exposure to fire. The spalling depth is measured perpendicular to the original concrete surface.

3.10
spalling test
Type of test that is suitable to determine the spalling behaviour of concrete, or concrete with a fire protection system, during exposure to fire.

3.11
thermal insulation test
Type of test that is suitable to determine the insulating properties of a fire protection system (medium scale test), or is suitable to determine the insulating properties and structural integrity of a fire protection system (large scale test) during exposure to fire.

4. SPALLING TEST

4.1 INTRODUCTION

Spalling tests are required to assess the suitability of a concrete structure for real-world applications, given the possibility that during a fire unacceptable damage to the structure may occur due to fire-induced spalling of the concrete. The test therefore comprises the concrete structure, including intended measures to prevent spalling such as the application of an external fire protection system, the addition of polypropylene fibres to the concrete mix and/or other adjustments of the concrete formula.

The test specimens shall resemble the practical situation as closely as possible, including a representative concrete mix and any fire protection measures. A spalling test shall incorporate at least the following characteristics based on the real situation:

- representative concrete mix (proportions, sizes and types of all components, if applicable: including the polypropylene fibres and additives);
- representative compressive load to the concrete element;
- representative conditioning of the specimen; and
- if applicable: fire protection system (including curing conditions and a representative moisture content).

The phenomenon of spalling is very complex and involves a combination of physical, chemical and mechanical processes, which influence each other. This is one of the reasons why tests that are insufficiently large in scale, or computer modelling, are considered inadequate to be able to draw conclusions on the spalling risk for a given situation.

In order to have a valid test result, tests shall be performed at least twice on identical, large scale (preferably 1:1) specimens, with identical concrete composition, fire protection system, thickness, loading and heating conditions, etc[3]. The requirements for the concrete test specimen, fire protection system, conditioning, fire test and reporting are described in this chapter. Because the test specimens need to resemble the real tunnel as closely as possible, the test result in principle is only valid for the tunnel for which the test was performed.

The procedure for performing a spalling test is described in the remaining part of this chapter.

4.2 TEST SPECIMEN

When designing a test specimen for a spalling test, a number of aspects shall be considered. These aspects are described in the following paragraphs.

4.2.1 Geometry

The geometry of the specimen shall resemble the real tunnel situation. For prefabricated segmental linings this means that full segments shall be tested, with a view to avoiding unwanted (namely uncontrollable, unpredictable and unrealistic) effects of artificially introduced boundaries.

For large (cast in situ) structures, a sufficiently large specimen shall be made in order to avoid edge effects, since spalling at the edges of a slab or wall specimen may be less severe.
For walls and slabs, the thickness shall be equal to the thickness in practice. If this thickness exceeds 0.4 m, for practical reasons it is allowed to limit the thickness of the specimen to 0.4 m.
For tests on bare concrete, the exposed surface area of the slab or wall specimens shall be at least 5 m^2 in order to account for edge effects. For tests on specimens with an external fire protection system, the exposed area of slab or wall specimen shall be at least 8 m^2. Additionally,

[3] Spalling is very difficult to predict, because many parameters play a role and the combined effects of these parameters can be surprising. Also, small changes in assumptions may lead to a very different result. Therefore it is necessary to confirm that the obtained test result is reproducible by performing a second identical test.

for both bare concrete and fire protection systems the exposed width of the test specimen shall be at least 1.6 m.

In situ test specimens, such as TBM-elements, shall be tested at full size. These test specimens may have dimensions smaller than the dimensions mentioned above.

For beams, columns or other structural elements, the required test setup depends on whether the element is exposed to fire on one, two, three or four sides. The heated length of the element shall be at least 4 times the width or height (the largest value prevails). If the width and/or height exceeds 1.0 m, for practical reasons it is allowed to limit the dimension to 1.0 m.

4.2.2 Reinforcement

The reinforcement (typically of steel) in the concrete shall be representative of the real tunnel situation. This applies to:

- bar diameter;
- bar centre-to-centre distances;
- concrete cover; and
- type of spacers.

Small amounts of additional reinforcement may be applied to guarantee proper transport and lifting, as well as installation of thermocouples and application of mechanical loads. Additional reinforcement shall always be discussed with the client because of the possible influence on the results of tests. In the report, a statement shall be made on this matter.

4.2.3 Casting of the specimens

The manufacturing process of the test specimens shall be as close to the actual manufacturing process as reasonably possible. This is with a view to excluding the unwanted effects of differences in the actual concrete properties. Details including but not limited to the following may be of influence: the surface (material, roughness, permeability) of the formwork, the formwork removal oil and the type and size of reinforcement spacers.

For cast in situ structures this means that ceiling specimens shall be cast in a horizontal formwork, with the bottom (formwork) side being the one that will be exposed to fire.

Wall specimens may be cast in horizontal formwork if the fire exposed surface during the fire test is the bottom (formwork) side.

4.2.4 Loading

The compressive loading which exists in practice shall also be applied to the specimen. A uniformly distributed compressive loading shall be applied to the specimen. The value of the compressive stress at the fire exposed surface of the test specimen shall be equal to the maximum compressive level of the fire exposed surface of the actual tunnel structure under the characteristic load that can occur during a real fire.

Application of the compressive load with the help of an external loading frame is common practice. In the absence of a loading frame, or when the required stress in the specimen is higher than the stress that the loading frame can apply, it is possible to apply the load by means of an internal post-tensioning system. To achieve this, appropriate ducts shall be incorporated in the specimen before the concrete is cast. The anchorage of the prestressing rods or strands shall be carefully designed in order to distribute the load uniformly.

The compressive level on the test specimen shall be equal to the compressive level of the fire exposed surface of the real tunnel. It is allowed to apply eccentric compression to the specimen as long as the compression of the fire exposed surface matches the real tunnel and the eccentricity is not greater than in reality.

If a loading frame is used, the test specimen shall be placed accurately in the frame to ensure a uniform load distribution over the specimen. In the case of horizontal load application, this can be achieved by using plates with the same dimensions as the cross-section of the test specimen. Similarly, if vertical point loads are used, additional load distributors shall be used to ensure a uniform load distribution over the specimen.

In the same way, the exact positioning of post-tensioning ducts is also important when utilizing a post-tensioning system. Especially when external anchor blocks are used, the positions of the ends of the ducts shall be within a tolerance of 5 mm, in order to achieve a constant load on the test specimen and to prevent loss of prestressing due to friction. In Figure 1 the principle behind prestressing of a TBM element is shown.

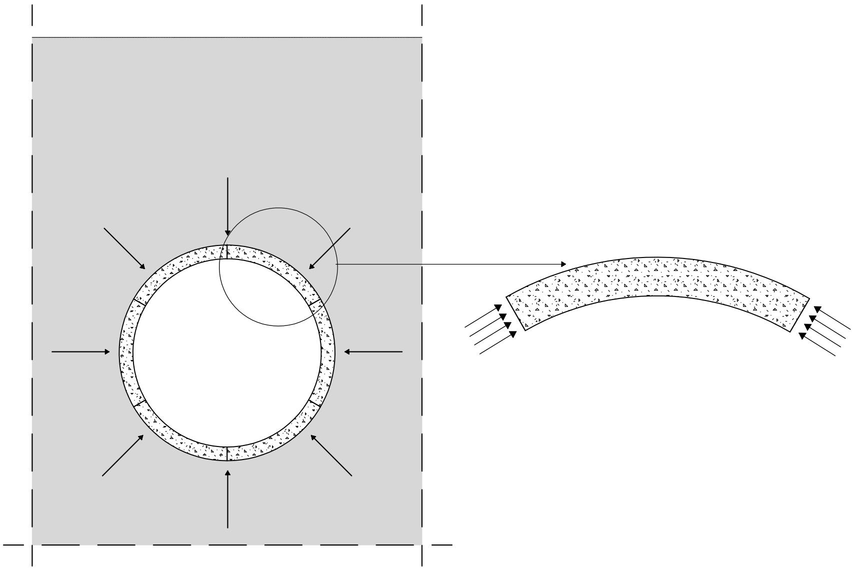

Figure 1 Principle of representing compressive ring forces by prestressing.

4.2.5 Concrete mix

The same concrete mix as is intended to be used in practice shall also be used for the test specimens. This includes aggregate types and particle sizes, cement type and quantity, water-cement ratio, possible micro-fillers, type and dosage of polypropylene fibres, etc., see Table 1. Recording of concrete mix data could be used to ensure that the concrete mix of the specimen is the same as that used in practice.

Table 1 Recommended (non-compulsory) recording of concrete mix data

RECOMMENDED (NON-COMPULSORY) RECORDING OF CONCRETE MIX DATA		
Moment in time	*Component*	*Data*
At casting of concrete	Concrete mix	Sieve analysis of the grain distribution in the mix
		Weight of all the individual components of the concrete mix
	Cement	Brand, type and supplier of the cement used
	Fine aggregate	Type, origin and supplier of the fine aggregate used (extraction site / quarry)
	Coarse aggregate	Type, origin and supplier of the coarse aggregate used (extraction site / quarry)

RECOMMENDED (NON-COMPULSORY) RECORDING OF CONCRETE MIX DATA (CONTINUED)		
Moment in time	*Component*	*Data*
At casting of concrete	Additives (including fibres)	Brand and type of the additives used
	Formwork oil	Brand and type of the formwork oil used
28 days after casting	Concrete mix	Compressive and splitting tensile strength of at least 3 samples per test type
91 days after casting (or day of testing)	Concrete mix	Compressive strength of at least 3 samples

4.2.6 Temperature measurements

All of the thermocouples applied to the test specimen shall have characteristics appropriate to the range of the temperatures to be measured and the required accuracy. Thermocouples of the type chromel-alumel (type K) meet these requirements, but other suitable types may be used as well. In addition, the responsiveness of the thermocouple needs to be taken into account (reaction time to the change in temperature). At least three quarters of the thermocouples shall be working throughout the fire test.

Concrete temperatures

A spalling test aims to establish whether or not spalling occurs. Therefore, in principle, it is not necessary to measure concrete temperatures. Nevertheless, it is highly recommended to measure the temperatures at a number of locations (reinforcement, concrete surface, concrete cover zone, etc.) in order to follow possible spalling progress. This may also be required by the client/authorities, especially if thermal criteria are imposed on top of the criteria concerning spalling.

These thermocouples shall be installed in the formwork (and attached to the reinforcement) before casting of the concrete. The positioning and fixing of the thermocouples shall be done in such a way that this does not influence the measured values, and that the thermocouples do not move during casting of the concrete. A reliable method to measure reinforcement temperatures is to position the thermocouple wire parallel to the rebar and to the fire exposed surface, and to fix it using small cable ties. The length of the part of the thermocouple that is parallel shall be at least 50 mm.

Typically, RWS requires the following amounts and positions of thermocouples:

- Positions of thermocouples in the depth shall be as follows: on the underside of the bottom of the reinforcement and midway between the concrete surface and underside of the reinforcement with a step of maximum 35 mm. Behind the reinforcement, thermocouples shall be positioned in steps of maximum 50 mm until a depth of 200 mm.
- Temperatures at each depth shall be measured at a minimum of 6 locations, uniformly distributed over the surface of the test specimen.

In Figure 2, examples of positions of thermocouples are given.

Concrete surface temperatures

Surface thermocouples are typically installed when a concrete specimen with external fire protection system is being tested. These thermocouples are installed after casting of the concrete. Surface thermocouples shall not be positioned in the direct vicinity (Ø 100 mm) of anchors in order to avoid the anchors influencing the thermocouple measurements.

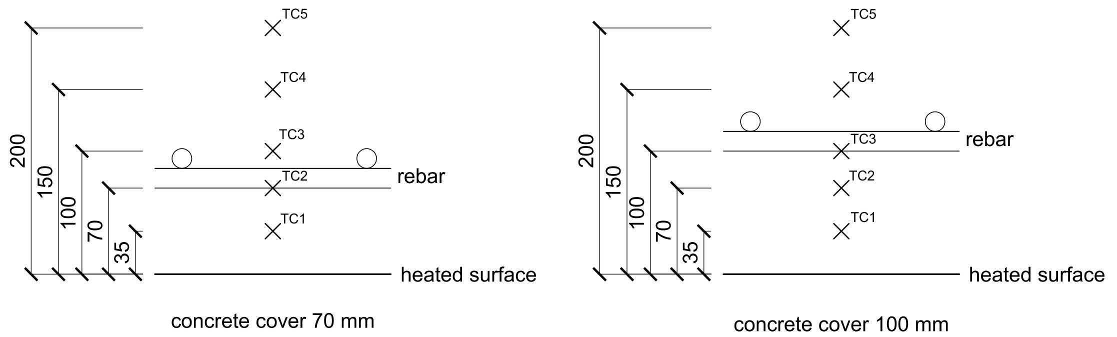

Figure 2 Examples of positions of thermocouples for two concrete covers with different thicknesses.

If a board external fire protection system is being used, the distance between the thermocouple and the unexposed edge board shall be at least 300 mm. The thermocouple shall be installed just below the concrete surface and the measuring tip shall remain in direct contact with the concrete, i.e. it may not protrude from the concrete.

Typically, RWS requires the following amounts and positions of thermocouples:

- At least 12 thermocouples shall be installed on the concrete surface (i.e. depth of 0 mm) once the concrete is cast and hardened in order to ensure correct location of the measuring point. The thermocouples shall be uniformly distributed over the surface of the test specimen (not behind edge boards). In the case of a board protection system with joints, one third of the total number of thermocouples (e.g. 3 thermocouples out of a total of 12) shall be positioned behind a longitudinal joint. Moreover, joints representative of the actual fire protection system shall be present. If a T-joint or X-joint is used in practice, the same type of joint shall be part of the test specimen. Additional thermocouples shall be placed behind T-joints and X-joints. For each type of joint, at least two thermocouples shall be installed, see Figure 3.
- If the fire protection system also involves an air void (e.g. suspended ceiling or a system with backing strips), 3 additional thermocouples shall be applied to measure the air temperature in the void.
- For spray applied systems at least three quarters of the thermocouples shall be working throughout the fire test. For board systems three quarters of the thermocouples behind joints and three quarters of the thermocouples behind the fire exposed boards shall be working throughout the fire test. Two thirds of the thermocouples in air voids, and half of the thermocouples behind T-joints or X-joints, shall be working throughout the fire test.

In Figure 3 and Figure 4 typical positions of thermocouples are given.

4.3 FIRE PROTECTION SYSTEM

If it is intended to apply an external fire protection system in the practical situation, this system shall be part of the test specimen. This paragraph describes how the fire protection system shall be applied to the concrete test specimen in order to be representative for the practical situation.

A number of external fire protection systems are available:

- spray mortar;
- coating;
- pre-cast mortar (protection material poured into the formwork before casting of the concrete);
- post-fixed board;
- pre-fixed board (fire protection material applied in the formwork before casting of the concrete); and
- systems that combine fire resistance with other functions (e.g. fire resistant linings that also serve as a leakage water drip shield, acoustic lining, etc.).

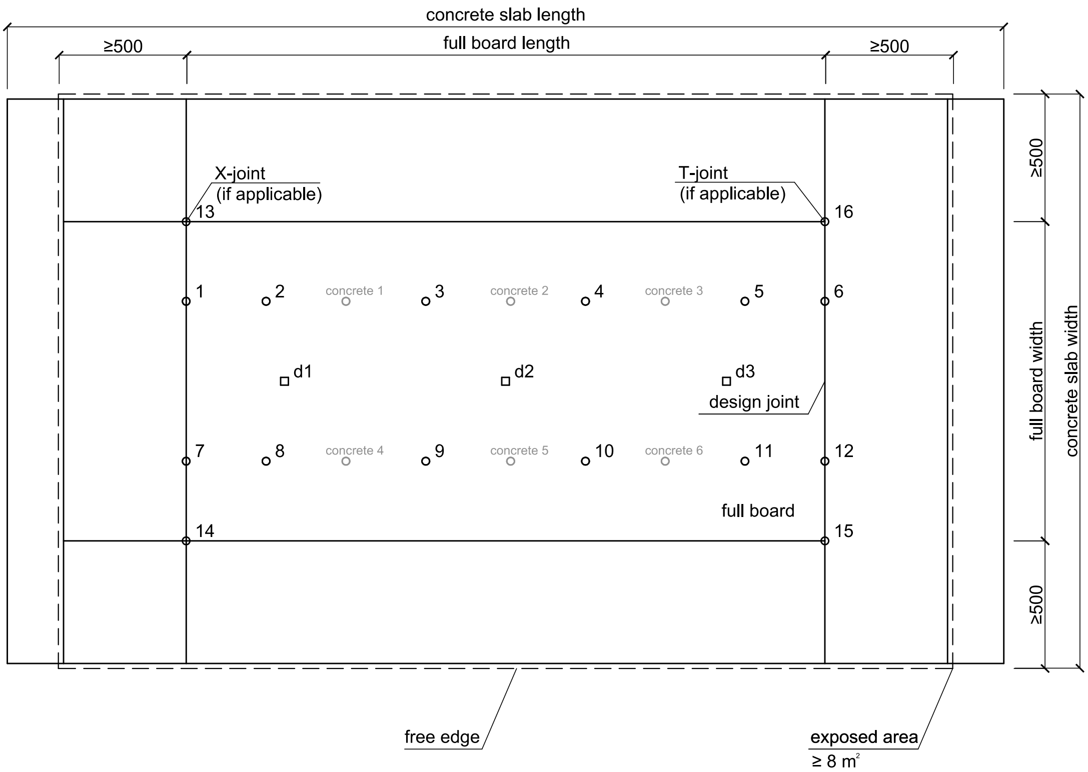

Figure 3 Test specimen with a board system. Thermocouples 1, 2 etc. denote concrete surface thermocouples. Concrete 1, 2 etc. denote concrete thermocouples (i.e. thermocouples cast in the concrete). d1, d2 & d3 denote locations at which the deformation of the test specimen is measured (see 4.5.1).

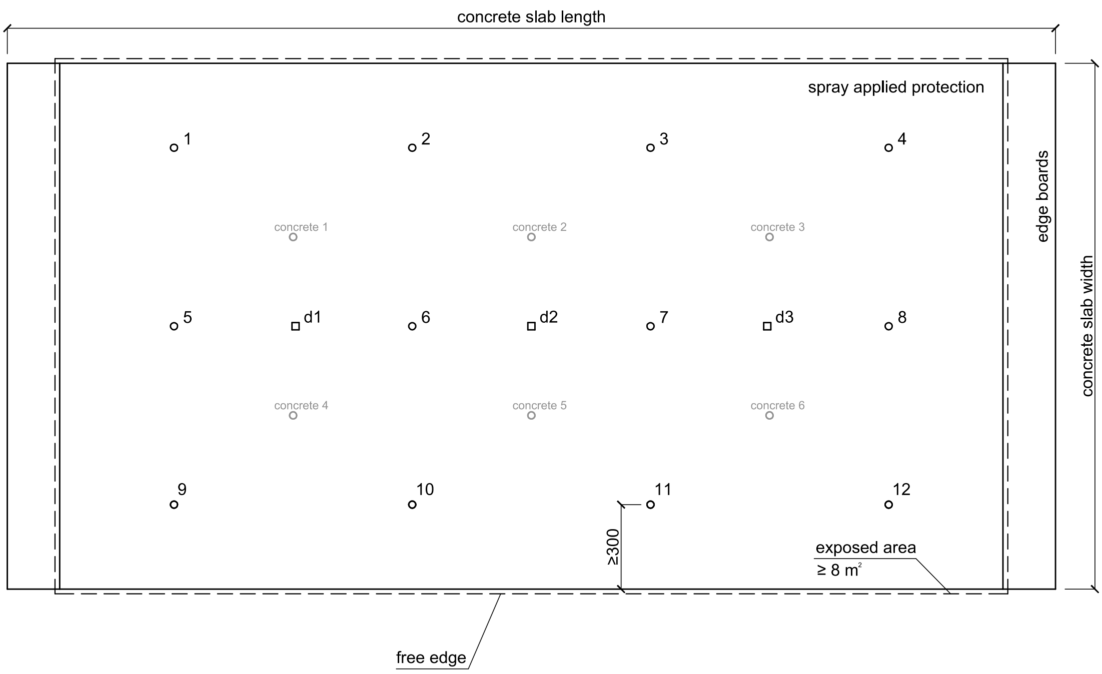

Figure 4 Test specimen with a spray applied system. Thermocouples 1, 2 etc. denote concrete surface thermocouples. Concrete 1, 2 etc. denote concrete thermocouples (i.e. thermocouples cast in the concrete). d1, d2 & d3 denote locations at which the deformation of the test specimen is measured (see 4.5.1).

With respect to the fire protection system the supplier shall provide to the test laboratory - on a confidential basis - at least the following information:

- the nature of the different components of the material;
- expected density of the materials (in kg/m^3);
- the official name of the fire protection system and its components;
- expected equilibrium moisture content;
- maximum allowable joint width (if applicable);
- description of the fixing system (if applicable);
- expected drying/curing time; and
- material safety data sheet.

The exposed-to-fire area of the test specimen shall be at least 8 m^2. In situ test specimens, such as TBM-elements, shall be tested at full size. These test specimens may have dimensions smaller than 8 m^2.

4.3.1 Board protection system

The board protection system shall include at least one full size board in order to evaluate reliably possible shrinkage and deformation of the board.

The fire protection system of the test specimen shall fully correspond to the system in practice, including fixing system (type, amount and spacing of anchors) and type of joints (butt joint, rebate joint or joint with backing strip or any other joint types, see Figure 5). The manufacturer of the protection system, or the authorities, shall determine the maximum allowed joint width that shall be incorporated in the test specimen. The maximum allowable joint width shall be used for every joint of the fire protection system. The actual joint width of the system applied on the test specimen shall be measured and reported.

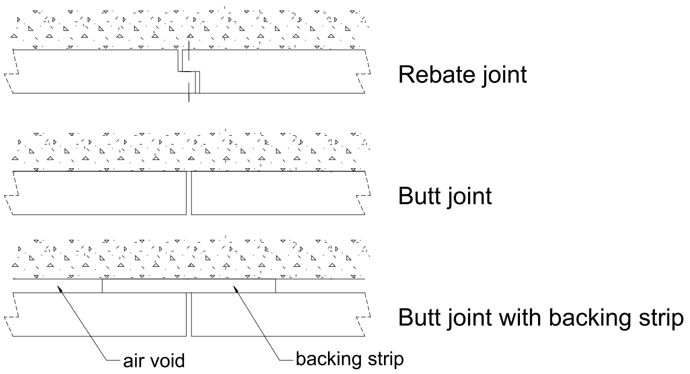

Figure 5 Joint types

The full board shall be surrounded by edge boards with a width of at least 500 mm. A butt joint shall be realised along the perimeter of the exposed area so that the exposed-to-fire protection system can fall down during heating, i.e. to avoid additional support due to furnace walls (at the supported sides, see Section 4.5.1. Typically, a test specimen shall have two supported sides and two free sides). A typical setup is given Figure 3.

In situ test specimens, such as TBM-elements, may have dimensions smaller than the size of the fire protection boards that will be installed in the actual tunnel. In that case, edge boards may not be feasible and may be omitted. In situ test specimens shall still be supported at two sides only and have two free edges.

4.3.2 Spray applied fire protection systems

When it is expected that the position of the concrete slab in the real tunnel affects the way the fire protection system is applied to the concrete, the position of the concrete slab shall be representative for that situation. Application to the ceiling is usually the most difficult, so in the laboratory the slab shall be positioned horizontally with the surface to be protected at the underside. The protection shall be applied by overhead spraying, see Figure 6.

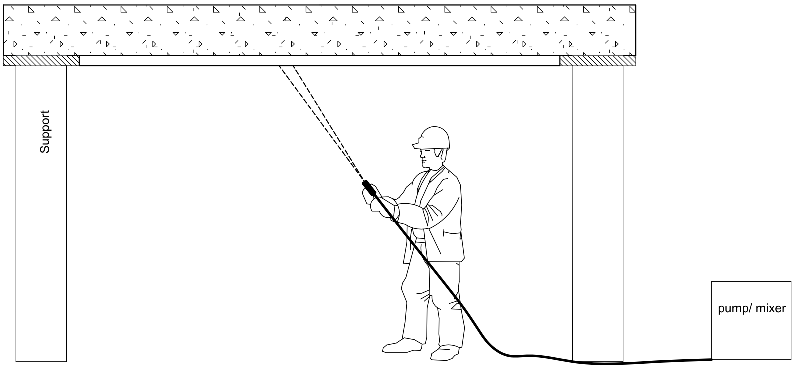

Figure 6 Overhead spraying of spray mortar or coating

The fire protection material shall be applied only over the directly exposed-to-fire area in order to avoid additional support of the material by the furnace. The remainder of the underside of the concrete slab shall be protected by fire protection boards of the same thickness as the main fire protection system. In this way, the main fire protection system is not additionally supported by the furnace.

Typically, test specimens shall be supported at two sides and have two free edges (see Section 4.5.1). Therefore, it is necessary to apply the fire protection also to the sides of the specimen, to avoid heating of the sides of the specimen due to leakage of hot air. A typical setup is given in Figure 4.

4.3.3 Requirements for the reinforcement and fixing systems for fire protection materials

All fire protection materials shall be applied to the concrete in such a way that the protection material, when used in practice, remains secured to the tunnel structure during tunnel operation and during a fire. The fixing system (direct bonding, anchors, wire mesh, etc.) is the client's choice. The system that will be applied in the tunnel shall correspond to the system that is subjected to the fire test.

The bonding of spray mortars/coatings to the surface is strongly influenced by the surface treatment of the concrete before spraying. If the concrete surface is roughened e.g. by high pressure water jet washing, the test result is only valid for tunnel situations in which the concrete is treated according to the same procedure.

If a wire mesh is used to fix a spray mortar to the concrete, the same type of wire mesh (mesh size, diameter, shape, material, fixings incl. centre-to-centre distance, etc.) shall be applied in the test specimen as in practice.

If anchors are used to fix the material (board, or the wire mesh for spray mortar) to the concrete, the fixing pattern shall resemble the real tunnel situation as closely as possible:

- the same number of anchors per square metre;
- the same centre-to-centre distance between two anchors; and
- the same distance between anchor and board joint (boards only).

4.3.4 Thickness of fire protection materials

The thickness of the fire protection material shall be measured as follows:

- *Sprayed material and pre-cast mortar (in wet condition):*
  On the test slab/lining element: measurement in a grid of maximum 300 mm x 300 mm, and a minimum total of 25 measurement points, with measurement points including the thermocouple locations.

- *Board materials:*
  Before application of the fire protection on the test slab/lining element, measurements shall be taken at least at 10 locations.

The thickness presented in the report will take the form of a table in which the measurements include the mean thickness, as well as the minimum and maximum values and a standard deviation based on a normal distribution. Equation 1 is used to calculate the 95 % characteristic thickness, where the value of t can be found in Table 2.

Equation 1:

$$d_{95\,\%} = \bar{d} + t \cdot \sigma$$

where:

$d_{95\,\%}$ is the 95 % characteristic thickness
$\bar{d}$ is the average measured thickness
σ is the standard deviation

Table 2 t-values for a 95% characteristic value based on the Student's t-distribution

Number of measurements	*t*
≥ 25	1.708
≥ 40	1.684
≥ 60	1.671
≥ 100	1.660

When applying a system such as spray mortar a few small markers may be applied to indicate the correct layer thickness. Such markers shall be plastic or wood, because a steel marker might in fact anchor the spray mortar to the surface (a situation that is not deemed to be conservative).

4.3.5 Steel fixings

The fixing system that will be used for fixing fire protection materials to the particular tunnel concrete structure shall also be used for the test specimen. In the case of a board protection system, such a fixing system typically consists of a stainless steel fixing.

Additionally, a different type or size of steel fixing is present in most tunnels for installations of jet fans, traffic lights, etc. If such a steel fixing penetrates the fire protection system, the heat is easily conducted into the concrete. Also, if concrete with polypropylene fibres is used, the steel fixing will conduct the heat deeper into the concrete.

Little conclusive information is available as to the appropriate configuration of such fixings, but any fixing with a diameter of more than 8 mm is suspected to negatively influence the spalling behaviour. Such configurations shall be made part of the spalling test in order to evaluate whether they have any influence on spalling. In order to simulate the stresses in the concrete around the steel fixing, it is recommended to apply a load to the fixing which represents the load which will be applied in practice. Thermocouples may be applied to or around the steel fixing in order to obtain an indication of the temperature development near the fixing.

4.4 CONDITIONING AND MATERIAL PROPERTIES

4.4.1 Drying time of the test specimen

Test specimens shall be sealed in a plastic wrap after casting. The plastic wrap shall be removed after 28 days. Frost and direct sunlight shall be avoided. The application of the spray mortar may commence at a concrete age of at least 28 days.

The fire test shall not take place before both the concrete and the fire protection material have reached the following conditions:

- The concrete specimen shall be at least 91 days of age in order to achieve a sufficiently mature micro-structure[4]; and
- Average moisture content of fire protection materials shall be representative of the moisture content in practice, and equilibrium moisture content, under representative ambient conditions[5], shall have been reached by the day of the fire test.

For a test on a concrete specimen protected by post-fixed or pre-fixed boards, or sprayed materials, it is allowed to speed up the process of drying of the fire protection material by artificial means (slightly increased temperature, low relative humidity). However, special attention shall be paid to the concrete slab, because a dry slab will be less prone to spalling and therefore does not represent a conservative case.

The heating shall remain below a certain level so that it is not detrimental to the fire protection material (e.g. max. 40 °C). Moreover, for spray mortars, it is required to wait at least 28 days after spraying before accelerated drying is started, because the strength of the mortar, and the bond strength of the mortar to the concrete, need to be fully developed first. Also, the accelerated drying may not be prolonged for more than 28 days.

In Table 3 the time schedule of manufacturing and treating the concrete specimen is given.

Table 3 Time schedule of manufacturing and treating the concrete specimen

	Time [days]	Activity
t_0	-	Casting of the concrete specimen and covering by a plastic wrap
t_1	$t_0 < t_1 < t_2$	Demoulding, wrapping the specimen in plastic wrap
t_2	$t_2 \geq t_0 + 28$	Removal of plastic wrap and application of fire protection (spray mortar), if applicable
t_3	$t_3 \geq t_1 + 28$	Initiation of accelerated drying of spray mortar (max. 40 ºC unless it can be shown that a higher temperature is applicable)
t_4	$t_4 \leq t_3 + 28$	End of accelerated drying
t_5	probably $t_5 \geq t_2 + 60$	Fire protection has reached an equilibrium moisture content
t_6	$t_6 \geq t_0 + 91$ and $t_6 \geq t_5$	Fire test

Note: Frost and direct sunlight on the specimens shall be avoided

It is important to execute the tests with a moisture content which represents the actual situation during the operation of the tunnel. Therefore, the fire protection material may not be too wet,

[4] Spalling is strongly dependent on the microstructure of the concrete. The generally accepted age of 28 days for determination of e.g. the compressive strength is insufficient for a spalling test. After 28 days, hydration of the cement will still continue and the microstructure of the concrete will change. The effect of ageing on the microstructure of the concrete is strongly dependent on the mix (cement type, micro-fillers, etc.). Due to lack of detailed information on the influence of concrete ageing on spalling, a value of 91 days is recommended as a minimum age for concrete specimens to be used in a spalling test.

[5] The moisture content of the fire protection material has a major influence on its thermal insulation. Therefore the moisture content of the fire protection material applied on the test specimen should be less than or equal to the moisture content in the tunnel.

because this has the effect of slowing down the temperature rise in the fire protection material and, more importantly, also in the concrete.

For some fire protection systems high moisture contents may prove to be detrimental to the structural integrity of the system during fire exposure. Therefore, it is recommended to perform fire tests on such fire protection systems either at a moisture content at which problems with the structural integrity of the system can be expected, or at fully saturated conditions. For the fully saturated case, the fire test shall be commenced within 24 hours after reaching the saturation.

4.4.2 Monitoring of moisture content (protection material)

Each fire test specimen shall be accompanied by two samples of the fire protection material from the same batch as is used for protecting the main test specimens. These samples are needed to monitor the moisture content of the fire protection material in order to determine whether the equilibrium moisture content[6] is reached. They shall be stored together with the main test specimens.

Spray mortar and coating

The fire protection material shall be applied in a metal tray (A ≥ 200 cm^2) in a horizontal position and in the same direction as the test slab/lining element, and to the same thickness. See Figure 7. The tray shall be weighed before and directly after the application of the fire protection material. The tray shall be stored together with the test specimen. The tray shall be weighed at regular intervals, to monitor the decreasing moisture content of the fire protection material.

Figure 7 Steel tray with spray mortar

Boards

The board samples shall have dimensions of at least 300 mm x 300 mm and their thickness shall be the same as the thickness of the boards applied on the main test specimens. The samples shall be weighed at regular intervals, to monitor the decreasing moisture content of the fire protection material.

4.4.3 Final determination of moisture content (fire protection material and concrete)

The following samples are needed for the final determination of the moisture content and density of the fire protection material, and of the moisture content of the concrete:

- For post-fixed boards, the samples shall consist of 2 pieces of board from the same batch as is used for protecting the specimen. The piece of board shall be at least 300 mm x 300 mm and the thickness shall be the same as the thickness of the boards applied on the main test specimen.
- For post-applied spray mortars, the sample consists of a small concrete tile (measuring at least 300 mm x 300 mm x 60 mm) protected with the mortar of the same thickness as that on the main test specimen. The slab shall be protected by spray mortar in the same way as the fire test specimen, but without wire mesh reinforcement. The vertical sides and bottom of the tile and of the spray mortar shall be prevented from drying, e.g. by leaving a formwork around it.
- For pre-fixed materials, the sample consists of a small concrete tile (measuring at least 300 mm x 300 mm x 60 mm) protected with a fire protection material of the same thickness as that on the main test specimen. The small slab shall be produced by casting the concrete on top of the pre-applied material. The vertical sides of the sample shall be prevented from drying, e.g. by leaving a formwork around it. See Figure 8.
- For concrete, two samples of at least 75 mm x 75 mm x 150 mm shall be made with each concrete specimen, using the same concrete mix composition as the main concrete

[6] Equilibrium moisture content is considered to be reached when two successive weighings at 24 hour intervals differ by less than 0.1%.

specimen. These samples shall be exposed to the same conditions as the test specimens at all times.

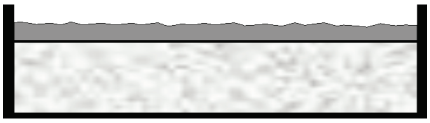

Figure 8 Concrete sample in its formwork, with spray mortar applied to the top surface

The samples shall be weighed, then dried in an oven for 24 hours and be weighed again. This shall be repeated until the difference between two successive weighings is less than 0.1 %. The temperature in the oven shall be (50 ± 5)°C[7] or (105 ± 5)°C depending on the temperature needed to maintain the chemically bound water within the tunnel lining or fire protection material.

The average moisture content shall be calculated as follows:

Equation 2:

$$\text{Moisture content in \% mass by mass} = \frac{M_w - M_d}{M_d} \cdot 100\ \%$$

where:

M_w is the mass of the moisture sample before drying
M_d is the mass of the moisture sample after drying

4.4.4 Additional samples related to the concrete

In order to determine the density, and compressive and splitting tensile strength of the concrete, twelve test cubes (each 150 mm x 150 mm x 150 mm) shall be cast together with the main test specimens. The compressive and splitting tensile strength is determined according to applicable standards (such as EN 206). The following shall be determined:

- the density of the concrete 28 days after casting;
- the 28 day compressive and splitting tensile strength (on 3 cubes for each test); and
- the 91 day, or day of fire test, compressive strength (on 3 cubes).

The test cubes for the 28 day compressive and splitting tensile strength tests are prepared according to the requirements in the applicable standard (i.e. kept under water at 20 °C for 28 days). The specimens for the 91 day, or day of testing, compressive strength tests shall be exposed to the same conditions as the fire test specimens.

4.5 FIRE TEST

4.5.1 Positioning and orientation of test specimen

The specimen shall be placed on the furnace in the same orientation as the position of the structural element it represents.

- A horizontal test result (exposed side down) is valid for both horizontal and vertical applications[8].
- A vertical test result is only valid for a vertical application.

Examples of tests and the structures for which they are considered representative are given in Figure 9, Figure 10 and Figure 11.

[7] Applicable for gypsum-based materials only.

[8] This is important because gravity may influence the spalling process. It is conservative to test horizontally with the exposed side down, because in that case gravity will pull loose pieces of concrete away from the specimen.

Test specimens shall be supported at two sides, with two free sides, during fire testing. Loading (if applicable) shall be applied at the supported sides. If two-sided supporting is considered to be too conservative for the application at hand the test specimen may be supported at four sides.

At three locations, the deformation shall be measured perpendicular to the surface of the test specimen. The measuring points shall be at the centreline of the test specimen and evenly distributed on the heated area.

Note: loading conditions during the test are specified in Section 4.2.4.

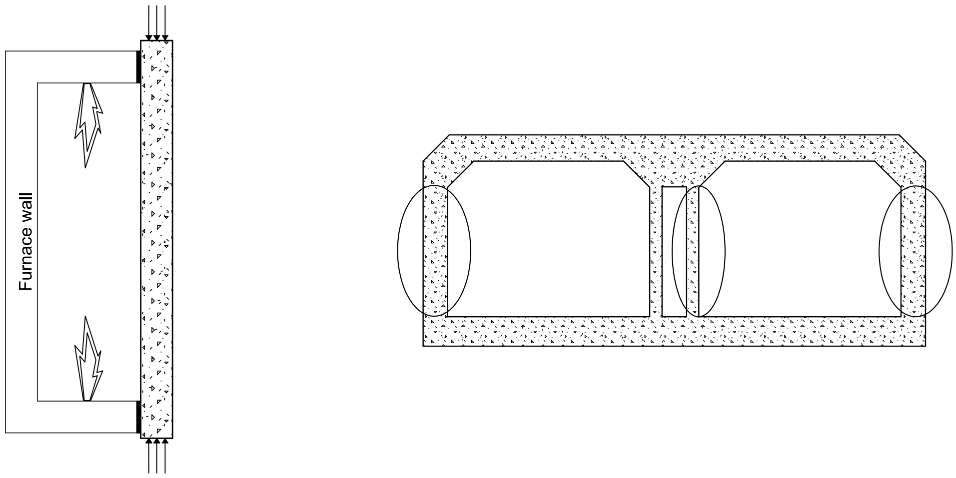

Figure 9 Vertical test, representing the tunnel walls.

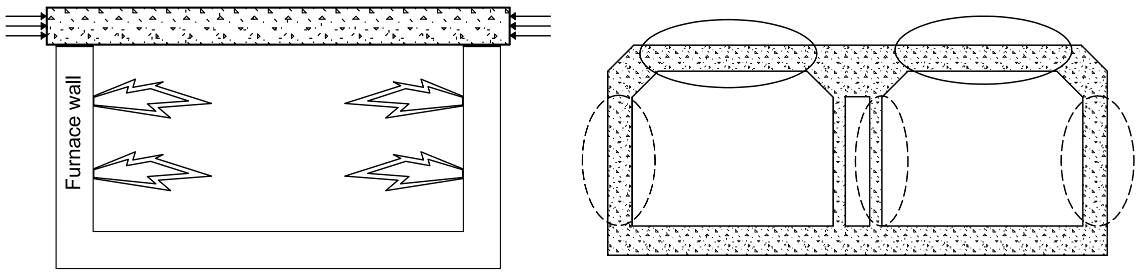

Figure 10 Horizontal test, representing a tunnel ceiling but the results are also valid for vertical applications.

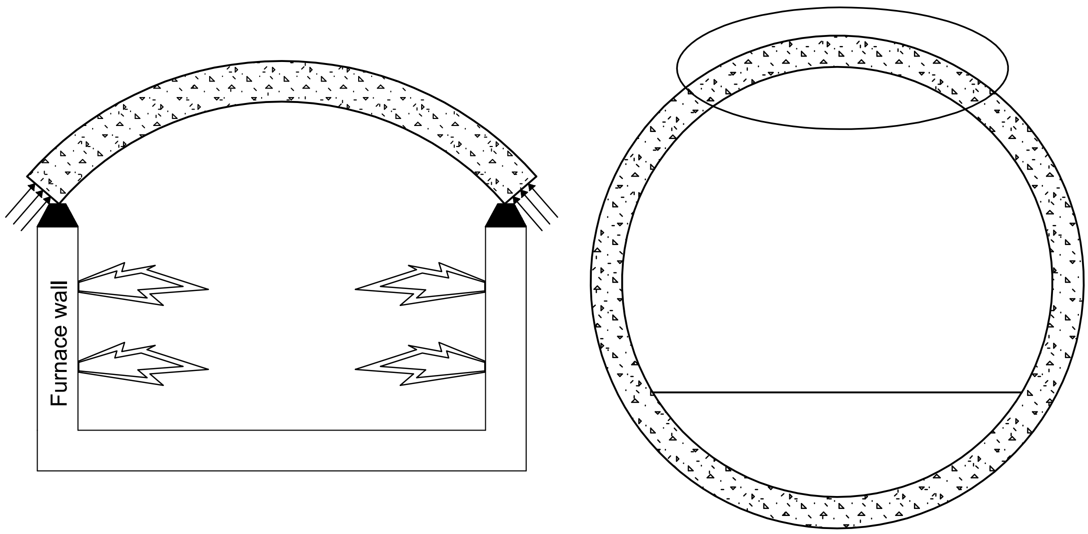

Figure 11 Test on a curved tunnel segment, representing all tunnel elements of the ring.

4.5.2 Furnace camera

It is strongly recommended to use at least one camera inside the furnace to film the exposed surface during a fire test. Recordings help to improve the identification and understanding of possible spalling and tunnel lining behaviour. Screenshots of the recordings can add valuable information to the report. The full recording may be securely stored at the test institute if needed for future investigation and comparison.

4.5.3 Pressure conditions

The specified pressure conditions in the furnace shall follow the principles given in EN 1363-1. The pressure conditions in the furnace shall be as follows.

- *Monitoring and control*:
  The furnace pressure shall be monitored and controlled. From 10 min after the commencement of the test, the furnace pressure shall be ± 20 Pa of the nominal pressure specified for the test for this particular specimen.

- *Monitoring position*:
  The pressure distribution over the height of a furnace is mainly influenced by the natural buoyancy effect of the gases. For the purpose of controlling the pressure, it can be assumed that the pressure gradient in the furnace will be approximately 9.6 Pa per metre height of the furnace[9].

- *Horizontal elements*:
  The furnace shall be operated such that the pressure on the underside of the test specimen equals a nominal pressure of 50 Pa[10] within the specified time and accuracy. The pressure condition shall be established 100 mm below the underside of the test specimen.

- *Vertical elements*:
  Unless specified otherwise in specific test standards, the furnace shall be operated so that the neutral pressure plane (a pressure of zero) is established at notional floor level. Where a pressure greater than 50 Pa is expected at the top of a vertical test specimen, the nominal pressure of the furnace shall not exceed 50 Pa. This requirement may result in an adjustment of the height of the neutral pressure plane.

4.6 FIRE CURVE

4.6.1 Heating phase

The heating of the furnace shall be according to the prescribed temperature/time curve of Table 4 and Figure 12. The prescribed temperature/time curve is referred to as the RWS fire curve in this document.

RWS has specified its requirements for road tunnels and other subsurface road structures[11] in which the fire duration and the temperature/time curve depend on the type of the tunnel. For underwater tunnels, an exposure according to the prescribed temperature/time curve for 120 minutes is required. The temperature/time curve was defined in the Netherlands and represents a pool fire due to a fuel leak from a 50 m^3 tanker that has been involved in a collision. The burning pool area is 150 m^2. However, it has been demonstrated that the high temperatures of the RWS curve can also be reached in a tunnel environment during a fire of a heavy goods vehicle with a solid cargo.

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[9] Note: in EN 1363-1 a lower pressure of 8.5 Pa per meter height is specified, but because of the higher temperatures of the RWS fire curve a vertical pressure gradient of 9.6 Pa per meter height is more appropriate.
[10] Note: the nominal pressure of 20 Pa in EN 1363-1 is replaced by a nominal pressure of 50 Pa.
[11] See the Dutch document “Richtlijn Ontwerp Kunstwerken (ROK) 1.4” (Guidelines Design Infrastructure Works 1.4). ROK 1.4 will be replaced by ROK 2.0 shortly.

Table 4 RWS fire curve

Time [min]	Temperature [°C]
0	20
3	890
5	1140
10	1200
30	1300
60	1350
90	1300
120	1200
>120	1200
Cooling down phase	See 4.6.2

Depending on the situation, authorities can prescribe another fire curve (such as HC, HCM, RABT or another recognized fire curve) and they may also add a prescribed cooling down phase if they expect significant temperature penetration or other physical effects during the cooling down phase. See Section 4.6.2.

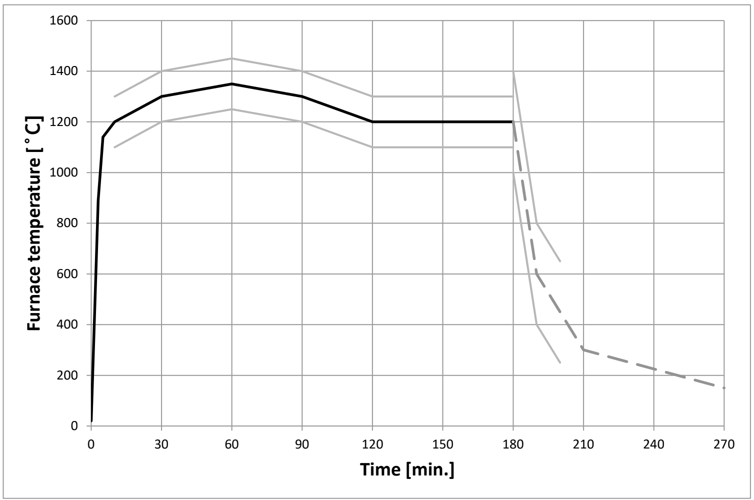


Figure 12 RWS fire curve (black solid line). In dashed grey: cooling down phase. In solid grey: tolerance lines.

The gas temperatures in the furnace shall be measured with mineral insulated sheathed thermocouples with a suitable temperature range and response. Furnace thermocouples shall be placed approximately 200 mm from the exposed surface of the test specimen. The number of furnace thermocouples shall be between ½ and 1 times the exposed surface area of the specimen in square meters. At least 75 % of them shall be working throughout the fire test.

The percentage deviation, d_c, of the area under the average temperature/time curve recorded by the specified furnace thermocouples, from the area under the prescribed temperature/time curve shall be within:

$d_c \leq 15$ %	for $5 < t \leq 10$
$d_c \leq 15 - 0.5 \cdot (t - 10))$ %	for $10 < t \leq 30$
$d_c \leq (5 - 0.083 \cdot (t - 30))$ %	for $30 < t \leq 60$
$d_c \leq 2.5$ %	for $t > 60$

where:

Equation 3:

$$d_c = \frac{A - A_s}{A_s} \cdot 100\ \%$$

in which:

d_c is the percentage deviation
A is the area under the actual furnace temperature/time curve in °C
A_s is the area under the prescribed temperature/time curve in °C
t is the time in minutes

The above requirements for the percentage deviation, d_c, are only applicable to the part of the fire curve that corresponds to actual heating (i.e. not for the cooling phase).

All areas shall be computed by the same method, i.e. by the summation of areas at intervals not exceeding 10 seconds and they shall be calculated from time zero.

At any time after the first 10 minutes of the test, the temperature recorded by any thermocouple in the furnace shall not differ from the corresponding temperature of the prescribed temperature/time curve by more than 100 °C. During the cooling down phase, this tolerance is 200 °C and is only required for temperatures down to 450 °C.

If spalling of concrete occurs, the temperatures in the furnace will be reduced due to the ongoing exposure of new, cold, concrete surfaces. In that case, it cannot be guaranteed that the furnace temperature remains within the tolerances.

All measurements (furnace/test specimen temperatures, pressures, etc.) shall be continuously measured and recorded during fire testing. The measurement interval shall be less than or equal to 10 s.

4.6.2 Cooling down phase

Depending on the situation, authorities may add a prescribed cooling down phase if they expect significant temperature penetration or other physical effects during the cooling down phase. A temperature/time curve representing expected thermal conditions in real tunnel fires is given in Table 5. The cooling down curve starts immediately after the end of the main fire curve.

Table 5 Cooling down curve

Time after start cooling down phase [min]	Temperature [ºC]
0	1200
10	600
30	300
60	225
90	150

4.7 PERFORMANCE CRITERIA

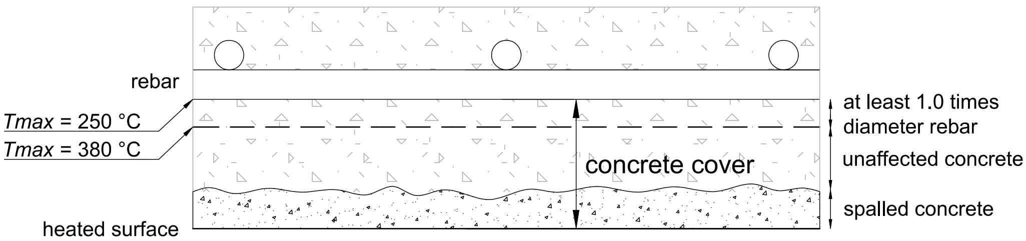
The objective of this document is to provide a uniform fire testing procedure for concrete tunnel elements. The actual required performance in such tests is a decision made by the client/authorities. In general, performance requirements could include:

- maximum values for the concrete surface temperature;
- maximum values for the steel reinforcement temperature (to be measured on the side of the steel bar which is closest to the fire exposed concrete surface);
- maximum values for the temperature at another depth in the concrete structure; and
- maximum allowable spalling depth, or simply "no spalling".

In Table 6 recommended (non-compulsory) performance criteria are given.

Table 6 Recommended (non-compulsory) performance criteria

RECOMMENDED (NON-COMPULSARY) PERFORMANCE CRITERIA
Criteria for bare concrete



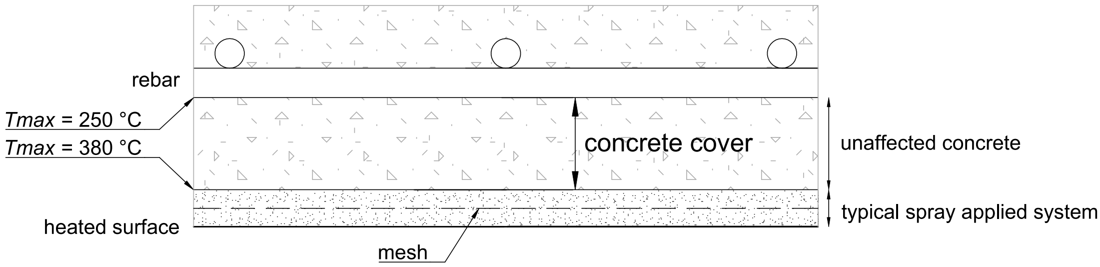
For bare concrete under compression in a tunnel of major importance, the requirements are

- T_{max} < 250 °C for steel reinforcement bearing internal forces of the construction. If steel reinforcement consists of prestressing steel the following requirements are applicable:
  - T_{max} < 150 °C for cold worked (cw) prestressing steel;
  - T_{max} < 75 °C for quenched and tempered (q & t) prestressing steel.
- T_{max} < 380 °C at a distance of 1.0 times the diameter of the first rebar;
- Spalling depth is less than 35 mm for 95 % of the heated area (edge effects not taken into account).

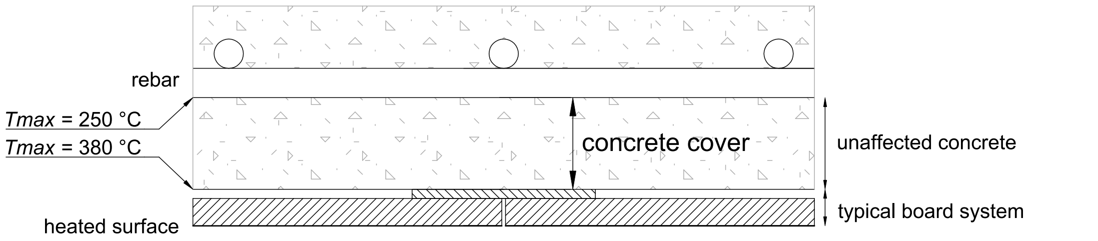
RECOMMENDED (NON-COMPULSARY) PERFORMANCE CRITERIA (CONTINUED)

Criteria for concrete with a fire protection system

Spray applied system



Board system



For concrete under compression with a fire protection system in a tunnel of major importance, the requirements are:

- T_{max} < 250 °C for steel reinforcement bearing internal forces of the construction. If steel reinforcement consists of prestressing steel the following requirements are applicable:
  - T_{max} < 150 °C for cold worked (cw) prestressing steel;
  - T_{max} < 75 °C for quenched and tempered (q & t) prestressing steel.
- T_{max} < 380 °C at the concrete surface;
- Spalling of concrete is not allowed.

In order to have a valid test result, tests shall be performed at least twice on identical, large scale (preferably 1:1) specimens, with identical concrete composition, fire protection system, thickness, loading and heating conditions, etc. Cherry picking from a large set of test results is not allowed. If a test is unsuccessful, changes to the test specimen (either the concrete test element and/or fire protection system) shall be made in order to increase the fire resistance performance. If a test does not fulfil the requirements set out in this document with respect to the test conditions, the result of the test does not have to be taken into account.

The maximum concrete surface temperature is applicable at the joints (for longitudinal joints, X-joints and T-joints, etc.)

For each of the requirements it is advisable to specify the number of measurement points and the handling of scatter in results. For temperature measurements, this means that the number of thermocouples at a certain depth should be prescribed, along with a statistical approach, e.g. to use a 95% characteristic value of all measured temperatures, at a given time.

If a board system with backing strips is used, the measured temperatures behind backing strip and full board deviate considerably. Temperatures behind backing strips are much lower than temperatures behind full boards. Therefore, the measurements, and associated calculations, for backing strip and full board shall be treated separately.

For measurement of the spalling depth, the intermediate distances of the measurement grid shall be specified (e.g. a grid of max. 25 cm x 25 cm) along with a statistical approach e.g. to use a 95% characteristic value of all measured spalling depths.

The spalling depths at the outer 400 mm of the sides of the slab specimen (heated area) shall not be taken into account because of edge effects.

4.8 REPORT

The test report shall contain at least the following information:

a) the name of the tunnel project for which the test specimens are representative;
b) the name and address of the sponsor of the test(s);
c) the reference number of the test(s), and date of the test(s). If a series of tests is being carried out, the reference number shall indicate the position of the test in the series;
d) the name of the manufacturer of the fire protection system and the trade name of the product (or components) together with identification marks, as well as a global description of the composition (and in case of board protection system: actual joint width between the boards);
e) construction details of the test slabs, i.e. a description, drawings and the exact position of the thermocouples, as well as a statement concerning the fire laboratory involvement in the manufacturing of the test slabs;
f) the method of applying and fixing the fire protection system on the concrete slab(s), including materials used (fixing system);
g) details and dates with respect to the manufacturing and conditioning of the test slabs and test samples;
h) the details concerning concrete mix as required in Section 4.2.5;
i) the measured compressive and tensile strength, densities and moisture content of the concrete;
j) the measured thickness, densities and moisture content of the protection material;
k) the measured temperatures in the furnace;
l) the measured concrete temperatures;
m) the measured concrete surface temperatures (if applicable). For board systems the temperatures shall be split according to their locations (i.e. behind full board, behind a joint, etc.);
n) the measured deformation;
o) the measured spalling depths;
p) the applied compression to the test specimen during the fire test;
q) the conclusion with respect to the performance criteria;
r) for sprayed materials, the report shall also include or refer to the supplier's/manufacturer's directions for application and the conditions for application in practice (such as spraying equipment and spraying distance) to guarantee the quality of the material; and
s) a description of observations with regard to the nature of the spalling process (time of occurrence, noises, visible effects, etc.).

Besides providing a test report, the fire laboratory may deliver a video recorded inside the furnace if a furnace camera has been used. Such a video can provide a useful understanding of the actual structural behaviour during a fire.

5. THERMAL INSULATION TEST

5.1 INTRODUCTION

The thermal insulation of an external fire protection system can be determined by performing a thermal insulation test on a concrete slab that is fitted with a fire protection system at the fire exposed side. This type of test is not necessarily linked to a specific tunnel project. The test results can be used for any concrete with comparable thermal properties.

The thermal insulation test aims to:
- assess the suitability of the fire protection material to withstand the temperature during a fire according to a prescribed temperature/time curve (e.g. the RWS fire curve);
- assess if the fire protection system remains properly fixed to the concrete during heating (evaluation of structural integrity of the system and its fixings); and
- assess the required thickness of the fire protection material in relation to the stated temperature requirements.

The test result does not provide any answers with regard to spalling of concrete, because the concrete specimen is simplified to a simply supported slab, without taking into account all other conditions (geometry, loading, conditioning, mixture, etc.) that can influence spalling. If the test aims to demonstrate spalling behaviour, spalling tests according to Chapter 4 shall be done.

The composition of the concrete mix shall be optimised in order to avoid spalling, because spalling of concrete is not the objective of this test. Therefore, the moisture content shall be low.
The subject of the test is the fire protection system including application procedure, curing conditions, fixing system, joints, and a low (or a representative) moisture content.

It is recognised that a passive fire protection system comprises the application, the material, the fixing system, etc. Moreover, some materials shrink or expand when heated, which may result in unwanted heating of concrete through cracks or joints. The size of the protection element (e.g. boards), as well as the deformation of the concrete structure, plays an important role in the formation of gaps at joints during heating. Therefore, the test specimens shall have a representative scale to investigate the behaviour of the complete system. In general, the larger the test specimen, the more reliable and more representative the test results.

Two scales of thermal insulation tests are defined, namely:
1. Medium scale thermal insulation test.
2. Large scale thermal insulation test.

The medium scale test has a relatively small exposed-to-fire area (≥ 1.15 m x 1.15 m) and therefore the results of this type of test provide only an indicative answer to the question whether the tested thickness provides sufficient thermal insulation. The medium scale test can provide a good indication in, for example, the research and development phase of a new fire protection system.

However, in order to evaluate reliably the whole fire protection system, a large scale test shall be performed. Also, if other parameters need to be assessed, such as “stickability” (i.e. whether the protection system remains attached to the concrete structure), integrity of the fire protection layer and influence of heat leakage through any joints of the protection system, a large scale thermal insulation test shall be conducted. During the large scale test, the test specimen is exposed to fire over an area of at least 8 m^2 and the protection system shall be fixed to the concrete slab using the same method as that used in practice. If the protection consists of boards, at least one full board shall be included in order to be able to evaluate reliably any shrinkage and deformation of the boards.

The procedure for performing a thermal insulation test is described in the remaining part of this chapter.

5.2 TEST SPECIMEN

5.2.1 Concrete slab

The used concrete shall remain intact during the test, and the used type of aggregate (siliceous or calcareous) shall be the same as in practice so that the concrete slab has representative thermal properties. Other parameters, such as the concrete strength, are not of major importance. However, the 28 days concrete strength shall be determined and reported.

The moisture content of the concrete shall be sufficiently low[12]. Storage of the concrete test specimen indoors (ambient temperature > 0°C) for 7 days before the fire test is deemed to be sufficient to reach a sufficiently low moisture content at the surface of the concrete.

5.2.1.1 Medium scale

The exposed-to-fire area of the concrete slab used for the application of the fire protection and for the fire tests shall have dimensions of at least 1.15 m x 1.15 m and the concrete slab shall have a nominal thickness of 0.15 m. The steel reinforcement mesh may consist of Ø10-150 mm or Ø12-200 mm bars with a concrete cover of 25 mm.

5.2.1.2 Large scale

The exposed-to-fire area of the large scale test specimen shall be at least 8 m^2. The thickness of the concrete slab shall be at least 0.20 m and the steel reinforcement shall consist of Ø10-150 mm or Ø12-200 mm bars with a concrete cover of 25 mm. The thickness of the slab may deviate, but the results are valid for the same (or higher) thickness as tested.

5.2.2 Temperature measurements

Just below the surface of the concrete slab a number of thermocouples shall be applied. The measuring tips of the thermocouples at the concrete surface shall remain in direct contact with the concrete, i.e. they may not protrude from the concrete. If a concrete mix is used with unknown thermal properties, an additional 9 thermocouples at the lower reinforcement shall be applied. If required, additional information can be obtained by applying extra thermocouples at other depths.

The positioning and fixing of the thermocouples shall be done in such a way that they do not influence the measured values. The thermocouples shall not move during casting of the concrete. No anchors may be positioned in the direct vicinity (Ø 100 mm) of the thermocouples in order to avoid influencing the thermocouples' measurements. The distance between a thermocouple and the unexposed edge board shall be at least 300 mm.

A reliable method to measure reinforcement temperatures is to position the thermocouple wire parallel to the rebar and to the fire exposed surface, fixing it using small cable ties. The length of the parallel thermocouple part shall be at least 50 mm.

Thermocouples shall have characteristics appropriate to the range and accuracy of the temperatures to be measured. Thermocouples of the type chromel-alumel (type K) meet these requirements, but other suitable types may be used as well. In addition, the responsiveness of the thermocouple needs to be taken into account (reaction to temperature change).

5.2.2.1 Medium scale

In total 9 thermocouples shall be installed at the surface of the concrete slab. In the case of a board protection system with a joint, 3 of the thermocouples shall be positioned behind the joint. See Figure 13. If the fire protection system also involves an air void (e.g. suspended ceiling or a system with backing strips), 3 additional thermocouples shall be applied to measure the air temperature in the void.

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[12] If a wet concrete slab is used for the test, it will absorb more thermal energy and therefore heat up more slowly than a dry slab. Additionally, concrete with high moisture content is more susceptible to spalling.

For spray applied systems at least two thirds of the thermocouples shall be working throughout the fire test. For board systems at least two thirds of the thermocouples behind joints and two thirds of the thermocouples behind the fire exposed boards shall be working throughout the fire test. Two thirds of the thermocouples in air voids shall be working throughout the fire test.

5.2.2.2 Large scale

At least 12 thermocouples shall be installed on the surface of the concrete slab. See Figure 14 and Figure 15. The thermocouples shall be uniformly distributed over the surface of the test specimen (not behind edge boards). In the case of a board protection system with joints, one third of the total number of thermocouples (e.g. 3 thermocouples out of a total of 12) shall be positioned behind a longitudinal joint.

Moreover, joints representative of the actual fire protection system shall be present. If a T-joint or X-joint is used in practice, the same type of joint shall be part of the test specimen. Additional thermocouples shall be placed behind T-joints and X-joints. For each type of joint, at least two thermocouples shall be installed.

If the fire protection system also involves an air void (e.g. suspended ceiling or a system with backing strips), 3 additional thermocouples shall be applied to measure the air temperature in the void.

For spray applied systems at least three quarters of the thermocouples shall be working throughout the fire test. For board systems three quarters of the thermocouples behind joints and three quarters of the thermocouples behind the fire exposed boards shall be working throughout the fire test. Two thirds of the thermocouples in air voids and half of the thermocouples behind T-joints or X-joints shall be working throughout the fire test.

5.3 FIRE PROTECTION SYSTEM

The provisions of Section 4.3 apply. Important objectives of the fire test are to evaluate: whether the fire protection system remains intact during the exposure to fire, whether its thickness provides sufficient thermal insulation, and whether there is any influence due to possible joints.

If the fire protection system consists of a spray-applied material, the area of the applied fire protection system shall correspond to the exposed-to-fire area. The remainder of the underside of the concrete slab shall be protected by fire protection boards of the same thickness as the main fire protection system. In this way, the main protection system is not additionally supported by the furnace.

5.3.1 Medium scale

The fire protection system shall consist of a layer of the protection material. The fixing system shall be as close as possible to the system in practice. However, due to the small size of the test specimen, some deviations such as spacing of possible anchors are inevitable.

When testing a fire protection board system, the fire protection system shall consist of two boards (panels A and B). In this way, an indication of the influence of a joint between the boards can be obtained. Some of the thermocouples at the concrete surface shall be positioned directly behind the joint. The two boards protect the area that will be exposed to fire (at least 1.15 m x 1.15 m). The remaining surface of the slab shall also be protected by strips of the same material with a width of at least 150 mm. Along the edges of the test specimen, a butt joint shall be realised so that panels A and B are not supported by the furnace walls and can fall down during the duration of the fire test (see also Figure 13).

Alternatively, a layer of the fire protection material may be applied to the concrete slab without any joints. In this way, only the thermal insulation of the material will be investigated, but no conclusions regarding the stability and influence of joints will be drawn.

5.3.2 Large scale

The exposed-to-fire area of the test specimen shall be at least 8 m^2. The fire protection system of the test specimen shall fully correspond to the system in practice, including fixing system (type, amount and spacing of anchors) and joint type (e.g. butt joint or rebate joint and T-joints and/or X-joints), with the exception of the edge boards.

In the case of a board protection system, the exposed-to-fire area shall consist of at least one full board surrounded by edge boards with a width of at least 0.5 m. A butt joint shall be realised along the perimeter of the exposed area so that the exposed-to-fire protection system can fall down during heating, i.e. to avoid additional support due to furnace walls.

5.4 CONDITIONING OF TEST SPECIMENS

The provisions of Section 4.4.2 and Section 4.4.3 apply. However, it is not necessary to determine the moisture content of the concrete test specimen provided that the fire test is conducted at least 91 days after manufacturing the concrete test specimen, and that the specimen has been stored indoors (ambient temperature > 0 °C) for at least 7 days before the fire test.

For the thermal insulation test of post-fixed or pre-fixed boards and sprayed materials, it is allowed to speed up the process of drying of the protection material by artificial means (slightly increased temperature, low relative humidity) with no special attention to the concrete slab, for instance by restricting heating to a level that is not detrimental to the fire protection material. However, for spray mortars it is recommended to wait at least six weeks after spraying before artificial drying is started, because the strength and bonding of the mortar to the concrete need to be fully developed.

For some fire protection systems high moisture contents may prove to be detrimental to the structural integrity of the system during fire exposure. Therefore, it is recommended to perform fire tests on such a fire protection system at fully saturated conditions. The fire protection shall be saturated at least 24 hours before the test commences.

Summary of Section 5.1 to Section 5.3:

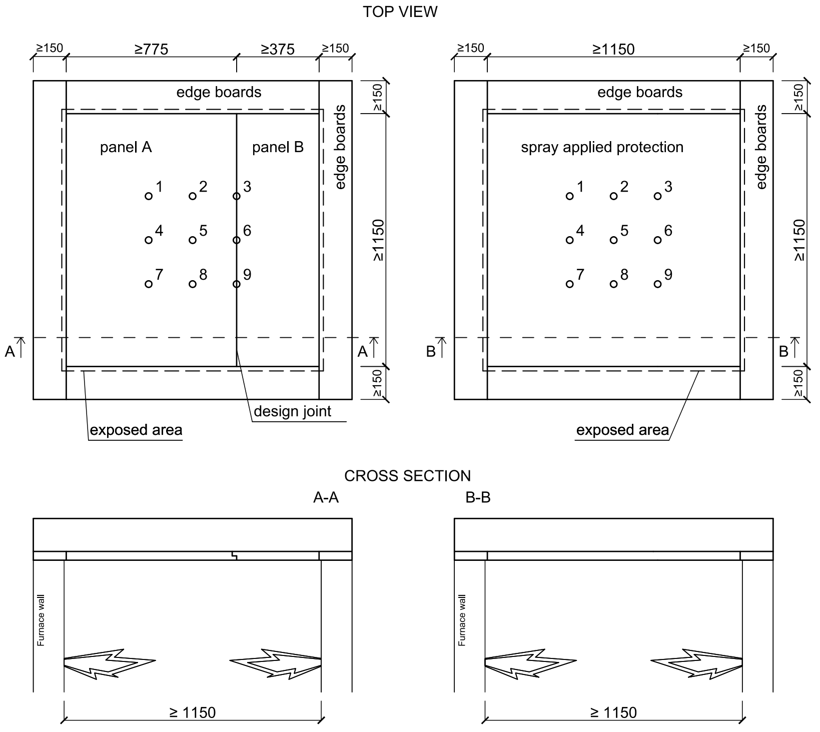

Figure 13 Medium scale test specimen

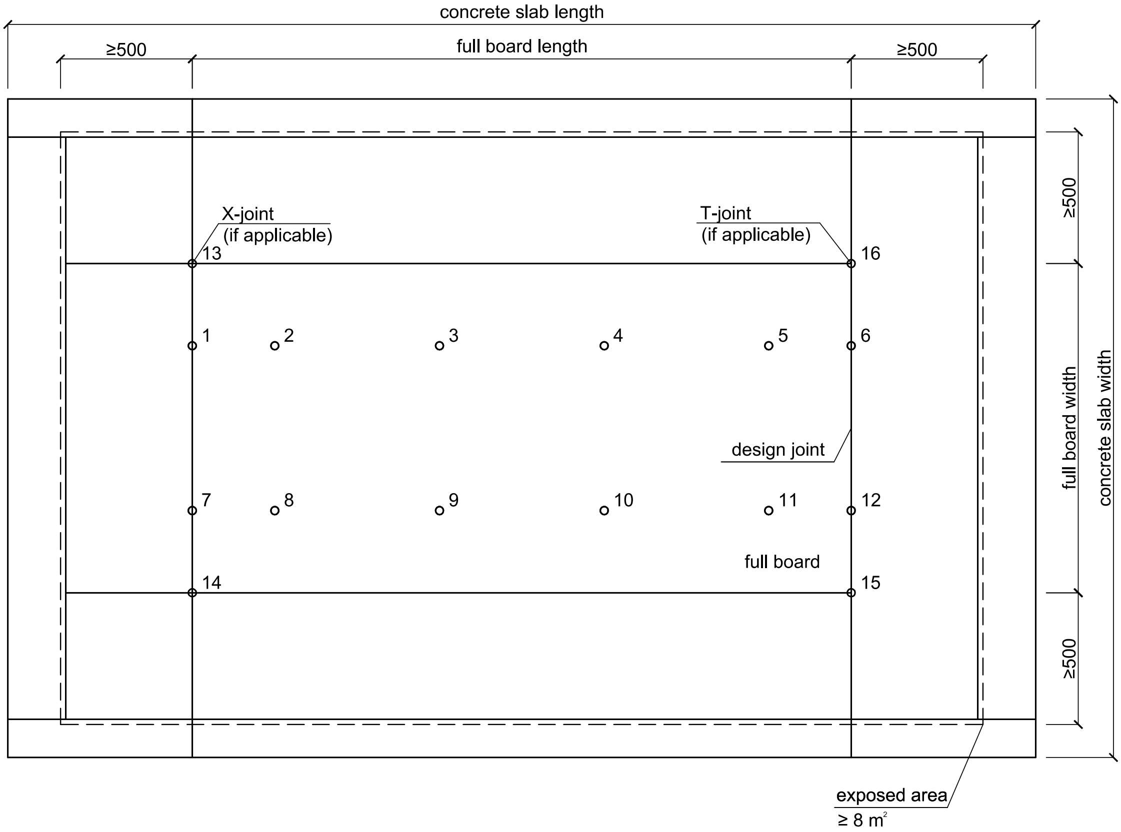

Figure 14 Large scale test specimen (board protection system)

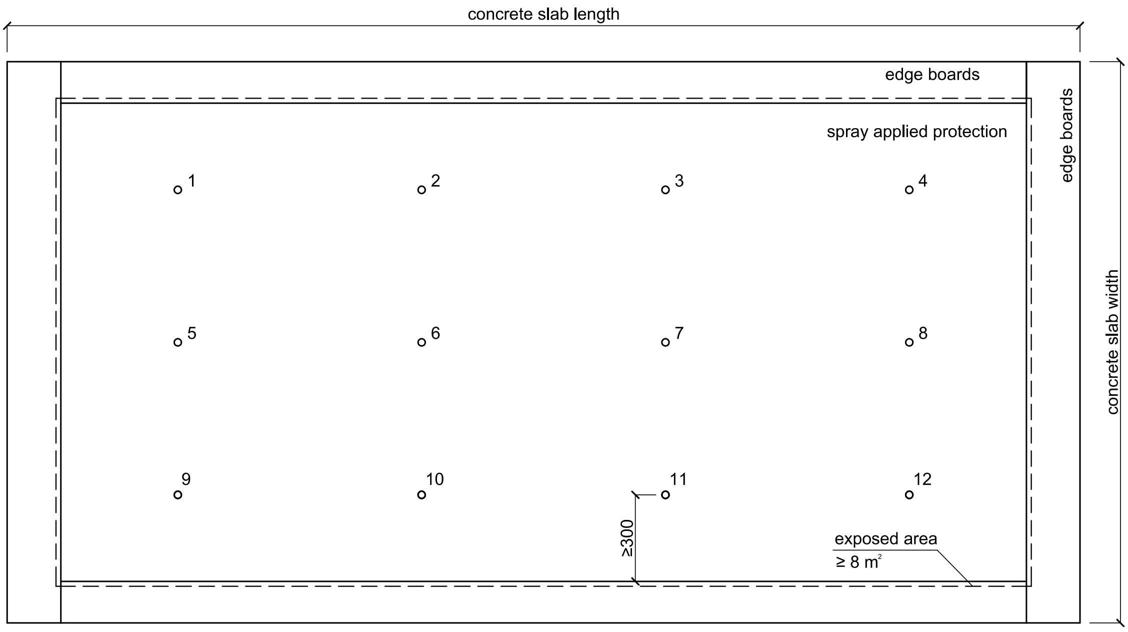

Figure 15 Large scale test specimen (spray applied protection system)

Table 7 Summary of thermal insulation tests

Thermal insulation test		
	Medium scale	Large scale
Exposed-to-fire area	≥ 1.15 m x 1.15 m	≥ 8 m^2
Fire protection system	- Thermal insulation properties of the fire protection material are properly assessed. - Not sufficiently representative of situation in practice with respect to dimensions, fixing systems, joints, etc. - For further details see Section 5.3.1.	- Representative of situation in practice with respect to the thermal insulation properties of the protection material. - Representative of situation in practice with respect to dimensions, fixing systems, joints, deformation during fire exposure etc. - For further details see Section 5.3.2.
The test aims to	- Assess the required thickness of the fire protection system in relation to the temperature requirements. - Indicate fire behaviour of the system, mainly for R&D purposes.	- Assess the suitability of the materials to withstand the fire exposure (shrinkage, expansion, mechanical stability, etc.). - Assess whether the fire protection system remains fixed to the concrete slab during the fire exposure. - Assess the required thickness of the fire protection system in relation to the temperature requirements.
Number of concrete surface thermocouples	- 9 thermocouples. For board systems only: - In case of a joint, 3 thermocouples shall be placed behind the joint. - See Figure 15.	- At least 12 thermocouples. For board systems only: - In case of joints, 1/3 of the thermocouples shall be placed behind the joints. - If X-joints or T-joints are present, extra thermocouples shall be placed behind these joints. For every type of joint at least 2 extra thermocouples shall be installed. - See Figure 13 and Figure 14.
Minimum number of working thermocouples	- 6 out of 9. For board systems only: - 2 out of 3 behind the joint. - 4 out of 6 behind the fire exposed boards.	- 9 out of 12. For board systems only: - 3 out of 4 behind the joint. - 6 out of 8 behind the main board. - Half of the thermocouples behind T-joints or X-joints.

5.5 FIRE TEST

5.5.1 Positioning and orientation of test specimen

The test slab shall be placed horizontally on top of the furnace and directly heated at its underside, as shown in Figure 13, Figure 14 and Figure 15. The test specimens shall be supported at four sides.

5.5.2 Furnace camera

The provisions of Section 4.5.2 apply.

5.5.3 Pressure conditions

The provisions of Section 4.5.3 apply.

5.6 FIRE CURVE

The provisions of Section 4.6 apply, but the gas temperatures in the furnace shall be measured with at least 4 (medium scale test) and 8 (large scale test) thermocouples. At least 75 % of the thermocouples shall be working during the test.

5.7 PERFORMANCE CRITERIA

The provisions of Section 4.7 apply.

The recorded temperature, *T*, shall be reported as the maximum, average and a 95% characteristic value of all temperature measurement positions at a specific depth for fire protection systems except for systems with varying thickness, such as board systems with joint backing strips. In that case, the 95% characteristic value is not appropriate in principle. At any given point in time, the 95% characteristic temperature shall be calculated with Equation 4, where *t* can be found in Table 8.

Equation 4

$$T_{95\%} = \bar{T} + t \cdot \sigma$$

where:

$T_{95\,\%}$ is the 95 % characteristic temperature
$\bar{T}$ is the average measured temperature
σ is the standard deviation

Table 8 *t*-values for a 95% characteristic value based on the Student's t-distribution

Number of measurements	*t*
6	1.943
7	1.895
8	1.860
9	1.833
10	1.812
11	1.796
12	1.782
15	1.753
>20	1.725

If multiple tests have been performed for the same system with different insulation layer thickness, linear interpolation for intermediate thickness values and corresponding temperatures is allowed. Interpolation shall be done between two temperature measurements at a chosen point in time (interpolation using temperature measurements that have been taken at different times is not allowed).

It is allowed to determine the temperatures inside the concrete at various depths with the use of FEM heat transfer calculations instead of installing thermocouples, utilizing the concrete surface temperature measurements recorded during a test together with appropriate concrete thermal properties, e.g. as given in the Eurocode EN 1992-1-2.

5.8 REPORT

The test report shall contain the information specified in Section 4.8 for items a, h, i, l, o, p and s. Additionally, the scale of the test specimen and the type of concrete aggregate that is used shall be included.

6. FIRE RESISTANCE TESTS OF OTHER TUNNEL COMPONENTS

6.1 INTRODUCTION

Tunnels have a significant number of elements, besides the concrete structure, that may be vulnerable during fire exposure. In this chapter, guidance is given for a selection of tunnel elements. This chapter is not exhaustive and other tunnel elements may exist that require attention.

For the following paragraphs (except Section 6.2.3) the furnace conditions of Section 4.6 and furnace pressure requirements of Section 4.5.3 are applicable.

The tunnel components should be installed in a supporting construction that resembles the practical situation as much as possible (i.e. a concrete wall or slab with the correct dimensions, concrete mixture, etc.).

6.2 TUNNEL DOORS

Fire resistance tests on tunnel doors that are located in the walls of a tunnel tube should be performed according to the European standards EN 1634-1 and EN 1634-3 with the following additions and modifications:

6.2.1 Performance criteria

For the determination of the fire resistance of doors in tunnels the following criteria are used:

- *Integrity (E):*
  This criterion is reached when hot gases or flames pass through the construction, or when an opening occurs in the construction such that it is possible to insert the prescribed gap gauge (with the prescribed procedure[13]) through the opening into the interior of the furnace.

- *Thermal insulation based on temperature (I_1):*
  This criterion is reached when the average temperature rise on the door leaf reaches 140 °C, or when the maximum temperature rise reaches 180 °C on the door leaf and/or the door frame. The first thermocouples on the door leaf are placed 25 mm from the edges.

- *Thermal insulation based on temperature (I_2):*
  This criterion is reached when the average temperature rise on the door leaf reaches 140 °C, or when the maximum temperature rise reaches 180 °C on the door leaf or 360 °C on the door frame. The first thermocouples on the door leaf are placed 100 mm from the edges.

- *Heat radiation (W):*
  This criterion is reached when the heat radiation measured at a distance of 1 metre from the centre of the door construction reaches 15 kW/m².

[13] See EN 1363-1

6.2.2 Classes for fire doors

6.2.2.1 Doors between tunnel tubes or between the traffic tube and a service tunnel (escape corridor)

The fire resistance of escape doors in tunnels should fulfil the criteria for class EI_1 and EI_2 for 60 minutes and EW for 120 minutes. The test should be based on the European standard EN 1634-1. The test setup should simulate the installation of the door in practice.

6.2.2.2 Doors between tunnel tubes and technical rooms

The fire resistance of tunnel doors between the tunnel and technical room should fulfil the criteria for class EI_1 and EI_2 for 120 minutes to protect the installations in the technical rooms.
The test should be based on the European standard EN 1634-1. The test setup should simulate the installation of the door in practice.

6.2.3 Smoke tightness

The smoke tightness of the fire doors should be determined using the standard EN 1634-3.

6.3 PENETRATIONS

Fire resistance tests on penetrations in tunnel walls should be performed according to the European standard EN 1366-3 with the following additions and modifications:

6.3.1 Additional temperature measurements and requirements

Besides the temperature measurements required by EN 1366-3 the following measurements should be performed:

- Three temperature measurements of the concrete surrounding the aperture at the heated side (i.e. at the interface of the fire protection system, if applicable). A measurement should be taken at the top and at the left hand and right hand sides of the penetration;
- Three temperature measurements of the concrete surrounding the aperture at a distance of 100 mm from the concrete surface at the heated side. A measurement should be taken at the top and at the left hand and right hand sides of the penetration;
- For conduits: Three measurements of the air temperature in the centre of the conduit at a distance of 200, 350 and 500 mm from the heated surface.

A conduit should be capped on the non-heated side, and open on the heated side. No cables should be fitted in the conduit.

6.3.2 Performance criteria

For the determination of the fire resistance of penetrations of, for example, pipes and cables in tunnels, the following criteria are recommended:

- *Integrity (E):*
  This criterion is reached when hot gases or flames pass through the construction, or when an opening occurs in the construction such that it is possible to insert the prescribed gap gauge (with the prescribed procedure[14]) through the opening into the interior of the furnace.

- *Thermal insulation based on temperature (I):*
  this criterion is reached when the maximum temperature rise reaches 180 °C on the penetration.

[14] See EN 1363-1

Besides the above performance criteria, the following additional criteria are applicable:
- spalling of the concrete is not allowed;
- concrete temperatures in the aperture are not allowed to exceed a temperature of 380 ˚C; and
- there are no requirements for the air temperatures in a conduit. These thermocouples can provide indicative information about any heat flow through the penetration.

6.3.3 Classes for penetrations

6.3.3.1 Penetrations between tunnel tubes or between a tunnel tube and service tunnel (escape corridor)

The fire resistance of penetrations in tunnels should fulfil the criteria for class EI for 60 minutes, and for E, with the additional performance criteria described in Section 6.3.2, for 120 minutes.

6.3.3.2 Penetrations between tunnel tubes and technical rooms

The fire resistance of penetrations between tunnel tubes and technical rooms should fulfil all of the given criteria for 120 minutes in order to protect the equipment in the technical room. The test setup should simulate the installation of the penetration in practice.

6.4 CABLE DUCTS

The fire resistance of cable ducts in tunnels should be tested according to EN 1366-11.

6.5 TUNNEL JOINTS

An important aspect of tunnel design are the joints in a tunnel. These joints may or may not have a structural purpose.

A structural joint in a tunnel may be subjected to axial force and bending moment (e.g. in underwater tunnels and in bored tunnels). The forces in a tunnel, and thereby the tunnel joint, result mainly from the ground and groundwater pressures. Additional bending stresses can also be a result of differential settlement, rotation of the tunnel segments/elements and/or distortion of the tunnel ring geometry (e.g. in the case of bored tunnels).

The joint can also be a non-structural joint. In such cases, the joint may serve as a construction joint which is placed to reduce shrinkage cracks in concrete (e.g. in cut and cover tunnels) or as an expansion joint to accommodate seasonal temperature variations.

Each type of tunnel is therefore characterized by a different joint type and a different load transfer mechanism to ensure the optimal transfer of forces through the joint. Joints are also often accompanied by seals/gaskets/waterstops (referred together as sealant in this document) which are placed to ensure water tightness in a tunnel.

The joints are more susceptible to damage during a fire as the mechanical forces in the joint may increase due to the local deformations caused by heating. Since the joint material, which is typically a non-rigid (rubber) profile, degrades at relatively low temperatures when exposed to fire, the damage and loss of function can affect the structural integrity of the tunnel.

Depending on the situation, different tests may be performed aiming to provide information on:
- temperatures of the components of the joint (joint insulation test);
- temperature of the concrete structure in the direct vicinity of the tunnel joint; and
- spalling behaviour of the joint (joint spalling test).

6.5.1 Joint insulation test

The influence of fire on the temperature distribution around a tunnel joint can be determined by performing a medium scale insulation test. If an external fire protection system is used to protect the joint, the test specimen should also include this system.

The test specimen should include a characteristic joint and its heated length should be at least 1.15 m.

Since only the thermal insulation of the joint with a possible fire protection system needs to be assessed, the components of the joint and their thermal properties shall be representative of the situation in practice, but the composition of concrete does not have to correspond fully to the composition in practice. It is important, however, that the concrete should have the same type of aggregate (siliceous or calcareous) as that in practice. The requirements and conditions as provided in Chapter 5.2.1 are also applicable here.

All the components of the joint, including the sealant used, should be representative of the situation in practice so that a realistic development of the temperature with time occurs during the test. The test setup provided in Figure 16 is a typical test setup of an underwater tunnel joint with an Omega profile protected with fire protection boards.

In order to determine the temperature distribution around the joint, thermocouples should be evenly distributed and installed on the joint components such as the sealant, steel profile used for securing the sealant in place and any other critical component. At least 3 thermocouples should be installed on each component that should be assessed.

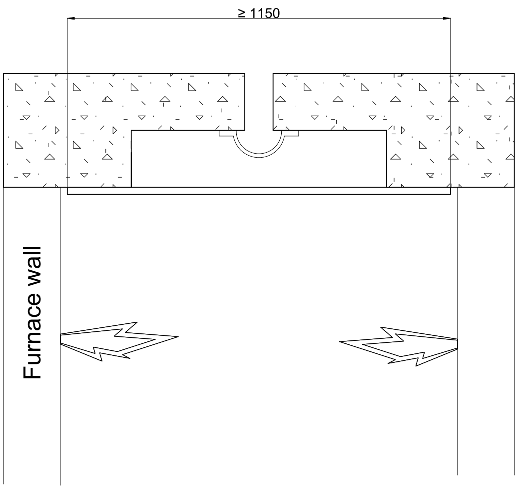

Figure 16 Joint insulation test for a typical underwater tunnel joint.

The fire protection system should also be able to accommodate the influence of seasonal temperature variations on the horizontal movement of the concrete linings (if applicable). Additionally, some authorities may have a requirement for regular inspection of the joint. In that case, it should be possible to remove the fire protection system temporarily.

6.5.2 Joint spalling test

The spalling behaviour of concrete around a structural joint can be determined by means of a full scale fire test. In order to evaluate this behaviour, the spalling test as described in Chapter 4 should be carried out with the joint included. Additionally, thermocouples may be installed on joint components such as the sealant, the concrete around the joint and other critical structural components such as steel bolts (e.g. in the case of bored tunnel joint).

It is recommended to install a minimum of 6 thermocouples on each component of the joint that should be evaluated. The test setup of a typical two half-segment bored tunnel joint is provided in Figure 17.

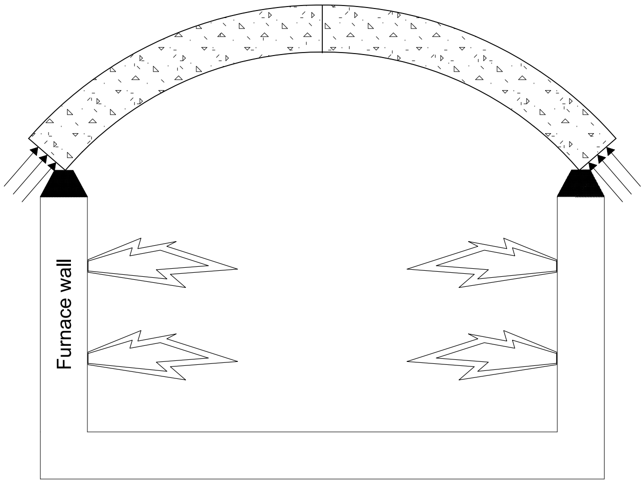

Figure 17 Joint spalling test for a typical two half-segment bored tunnel joint.

6.5.3 Performance criteria

Besides the criteria of Section 4.7, the performance criteria may include:

- maximum temperature values for the critical joint components, e.g. steel profiles and bolts;
- maximum temperature values for the joint material;
- maximum values for the concrete surface temperature around the joint; and
- maximum allowable spalling depth around the joint, or a “no spalling” criterion (if the joint is part of a spalling test).

For rubber sealants the recommended (non-compulsory) maximum temperature should be 80 °C.

6.6 EMERGENCY CABINETS

Usually tunnels have a significant amount of emergency cabinets. The concrete at the emergency cabinets may be at risk because heating from multiple sides may take place in the recess (or aperture) where the emergency cabinet is placed. Concrete that is heated from multiple sides is more vulnerable to spalling. An emergency cabinet usually does not have any fire resistance itself, so the tunnel structure should be well protected within the recess.

The emergency cabinet may be part of a fire resistant partition wall, for instance if the tunnel has a service tunnel with an escape corridor. In some tunnel structures, emergency cabinets are not part of the fire resistant walls (for instance for TBM-tunnels). In that case, the emergency cabinet does not have to fulfil a fire resistance function and no testing is necessary.

Emergency cabinets should be made part of a spalling test according to Chapter 4. The recess should resemble the practical situation, including the installation of the emergency cabinet (i.e. the way the cabinet is fixed to the concrete structure). Steel reinforcement around the recess should resemble the actual situation as much as possible. It is not necessary to include all the items that are usually located in an emergency cabinet.

Common configurations for emergency cabinets are given in Figure 18. For configuration I, the thickness of the test slab should be the depth of the emergency cabinet recess plus a maximum of 150 mm, or the thicknesses should correspond to the practical situation. For configuration II, the thickness of the test slab should correspond to the practical situation. In order to achieve the required fire resistance, the recess of configuration II is covered with a fire resistant board on the non-heated side.

Thermocouples may be installed to measure concrete surface temperatures, steel reinforcement temperatures and concrete temperatures in and around the recess. For configuration II it is recommended to install thermocouples at the non-heated side on the fire resistant board. Additionally, temperature criteria may be defined for the non-heated side (for instance a maximum temperature rise of 180 °C in accordance with the European standard EN 1363-1).

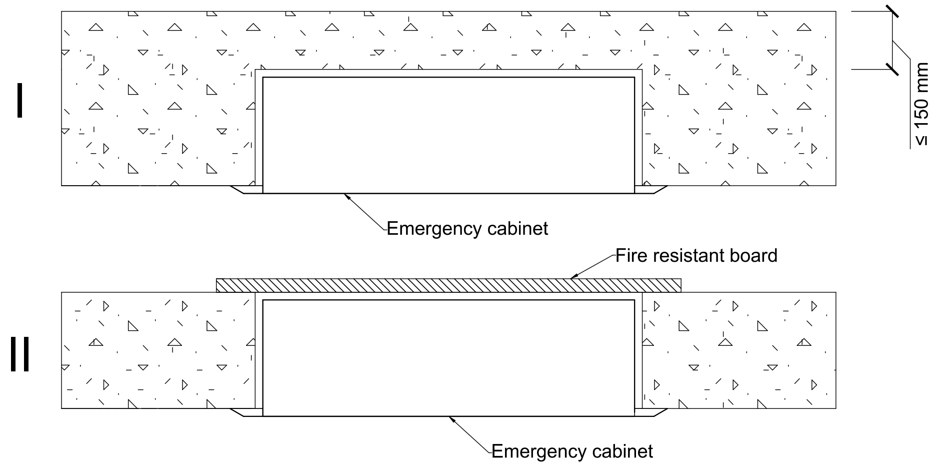

Figure 18 Common configurations for emergency cabinets (cross-section)

7. TEST PROTOCOL FOR MOBILE FURNACE TESTS

7.1 INTRODUCTION

The fire resistance for new tunnels may be verified in the design phase according to Chapter 4 of this document, i.e. with fire tests in a test laboratory using concrete and a fire protection system representative of the new tunnel. For existing tunnels, such an opportunity is not available since it is not feasible to bring the concrete of the tunnel to the test laboratory. Also, re-creating the concrete of an existing tunnel is virtually impossible. Therefore, the only practical way to determine the fire resistance of an existing tunnel is to perform a fire test in the actual tunnel.

For this purpose, fire tests are performed with a mobile furnace. Efectis has extensive experience with mobile furnace tests and these are considered to be a valuable tool in determining the fire resistance of existing tunnel structures.

Mobile furnace tests should be part of a larger analysis of the tunnel under investigation. Guidance for such analysis is given in Section 7.2.

Fire tests with the mobile furnace may be performed on bare concrete, existing pre-fixed and post-fixed fire protection systems, and new-to-apply post-fixed systems.

Mobile furnace tests do have their limitations and are not designed to replace the tests of Chapter 4 and Chapter 5. Due to practical reasons, mobile furnaces have a heated area that is limited in size in comparison to a stationary furnace in a test laboratory. This means that not all failure mechanisms of fire protection systems can be properly assessed (for instance shrinkage of fire resistant boards, loading of the fixing system etc. may not be properly assessed in medium scale mobile furnace tests). Therefore, it is highly recommended to perform large scale tests according to Chapter 5, if possible, with a representative fire protection system, in addition to mobile furnace tests so that the performance of the fire protection system can be assessed properly.

If properly used, mobile furnace tests provide valuable data and are essential for the analysis of the fire resistance of existing tunnels.

7.2 ANALYSIS OF THE TUNNEL AND VERIFICATION OF FIRE RESISTANCE (INFORMATIVE)

This document focuses on the test procedures that are necessary in order to verify the fire resistance of tunnel concrete linings and other tunnel components. Any other means of verifying a tunnel's resistance to fire do not fall within the scope of this document. However, some guidance is provided in the following sections with regard to the analyses that are necessary for verification.

It is not practical to test the entire surface of a tunnel. Only a limited number of locations in the tunnel can be tested. Therefore, in order to verify whether a tunnel meets the required performance criteria, an analysis of the tunnel construction is necessary. Such analysis should lead to a well-considered selection of test locations.

The analyses should help to determine the locations in the tunnel that are the most vulnerable during fire. The mobile furnace tests should be performed at these locations, which represent a reasonable worst-case in terms of fire resistance. The analyses should focus on, but are not necessarily limited to, the following:

- construction details;
- concrete mixture (sensitivity to spalling);
- compressive stresses (locations with higher compressive stresses are more sensitive to spalling);
- type and thickness of fire protection system;
- performance criteria; and
- practical issues such as accessibility of the test locations.

The analyses should include an assessment of the tunnel construction, test locations, test results and performance criteria in order to confirm that the test results are representative – or represent a reasonable worst-case – of the whole, or part of, the tunnel structure.

7.3 FIRE TEST ON BARE CONCRETE

7.3.1 General

Tests on bare concrete may be performed in order to establish whether or not spalling occurs.

7.3.2 Test surface

The heated area shall have dimensions of at least 1000 x 1000 mm (see Figure 19). Preferably, the test surface should be free of fixings or other objects that penetrate the concrete surface. The part of the concrete surface that extends beyond the edges of the heated area shall have a width of at least 150 mm, as measured from the edge of the heated area.

7.3.3 Temperature measurements

In principle, it is not necessary to measure concrete temperatures for this type of test. However, thermocouples may be installed to measure the temperatures at a number of locations (reinforcement, concrete surface, concrete cover zone, etc.) in order to monitor the development of any spalling. This may also be required by the client/authorities, especially if thermal criteria are imposed on top of the criteria concerning spalling.

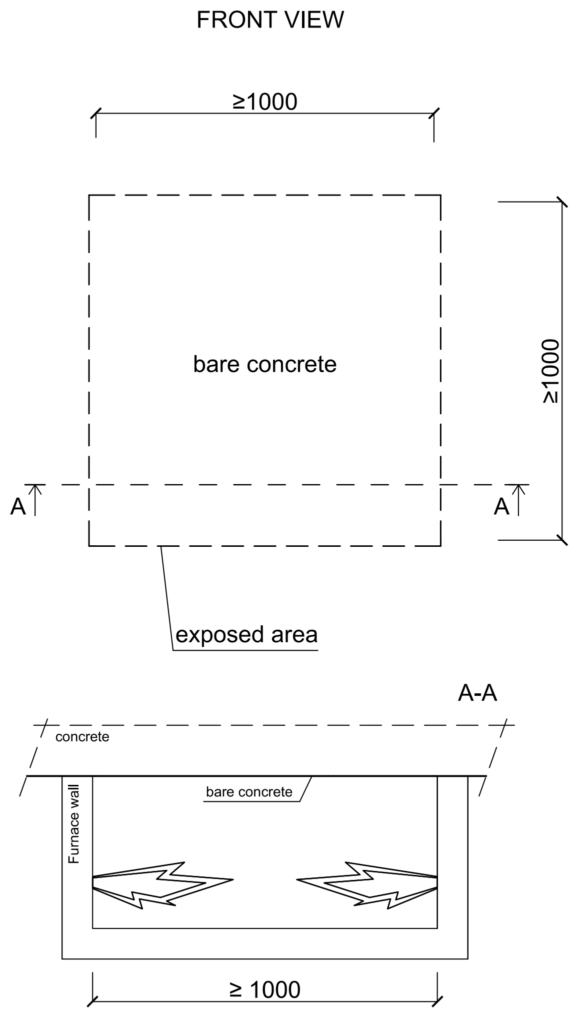

Figure 19 Fire test on bare concrete

7.3.4 Moisture content

Determining the moisture content of the concrete is not compulsory.
Usually it is not feasible to take concrete samples for moisture content determination since the methods available to take a sample will influence the moisture content (i.e. taking drill cores using a water-cooled diamond drill).

If a suitable method for taking samples is available, the samples shall be taken shortly before the fire test within a perimeter of 1 m of the test surface. The samples shall be treated according to Section 4.4.3.

7.4 FIRE TEST ON EXISTING PRE-FIXED AND POST-FIXED FIRE PROTECTION SYSTEMS

7.4.1 General

Tests on existing pre-fixed and post-fixed fire protection systems are performed to establish whether the existing fire protection measures are sufficient to ensure the required resistance to fire. No information is obtained about the actual temperatures on the concrete surface during fire due to the fact that no thermocouples are present.

7.4.2 Test surface

The heated area shall have dimensions of at least 1000 x 1000 mm (see Figure 20). The exposed-to-fire test surface shall be able to fall unobstructed into the furnace during heating. To this end, the furnace walls shall not support the fire protection system, and a groove on the perimeter of the test surface shall be cut. The groove shall have a depth equal to the thickness of the fire protection system. To avoid the high furnace temperatures reaching the bottom of the groove, the groove shall be filled with an appropriate fire protection putty or sealant that is able to withstand the fire curve. If the perimeter, or part of the perimeter, of the test surface coincides with an existing joint no groove is necessary at these parts of the perimeter.

The part of the fire protection system that extends beyond the edges of the heated area shall have a width of at least 150 mm, as measured from the heated area.

For board systems (both pre-fixed and post-fixed) an existing joint between the boards shall be a part of the heated surface. The existing joint shall divide the test surface at 200 mm from the centreline of the heated surface. This means that for a heated area of 1000 x 1000 mm, panel A shall have a width of 700 mm and panel B a width of 300 mm.

For board systems where the boards have a width less than 700 mm, the location of the joint may be moved in order to accommodate the smaller board dimensions. Also, the joint may be moved because of practical issues (for instance, due to obstacles in the vicinity of the test location).

For post-fixed board systems it may be necessary to add additional fixings close to the perimeter of the heated surface in order to fix securely the board system to the concrete. The fixing pattern on the test surface shall be as close as possible to, and in the spirit of, the original fixing pattern.

7.4.3 Moisture content

The provisions of Section 7.3.4 regarding the moisture content of the concrete apply.

For moisture content determination two cylindrical samples shall be taken with a diameter of at least 150 mm.

For pre-fixed and spray applied systems the samples shall be taken within a perimeter of 1 m of the test surface.

The moisture content samples shall be treated according to Section 4.4.3.

7.4.4 Thickness and density

For the samples taken of post-fixed board systems, the thickness and density shall be determined according to Section 4.3.4 and Section 4.4.3, respectively.

For pre-fixed and spray applied systems, drill cores may be taken of the concrete with fire protection layer in order to determine the fire protection thickness.

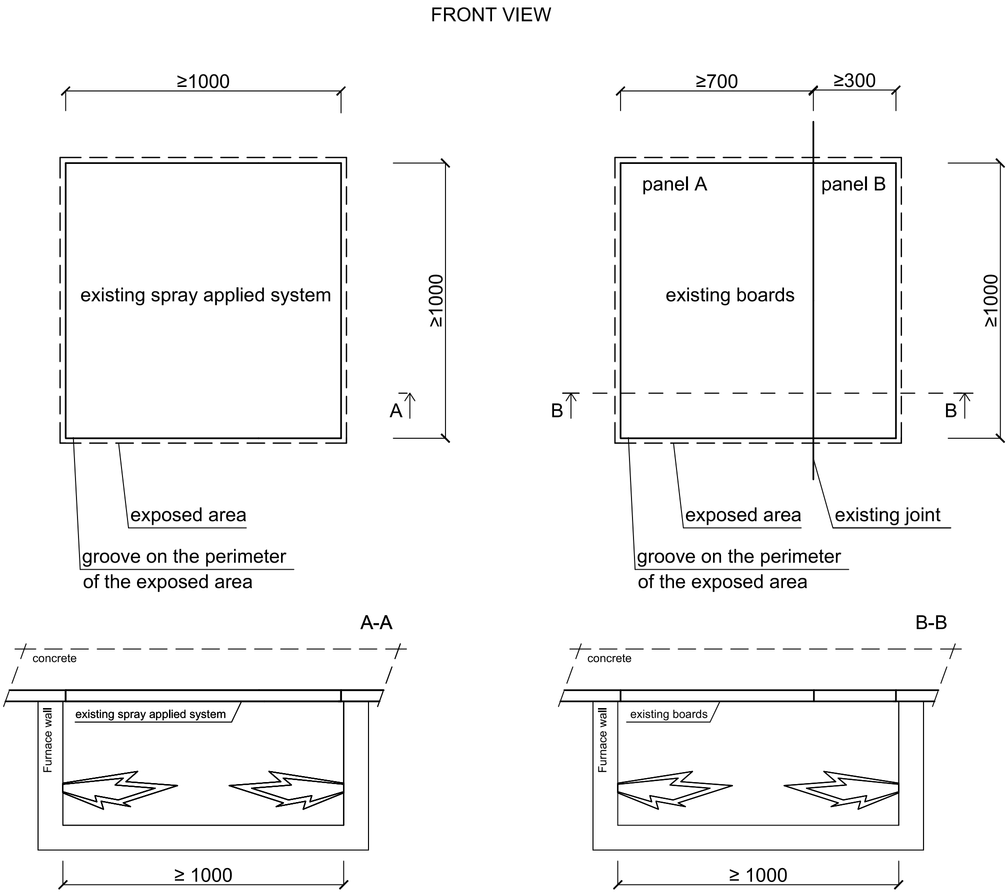

Figure 20 Fire test on existing pre-fixed and post-fixed fire protection systems

7.5 FIRE TEST ON NEW-TO-APPLY POST-FIXED FIRE PROTECTION SYSTEMS

7.5.1 General

Tests on post-fixed fire protection systems are performed to establish whether the thermal insulation and structural integrity of the system is sufficient to prevent spalling, and to determine whether a fire protection system has sufficient thermal insulation to conform to other performance criteria, i.e. conforms to a maximum temperature criterion on the concrete surface during fire.

7.5.2 Test surface

The heated surface shall have dimensions of at least 1000 mm x 1000 mm (see Figure 21).

The provisions of Section 4.3 apply. The fire protection system shall consist of a layer of the protection material. The fixing system shall be similar to the fixing system as used in practice. However, due to the small size of the test surface, some deviations are inevitable, for example deviations with respect to the spacing between fixings.

When testing a fire protection board system, the heated surface shall consist of two boards (panels A and B). In this way, the influence of a joint between the boards can be evaluated. The joint shall divide the test surface at 200 mm from the centreline of the heated surface. This means that for a heated area of 1000 mm x 1000 mm, panel A shall have a width of 700 mm and panel B a width of 300 mm. For boards with a width less than 700 mm, the location of the joint may be moved in order to accommodate the smaller board dimensions.

A spray applied system shall cover the concrete test surface over the entire heated area.

Beyond the perimeter of the heated surface the concrete is protected by strips of fire protection board with a width of at least 150 mm (for spray applied systems and board systems). For board systems this should be the same material and thickness as the boards used in the heated area. Also, along the perimeter of the heated surface, a butt joint shall be realised so that panels A and B can fall down during the heating.

7.5.3 Temperature measurements

For post-fixed fire protection systems a total of 9 thermocouples shall be installed just below the surface of the concrete, and the measuring tip shall remain in direct contact with the concrete, i.e. it may not protrude from the concrete. In the case of a board protection system with a joint, 3 of the thermocouples shall be positioned behind the joint. If the fire protection system involves an air void (e.g. suspended ceiling or a system with backing strips) it is advised to measure the air temperature in the void. A minimum of one thermocouple per void shall be used.

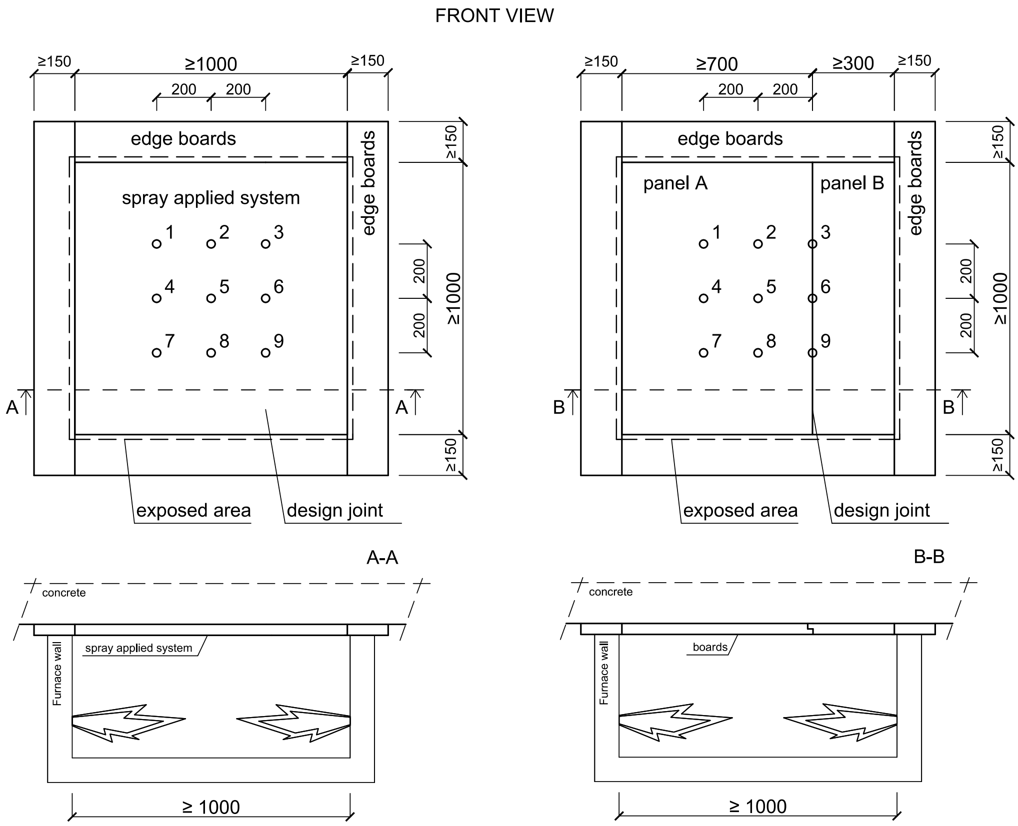

Figure 21 Fire test on new-to-apply fire protection systems

In principle the grid of 9 thermocouples shall be installed centrally in the test surface. If the board width is less than 700 mm, the grid of thermocouples shall be relocated accordingly. If fixings are close to the thermocouple locations (< 50 mm) the grid shall be moved to equalise the distances between the thermocouples and fixings.

7.5.4 Moisture content

The provisions regarding the moisture content of the concrete of Section 7.3.4 apply. The provisions of Section 4.4.2 and Section 4.4.3 regarding the moisture content of the fire protection system apply.

7.5.5 Thickness and density

The provisions of Section 4.3.4 and Section 4.4.3, respectively, for the determination of the thickness and of the density of the fire protection system apply.

7.6 CONDITIONS AT THE TEST LOCATION

Mobile furnace tests are performed on-site. Therefore, the environmental conditions are not easily controlled. It is recommended that the tests are performed in ambient temperatures above 0 °C.

The ambient temperature and relative humidity in the tunnel shall be recorded immediately before the fire test and immediately after.

7.7 FIRE TEST

7.7.1 General

In order to obtain a valid test result, tests shall be performed at least twice at locations with comparable concrete composition, compressive stresses and fire protection measures. In practice, this means that the tests shall be repeated in the same tunnel section with limited distance between the test surfaces. It is not allowed to repeat tests on the same test surface. In principle, single test results are only valid for the specific location where the test is performed. Only after careful analysis of the tunnel can a number of tests be performed at reasonable worst-case locations. In this case, such tests may be thought of as representative for other parts of the tunnel (see Section 7.2).

7.7.2 Heated area and furnace compartment

The heated area of the mobile furnace shall have dimensions of at least 1000 mm x 1000 mm. The depth of the mobile furnace shall be at least 500 mm. The furnace compartment shall be well insulated and be able to withstand the high temperatures of the prescribed fire curve. The design shall be such that the impingement of the burner flame on the heated surface will be kept to a minimum.

7.7.3 Orientation of the test surface

The fire tests may be performed either vertically (on the walls for tunnels with rectangular cross sections) or horizontally (on the ceiling for tunnels with rectangular cross sections). Depending on the design of the tunnel the most vulnerable areas could be either high on the walls (vertical test) or close to the corners at the ceiling (horizontal test). Therefore, the mobile furnace shall be designed in such a way that these areas can be reached.

7.7.4 Furnace camera

The provisions of Section 4.5.2 apply.

7.7.5 Pressure conditions

No provisions for the control of the furnace pressure are prescribed. And, as a consequence, no furnace pressure criterion is defined.

7.8 FIRE CURVE

The provisions of Section 4.6 apply. However, the gas temperatures in the mobile furnace shall be measured with at least four thermocouples. The thermocouples shall be evenly distributed over the heated area.

The design of the mobile furnace shall be such that the burner tip will not be blocked by pieces of spalled concrete.

7.9 PERFORMANCE CRITERIA

The (non-compulsory) performance criteria of Section 4.7 and Section 5.7 apply.

For measurement of the spalling depth, a measurement grid of 200 mm x 200 mm, or smaller, is recommended. The spalling depth shall be measured over the entire heated surface.

7.10 REPORT

The test report shall contain the following information:

a) the name of the tunnel;
b) the name and address of the sponsor;
c) the name and address of the supplier of the fire protection system (if applicable);
d) the reference number of the test(s), test location(s) (within the tunnel) and date of the test(s). If a series of tests is being carried out, the reference number shall indicate the position of the test within the series;
e) type of concrete (calcareous or siliceous based, addition of pp-fibres, etc.);
f) a drawing of the tunnel including the approximate test location in the tunnel;
g) a description of the test surface, including the following (if applicable):
    i. a description of the fire protection system including the protection material, the trade name of the product (or components) together with identification marks as well as a description of the composition, the method of application and method of fixing of the protection material;
    ii. a drawing of the test surface and/or fire protection system and thermocouple locations.
h) a description of the observations with regard to the nature of the spalling process (time of occurrence, noise, visible effects, etc.) and other relevant observations;
i) the measured temperatures in the furnace and the deviation of the fire curve;
j) the measured ambient temperature during the fire test;
k) the measured ambient temperature and relative humidity before and after the fire test;
l) the measured concrete temperatures (if applicable);
m) the measured temperatures on the concrete surface (if applicable);
n) photos of the test surface before and after the test;
o) the measured spalling depths (if applicable);
p) the moisture content of the pre-fixed protection system material (if applicable);
q) the thickness, density and moisture content of the post-fixed protection system material (if applicable);
r) the conclusion with respect to the performance criteria.