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Specification and Guidelines for Testing of Passive Fire Protection for Concrete Tunnels Linings

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Contents

1. Introduction and Definition

Following a succession of major tunnel fires across Europe, the need for effective fire protection for the structural concrete lining has become a matter of priority for both new and existing tunnels.

This guideline covers the assessment of passive fire protection systems. Passive fire protection forms a permanent part of the tunnel and does not require external activation in the event of a fire. These guidelines do not cover the assessment of active fire protection such as sprinkler systems.

The role of passive fire protection in tunnels is to:

- Minimise the rate of temperature rise within the concrete and structural steel reinforcement (if present) so that structural integrity is retained during and after the fire.
- To reduce or eliminate the risk of explosive spalling and loss of the concrete surface resulting from a build up of vapour pressure within the concrete.

Within the scope of these guidelines, passive fire protection of concrete for tunnel linings and members can be achieved by one of the following means:

- An applied protective coating or render.
- A preformed thermal barrier or board fixed to the concrete surface.
- Integral protection incorporated into the structural concrete, usually based on polypropylene fibres. Note that this system may require additional concrete thickness as some degradation of the concrete can occur.

A number of proprietary passive fire protection products and systems are available and these guidelines provide a common test procedure for:

- Provision of standardised data from suppliers.
- Initial product evaluation and selection by specifiers.
- Continued quality monitoring during a contract.

Testing to these guidelines is based on severe conditions; any deviation from the standard procedure must be reported and taken into account during risk assessment by site engineers for the contract.

2. Scope

This document provides a specification for the testing of passive fire protection systems for reinforced or un-reinforced concrete tunnel linings. It does not cover fire stops or fire protection for cables and installations. Neither does it provide information on the effects of aging on the protection system.

The aim of these Guidelines is to harmonize the test procedures and reporting within Europe.

These guidelines are not intended to form a basis for research work or scientific investigation into the effects of tunnel fires on concrete or the detailed effects of fire protection systems but reference is made to such work in the bibliography.

These guidelines are applicable to concrete structures where the protection is a spray applied coating, a surface fixed barrier or is integrally cast into the concrete.

3. References

EN 197-1: Cement – Part 1: Composition, specification and conformity criteria for common cements.

EN 206-1: Concrete – Part 1: Specification, performance, production and conformity.

EN 1363-1: Fire resistance tests – Part 1: General requirements.

EN 1363-2: Fire resistance tests – Part 2: Alternative and additional procedures.

EN 12390-1: Testing hardened concrete – Part 1: Shapes, dimensions and other requirements of specimens and moulds.

EN 12390-2: Testing hardened concrete – Part 2: Making and curing specimens for strength tests.

EN 12390-3: Testing hardened concrete – Part 3: Compressive strength of test specimens.

EN 12390-4: Testing hardened concrete – Part 4: Compressive strength – Specification for testing machines.

ENV 13381: Test methods for determining the contribution to the fire resistance of structural members.

4. Fire Loading

Fire Loading can be defined as: a specified temperature: time relationship for a concrete member subjected to a fire. Within the scope of these guidelines, the temperature is measured in a furnace at a distance of 100 mm from the face of the member.

The Fire Loading selected for testing and the performance required from the passive fire protection system will depend on factors relevant to a specific tunnel. It should be based on a risk assessment in the event of a worst case fire, taking into account the situation during the fire and also the subsequent safety and likely economic effects following the fire.

Relevant factors include:

- The type/construction, location, structural loads and intended use of the tunnel.
- The potential severity of a fire, the evacuation and fire control system.
- The tunnel remediation procedures envisaged following a sever fire.
- The economic and social consequences of prolonged closure of the tunnel

Taking these factors into account together with published data on tunnel fires, estimates can be made for the potential temperatures that will be reached in the tunnel over time and a ‘fire load’ curve derived. As well as the maximum temperature and duration of the fire, factors including the cooling period and the use of water to induce rapid cooling must be considered as these can have a significant impact on the structural integrity of the concrete.

4.1 Guideline fire load curve

The following fire load curve should be used with these guidelines. Other standard fire load curves are also given in clause 4.2.

Time after Ignition, min	Target Furnace Temperature ^{o}C	Maximum Deviation ± %
0	< 50*	
5	≥1150	≤ 10 min =15%
10	1200	
30	1300	≤ 30 min =10%
60	1350	> 30 min = 5%
90	1300	
120	1200	

* Not applicable to the small scale test furnace.

The Furnace should be shut down at 120 minutes after the start of the test but the sample should be left for a minimum of 1 hour before being moved. Temperature measurements in the sample should be continued and reported until the temperature of the thermocouples embedded in the concrete and nearest the furnace exposed face fall to below 200 ^{o}C or if cooling is slow, up to 240 minutes after the start of the test.

Note: controlled cooling is important as it may affect the condition of the concrete during post test assessment.

General comments on the temperature time curve:

- After 5 minutes the maximum deviation of the temperature time curve from the target value shall be within the requirements of EN 1363-2 (hydrocarbon curve). Appendix B outlines how the maximum deviation is calculated and assessed in respect to the energy consumption up to a certain time (see Table 1 in appendix B).
- The test report shall show the average furnace temperature (the mean of all the furnace thermocouples) against the target and maximum deviation. Appendix B gives an example of how the results should be presented in Graph 2.

Any deviation from these Fire Load requirements shall be reported, with details of the reason why the curve could not be followed.

4.2 Standard Fire Load Curves

A number of other standard fire load curves exist and may be specified for use with these guidelines.
Examples of standard fire load curves include:

- RWS (Rijkswaterstaat), Dutch regulations
- Hydrocarbon curve (HC) EN 1363-2
- Hydrocarbon curve (modified) HCm
- RABT – ZLT curve Germany
- ISO 834/ EN 1363-1
- EBA Guideline (German Railway Authority)
- Dublin Port Tunnel (DPT)

Further information on these Fire Load Curves is given in Appendix ‘A’.

Note: if specifying these fire curves, it is important that the maximum deviation from the target temperature is given and the results reported as shown in Appendix B. In the absence of a fire curve specified maximum deviation, the EN 1363-2 deviation should be used.

5. Test Principal

Fire protection is assessed on or in a concrete test slab.

The concrete test slab may contain the integral fire protection system or the fire protection may be applied to the surface of the slab.
The slab is not loaded during the test.
Two concrete test slab sizes are permitted as detailed in clause 6.

The concrete test slabs shall be 200 mm thick for surface applied protection or 250 mm for integral protection.
Spray applied mortars and thermal barriers are applied as an additional thickness to the surface of the test slab in accordance with the manufacturer's instructions.

Two humidity levels are to be tested by preconditioning the base slabs prior to test as detailed in clause 9.
The fire load shall be in accordance with requirements in clause 4 unless otherwise specified.

The test methods in these Guidelines are designed to assess the thermal gradient within the concrete during the test, the integrity of the bond for surface applied systems and the extent of damage to the concrete test slab.

The thermal and physical performance of the test slab under fire loading is reported in accordance with the requirements in clause 12 and 14of these guidelines.

6. Samples

These guidelines provide for two sizes of test:

- A small scale test method that can be used for development work, provision of indicative performance data on proprietary products and for quality monitoring during product production and during a contract.
- A large scale test method, used to demonstrate that a protection system fulfils all the requirements of a job specification.

The small scale test provides useful data about the temperature profile as a function of time through a non-reinforced concrete slab with an exposed area of at least 400 x 400 mm. The test results are indicative of the performance of fire protection systems and may be used as a route to initial selection but the small scale test may not provide the quality or range of data provided by a larger scale test.

The large scale test provides data on a test specimen with an exposed area of at least 1500 x 1500 mm. This is normally tested in a horizontal orientation and where edge effects are largely eliminated within the test area. Reinforcement is included unless otherwise specified. Joints shall be included. The test gives the temperature profile as a function of the exposure time and information is also obtained about likely performance, stability and integrity of both the protection system and the reinforced concrete following a fire in the actual construction, including information on strength and spalling.

6.1 Samples for small scale tests

The concrete test slab shall have a nominal minimum area of 400 mm x 400 mm that is exposed to the furnace. For the investigation only a central square of 200 mm x 200 mm has to be taken into account.

The thickness of the concrete test slab shall be 200 mm ± 5 mm (250 ± 5 mm for integral protection systems) and shall be un-reinforced. Integral protection systems are included in the 250 mm thickness. A second test slab or two 150 mm cubes shall be cast and cured alongside the test slab to determine the humidity and core strength of the concrete at the time of fire testing.

Integral protection systems shall be dosed and mixed in accordance with the manufacturers instructions as part of the manufacture of the concrete test slabs.

Spray applied mortars and thermal barriers are applied as an additional thickness to the cast face of the concrete test slab in accordance with the manufacturer's instructions.

Surface protection systems are applied on the cast face of the concrete test slab with a protection thickness and application procedure as proposed from the supplier.

6.2 Samples for large scale tests

The concrete test slab shall have a nominal minimum area of 1500 mm x 1500 mm that is exposed to the furnace. The test slab must in addition have a minimum overlap of 150 mm on each side of the furnace. Protection systems shall not be supported by the furnace walls. Test slabs of larger dimension may be used. For the investigation of thermal effects only a central square of 800 mm x 800 mm has to be taken into account.

The thickness of the concrete test slab shall be 200 ± 5 mm (250 ± 5 mm for integral protection systems) and shall contain 12 ± 1 mm reinforcement on a nominal 200 mm grid (working from the centre of the slab) at a cover depth of 75 ± 2 mm from the front surface for integral fire protection systems and at 50 ± 2 mm for other systems.

If testing is to be carried out for a specific project, the reinforcement layout detailed for that project may be accepted as an alternative to the above.

Where an un-reinforced lining is proposed the test samples may also be un-reinforced, but careful consideration shall be given to the safety issues associated with the stability of the sample during test and should only be specified after prior consultation with the test facility.

(Note: The presence and location of reinforcement changes the uniformity of the temperature profile within the concrete and may also affect the way that some protection systems perform.)

Integral protection systems shall be dosed and mixed in accordance with the manufacturers instructions as part of the manufacture of the concrete test slabs.

Surface protection systems are to be applied on the cast face of the concrete test slab with a protection thickness and application procedure as proposed from the supplier.
The test sample should be representative of the intended protection design and application method. The application should comprise:

- A connection area, with a single longitudinal joint for spray applied systems and a three element joint in the case of prefabricated thermal barriers. The longitudinal joints in the protection system shall be located along the line of the thermocouples on one edge of the central test area. The 3 element joint shall fall under a corner thermocouple number 1 or 9 (see figure 3) with the third element comprising a corner unit outside the central test area.

- Multiple layers where spray applied systems cannot be applied at the recommended thickness in a single layer for overhead applications

- Where sprayed systems are intended to be applied overhead in the tunnel, the sample slabs shall also be prepared by spraying up on to the base slab with suitable equipment similar to that recommended by the supplier.

- Protection linings shall be applied and fixed in accordance with the suppliers recommendations.

7. Concrete for test slabs

7.1 Reference concrete

The reference concrete shall meet the following specification:

- Cube strength (actual): 50 to 70 N/mm^2 at 28 days (based on the average of 3 cubes cured under standard laboratory conditions according to EN 12390-2)
- Cement: >350 kg /m^3 CEM I, ll or lII, of at least 42.5 grade (EN 197-1)
- W/C < 0.48
- Coarse aggregate: crushed limestone or granite with a maximum size D of between 16 and 20 mm.
- Plasticizing or superplasticizing admixtures may be used to give an appropriate W/C and consistence to the mix.

The concrete shall be cast in steel or high quality faced ply moulds.

7.2 Project Specific Concrete

Where testing is being carried out for a specific project, the reference concrete may be substituted for a mix that is representative of that to be used on the project. This may include sprayed concrete. These deviations from the guidelines shall be included in the test report.

This option should only be adopted if there are differences in the project concrete that are likely to significantly affect the results of the testing. This option should always apply if the concrete grade will result in concrete that has actual cube strengths above 70 N/mm^2

7.3 Prestressing

For assessment of Fire Protection Systems, it is not normally necessary to use prestressed test concrete. However, if appropriate to a specific project, the concrete test slab may be prestressed. Details shall be included in the test report.

8. Thermocouples.

8.1 General

All thermocouples in the concrete test slab shall be Type "K" (cased), diameter 1.5 to 3.0 mm, according to DIN 584 or IEC584, intrinsically safe.
Temperature measuring equipment shall be calibrated and the date of last calibration should be recorded in the test report.

Thermocouples should be set in the concrete test slab in a way that ensures a high coupling efficiency, avoiding any air space and providing a full physical contact between the thermocouple and the concrete.

It is recommended that a thin but rigid wire frame is used to accurately locate the thermocouples but the thermocouple ends shall not touch the wire frame.

Where reinforcement is present at the required location, the thermocouple should be affixed to the lower (furnace exposed) edge of the reinforcement but the thermocouple ends shall not touch the reinforcement.

8.2 Thermocouple Location, small scale test slabs.

See Figure 1 and 2 (Not to scale),

8.2.1 Surface applied protection systems.

3 thermocouples shall be fixed in the concrete at the protection interface.
2 thermocouples shall be fixed in the concrete at points 25 ± 2 mm, 50 ± 2 mm and 75 ± 2mm from the front (furnace exposed) face of the test slab.
2 thermocouples shall be fixed in the concrete at the back face of the concrete test slab.

8.2.2 Integral protection systems.

3 thermocouples shall be fixed in the concrete at 25 ± 2 mm, 50 ± 2 mm and 75 ± 2mm from the front (furnace exposed) face of the test slab.
2 thermocouples shall be fixed in the concrete in the back face of the concrete test slab.

Plan View of Small Scale Test Slab

(Not to scale)

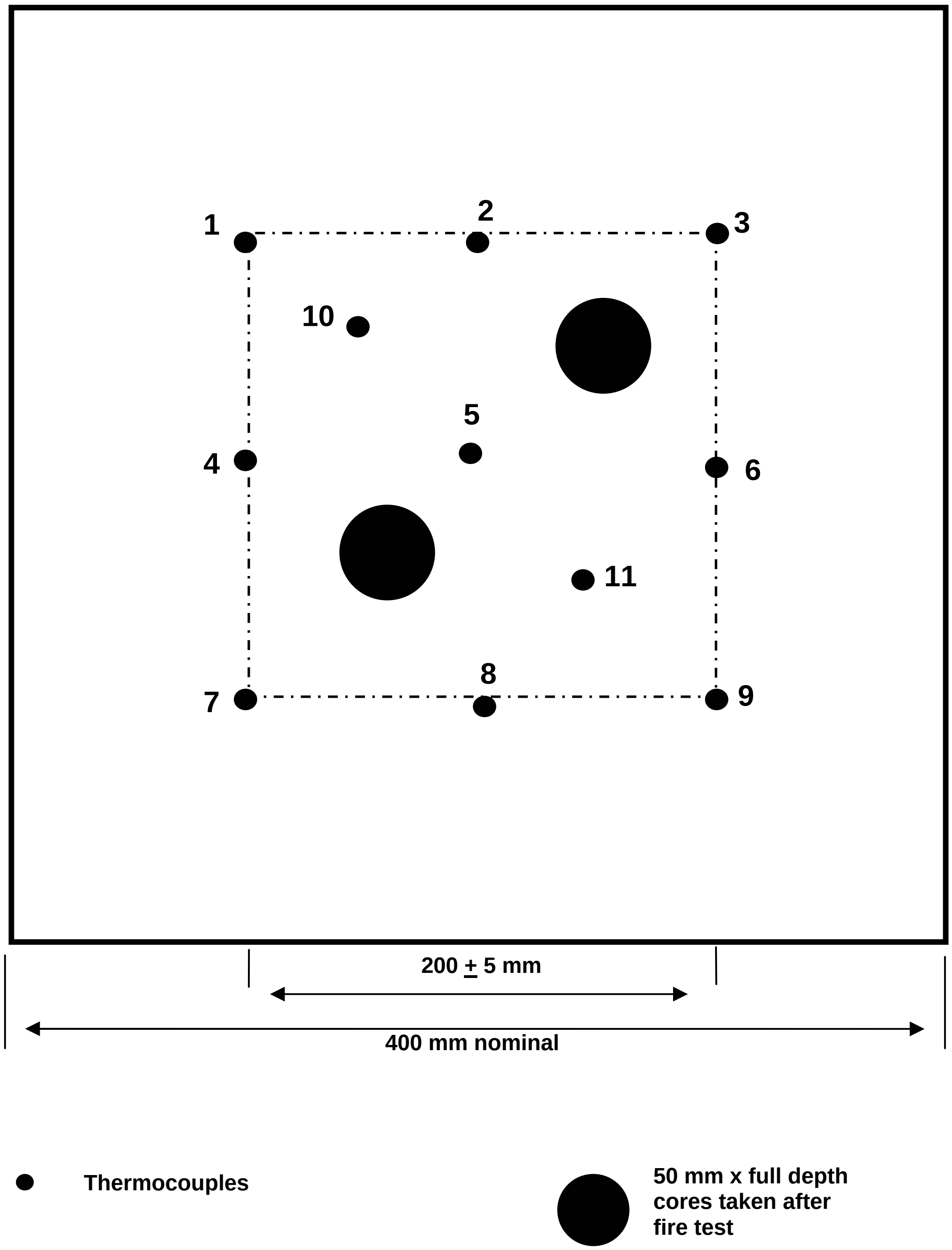
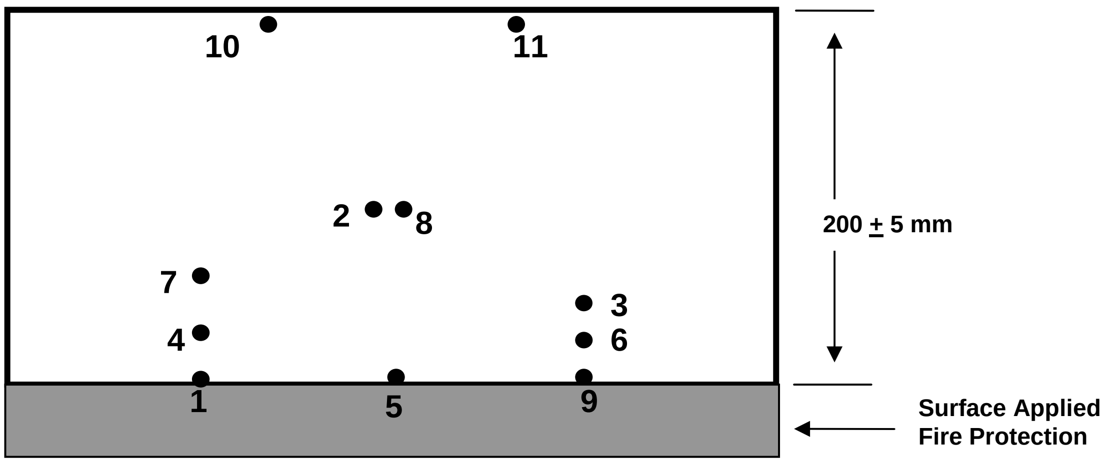


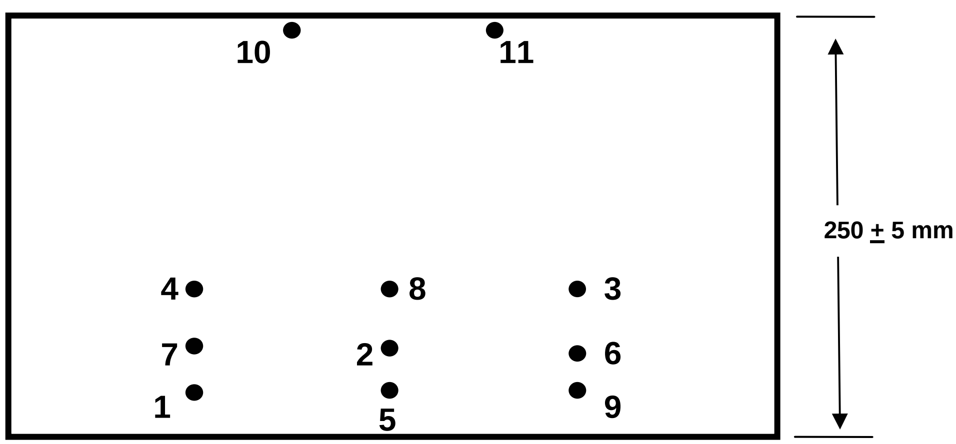
Figure 1.

Cross Section of Small Scale Test Slab
With Surface Applied Protection
(Not to scale)



3 thermocouples located at: the protection interface (1, 5, 9),
2 at 25 ± 2 mm (4, 6) , 2 at 40 ± 2 mm (3, 7), 2 at 75 ± 2 mm (2, 8), from the front surface of the concrete, plus 2 on the back face (10, 11).

Cross Section of Small Scale Test Slab
With Integral Protection
(Not to scale)



3 thermocouples located at: at 25 ± 2 mm (1, 5 & 9) , 3 at 40 ± 2 mm (2, 6, 7),
3 at 75 ± 2 mm (3, 4, 8), from the front surface of the concrete, plus 2 on the back face (10,11).

Figure 2.

8.3 Thermocouples, large scale test slabs.

See diagrams 3 and 4 (not to scale).

8.3.1 Surface applied protection systems.

4 thermocouples shall be fixed in the concrete at the protection interface.
5 thermocouples shall be fixed in the concrete at 25 ± 2 mm from the front of the test slab.
5 thermocouples shall be fixed to the underside of the reinforcement at 50 ± 2 mm
4 thermocouples shall be fixed in the concrete at 75 ± 2mm from the front of the test slab.
3 thermocouples shall be fixed in the concrete at the back face of the concrete test slab.

8.3.2 Integral protection systems.

4 thermocouples shall be fixed in the concrete at 25 ± 2 mm from the front of the test slab.
4 thermocouples shall be fixed in the concrete at 50 ± 2mm from the front of the test slab.
5 thermocouples shall be fixed to the underside of the reinforcement at 75 ± 2mm from the front of the test slab.
2 thermocouples shall be fixed in the concrete at 100 ± 2mm from the front of the test slab.
3 thermocouples shall be fixed in the concrete at the back face of the concrete test slab.

Plan View of Large Scale Test Slab

(Not to scale)

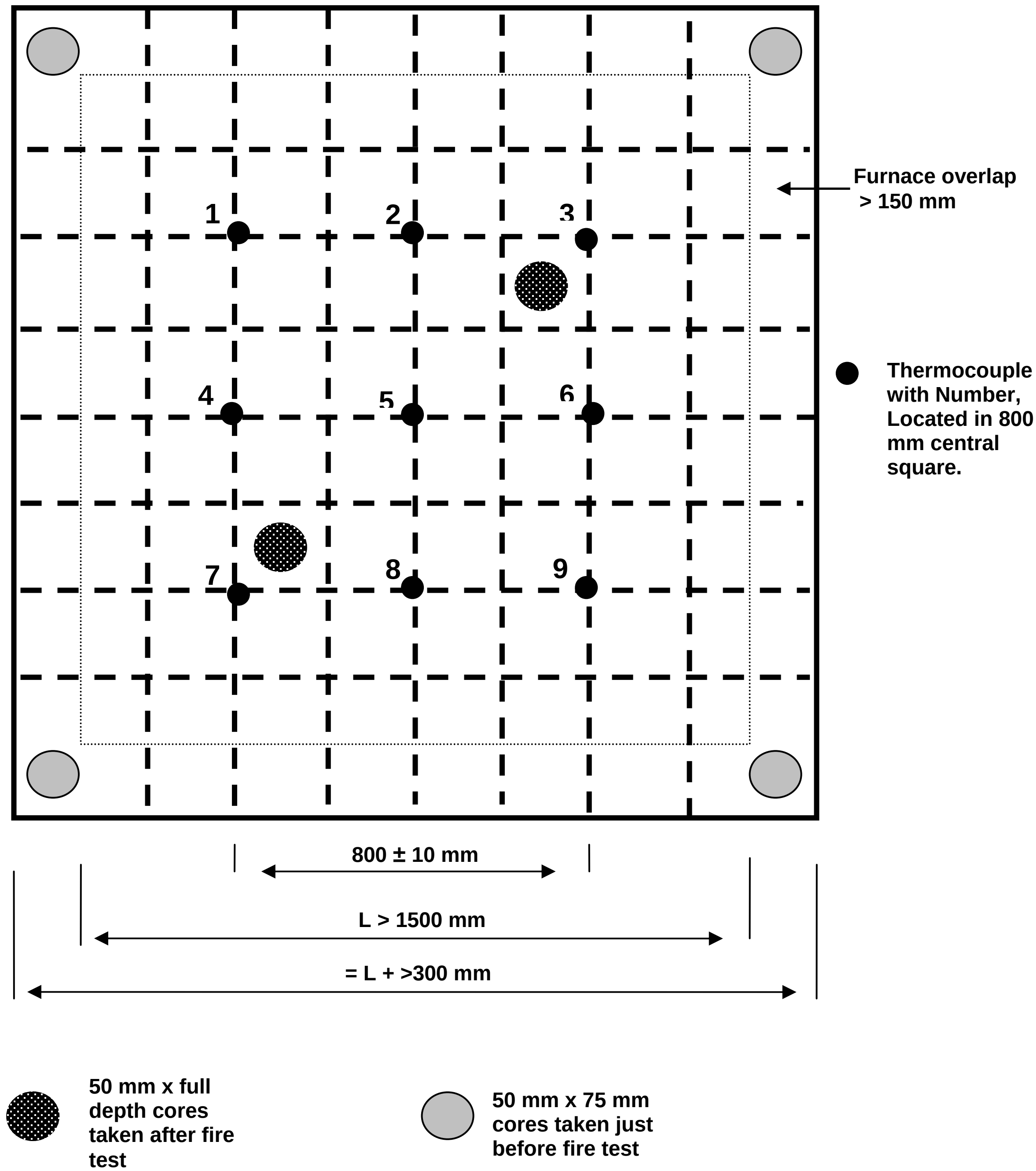
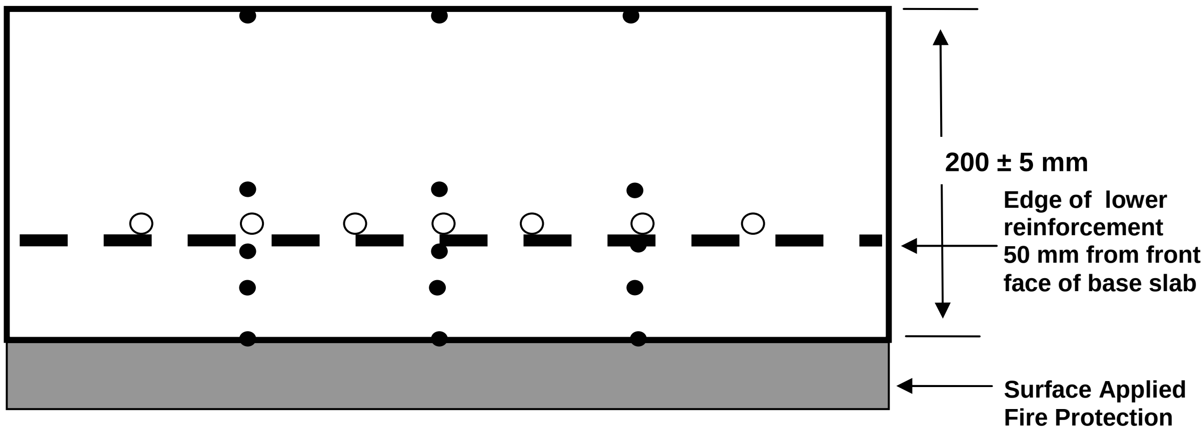


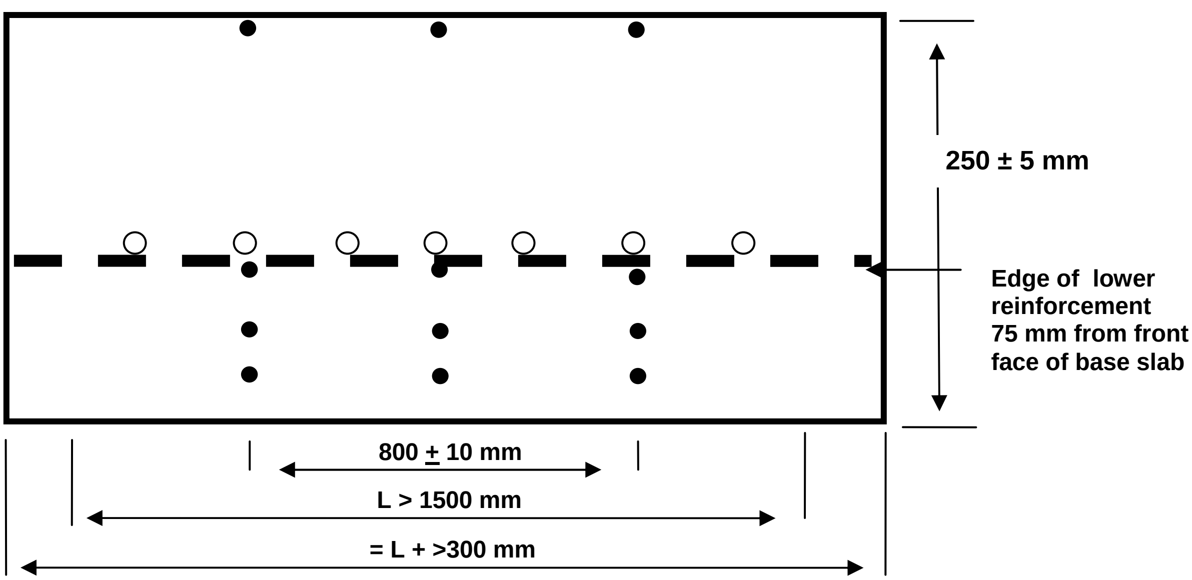
Figure 3

Cross Section of Large Scale Test Slab (Not to scale) With Surface Applied Protection



4 thermocouples located at: the protection interface (2, 4, 6, 8),
5 at 25 ± 2 mm (1, 3, 5, 7, 9,). 5 at 50 ± 2 mm fixed to underside of reinforcement (2, 3, 5, 7, 8),
4 at 75 ± 2 mm (1, 4 , 6, 9), from the front surface of the concrete.
3 thermocouples located the back face. (1, 5, 9)
See plan for number references.

Cross Section of Large Scale Test Slab (Not to scale) With Integral Protection



4 thermocouples 25 ± 2 mm the from the front surface of the concrete (2, 4, 6, 8),
4 at 50 ± 2 mm (1, 3, 7, 9) ,
5 at 75 ± 2 mm fixed to underside of reinforcement (2, 4, 5, 6, 8),
2 at 100 ± 2 mm from the front surface of the concrete (3, 7).. 3 the back face. (1,5,9)
See plan for number references.

Figure 4

9. Sample preparation and storage.

Requirements for sample preparation and storage apply to both small scale and to the large scale samples.

Two test regimes are given, a low humidity test slab and a high humidity test slab. The initial curing period is the same for both conditions.

The test slabs should be cast in accordance with the requirements of clauses 6, 7 and 8 of these guidelines.

If an integral protection system is being tested, this should be included in the concrete mix in accordance with the manufacturer's instructions.

Lifting eyes may be cast into the back of the slabs but should be sited as far from the thermocouples as possible (minimum distance 200 mm from any thermocouple).

In addition to the slabs, 3 cubes or cylinders shall be cast from the same batch of concrete for compressive strength testing to EN 12390 parts 1 to 4.

In the case of small scale tests coring the fire test slab to determine the humidity and core strength of the concrete is not technically acceptable. A 150 mm cube shall be cast and cured alongside each fire test slab and cored and tested as indicated in clauses 9.2 and 9.3.

9.1 Initial curing

The test slabs may be removed from the mould at any time after 24 hours.

From 24 hours after casting, the slabs shall be cured at 20 ± 2 ^{o}C and at >90 % RH till use.
Note: >90 % RH curing may be achieved by the use of wet burlap covered with plastic sheeting. The burlap shall be kept wet at all times.

Slabs shall be cured for at least 3 months before humidity conditioning as detailed in 9.2 and 9.3 below.
In the case of the small slabs, the 150 mm cube must be cured alongside the test slab at all times.

Comparative tests between different protection systems shall be carried out on slabs cast from the same batch and shall be tested at the same age.

If a cementitous protection system is being tested, the system shall be applied to the cast (mould formed) surface of the slab at any time after de-moulding, but before humidity conditioning, in accordance with the manufacturers recommendations and the requirements of clause 6.2 if applicable. Curing shall then continue as detailed above until at least 3 months after casting the slab.

9.2 Conditioning low humidity slabs

After the initial curing period, surface protection systems shall be applied / fixed to the cast (mould formed) surface of the slab in accordance with the manufacturers recommendations and the requirements of clause 6.2 if applicable.
The protection system should then be cured in accordance with the manufacturer's recommendations for the jobsite.

After applying/fixing and curing the protection system in accordance with the manufacturers recommendations, test slabs shall be stored at 20 ± 2 ^{o}C and 50 ± 10 % RH for not less than a further 28 days.

In the case of the small slabs, the 150 mm cube shall be cured alongside the test slab at all times.

Immediately prior to fire testing, a 50 mm diameter x 75 mm deep core should be removed from each of the back corners of the large slab or from the 150 mm cube in the case of the small slab. Two cores should be weighed, and then dried to constant weight at 110 ^{o}C to determine the free moisture content of the concrete.
From the other 2 cores, two 50 mm x 50 mm cores should be prepared and tested for in-situ compressive strength.

The slab should be fire loaded within 4 hours of removal from the storage condition.

9.3 Conditioning high humidity slab

After the initial curing period, the high humidity slab shall be stored under water at 20 ± 2 ^{o}C for 21 days.

In the case of the small slabs, the 150 mm cube shall be cured alongside the test slab at all times.

After this 21 day period, the surface protection system should be applied / fixed to the cast (mould formed) surface of the high humidity slab in accordance with the manufacturers recommendations and the requirements of clause 6.2 if applicable.
The protection system should then be cured in accordance with the manufacturer's recommendations for the jobsite.

The slab shall then be storage at 20 ± 2 ^{o}C and >90 % RH for at least 7 days.

Immediately prior to fire testing, a 50 mm diameter x 75 mm deep core should be removed from each of the back corners of the large slab or from the 150 mm cube in the case of the small slab. Two cores should be weighed, and then dried to constant weight at 110 ^{o}C to determine the moisture content of the concrete.
From the other 2 cores, two 50 mm x 50 mm cores should be prepared and tested for in-situ compressive strength.

The slab should be fire loaded within 4 hours of removal from the storage condition.

10. Furnace

10.1 Furnace for small scale samples

Furnaces shall have the capacity to increase the temperature up to 1400 °C at the time intervals required by the specified fire curve.

Samples may be placed horizontally or vertically in the opening of the furnace depending on the furnace design. The sample orientation must be included in the test report.

For precise placement of the sample a hydraulic sample holder is recommended.

The sample shall be sealed using fireclay sheets and rockwool packing to avoid heat loss and thermal gradients.

The furnace temperature shall be measured at a point 100 ± 5 mm in front of the sample in order to show compliance with the fire load curve.

If possible, the entire sample including the sample holder is placed on a balance to determine weight loss during the test. No part of the sample should touch the furnace walls to avoid reading errors. Heat loss and thermal gradients must also be avoided however some edge effects will occur and may result in different results from a fully sealed system.

10.2 Furnace for large scale samples

All samples, including those representing wall and ceiling elements shall be placed on a top opening furnace, unless otherwise specified.

The furnace shall have a minimum nominal top opening of 1500 mm x 1500 mm to accept the sample slab.

The furnace shall be designed to support the sample slab on two opposite sides only. The top shall be sealed with ceramic packing or a similar arrangement to prevent heat escaping from around any of the sides of the sample slab during the test.

The furnace may be fired with an oil burner or a gas burner and shall have the capacity to increase the temperature up to 1400 °C at the time intervals required by the tested fire curve.

The furnace temperatures should be measured at not less than 4 points 100 ± 5 mm below the face of the sample and not less than 100 mm from the walls of the furnace in order to show compliance with the fire load curve. The individual and average values shall be reported.

The oven should run at a positive pressure measured at a point 100 mm below the sample surface.

10.3 Furnace Temperature measurement and control

10.3.1 Type "K" thermocouples

Type K thermocouples, IEC 584-3, shall be used if the expected temperature is lower than 1100°C. A minimum of two thermocouples should be used to control the large furnace temperature, one for the small furnace.

10.3.2 Type "S" thermocouples

Type S thermocouples, IEC 584-3, shall be used if the expected temperature is higher than 1100°C. A minimum of two thermocouples should be used to control the large furnace temperature, one for the small furnace.

Thermocouples shall be calibrated and the date of last calibration of temperature measuring equipment should be recorded in the test report.

11. Fire test procedure

11.1 Handling

- A device to lift the samples into position on the furnace shall be used.
- The lifting device shall not be attached to or influence the test surface of the sample.
- The sample should be handled carefully to avoid any stress in the sample.
- The exposed surface shall be in a non-damaged condition at the start of the test.
- The test slab shall be located in such a way that no support is offered to the protection system by the furnace walls.

11.2 Start of test

- The fire load test can start only if:
- The temperature of the sample is lower than 50 °C.
- All measurement equipment has been calibrated and shown to be working.
- The sample is correctly placed on the furnace and all edges sealed.

11.3 End of the test

- The heating shall be stopped in accordance with the specified fire load curve
- Heating shall also be stopped if safety problems occur (stability of the sample)
- Monitoring shall be continued during the cooling phase according to the specified fire load
- If the test has to be stopped before the scheduled end, the reason has to be documented in the report.

12. Test parameters

The following parameters give information concerning fire protection and should be measured or observed during the fire test and included in the test report:

- Temperature time profile in the furnace
- Temperature time profile at the fire protection interface for surface applied protection systems.
- Temperature time profile at 25, 50, 75 and 200 or 250 mm from the front (furnace exposed) surface of the concrete test slab.
- Humidity for the concrete immediately prior to the start of the test.
- Spalling during and after the test
- Cracking during and after the test
- Behaviour of surface, observed after the test
- Core report, detailing observed damage with depth
- Compressive strength of structural concrete before and after testing.

Photographs of the test surface of the slabs should be taken before and after testing. Photographs should also be taken if there is observable damage to other faces of the slab after testing.

12.1 Temperature Time Profile

The test is intended to assess the temperature profile in the furnace, at the fire protection interface with the structural concrete and through the structural concrete. This will provide information on the thermal transmission of the fire protection and be indicative of likely residual strength of the concrete and the effect on any reinforcement placed within the concrete.

This information together with any samples taken from the test panel will enable the designer to establish the potential stability of the lining after exposure to a fire.

Graphs of the temperature time profiles at the interface, and each thermocouple level, should be drawn to assess the rate of heat transfer through the sample.

12.2 Humidity

Humidity of the structural concrete significantly affects its performance under fire load. The higher the humidity the greater the probable damage to the concrete, especially cracking and spalling.

The humidity in the concrete is determined as percentage moisture loss in 50 mm cores taken from the back corners of the slab, just before the fire test (clauses 9.2 and 9.3) as a percentage of the dry sample weight.

12.3 Spalling

Spalling may be difficult to observe during the test but may be audible to the technician.
If spalling occurs the following parameters must be reported:

- Time when spalling occurs (if detectable)
- Size of the spalled particles
- Area of spalling and maximum depth of spalling
- Amount of spalled material

Layers of material which are loosened during the test are assessed and reported.

For example, if steel fibres are used, some of the spalled particles are still connected by one fibre to the concrete.

It is also possible that a protection system has loosened from the construction. But for some reasons which depend on the construction of the sample/ test furnace this layer is still in place.

12.4 Cracks

Especially when the samples have a high bending rate, horizontal and vertical cracks may occur. If this can be observed during the test, the time when it occurs should be noted.
The location, number, width and spacing distance of these cracks shall be reported.

12.5 Behaviour of Surface

If the structure of the surface changes this has to be reported up to 48 h after the fire test. This could mean spalling, fragmentation or powdering.

The surface should be subject to mechanical probing to assess the depth of any soft or loose material.

The interface of surface applied materials should be checked for loss of adhesion.
The concrete below surface applied material should be checked for damage.

Some minerals will react after the fire test with the atmospheric humidity and degrade. This will normally happen within 48 h after the fire test.

12.6 Core report and compressive strength

At least one and preferably two full depth cores should be taken, close to the centre of the slab, coring from the back (non-fire exposed) face.

The core(s) should be inspected for all signs of damage to both the structural concrete and the fire protection system.
Particular attention should be given to the fire protection/concrete interface.

A report on the condition of the core should be produced in the form of a labelled diagram giving the condition and strength of the cores against depth from the front (fire exposed) surface. Photographs of the core should also be included in the report.

After completion of the visual examination of the core, a series of 50 mm x 50 mm cylinders shall be prepared, working from the exposed face of the concrete, and shall be tested for compressive strength in order to give a strength profile through the concrete. The strengths shall be shown a percentage of the strengths of the cores taken from the back of the slab just before fire testing. If the exposed face of the full depth core is too weak to be tested for compressive strength, the first 50 mm x 50 mm core should be taken from a point as close to the fire tested face of the full depth core as is reasonable and its location and those of subsequent 50 mm x 50 mm cores clearly shown on the core log.

13 Further Parameters

Further parameters may be requested in order to assess a fire protection system under specific conditions. For example:

- Behavior of the system under extinguishing water
- Residual bond strength of surface applied material
- Deformation of the slab or protection system

The above mentioned parameters will only be checked and tested when required by the client.

14 Test report

The test report shall contain the following:

a) Details of the testing establishment
- Name and address of the test institute
- Report number
- Name of technician conducting the test
- Date of test
- Sample references

b) Details of client:
- Name and address of client
- Details of tests requested:
  - Sample size
  - Humidity
  - Special instructions
- Information on materials/samples supplied by client

c) Details of deviations from these guidelines

d) Test concrete information:

- Mix design and materials details including cement type and aggregate type and size.
- A drawing of the test slab showing reinforcement size and location
- Date of mixing
- Sample size
- Compressive strength
- Curing regime (date log showing each stage, including length of curing, application and curing of protection system if applicable)
- Moisture content just before the test

e) Fire protection system:

- Name, supplier, reference of protection system
- Type and technical information
- Date of application
- Details of slab preparation before application of the protection system
- Method of application
- Drawing of the protection system showing the fixing and joint detail

f) Embedded thermocouples:

- Type
- Location (diagram)
- Calibration

g) Furnace:

- Furnace size and heating/combustion system
- Orientation of the test slab
- Type and location of thermocouples
- Calibration

h) Test results:

- Ambient temperature
- Average furnace temperature/time graph compared with specified fire load and the maximum deviation (see example in Appendix B).
- Individual Furnace thermocouple temperature/time graphs.
- Individual test slab thermocouple temperature/time graphs. (note which thermocouples are adjacent to joints/corners in the protection system)
- Average temperature/time graph from exposed to back of test slab.
- Information on spalling and cracking (12.3 and 12.4). Including drawing showing crack pattern if possible.
- Observation of surface after cooling (12.5)
- Specific observations on the protection system and underlying concrete at joints. This shall include details of any abnormal temperature profile at these locations.
- Core log (12.6)
- Compressive strength profile (12.6)
- Photographs before and after testing
- Other requirements or observations on test

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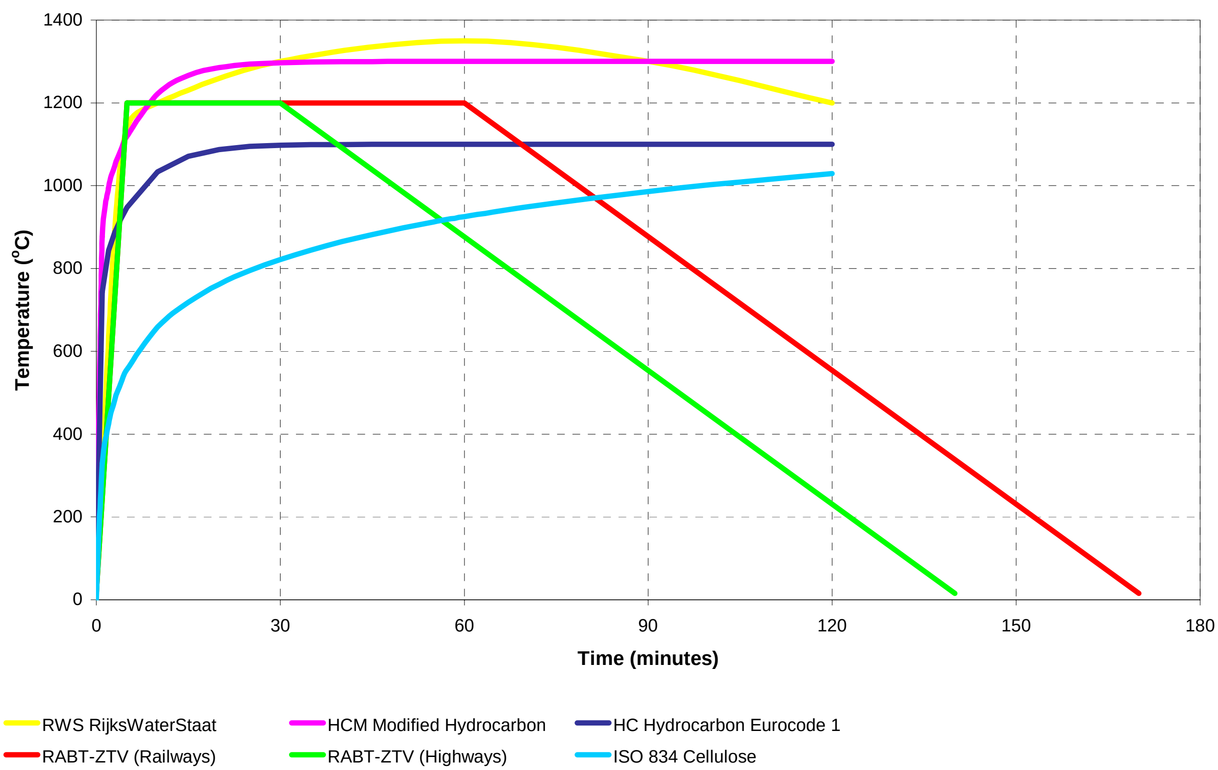
16 Appendix A: Examples of Fire Load Specifications.

This section outlines the fire loads typically used within Europe. Six "nominal" fire scenarios are shown, covering a wide range of fire conditions and fire severities.



RWS curve:

Specified by the Rijkswaterstatt, the Netherlands Ministry of Transport and one of the most widely used fire load curves for tunnels and is almost identical to the one specified in these guidelines. The RWS curve simulates a $50m^3$ petrol tanker fire with a fire load of 300MW lasting for 120 minutes. Originally based on testing in 1979, the curve has recently been verified following full scale tests in the Runehamar tunnel in Norway in the frame of the UPTUN project ordered by the European Commission. The tests demonstrated that fires by large vehicles develop temperatures as described by the RWS time – temperature curve.
The requirement is that the temperature of the reinforcement should not exceed 250 °C and the interface between the fire protection and the concrete should not exceed 380 °C.

Hydrocarbon curve (HC):

Developed for smaller hydrocarbon / chemical fires including those for the offshore and petrochemical industries where the fire is often less contained but the curve has also been used for tunnels and structures covered by Eurocode 1.

Modified Hydrocarbon curve (HCM):

A more severe version of the HC curve, developed to meet French regulations.
Recently, it has been proposed to replace the RWS curve with the HCM modified hydrocarbon curve (HCM). The RWS curve has a maximum temperature of 1350°C. The HCM curve has a maximum temperature of

1300 °C (both temperatures are near the melting temperature of concrete) but maintains it for a longer period than the RWS. The situation at the current time is that the RWS curve is still the more prevalent of the two and that some organisations are proposing that the RWS and HCinc live side-by-side and are essentially similar in terms of fire severity. It should be noted that fire “severity” is not only measured by the rate of heating (i.e. rate of temperature increase) and the maximum temperature, but also by the duration of the fire. Some fire curves contain a cooling branch, considered to represent more realistically the actual fire load scenario in tunnels.

RABT ZTV curve:

German requirement for tunnel fires. The temperature rises rapidly to 1,200 °C after 5 minutes, this temperature is maintained at a constant value for 25 minutes for highway tunnels and 55 minutes for train tunnels. It is then followed by 110 minutes of constant cooling to reach 20 °C. The requirement is that the temperature of the reinforcement should not exceed 300 °C.

ISO 834 curve:

Similar to the Cellulosic curve and given in some National Standards e.g. BS 476 DIN 4102, AS 1530. Originally intended for building applications and based on the burning rate of materials used in general building construction but it also been used for tunnels.

Dublin Port Tunnel (DPT):

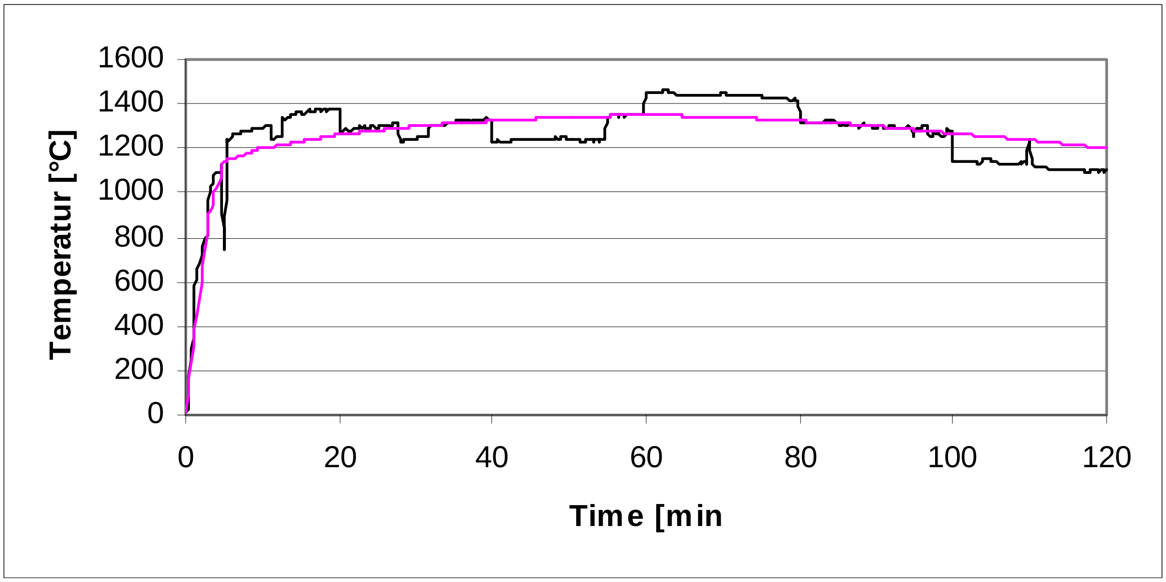
Fire curve for tunnels in which the temperature rises rapidly to
1020 °C after 4 minutes, 1130 °C after 10 minutes, 1170 °C after 15 minutes, 1190 °C after 20 minutes and 1,200 °C after 30 minutes. The 1,200 °C temperature is maintained at a constant value up to 120 minutes from start of the fire. It is then followed by a linear cooling rate commencing 120 minutes from start of fire to reach 20 °C after 230 minutes from start of fire.

17 Annex B: Fire Load – maximum deviation calculation and reporting

This annex gives an indication how to present and assess the fire load curve used in the fire test. The assessment process is independent from the actual used fire curve. Other requirements which are necessary for the full report (Chap.14) are not covered in this annex.

The example given is a fictional fire load curve which could have been realized in a fire test according the RWS-curve. The example shows that such a curve will fulfil the standards requirements concerning deviation.

Fig 1, Fictive results against RWS fire load



Continued:

Table of the fictive results for RWS curve

Time (min)	T_{RWS}	A_i	Σ A	$T_{measured}$	T_{max}	T_{min}	A_i measured	Σ A measured	Delta [%]	max	min
0	15			17							
0.25	88			50							
0.5	161			120							
0.75	234			245							
1	307			450							
etc											
4.75	1109			1132							
5	1140			750							
5.25	1143	285	285	1237	1314	972	106	106	-62.8	15	-15
5.5	1146	286	572	1232	1318	974	25	131	-77	15	-15
etc											
10	1200	300	5850	1292	1380	1020	25	581	-90.1	15	-15
10.25	1202	300	6150	1297	1322	1082	25	606	-90.1	10	-10
etc											
30	1300	325	30960	1245	1430	1170	311	14257	-54	10	-10
30.25	1301	325	31285	1246	1366	1235	311	14568	-53.4	5	-5
etc											
59.75	1350	337	70513	1350	1417	1283	338	52314	-26	5	-5
60	1350	337	70850	1450	1417	1283	350	52664	-25.7	5	-5
etc											
90	1300	325	110740	1301	1365	1235	325	94509	-14.7	5	-5
90.25	1299	325	111065	1308	1365	1235	326	94835	-14.6	5	-5
etc											
120	1200	300	148280	1098	1260	1140	274	129818	-12.5	5	-5

Key:

Time	Time from start of test in minutes
T_{RWS}	RWS fire load curve
A_I	Area under the specified temperature-time curve for on time interval
Σ A	Cumulative area under the specified temperature-time curve
$T_{measured}$	Temperature measured 100 ± 5 mm in front of the sample
T_{max}	Maximum allowed temperature, based on deviation
T_{min}	Minimum allowed temperature, based on deviation
$A_{i\ measured}$	Area under the actual test curve
$\Sigma A_{measured}$	Cumulative area under the actual test curve
Delta [%]	Deviation of scheduled energy consumption
max	Maximum allowed temperature deviation
min	Minimum allowed temperature deviation

Presentation of results against allowed deviation and assessment of realized fire load curve

The following graph shows the energy absorption of the fictional fire load curve presented in annex B Fig.1
The red bars mark the allowed deviations.

Up to 5 minutes there are no limitations concerning the deviation.

Between 5 and 10 minutes after starting the fire test a deviation of +/- 15 % of the scheduled energy consumption (100 – (Area under the measured temp.-time curve divided by the Area under the scheduled temp.-time curve [%]) is allowed.

From 10 to 30 minutes the allowed deviation drops to 10 %. After 30 minutes testing time the deviation should not be more than 5%.

Fig 2, Presentation of results against allowed deviation