Tunnel fire safety

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In forthcoming years, public and private transport in Europe requires large investments in infra-structural works. A significant part of the infra-structural works will consist of tunnels and other underground structures. Such structures have specific safety aspects. The safety of underground structures such as tunnels, is a point of increasing concern, both in Europe and elsewhere.
Main reason is the increasing road and rail traffic and increasing tunnel lengths. New innovative safety measures have to be defined to avoid an increasing incident frequency in tunnels and to avoid increasing consequences of the incidents both in terms of causalities and material damage, including traffic obstruction.
This paper briefly reviews the various aspects involved in the assessment of the structural integrity. Results of extensive research into three major infra-structural works are be presented: the fire safety of the tunnels in the High Speed Link, Betuweroute and the Western Scheld tunnel in the Netherlands. The results incorporate full scale fire tests investigating the structural integrity of high strength concrete tunnel linings.

Key words: tunnels, fire safety, concrete, structural integrity

1 Introduction

In the Netherlands, a large number of tunnel projects is currently being undertaken, e.g. (1) the Betuweroute, (2) the High Speed Link and (3) the Western Scheld tunnel.

Ad (1) The Betuweroute is a 160 km double track freight railway linking the Port of Rotterdam directly to the European hinterland [1].
Tunnels and covering (to a total of 20 km) include:
- Botlek: double bore 1.9 km tunnel
- Barendrecht covering: 1.5 km long covering both the tracks of the Betuweroute and the High Speed Line - a total of nine tracks
- Pannerdensche Canal Tunnel
- Sophia rail tunnel: double bore 7.8 km tunnel

Ad (2) In the High Speed Link from Amsterdam to Paris, the Dutch track has a large amount of civil engineering constructions covering tunnels, bridges and viaducts. The most important tunnel is the Green Hart tunnel: a single bore 15 m diameter 8 km long tunnel[2].

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Ad (3) The Western Scheld tunnel is a double bore 6.5 km long tunnel. Every 250 m, a connecting tunnel provides access from one tube to the other[3].

Besides these tunnel projects, bored subway tunnels and stations are planned in Amsterdam (North-South Line) and a rail system connecting major cities in the Western urban area (Randstad Rail). Also south of Rotterdam, the Benelux tunnel crossing is extended with an second immersed tunnel, comprising a separate road and subway section.

A key issue is that sections of the above tunnels had to be constructed in water bearing soil, and the survivability of the tunnel linings with regard to their structural integrity following a potential severe fire, was of particular concern.

Traditionally, in the Netherlands, tunnels were of the immersed type. The (normal weight) concrete quality for these types of tunnels is rather low (strength class up to C30). In the event of a fire, passive fire protection is applied on the roofs of the tunnel, extended to 1.0m over the walls. The main purpose of the passive fire protection is to limit the temperature rise of the (sagging) reinforcement in the roof, and thus prevent the premature collapse of the roof (development of a sagging plastic moment) and -as a consequence- leakage of the tunnel. This is schematically illustrated in Figure 1. Note that the walls are largely unprotected. The reason is that wall-reinforcement needs no or very little protection in thick walls.

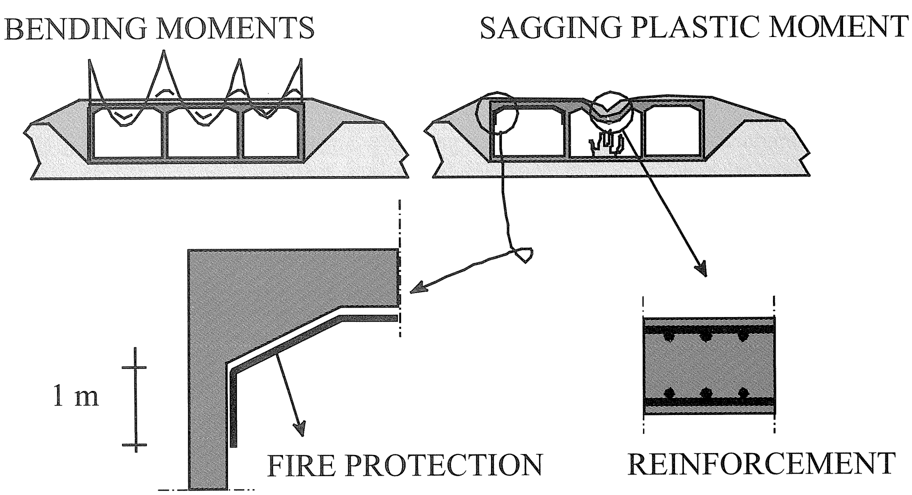

Figure 1. Protection of roofs and upper parts of the walls of immersed tunnels to limit the probability of structural collapse of the roofs in the case of fire.

Recently, another tunnelling technique is becoming popular in the Netherlands: bored tunnelling. Up to now, these tunnels are designed with segmented reinforced concrete linings. The reinforcement in the segments mainly functions during handling and during boring (jack pressures). After completion, the reinforcement in the segments is in fact obsolete; at least, the reinforcement is not there to take tension forces in sagging moment regions, because the concrete will be in compression (in ring direction). Another difference with respect to immersed tunnelling is that higher concrete strength classes are commonly applied (C50 and beyond). It is well known that -generally speaking- high strength concrete is more prone to so-called thermal spalling. Under thermal spalling is understood the sudden explosive disintegration of fire exposed concrete. Thermal spalling can be attributed to the combination of moisture clogging and stress clogging inside the concrete. The main function of the passive fire protection is therefore -only- to prevent explosive concrete spalling.

The behaviour of concrete under fire exposure is determined by the properties of the aggregates and the cement matrix, the moisture content, the pore structure and the loading conditions, in addition to the rate of heating and maximum temperatures attained.

The occurrence of thermal spalling depends on several factors, such as:

- the temperature development at the exposed side and consequently the occurrence of thermal stresses due to (partial) restraint of thermal expansion;
- external forces leading to (compressive) stresses in the concrete element;
- concrete composition and material properties (permeability, porosity, thermal expansion coefficients of its constituents, thermal conductivity, specific heat, compressive strength, fracture energy, etc.), as well as the (free) moisture contents (important in this respect are therefore also the compaction and curing conditions).

The above indicates that in general the concrete cube or cylinder strength determined 28 days after concrete casting has only little direct relation to the sensitivity of the concrete to thermal spalling.

For the assessment of the damage level due to thermal spalling for concrete tunnel linings which in service life may be exposed to severe fires, up to now, no adequate design guidance is at hand. In some tunnel projects, limitations are given to the concrete cube or cylinder strength, but as mentioned above that is only a (small) part of the story. Consequently, experiments are needed to approve certain solutions.

Mitigating measures against spalling focus at the first and latter influencing factors indicated above. In this paper, the results are described of recent full scale fire tests. In section 2, mitigating measures aiming at reducing the heat flow into the tunnel lining are discussed. In section 3, mitigating measures aiming at improving the lining resistance to spalling are described. Conclusions are presented in section 4.

2 Thermal insulation of the tunnel lining

Thermal

As mentioned earlier, most tunnels in the Netherlands were of the immersed type. In most cases, thermal insulation was provided by placing a board type material inside the formwork, prior to concrete casting of the tunnel. In road tunnels through which hazardous goods may be transported (except for e.g. LPG), the Dutch Ministry of Transport requires the structural integrity to be assessed on the basis of a severe 2 hour hydro-carbon fire, with maximum temperatures reaching 1350°C (the so-called RWS fire).

The Dutch Ministry of Transport had commissioned TNO to investigate the effect of the moisture content in the concrete of typical Dutch immersed tunnel concrete (340 kg/m^3 CEM III; river gravel aggregate; wcf 0.5) on the sensitivity to thermal spalling, under RWS fire conditions. Fire tests on unloaded concrete slabs, protected with 27 mm calcium silicate board (Promatect-H) indicated that with relatively high moisture content in the concrete (some 6% by weight), in combination with low moisture content in the insulation material (some 3% by weight), no spalling occurred[4]. Previous tentative research on test specimens cannibalised from existing tunnels in the Netherlands in the winter time, as well as laboratory tests indicated that the equilibrium moisture content of typical insulation materials is in the order of magnitude of 4-5 % by weight[5].

For the Western Scheld tunnel, the tunnel lining is made of -relatively- high strength concrete segments (C50-60; the concrete mix comprised CEM I (310 kg/m^3), river gravel (Rheinkies) and 80 kg/m^3 fly ash; wcf 0.36) with a thickness of 0.45 m and a width of 2 m. The tubes have a diameter of some 11 m. The tunnel is designed such that it can withstand the effects of the RWS fire, since it is open for the transportation of hazardous goods. RWS fire tests were conducted on full scale loaded segments. The loading, representative for the ground- and water pressure after completion of the tunnel, is applied by means of an internal pre-stressing system such that an overall uniform compressive stress (in ring direction) of some 12 N/mm^2 is achieved[6]. Results of the tests on protected tunnel segments are presented in Figure 2, in terms of measured concrete surface temperatures. The results of three tests are presented: with 23, 27 and 44 mm of calcium silicate board material (Promatect-H). Thermal spalling is indicated by the sudden sharp increase in temperatures; it occurred after some 30, 60 and 119 minutes of fire exposure. The later the onset of spalling, the more violent it appeared to be; also the thickness of the first pieces of concrete that spalled seemed to increase as the onset of spalling occurred in later stages of the fire.

From this Figure it becomes apparent that for the investigated cases, thermal spalling already occurs at temperature levels at the concrete surface ranging from some 160-220°C. Note that the moisture contents of the concrete were some 4% by weight and for the board some 3% by weight.

The relevance of the moisture content in the insulation material was demonstrated in a fourth fire test for the Western Scheld tunnel project, on a similar loaded tunnel segment, protected with

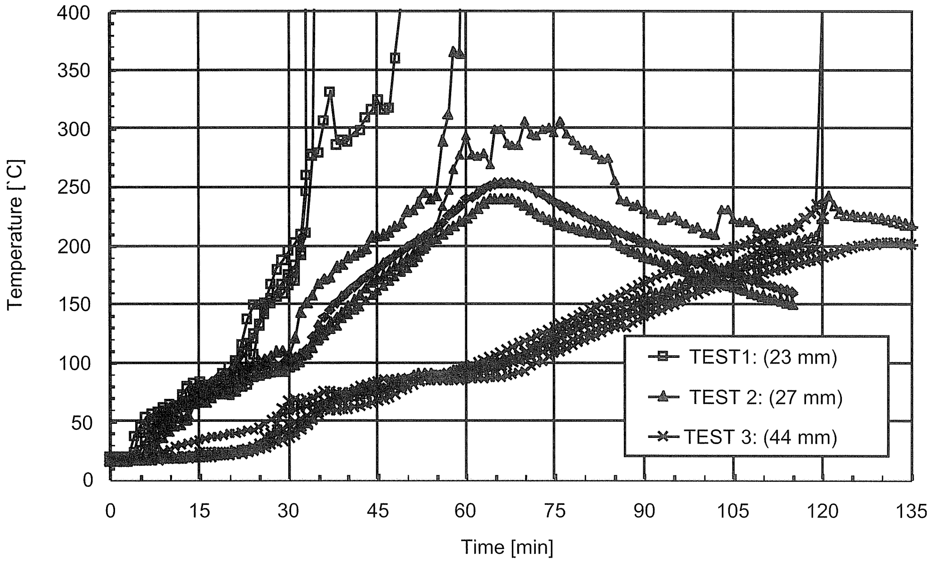

Figure 2. Results of RWS fire tests in terms of measured concrete surface temperatures: influence of board thickness.

51 mm layer of a cementitious vermiculite spray mortar (Fendolite MII). The moisture content was some 18% by weight. Apart from the insulation system, the test specimens and test arrangement was equal to the "Promatect-H" tests. Due to the unrealistically high moisture content in the insulation material[5], temperatures at the concrete surface did not rise above 100°C within 2 hours of RWS fire exposure. After that period, temperatures gradually increased up to nearly 300°C during additional 3 hours of heating at 1200°C, without any spalling[7]. Apparently the thermal gradients and heating rates in the concrete remained below critical levels.
Additional fire tests were performed with lower moisture contents in the Fendolite (some 4% by weight). Three tests, with a test arrangement identical to the "Promatact-H" tests, were performed: one with 42 mm and two with 45 mm. In the test with 42 mm, violent thermal spalling occurred after 170 minutes of fire exposure[8]. However, due to the scatter in results, it is extremely difficult to make conclusions about critical combinations of heating rate, thermal gradient and actual temperature level at the concrete surface, for this particular concrete and the applied external loading conditions. It is even more difficult to extrapolate to other concretes and other loading conditions and tunnel segment geometries.

Therefore, the Dutch Ministry of Transport also commissioned TNO to investigate the above mentioned assumption that the walls of immersed tunnels could be unprotected. For that purpose, a model was made of a part (2x2x0.8m) of an external wall of an immersed tunnel. The upper part of the test specimen (700 mm) was protected with Promatect-H (27 mm). External loading in compression was applied to a level of 10 MPa.

During the test on the loaded test specimen, no significant spalling occurred, only superficial damage occurred in the unprotected area.

The test furthermore proves[9] that the hypothesis of unprotected walls (with the Dutch immersed tunnel concrete!) is justified; i.e. the structural integrity of the walls is not seriously affected in RWS fire conditions.

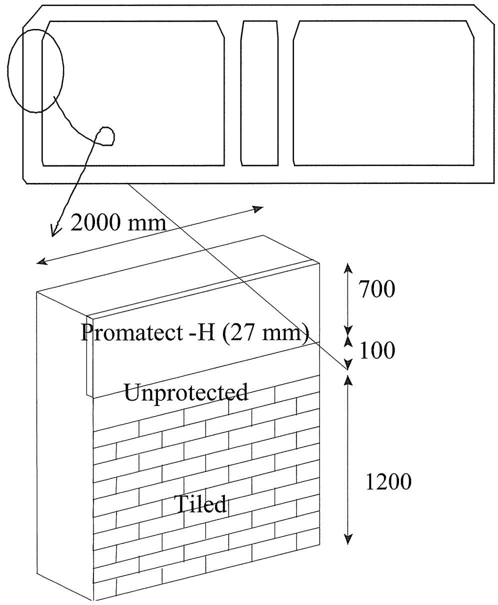

Figure 3. Test arrangement for wall of an immersed tunnel.

Effect of anchors

Anchorage systems used to suspend e.g. ventilators from the crown of the tunnel may cause problems. It is beyond the scope of this paper to address the failure mechanisms of the anchorage systems. However, in this paper, the adverse effect of the "heat leakage" into the concrete is discussed. It was found during tests for the Western Scheld tunnel that a sufficiently large heat leakage could invoke thermal spalling, despite the protection of the concrete surface with an insulation system. The separate fire tests were performed on loaded tunnel segments of running dimensions, under RWS fire conditions (for concrete mix details and the test arrangements and loading conditions, refer to the above mentioned "Promatect-H" tests). The tunnel segments were protected with 45 mm Fendolite MII (moisture content some 4% by weight); the anchorage systems were loaded to a realistic level at the onset of the fire tests, in order to create realistic boundary conditions. The research is ongoing, but already revealed that for the investigated cases, anchorage systems with unprotected single M8 and M10 bolts, protruding the Fendolite MII, the risk of thermal spalling did not significantly increase. However in the case of an anchorage system based on M16 bolts and a partly unprotected T- or L-steel plate (for suspension of ventilators), thermal spalling, reducing the structural integrity to an unwanted level, may occur. Research is now focussing on improvement of the ventilator anchorage system, a.o. by reducing the area of unprotected steel. To that end, 3D FEM simulations were made to optimise the anchorage system with respect to heat leakage[10,11]. Some typical results are plotted in Figure 4. In that Figure, the temperature distribution after 2 hours of fire exposure for the bolt (for practical reasons modelled as a square bolt) and the steel T-plate are plotted.

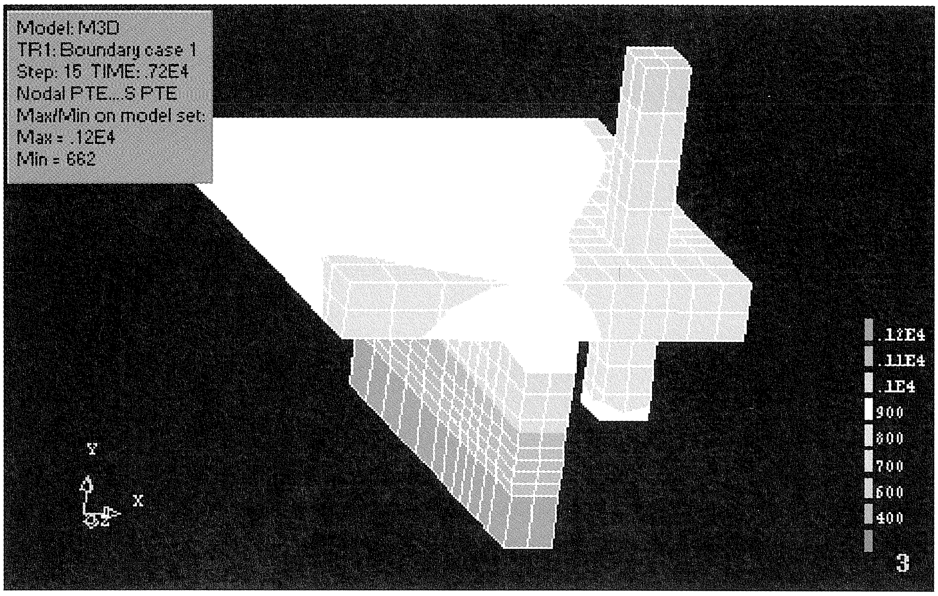

Figure 4. FEM simulation of penetration of heat via steel plate and M16 bolt.

Sprinkler fire test

In the Betuwe route, the safety concept prepared by the Dutch Ministry of Internal Affairs, prescribes a sprinkler system in the tunnels to be built. TNO was asked to prepare indicative tests, in order to determine a possible positive effect of the sprinkler on the structural integrity of the concrete lining in the event of a severe hydro-carbon fire which could not be extinguished by the sprinkler system. By means of hand calculations one could show that even a thin water-film on the concrete surface would be able to absorb the energy released from a severe hydro-carbon fire to such an extent that concrete surface temperatures would not exceed 100°C. Generally it is felt that the risk of loss of structural integrity due to thermal spalling is negligible at such low surface temperatures. A picture taken during the test is given in Figure 5.

Figure 5. "Sprinkler fire test".

Indicative fire tests on unloaded tunnel segments of running dimensions for the Botlek rail tunnel (concrete mix unknown) have shown that the hypothesis of water cooling of the concrete surface may work. It is noted specifically that the tests were not meant to demonstrate the effectiveness of the sprinkler system with respect to its primary function: prevent fire spread from one tanker-wagon to the other[12].
Based on the anchorage tests performed for the Western Scheld tunnel, it must be realised that even a small heat leakage may cause the onset of thermal spalling, which may lead to partial loss of functionality of the sprinkler system. Further research into this matter is therefore highly recommended.

3 Improving resistance of concrete tunnel linings to thermal spalling

As an alternative to external mitigating measures, one could think of internal measures. In principle, there are three options to improve the resistance to thermal spalling:

1 increase the permeability (preferably during fire, to avoid durability problems);
2 increase the fracture energy;
3 decrease differences in thermal expansion coefficients between aggregates and matrix.

The advantage of improving the resistance of the tunnel lining is that also in the construction phase additional structural fire safety is obtained.

As an alternative to these three options, one might consider composite steel-concrete tunnel linings. A limited number of such tunnel linings were actually used (in the USA and in Japan). In the Netherlands a desk study was performed as part of a feasibility study for the second Coen tunnel near Amsterdam. Because of the fact that the desk study showed that the composite steel–concrete lining was less cost-effective, further research was temporarily cancelled[13].

The theory behind thermal spalling in concrete tunnel linings is not yet fully developed. It is however felt by the majority of researchers that the development of high vapour pressures is a key factor. Mitigating measures have aimed at increasing the permeability at elevated temperatures by adding low-melt point polypropylene fibres to the concrete mix (option 1).

Polypropylene fibres
In the international literature on thermal spalling, the application of low-melt fibres in the concrete mix has been reported as a possible measure to prevent or limit thermal spalling. However, some researchers have serious doubts as to the actual effect of the fibres as well as the practical application. For that reason, the Dutch Ministry of Transport commissioned TNO to investigate on the basis of indicative tests the effect of polypropylene fibres on the fire behaviour of concrete slabs. Two different fibres were tested on unloaded slabs (1.5x1.5x0.35m; moisture content some 4% by weight), under RWS fire conditions, using the Western Scheld tunnel concrete mix design: test specimen 1 had 2 kg/m^3 monofilament fibres (type "23", length 12 mm, diameter 18 μm) test specimen 2 had 2 kg/m^3 fibrillated fibres (type 12-60F, length 12 mm, diameter 60 μm). The test results

showed that with monofilament the damage was only superficial, whereas with fibrillated fibres, the damage extended the whole heated surface and locally some 35 mm had spalled off[14].

The positive results with monofilament fibres lead to further research on loaded tunnel segments. For that purpose, 4 additional tests were performed with the same concrete mix, on loaded Western Scheld tunnel segments with running dimensions. The external loading amounted to 6 MPa; RABT-ZTV fire conditions were applied, with the modification that the gas temperatures after reaching 1200°C were kept constant at that level up to 120 minutes. In the 4 test specimens, the following dosages of fibres was used: 0, 1, 2 and 3 kg/m^3. It was found that the fibres had no significant effect on the compressive strength (some 60 MPa after 28 days) nor on the moisture content (4% by weight).

The results of the fire tests are presented below in terms of measured spalling depths[15].

Table 1: Recorded spalling depths (mm).

	0 kg/m^3	1 kg/m^3	2 kg/m^3	3 kg/m^3
Average	95	37	32	7
Minimum	5	0	0	0
Maximum	265	95	90	25
Standard deviation	65	26	29	8
Characteristic	203	80	79	20

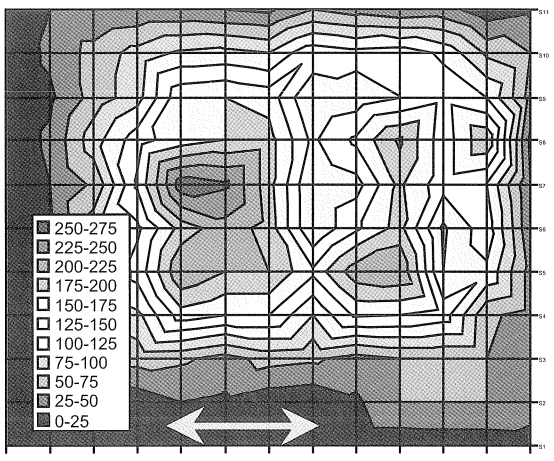

Figure 6. Spalling depths test 1 (0 kg/m^3)

From the point of view of structural integrity in fire, the test results suggest for the investigated cases the following conclusions:

- Without any measures, the structural integrity can not be maintained.

- The thermal spalling seems to be controllable using polypropylene fibres.
- Usage of polypropylene fibres to maintain structural integrity in fire deserves further attention in research programmes. The fibre volume and fibre type should be optimised for different applications (loading and heating conditions, concrete mix, ...);
- the workability of the mortar and durability of the concrete are items for further research.

Steel fibres

As thermal spalling is in fact a concrete cracking process, another way of mitigating damage could be by introducing steel (fibre) reinforcement (option 2). One must realise however that due to restraint to thermal expansion a complex stress situation occurs, with compressive stresses in the concrete close to the heated surface and tensile stresses further away from the heated surface. This situation may become critical if reinforcement allows the development of large tensile forces. Results of recent tests have suggested however that by adding steel fibres, spalling could be stopped. In a study commissioned by ITM, TNO first performed indicative fire tests to select the most appropriate mix (with and without polypropylene and steel fibres; C30 and C50 concrete). The polypropylene fibres were of the coarse fibrillated type, to an amount of 900 gr/m^3. For the steel fibres, 50 kg/m^3 was used. The indicative tests were done using 235 mm diameter, 500 mm long, cylinders, which were pre-stressed to 17 MPa. In the indicative cylinder tests, heating conditions were according to the German RABT-ZTV standard (hydro-carbon), with a modification that the maximum temperatures were kept constant at 1200°C for 2 hours. The test set-up was as depicted in Figure 7. By determining the weight loss, the spalling (rate) could be monitored during the fire tests. From the indicative tests it became apparent that the fibrillated fibres (at an amount of 900 kg/m^3), for the investigated cases, could not significantly improve the resistance to thermal spalling[16]. On the other hand, the steel fibres enhanced the fire performance. It was therefore decided, also on the basis of other practical reasons, to select the C50 mix for further investigation.

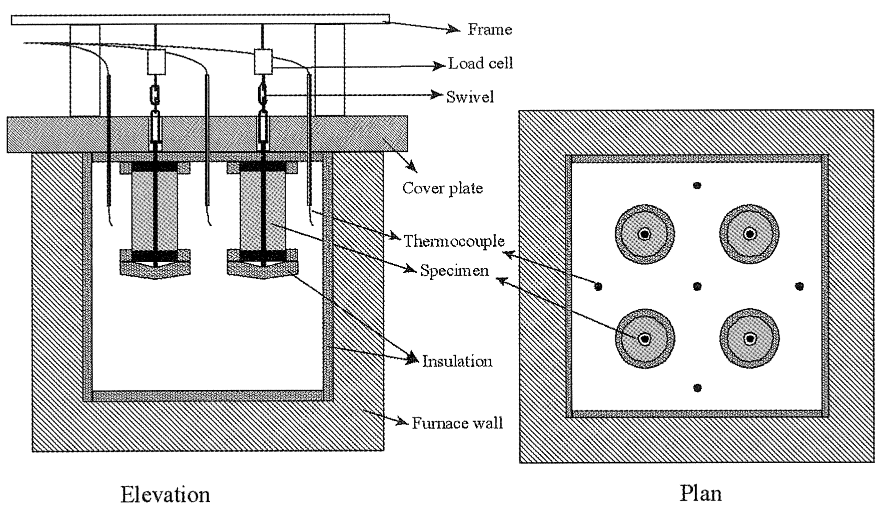

Figure 7. Test arrangement cylinder tests.

For that purpose, large scale segments were cast, with a thickness of 450 mm, for a tunnel with an internal diameter of 9 m. The tunnel segments were loaded to a ring stress level of 15 MPa. The test was duplicated in order to investigate the scatter in results.
The damage results were: average spalling depth of some 30 mm and standard deviation of approximately 20 mm (yielding a characteristic spalling depth of some 60 mm). The main conclusion was that although spalling was not completely prevented, the spalling seemed "controllable" by applying steel fibres. After cooling down, cores were taken from the test specimens to be used in microscopic analyses . This analysis revealed an additional layer of un-spalled, yet, damaged concrete of some 50 mm. This means that after a severe hydrocarbon fire of the RABT-ZTV type, some 110 mm must be considered as lost. For the investigated case, this was considered as feasible[17].

Additional problems arise due to the fact that by adding fibres, either steel and or polypropylene, the workability and/or the durability of the concrete may be adversely affected. Recent research aims therefore at combining fibres with other measures to improve for instance frost-resistance. It is considered of vital importance that a proper numerical model is developed, allowing to investigate the physical mechanisms and its relative importance, resulting finally in adequate combinations of mitigating measures. The Dutch concrete industry is preparing plans to investigate such a "cocktail" approach.

4 Nominal fire curves for the assessment of the structural integrity of tunnel linings

A realistic fire description can not be done in terms of nominal temperature time curves. Indeed a large number of factors would influence the temperature distribution in tunnels (ventilation, thermal inertia of the lining, fuel type and distribution, fire spread to other objects (cars, trains, ...), effects of active measures like sprinklers, etc.). The main factor is assumed to be the fuel type and its distribution (area) inside the tunnel, since these will determine to a large extent the heat release rate (MW). In design, to determine for each tunnel a realistic fire description is an impossible task, and design would be hampered.

For structural design therefore, simplifications can and should be made, as it is also done for buildings. For buildings, the fire safety is assessed by a "classification system" based on the ISO curve. The required fire resistance times (at 30, 60, 90, 120, 180, 240 min) depend e.g. on the "value", the height and complexity and use of the building and are primarily meant to allow for egress of occupants and intervention of the fire brigade.
In the Netherlands, a deterministic 2h 300 MW pool fire scenario (representative for a leaking crashed 50 m^3 petrol tanker) was agreed upon for immersed concrete tunnels through which limited hazardous goods are allowed to be transported, and a scale 1:2 test was developed to determine the effect of thermal insulation on the temperature development in the concrete linings. The tests indicated that, with an insulated ceiling gas temperatures could reach 1200-1400°C.
The curve extracted from these tests is the so-called RWS fire.

It should be noted that above 1100-1200°C, a significant number of ordinary building materials will disintegrate and would therefore be inappropriate to perform a thermal insulating function in higher temperature regimes.

For concrete tunnel linings, the RWS and the newly proposed (by PIARC) "modified hydro carbon fire" denoted as HCM fire ($(T(t) = 1280 * (1 - 0.325*\exp(-0.167*t) - 0.675*\exp(-2.5*t) + 20)$ will produce very similar safety levels, since the penetration of heat will be very similar and as also in the first minutes both curves rise very quickly, the effect of such fire scenarios will be similar regarding concrete spalling. Technically, the choice seems therefore rather arbitrary.

Both the RWS and HCM curve are hydro-carbon fires; whereas e.g. the ISO-834 curve is a cellulosic fire, which shows a much slower increase, and would not reach (only after very long fire exposure times) temperatures in excess of 1200°C. This means that by applying an ISO fire scenario, the risk of concrete spalling is underestimated in the case of tunnels through which hydro-carbons are allowed to be transported. The suggestion is to use only one fire curve (RWS or HCM) and vary in exposure time to underscore differences in "economic value" of the tunnel and length of the tunnel (ease for fire brigade to intervene; and for long underwater tunnels also for the safety of end-users!).

Finally, it is a good idea to try to distinguish in fire exposure times. Although the recent fires have shown fire exposure times can be much longer than 2 h. If reinstatement and retrofitting at acceptable costs is an issue for a certain tunnel, than it would be wise to -besides an RWS/HCM requirement of 2 h- to also consider the requirement of sufficient resistance to longer fire exposure times (at lower temperatures), up to say 4 to 8 h, especially for long tunnels and single bore tunnels for which it will be difficult for the fire brigade to reach the fire zone.

5 Conclusions

If the structural integrity in and after fires in tunnels is a point of concern, e.g. in the case that tunnels are located in water bearing soil, or when part(s) of the tunnel structures are used to maintain evacuation and rescue routes and ventilation channels, there are a number of options to maintain the integrity.
In the case of concrete tunnel linings, loss of integrity due to thermal spalling is a point of concern in the case that severe hydro-carbon fires can and must be expected in the tunnel.
In this paper the most current options to maintain the structural integrity during hydro-carbon fires are discussed on the basis of results obtained in large scale fire tests:

- application of passive fire protection by using thermal insulation;
- improving the resistance to thermal spalling by adding polypropylene and or steel fibres to the concrete;
- application of sprinklers.

The project organisations of the large tunnel projects currently undertaken in the Netherlands have commissioned TNO to investigate these options. It appeared from the tests that in all cases thermal spalling can be prevented or limited to acceptable levels; it is however premature to draw general conclusions for other situations (other concrete mixes, other heating and loading conditions etc.). The main reason is that the thermal spalling mechanism is only qualitatively understood and still not fully quantitatively. Further research in this area is highly recommended; the alternative is costly full scale testing for every tunnel project and consequently limited possibilities to investigate alternative mitigating measures. Finally research is recommended with a view to be able to determine the positive secondary effect of sprinklers on a more realistic scale.

6 Future

Obviously, the structural integrity is only one out of many issues to be dealt with in the case of fires in tunnels. It is beyond the scope of this paper to address these issues. However, the European Commission has emphasised the relevance of addressing all issues related to fires in tunnels. In fact three projects are recently granted in the scope of the 5th Framework Programme (the EU research and development programme): a thematic network (Fire In Tunnels – FIT) and two R&D projects (Durable and Reliable Tunnel Structures – DARTS; cost-effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels - UPTUN). In these projects, a.o. human factors and active suppression systems will be investigated and evaluated. FIT and DARTS have started in 2001; UPTUN has started in September 2003. In all projects, active dissemination is dealt with in dedicated tasks or work-packages, which no doubt will be brought to the attention of all those interested in future conferences and seminars. (www.uptun.net)

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