FIRE PROTECTION OF CONCRETE TUNNEL LININGS

Peter Shuttleworth
Rail Link Engineering. UK

ABSTRACT

The Channel Tunnel Rail Link (CTRL) is the UK's first major new railway for over a century – a high-speed line running for 108km (68) miles between the Channel Tunnel and central London. The project includes over 40 kilometres of 7.15 metre diameter, precast concrete lined bored tunnels, sections of which are to be constructed in water bearing sand.

Following the major fire in the Channel Tunnel in 1996 and the resultant damage caused by explosive spalling to the conventionally reinforced concrete tunnel lining, concerns were raised regarding the survivability of the tunnel lining with regard to its structural integrity following a potential fire

This paper outlines a series of tests that were commissioned to evaluate how different materials performed in a fire, to determine under what circumstances spalling occurs and how to improve the integrity of the lining when exposed to credible fire scenario.

1 INTRODUCTION

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

When heat penetrates concrete it results in desorption of moisture in the outer layer most of the water vapour formed will flow towards the cold interior of the concrete and be reabsorbed in the voids. As the thickness of the heated outer layer gradually increases, an accumulation of water and vapour occurs in the voids behind.

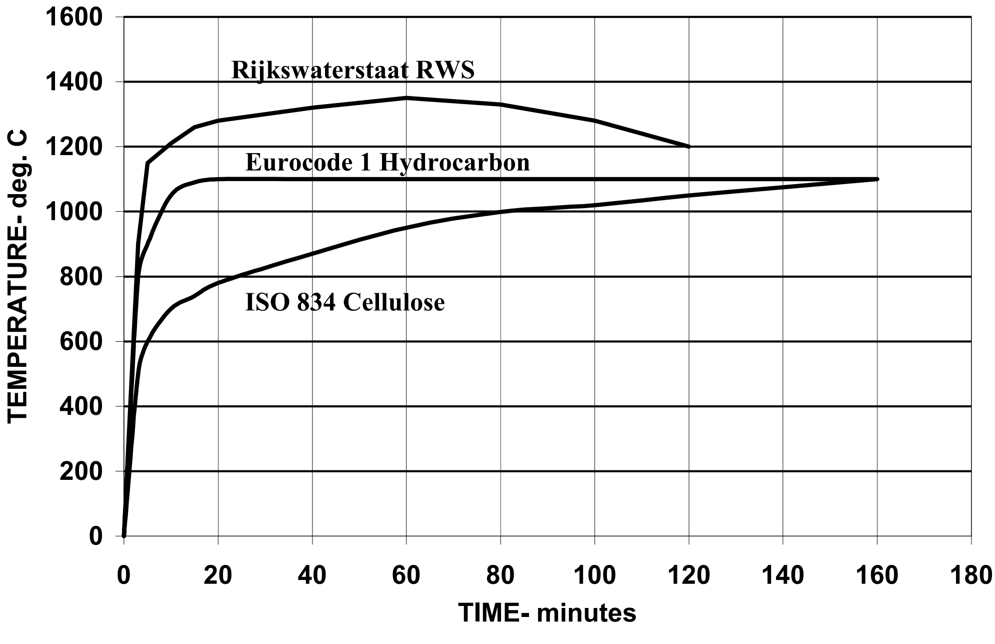
The rate at which this moves away from the heated face depends on the interior void structure and the heating rate. Once the saturated layer cannot move fast enough through the pore structure it is overtaken by the advancing heat front, which causes the water to evaporate at the interface and due to the rapid rise in temperature and the restrained expansion, the vapour pressure rises rapidly. If the tensile strength of the concrete is not sufficient to resist the tensile forces produced by the vapour pressure, a layer of shallow depth will be dislodged suddenly from the surface in the form of explosive spalling. This can occur repeatedly. High strength, low permeability concretes are more prone to this mode of failure, particularly if they have a high internal moisture content.

1.1 Preliminary Investigations

Whist at present no standard test methods exist to determine the serviceability of tunnel linings, the test programme instigated for the CTRL project was designed to simulate the effects of a fire on an insitu lining by exposing samples to a fire loading on one side only. The object was to obtain data on the propensity for explosive spalling and the measurement of thermal and mechanical properties during and after exposure to fire

Various time temperature curves exist that represent different fire scenarios and three commonly used standards were applied to the CTRL trials, which increased in severity as the proposed options were narrowed down. [*1*]

Fig 1. STANDARD FIRE CURVES USED IN CTRL TESTS



At the outset there were many alternative material sources available to any prospective segment manufacturer in the UK or indeed throughout Europe and therefore a preliminary desk top study was carried out to identify the most viable options based on documented evidence of their performance in conventional fire tests.

This report concluded that three types of aggregates should be investigated: -

Limestone – considered the best naturally occurring aggregate in fire and plentiful supply.
Granite – Low coefficient of thermal expansion. Plentiful supply.
Lightweight Aggregate – Used in common building blocks and refractory concrete.

Additionally, polypropylene fibres had been reported to reduce the risk of explosive spalling in high strength concretes [2,3,4], so two types of fibres commercially available were included in the trials. These were monofilament and fibrillated fibres.

Steel fibres had already been specified for inclusion in the tunnel segments in place of conventional reinforcement and therefore were also included to assess their contribution to fire resistance.

2 INITIAL TEST PROGRAMME

Given the various material sources identified above, the initial test programme was developed to enable all possible combinations of mix constituents to be fire tested under identical conditions and a comparative assessment made of the performance of each individual component

With this aim a total of 15 rectangular concrete slabs were cast with different combinations of aggregates and fibre types (see table 1). These were all cast and conditioned in exactly the same way to prevent any moisture loss prior to testing.

The slabs were simply supported over an open top gas fired furnace and exposed to a standard cellulose fire to the ISO 834 curve for a period of 2 hours. Although not considered to be a particularly extreme fire, it did demonstrate that spalling occurred on all concretes not containing fibres, whereas the addition of polypropylene fibres did significantly reduce the risk of spalling.

This was no more clearly demonstrated than with the mixes containing lightweight aggregate, which totally disintegrated during the test due to the high moisture content of the concrete caused by absorption in the individual particles of coarse aggregate. However with the addition of polypropylene fibres to the same mix there was no evidence of any spalling. There was also evidence that suggested monofilament fibres provided greater resistance to spalling than fibrillated fibres and that the addition of steel fibres had no beneficial effect on the propensity for spalling.

Table 1 – Initial test data

MIX	AGGREGATES	STEEL FIBRES	MONO FIBRES	FIBRIL FIBRES	OBSERVATIONS DURING TESTS
1	GRANITE	x	x	x	SPALLING VISIBLE AFTER 30 MINS
2	GRANITE	YES	x	x	SPALLING VISIBLE AFTER 20 MINS
3	GRANITE	YES	YES	x	NO EVIDENCE OF SPALLING
4	GRANITE	YES	x	YES	MINOR SPALLING VISIBLE
5	GRANITE	x	YES	x	NO EVIDENCE OF SPALLING
6	LIMESTONE	x	x	x	SPALLING VISIBLE AFTER 20 MINS
7	LIMESTONE	YES	x	x	SPALLING VISIBLE AFTER 20 MINS
8	LIMESTONE	YES	YES	x	NO EVIDENCE OF SPALLING
9	LIMESTONE	YES	x	YES	MINOR SPALLING VISIBLE
10	LIMESTONE	x	YES	x	NO EVIDENCE OF SPALLING
11	LYTAG	x	x	x	EXTENSIVE VIOLENT SPALLING
12	LYTAG	YES	x	x	EXTENSIVE VIOLENT SPALLING
13	LYTAG	YES	YES	x	NO EVIDENCE OF SPALLING
14	LYTAG	YES	x	YES	EXTENSIVE SPALLING
15	LYTAG	x	YES	x	NO EVIDENCE OF SPALLING

3 TESTING OF INSITU LINING MIX

On the basis of this information further testing was then carried out with the proposed mix for the cast insitu lining of the North Downs Tunnel in the Kent section of the project, which was then under construction.

Samples containing granite aggregates and monofilament polypropylene fibres were exposed to the more severe hydrocarbon fire curve that rises rapidly to 800°C in 3 minutes and peaks at 1100°C. These tests also compared the performance of two sizes of monofilament polypropylene fibres, 18µm and 32 µm diameter, at dosage rates of 1 and 2 Kg/m³.

The samples were also subjected to compression forces during the test equivalent to the design loadings predicted in the tunnel lining, to resist some of the early thermal tensile cracking witnessed during the previous trials.

All samples performed well in the tests with no evidence of explosive spalling on any test pieces apart from a plain control sample without any fibres included which suffered extensive damage within the first 20 minutes of the test. Fig. 2.
This confirmed the evidence obtained from the initial test program.

Fig 2 Samples After Test

CONTROL WITH POLPROPYLENE FIBRES

4 FULL SCALE SEGMENT TESTS

To provide final confirmation of the fire resistant properties of the CTRL precast concrete tunnel segments, a single fire test was performed at the TNO Fire Research Centre in the Netherlands. Three full scale segments of identical dimensions but different concrete mixes were simultaneously exposed to a very severe fire scenario represented by the Rijkswaterstaat (RWS) curve, developed by TNO for the Ministry of Transport in the Nertherlands,

The segments had an internal radius of 3575 mm, a width of 1350 mm and a thickness of 350 mm. Each segment contained 4 pre-stressing ducts spaced evenly over the width of the segments, positioned at mid thickness to enable an equally distributed compressive stress in ring-direction of 10 Mpa to be applied, equivalent to the maximum service conditions in the CTRL tunnels.

4.1 Concrete mixes

The 3 test specimens were made containing polypropylene and steel fibres with both Granite and Limestone aggregate, as the previous tests had not established any appreciable difference between the performance of the two aggregates types. The effectiveness of both the 18 and 32 µm diameter polypropylene fibres was again assessed with the more severe fire loading.

Table 2 Concrete mixes.

Mix A	C60 Granite mix	
	cement	438 kg/m^3 cement
	water/cement ratio	0.35
	steel fibres	30 kg/m^3 Steel Fibres
	polypropylene fibres	1 kg/m^3 18 micron monofilament
Mix B	As Mix A, except for:	
	polypropylene fibres	1 kg/m^3 32 micron monofilament
Mix C	C60 Limestone mix	
	cement	400 kg/m^3
	water/cement ratio	0.34
	steel fibres	30 kg/m^3 Steel Fibres
	polypropylene fibres	1 kg/m^3 18 micron monofilament

Immediately after de-moulding, the test specimens and cubes were tightly wrapped in polythene sheeting and stored indoors until transportation to the testing facility. The polythene was removed two days before testing to allow for preparation of the sample on to the furnace.

4.2 Instrumentation and measurements

Thermocouples were positioned at 6 locations within the samples at 4 depths from the surface to be exposed to fire (25, 50, 100mm and at the pre-stressing duct) to measure the temperature profile throughout the samples during testing.

The gas temperatures in the furnace were measured with 8 mantle thermocouples, positioned in the two joints between the test specimens
The gas temperatures and the temperatures in the concrete were recorded every minute.

The test specimens A, B and C were positioned on the horizontal furnace and the joints between the test specimens were sealed with ceramic blanket and on the extrados covered with mortar.

Besides the thermocouple readings, the following items were measured:

- Cube samples were taken from each mix and cured under similar conditions to the segments. Compressive strength, density and moisture contents were obtained a day prior to the fire test;
- 4 cylindrical cores were taken from each segment after fire testing and the retained strength was determined on the basis of three cylinders taken from each core for compressive strength.

Table 3 Measured strength properties and densities of concrete.

Mix	compression [MPa]	density [kg/cu.m]	Moisture Content
A	81.6	2370	3.4
B	75.2	2415	2.9
C	85.6	2440	3.0

4.3 Observations

Table 4 describes the observations noted during the actual test period, which could only be monitored remotely by video and sound transmission for safety reasons.

Table 4 Observations during fire test.

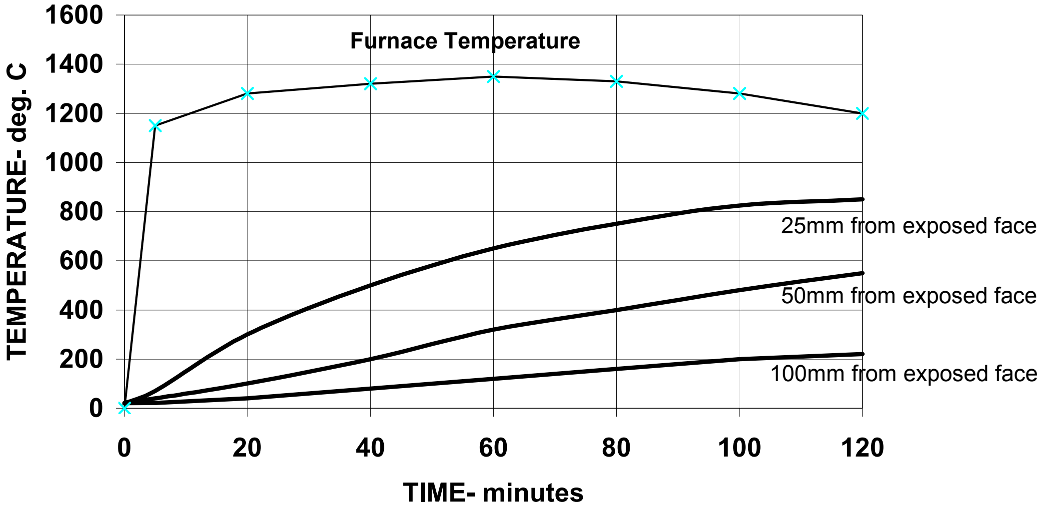
Time [min]	Observation
0	start of the fire test
2	light crisping noises, indicating spalling
3	moisture escapes from the sealing at the edges
6	crisping spalling noises, but also small popping sounds
15	crisping sound has stopped, no spalling sounds audible
18	cracks on extrados of A1 and C1, above and parallel to ducts, moisture escapes through crack
20	also first crack on extrados of B1
50	3 to 4 cracks have developed on extrados of all test specimens
120	heating stopped; end of measurements

Figure 3 represents the typical temperatures recorded within the test specimens which for segments A and C were quite constant across the exposed area, Mix A (Granite) showing slightly higher recorded temperatures than mix C (Limestone)

However in segment B the readings of 3 thermocouples at 25mm depth went as high as the furnace temperature which suggested the thermocouples had been exposed in that area due to loss of covering concrete.

The thermocouple readings and spalling noises heard during the test suggest that the spalling occurred within the first 2-20 minutes. In that period the temperature of the pre-stressing strands hardly increased, so no significant reduction in pre-stressing loads are likely to have occurred.

Fig.3 Typical temperatures within segments during test



4.4 Spalling depth / loss of thickness

After completion of the test and the samples had cooled down they were removed from the furnace and visually inspected.

The exposed surfaces of the test specimens A and B (granite mixes) were coloured shiny black, as opposed to the mostly dull white/yellow surface of test specimen C (limestone mix). The overall exposed surface of A and B and some parts of the exposed surface of C showed a thin layer of coagulated material, probably melted cement. Furthermore, especially the exposed surface of A and B showed small 1-3 cm black stalactites, probably also melted cement and or granite. At some places, in all cases, it was possible to take small pieces up to a thickness of some 5-10 mm of concrete, which could easily be crumbled (both cement paste as well as aggregate had completely dehydrated and disintegrated). Horizontal cracks, parallel to and at some 5-20 mm from the intrados could be observed at some locations in all test specimens.

The spalling depths were measured at 63 points, in a regularly spaced grid, which showed a reasonably regular pattern for test specimens A and C with an average loss of thickness between 5 and 15mm. However on segment B there had been an area approximately one third of the specimen (which had been the lower area during casting) that had suffered deeper spalling, between 20 and 60mm deep. The remaining area, being similar to the other samples.

The results are summarised in the table below.

Table 4.3 Measured total loss of thickness i.e. spalling depths in mm (the charactersitc value is determined as average + 1.64 standard deviation).*

	min	max	average	st.dev	Characteristic value
A1	0	15	6.0	3.6	11.9
B1	0	60	19.6	17.2	47.7
C1	5	25	14.3	4.9	22.2

As the measurements were taken after cooling down, the measured total loss of thickness can be larger that the actual spalling depth (loss of thickness during heating), since after cooling down material may have fallen off as contraction of the concrete takes place.

4.5 Retained strength properties

From each tested segment 4 cores, diameter 100 mm, were taken. The cores were bored through the entire (remaining) thickness of the segments. The upper 300mm (relative to extrados) from each core was used to make 3 "individual" cores, which, after cutting, had a length of 95 mm.

From the individual cores, the compressive strength was determined. The average results are given in Table 6 a-c together with the retained strength expressed as a percentage of the results obtained from the cubes. In general, the cores outer surface did not show significant damage or extensive cracking. Only in the unused area, damage (mostly horizontal micro cracks) was visible.

Table 6a - Retained Strength Properties Mix A

Core Depth From Exodos	Compressive Strength Mpa	% Retained Strength
0-100mm	76.5	94.0
100-200mm	70.5	86.5
200-300mm	59.5	72.5

Table 6b - Retained Strength Properties Mix B

Core Depth From Exodos	Compressive Strength Mpa	% Retained Strength
0-100mm	75.5	100
100-200mm	69.0	92.5
200-300mm	59.3	79.0

Table 6c - Retained Strength Properties Mix C

Core Depth From Exodos	Compressive Strength Mpa	% Retained Strength
0-100mm	82.0	95.5
100-200mm	73.6	86.0
200-300mm	61.0	71.5

Although the number of tests results are not sufficient to make any statistical assessment the figures would indicate that the percentage retained strengths are of similar values for all 3 mixes with the area nearest the exposed face having an average retained strength of some 74%.

5 CONCLUSIONS

The concrete linings of the tunnels along the Channel Tunnel Rail Link (CTRL) need to have sufficient structural integrity in the event of fire.

After two initial test programs that gave good indications of the most effective mix constituents for passive fire protection a full scale fire test was carried out to investigate the behaviour of three concrete mix designs under specific loading (both thermal and mechanical) comparable with service conditions.

From all measurements, and visual observations during and after the fire tests, the following conclusions are drawn:

(1) The inclusion of $1Kg/m^3$ of monofilament polypropylene fibres in the high strength, low permeability mixes tested significantly reduced the risk of explosive spalling when exposed to severe hydrocarbon fires.
(2) There appeared to be no significant difference in the performance of Limestone or Granite aggregates in the test programme.
(3) Steel fibres did not contribute to the ability of these concrete mixes to resist explosive spalling when used without polypropylene fibres.
(4) The retained strength of concrete towards the face exposed to the severe hydrocarbon fire (RWS), where the internal temperatures exceeded 800ºC was in the region of 75% of the comparative cube strength of the mix.

6 REFERENCES

[1] Both, C., Haar, P.W. van de., Tan, G.L., Wolsink, G.M., 1999, "Passive fire protection measures for concrete tunnels", Fire security in hazardous enclosed spaces, 8 & 9 November 1999, Vernon, France.

[2] Both, C., Graaf, J.G. van der, Wolsink, G.M., 1999, "Fibrous concrete, safe and cost effective tunnels", Tunnel fire and safety – Int. conference 2&3 December 1999, Rotterdam, The Netherlands

[

[3] Nishida A et al, Schneider U. and Diederichs U. " Study on the properties of high strength concrete with short polypropylene fiber for spalling concrete." Proceedings of the International Conference on Concrete Under Severe Conditions (CONSEC '95) Sapporo Japan June 1995 pp1141-1150

[4] T. Lennon and N. Clayton, "Fire tests on high grade concrete with polypropylene fibres" 5^{th} International Symposium on the Utilisation of High Strength/High Performance Concrete, Savdejord, Norway, June 1999