Spalling of high strength concrete in fire

O Lalu1, R Darmon2* and T Lennon1

1 Building Research Establishment, Watford, United Kingdom
2 Technical University of Cluj-Napoca, Romania

* ruxandra.darmon@ccm.utcluj.ro

Abstract. This paper reviews a series of experimental tests programmes undertaken at BRE in the UK on the performance in fire of high strength concrete with a particular focus on mix design to assess the effects of spalling. The experiments include a series of fire tests on reinforced and unreinforced concrete columns and tunnel linings. The paper will provide information on the parameters that lead to explosive spalling of tunnel linings in a fire situation and on the measures available to mitigate this hazard.

1. Introduction

Concrete structures generally perform well during and after a fire and the majority of fire-damaged concrete structures have been repaired and reused [1, 2]. Although spalling of concrete structures following real fires has been observed, it does not necessarily have implications for the stability of the structure [3, 4]. There is a need to establish the circumstances under which spalling would have serious consequences. The use of high strength concrete in buildings is an important innovation that can reduce the size of structural elements compared to those made from normal strength concrete. This can provide for more efficient construction such as maintaining a constant column size throughout the building by using high grade concrete for the lower storey columns carrying the highest loads. One restriction to its widespread use however is concern over its performance in fire, in particular its increased susceptibility to spalling. A consideration of the literature and experience gained over the course of many years suggest that spalling is more likely in the event of high moisture content, high concrete strength, rapid increase in temperature or high levels of restraint (or applied load) or any combination of these factors.

The purpose of this paper is to bring together information derived from a number of experimental programmes, to identify the significant parameters that influence spalling and to highlight areas where further research is required. The information and expertise derived from experimental programmes into the behaviour of high strength concrete in fire has been used to undertake a number of high-profile commercial testing programmes to assess and evaluate the performance of tunnel lining segments in the event of a fire.

2. Mechanisms of spalling

Given certain conditions virtually all types of concrete will spall in a fire situation. The most significant parameters contributing to the spalling of concrete structures are heating rate, moisture content, permeability, strength, restraint to thermal expansion, aggregate type, curing regime, geometry and nature and extent of reinforcement.
It is generally recognized that there are three main categories of spalling: aggregate, corner and explosive. Of these explosive spalling is the most significant in terms of its impact on structural performance. For normal strength concrete and for high strength concrete covered by European Class 1 and 2 with silica fume contents less than 6% by weight of cement explosive spalling is assumed to be principally a function of the moisture content and the environmental conditions. EN 1992-1-2 [5] states that where the moisture content is less than 3% by weight and where members are designed to exposure class X0 (concrete inside buildings with very low air humidity) and XC1 (concrete inside buildings with low air humidity) then explosive spalling does not need to be considered explicitly. The current revision of the fire part of the Eurocode for the design of concrete structures will revisit these assumptions and update the rules based on the current state of knowledge in relation to spalling and the material behaviour of high strength concrete.

The difference between high strength concrete and normal concrete lies principally in the water to cement ratio used in the mix. For high strength concrete, lower water to cement ratios are used, the required workability of the fresh concrete being provided by superplasticisers. The effect of lowering the water to cement ratio is a reduction in the permeability of the hardened concrete, which, in most structural contexts, increases both strength and durability. Unfortunately, the reduction in permeability has been found to be detrimental to performance in fire. This is because pore pressure is produced in concrete at high temperatures. Unless there is an escape route for the steam, internal pressures are generated that, in conjunction with other stresses can exceed the tensile strength of the concrete. The overall result of all the factors relating to the increase in concrete grade is an increased susceptibility to spalling. The danger of spalling of concrete in fire is not only the loss of section but also the possibility of early yield of the steel reinforcement as it becomes directly exposed to high temperatures.

3. Fire performance of high strength concrete columns
Initial research on the performance of high strength concrete columns in fire aimed to investigate the effect of the use of monofilament polypropylene (p/p) fibres to improve performance. At this time (1997-1998) the use of p/p fibres for fire performance was an innovative application of an existing technology generally used to prevent early age cracking of floor slabs.

![Figure 1. Experimental set-up for fire testing of concrete columns.](image)
Two different experimental programmes were undertaken on both unreinforced and reinforced columns [6]. The fire test facility is shown in figure 1. The columns were placed inside a gas fired furnace with the fuel input controlled to follow the standard fire curve 4 for a period of 45 minutes. The columns were subject to an axial compressive load kept constant for the duration of the fire exposure.

The initial programme of tests was undertaken on unreinforced columns to provide a worst-case scenario in terms of spalling. The columns measured 1500 mm high x 200mm x 200mm. The concrete mixes were C85 and C105 (with micro silica). The coarse aggregate was crushed limestone and the moisture content at the time of test was 3.5%. Half the columns included 3 kg/m³ of p/p fibres (12mm long x < 0.1 mm thick). Half the columns were tested whilst under 40% of the calculated ultimate load and the other half tested under 60% of the calculated ultimate load.

The results are illustrated in figure 2. Only four specimens (of 30) remained intact at the end of the test and of these three included p/p fibres. None of the specimens under 60% load survived the test regardless of the inclusion of p/p fibres. Figure 3 is a comparison of the one specimen without fibres that survived the test and the corresponding sample including fibres. The results show two things very clearly. Firstly p/p fibres can reduce, delay or eliminate spalling in high strength concrete and secondly the predominate factor in terms of fire performance is the load ratio or degree of utilization of the columns.

The second programme of tests were on reinforced columns of the same overall size as the unreinforced specimens. The reinforcement details are illustrated in figure 4. The range of concrete grades was extended to cover C45 and C65 grades as well as the C85 and C105 grades used previously. Two different fibre dosages were used, 3 kg/m³ and 6 kg/m³, the moisture content was 3% and the test procedure was the same as that used previously. In all cases the applied axial load was one third of the calculated ultimate capacity.

No collapses occurred for any of the reinforced columns although the degree of spalling varied according to the mix design. Figure 5 is a comparison of three of the C85 columns containing from left to right no fibres, 3 kg/m³ p/p fibres and 6 kg/m³ fibres.
Figure 3. Comparison between high strength unreinforced columns with (right) and without (left) fibres.

Figure 4. Reinforced concrete columns – section, with high tensile strength reinforcement

Figure 5. Comparison of C85 test specimens after test (no fibres on left, 3 kg/m³ p/p fibres in middle and 6 kg/m³ p/p fibres on right).

Table 1. Residual compressive strengths of the fire tested columns.

| Concrete Type (F = 3 kg/m³ p/p fibres, FF = 6 kg/m³ p/p fibres) | Residual Strength (percentage of calculated ultimate failure load prior to testing) |
|---------------------------------------------------------------|----------------------------------------------------------------------------------|
| C45                                                          | 70%                                                                              |
| C45F                                                         | 75%                                                                              |
| C45FF                                                        | 75%                                                                              |
| C65                                                          | 60%                                                                              |
| C65F                                                         | 65%                                                                              |
| C65FF                                                        | 65%                                                                              |
| C85                                                          | 55%                                                                              |
| C85F                                                         | 70%                                                                              |
| C85FF                                                        | 70%                                                                              |
| C105                                                         | 55%                                                                              |
| C105F                                                        | 60%                                                                              |
| C105FF                                                       | 65%                                                                              |
4. Fire performance of high strength concrete columns
A large-scale fire test was undertaken on the ground floor of the European Concrete Building Project (ECBP) at BRE’s large scale test facility at Cardington in 2001 [7]. The flat slab was supported by a number of high strength (C85) concrete columns containing 2.7 kg/m³ monofilament p/p fibres to reduce the tendency for explosive spalling. The test area included one completely exposed internal column and eight partially exposed columns at the boundaries of the compartment.

All of the columns survived the fire test without any significant spalling suggesting that the p/p fibres had a significant impact particularly in the light of spalling to the soffit of the flat slab (figure 6).

5. Fire performance of tunnel linings and explosive spalling
Explosive spalling is a very complex phenomenon which poses a great threat to structural performance of some reinforced concrete structures in fire [8]. The most significant in relation to explosive spalling (as opposed to spalling in general) is the rate of temperature rise, the presence of restraint against thermal expansion and the permeability (related to porosity, density and strength) of the concrete. Tunnels often involve the use of high strength concrete. The nature of the construction involves significant restraint to thermal expansion and the nature of the potential fire load (petro-chemical fuel tankers) leads to a rapid rise in temperature in the event of a fire.

Given the potential consequences of failure to a tunnel lining, the nature of tunnel fires and the form of construction used in tunnels it is essential to ensure that the proposed design solution is capable of resisting a hydrocarbon fire exposure while under load.

There is currently no standardised approach for the testing and approval of tunnel lining segments in terms of fire performance. Some attempts have been made to produce standardised procedures while still allowing some flexibility in the fire exposure curve to be adopted. However, the specification does not require the specimens to be tested under load. For major infrastructure projects the requirements are often tailored to the specific circumstances of the project.

5.1 Tunnel fire testing
BRE have been involved in fire tests in a number of high-profile infrastructure projects to demonstrate compliance with client requirements for both road and rail tunnels. Figure 7 is a comparison of
specimens with and without p/p fibres tested under load and subject to a hydrocarbon fire exposure for a high-speed rail tunnel. Figure 8 is a comparison between (from left to right) panels subject to a hydrocarbon fire exposure while under load and containing 1 kg Polyvinyl alcohol (PVA) fibres, no fibres and 1 kg p/p fibres. The expertise derived from projects such as this provided input to the specification for fire testing for sprayed concrete linings for the Crossrail project.

![Figure 7. Comparison of test specimens with (right) and without (left) p/p fibres.](image1)

![Figure 8. Comparison of specimens following hydrocarbon fire test (1 kg/m³ PVA fibres on left, no fibres in middle and 1 kg/m³, p/p fibres on right).](image2)

Two different specifications were provided for fire testing of specimens for the Crossrail project. One for precast linings and one for sprayed concrete linings (SCL). Both test methods specify exposure to the Eureka time-temperature curve illustrated in figure 9. The specification for SCL defined the parameters for both large panel tests for compliance and smaller scale tests on unloaded cylinders to establish the potential suitability of trial mixes. The specification for testing of large panels for SCL consists of loading panels with nominal dimensions of 1.5 m high by 0.75 m wide by 0.3m thick to the prescribed load level and subjecting one face of the panel to a hydrocarbon fire exposure corresponding to the Eureka fire curve. The performance criteria were based on depth of spalling, temperature rise within the slab and an evaluation of the impact of temperature rise on the integrity of the waterproof membrane and the residual strength of the heated concrete.

![Figure 9. Eureka fire exposure curve in relation with time.](image3)
Thermocouples are installed in the specified locations on site (figure 10) at the time the panels are cast. Prior to testing the samples are stored and cured under controlled conditions (40°C and 60% RH) (figure 11) until the test date (nominally 28 days). The specification for precast linings used for Crossrail was completely different and required facilities not currently available within the UK.

The next major infrastructure project is the HS2 high speed rail link. A specification for fire testing of concrete used for underground tunnels has been prepared based largely on the specification used for Crossrail.

6. Conclusions
This paper has reviewed a number of experimental programmes undertaken at BRE to investigate the spalling of concrete structures with a particular focus on high strength concrete. The expertise derived was used to provide a means of test and assessment for a number of high-profile infrastructure projects where evidence was required of concrete performance when subject to a hydrocarbon fire exposure.

There is a need for a standardised approach to the assessment of the performance of tunnel linings in fire to be developed. However, any standardised test and assessment procedure should allow for the flexibility required for specific projects in terms of fire exposure and load level to be applied.

The Crossrail SCL specification and the current HS2 specification could provide a useful starting point to develop a standardised procedure that considers the most significant aspects of structural behaviour in fire without imposing an unreasonable financial burden on contractors.

References
[1] Tovey A K and Crook R N 1986 Experience of fires in concrete structures, in ACI Symposium on Evaluation and repair of fire damage to concrete, San Francisco, 16-21 March 1986, American Concrete Institute, Detroit, SP-092
[2] Iffat S and Bose B 2016 A Review of Concrete Structures in Fire, World Academy of Science, Engineering and Technology International Journal of Structural and Construction Engineering 10 2, pp. 123-128
[3] Jansson R 2013 Fire spalling of concrete – A historical overview, Concrete Spalling due to Fire Exposure Proceedings of the 3rd International Workshop, MATEC Web of Conferences 6
[4] Technical Note on Fire Damaged Reinforced Concrete—Investigation, Assessment and Repair 102, April, 2011
[5] British Standards Institution, BS EN 1992-1-2: 2004, Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design, BSI, London
[6] Clayton N and Lennon T 2000 Effect of polypropylene fibres on performance in fire of high grade concrete, BR 395 Published by Construction Research Communications (CRC)
[7] Lennon T, Bailey C and Clayton N 2002 The Performance of High Grade Concrete Columns in Fire, *Proceedings of the 6th International Symposium on Utilization of High Strength/High performance Concrete*, 1 pp. 341-354

[8] Deeny S, Stratford T, Dhakal R, Moss P, Buchanan A 2009 Spalling of Concrete - Implications for Structural Performance in Fire *Proceedings of the International Conference Applications of Structural Fire Engineering* pp. 202-207