Spalling of High Strength Concrete in fire

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1. Introduction

Concrete structures generally perform extremely well during and after a fire and the majority of fire-damaged concrete structures have been repaired and re-used [1]. Although spalling of concrete structures following real fires has been observed, it does not necessarily have implications for the stability of the structure. 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 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.

2. Performance of high strength concrete columns in fire

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 [2]. 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. Two different experimental programmes were undertaken on both unreinforced and reinforced columns. 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 for a period of 45 minutes [4]. 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 1500mm 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 < 0.1mm 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.

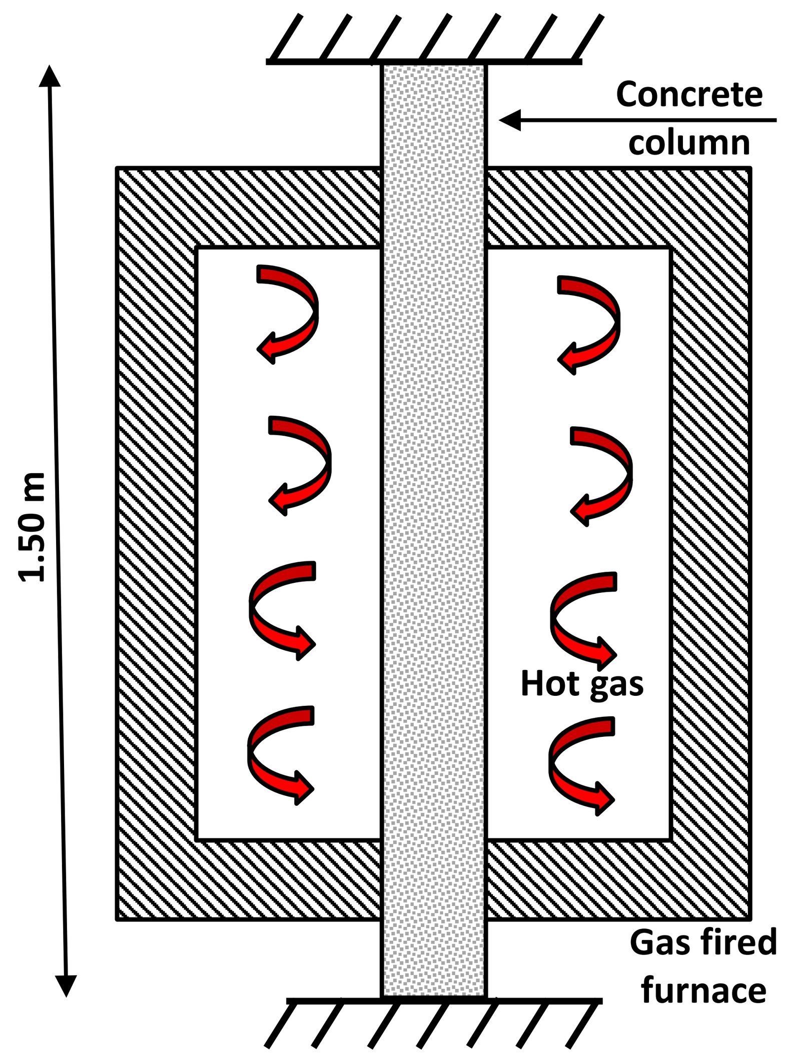

Figure 1 Experimental set-up for fire testing of high strength concrete

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 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, 3kg/m³ and 6kg/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, 3kg/m³ p/p fibres and 6kg/m³ fibres.

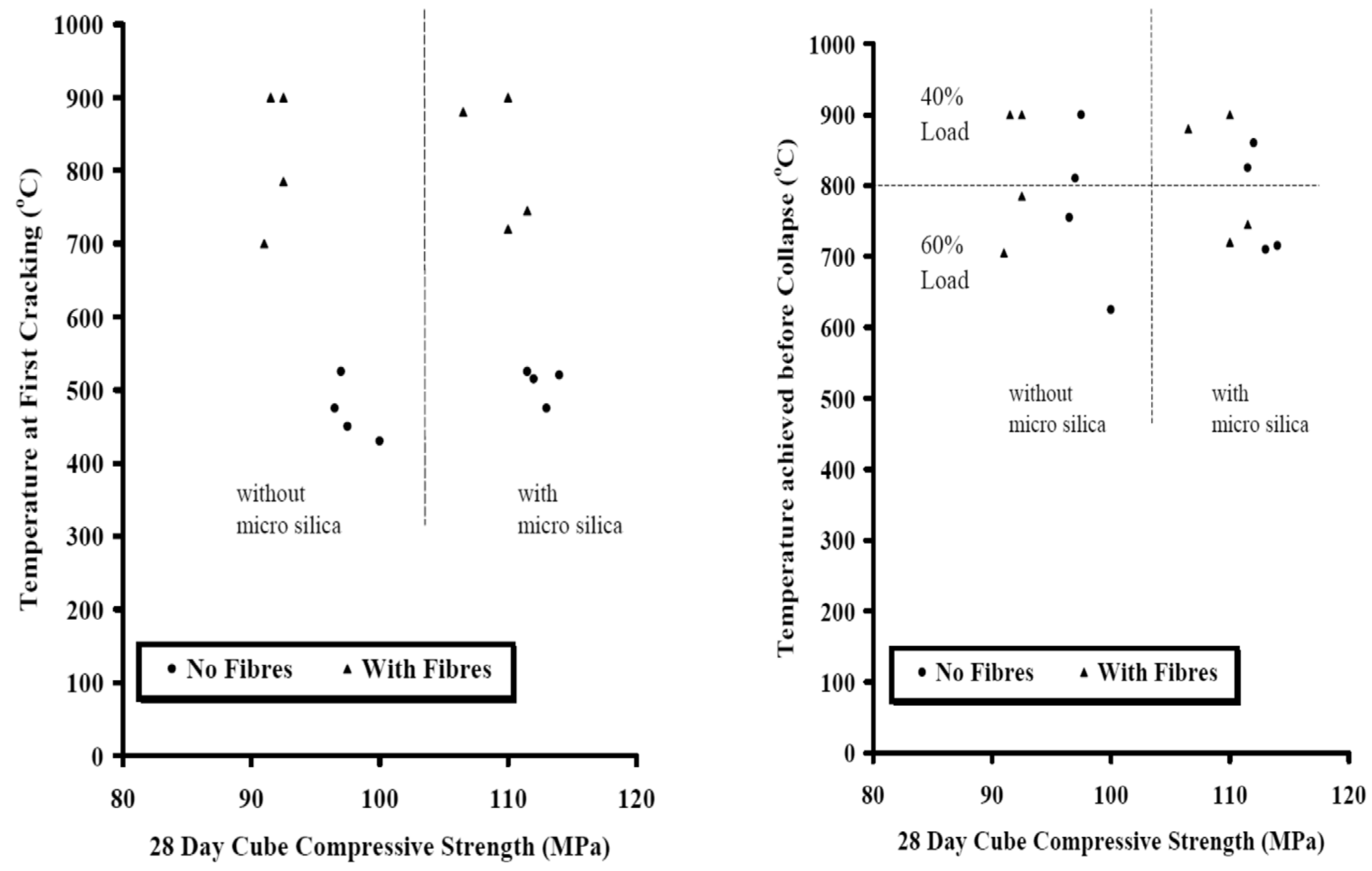

Figure 2 Temperature at first cracking and collapse temperature (unreinforced columns).

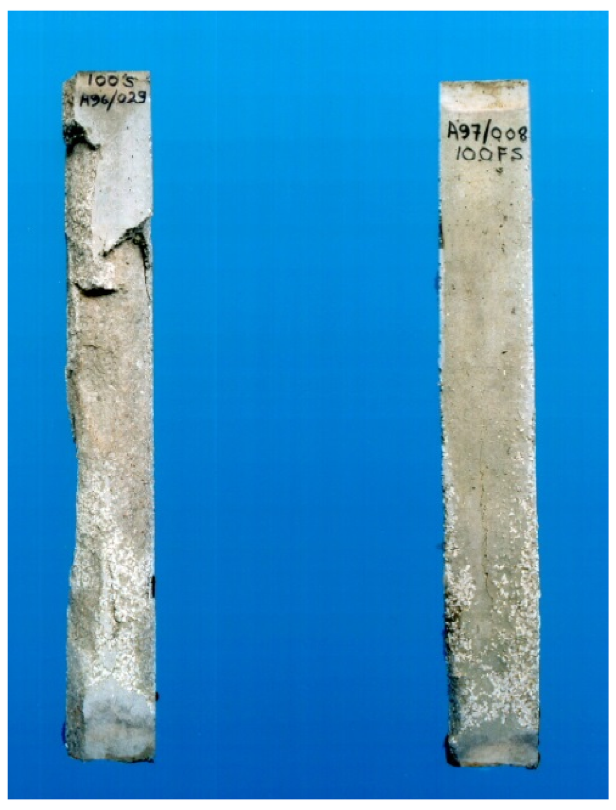

Figure 3 Comparison between high strength unreinforced columns with (right) and without (left) fibres

Figure 4 Comparison of C85 test specimens after test (no fibres on left, 3kg/m³ p/p fibres in middle and 6kg/m³ p/p fibres on right).

3. Residual strength results

The residual strength of all specimens was determined by compression testing following exposure to fire. The measured residual strengths are shown in Table 1, expressed as a proportion of the calculated ultimate load capacity at ambient temperature. The results show that for those members not containing p/p fibres there is a larger loss of residual strength and that this loss increases with increasing grade. This is in line with the observations of relative damage following the fire tests.

Table 1 Residual compressive strengths of the fire tested columns

Concrete Type (F = 3kg/m³ p/p fibres, FF = 6kg/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. 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 High Speed 2 (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., 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, Ref. SP-92.
[2] Clayton N and Lennon T, Effect of polypropylene fibres on performance in fire of high grade concrete, BR 395, Published by Construction Research Communications (CRC), 2000.
[3] British Standards Institution, BS EN 1363-1, Fire resistance tests – Part 1: General Requirements, BSI, London, November 1999.