Explosive Concrete Spalling during Large-Scale Fire Resistance Tests

Cover page

Title

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ABSTRACT

This paper presents a comprehensive investigation of explosive heat-induced spalling observed during a set of large-scale fire resistance tests (or standard furnace tests) on prestressed concrete slabs. The study, based on data from large-scale tests, examines the influence of numerous design parameters in the occurrence of spalling (age of concrete, inclusion of polypropylene fibres, depth of the slab, and prestressing level). Furthermore, a careful thermal analysis of the tested slabs is presented; a comparison of in-depth temperature distributions inside concrete slabs shows that spalling occurred for slabs with more rapid in-depth temperature increase. The analysis presented herein shows that the scatter of in-depth temperature increase experienced by concrete slabs tested simultaneously has a substantial influence in the occurrence of heat-induced concrete spalling.

INTRODUCTION & BACKGROUND

During (or even after) heating in fire, concrete at the exposed surface of structural elements flakes away in a more or less violent manner. This phenomenon is known as 'heat-induced concrete spalling' [1]. As a consequence, the concrete cover to the internal reinforcement is reduced, resulting in rapid temperature increase of the reinforcement and within the structural element, in addition to a direct influence on load bearing capacity due to the loss of physical or effective cross sectional area.

Two main mechanisms are widely considered to contribute to the occurrence of heat-induced concrete spalling. The first is a thermo-hydraulic mechanism associated with the transport and/or evaporation of free water (or capillary water) within the concrete microstructure; this is postulated to lead to generation of steam pressure and a 'moisture clog', and eventually to spalling. It is almost universally agreed that higher moisture content results in increased heat-induced spalling, all other factors being equal [2]. The second is a thermo-mechanical mechanism associated with internal mechanical stresses resulting from in-depth temperature distributions and incompatibilities in the thermal and thermo-mechanical behaviour of the components within the concrete matrix (e.g. coarse and fine aggregates, cement paste, chemically bound water, etc). This mechanism can also be described at the macro-scale, and linked to internal mechanical stresses resulting from external loading, restraining forces, and/or differential thermal stresses arising due to uneven heating, in-depth temperature distributions, and/or the presence of cold areas.

The relative significance of these two mechanisms for a particular concrete mix, under a particular thermal exposure in a given application, are not well known. Regardless of the unquantified risk of spalling, current design and construction guidance for spalling prevention (e.g. [3,4]) is based on prescribing a dose of polypropylene (PP) fibres which is presumed to assure limited spalling in applications with 'relatively high' spalling risk (e.g. high-strength concrete, high in-service moisture content, high in-service compressive stress, rapidly growing fires, etc). For example, European design guidelines for concrete in fire [3] recommends including at least 2 kg of monofilament PP fibres per cubic metre concrete for high-strength (>55 MPa cube compressive strength), high moisture content (>3% by mass) and/or concrete with high inclusion of silica fume (>6% by mass of cement). Australian design guidance for concrete in fire [4] states that the addition of 1.2 kg of 6 mm long monofilament PP fibres per cubic metre concrete has a "dramatic effect in reducing the level of spalling".

Within the scope of the work presented and discussed herein a careful thermal analysis of the tested slabs is done for one of the large-scale fire resistance tests (reefer to Figure 1). A comparison of in-depth temperature distributions inside concrete slabs shows that spalling occurred for slabs with more rapid in-depth temperature increase.

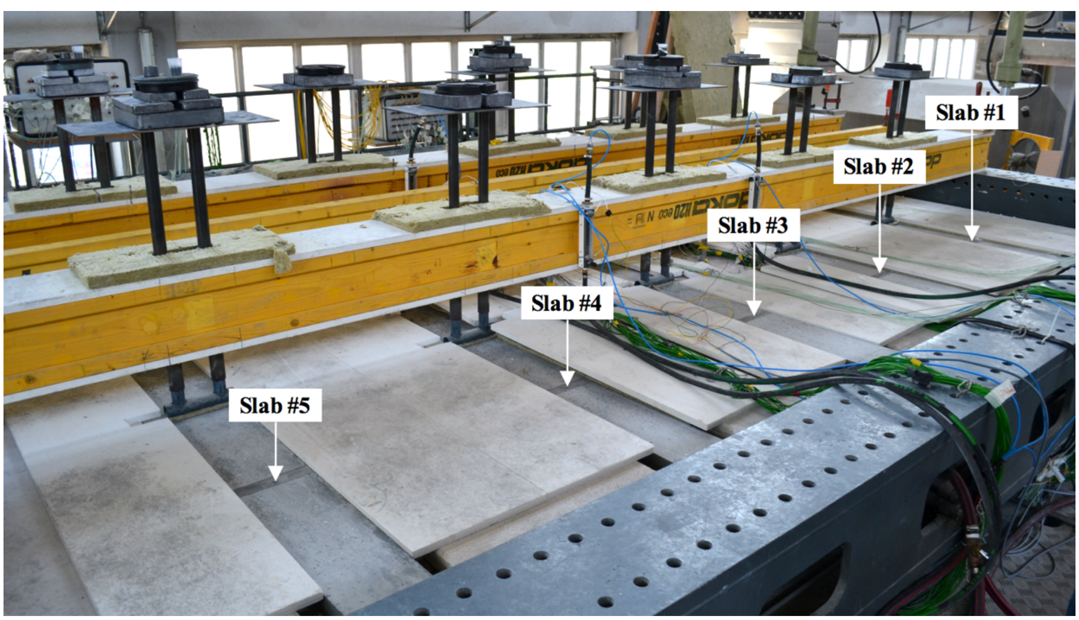

Figure 1. Photo of the fire resistance test setup showing positions of the respective slabs and sustained loading technique used.

TEST PROGRAM

A set of large-scale fire resistance tests were executed, each with five loaded prestressed concrete slabs simultaneously tested in a standard floor furnace test [5]. The design and test program of the prestressed slabs was aimed to evaluate the influence of: age of concrete, inclusion of polypropylene fibres, depth of the slab, and prestressing level. The parameters evaluated for the test examined within this paper is shown in Table 1 (reefer to Figure 1).

Table 1. Evaluated parameters, time-to-failure and failure mechanisms for slabs discussed herein.

Slab #	**Concrete mix**	**Depth of the slab [mm]**	**Applied load per point [kg]**	**Slab utilization factor**	**Time-to-failure [mm' ss'']**	**Failure mechanism**
1	A	45	25.0	0.23	42' 01"	Loss of anchorage
2	A	45	25.0	0.23	12' 37"	**Explosive spalling**
3	A	60	38.4	0.20	22' 10"	**Explosive spalling**
4	B	45	25.0	0.23	50' 27"	Loss of anchorage
5	B	60	38.4	0.20	93' 04"	Loss of anchorage

Test slabs

The tested slabs were similar to those used by the authors in prior research [5]. Their overall length was 3360 mm and they were prestressed with four circular pultruded, quartz sand-coated CFRP tendons stressed to an initial prestress level of 1,000 MPa. Initial prestress level was calculated based on the gross cross-sectional area of the tendons; i.e without considering the layer of sand coating (refer to Section 3.2.2 of this paper).

All CFRP tendons were located at the slab mid-depth, with a tolerance of ±2 mm, to obtain a nominally concentric prestressing force. The slabs were 45 or 60 mm thick (refer to Table 1), leading to clear concrete covers to the prestressed CFRP reinforcement of 19.5 mm and 27 mm, respectively. All slabs were 200 mm wide. Lateral clear concrete cover at the slab edges was 22 mm in all cases, with a tendon-to-tendon clear spacing of 44 mm.

High-Performance, Self-Consolidating Concrete (HPSCC)

All slabs were fabricated from a high-performance, self-consolidating concrete (HPSCC) of strength class C90 (minimum 28 day 150 mm cube compressive strength of 90 MPa). Given the high likelihood of spalling for this mix due to its high strength and the inclusion of microsilica in the mix [3], 2.0 kg of 3 mm long or 1.2 kg of 6 mm long PP monofilament fibres (32 μm in diameter) were included for mixes A and B, respectively. Detailed of both mixes are given in Table 2. Moisture content was measured by dehydration mass loss of control specimens. The average moisture contents at the time of testing were 3.6 and 3.9% by mass, for mixes A and B, respectively. Compressive and splitting tensile strengths were measured at 28 days and 6 months (close to the time of testing).

Table 2. Mix composition and slump flow for the HPSCC mixes.

		Mix #A	Mix #B
Water/(cement + microsilica + fly ash)	[-]	0.31	0.31
Cement (includes 20% microsilica)	[kg/m^3]	475	469
Fly ash	[kg/m^3]	120	120
Limestone aggregate (0-8 mm)	[kg/m^3]	1675	1669
Superplasticizer in % of cement	[%]	1.69%	1.75%
Polypropylene fibres	[kg/m^3]	2.0 (3 mm PPs)	1.2 (6 mm PPs)
Slump flow **Error! Reference source not found.**	[mm]	830	785
Compressive strength (28 days / 6 months)	[MPa]	92.6 / 93.3	96.2 / 98.5
Splitting tensile strength (28 days / 6 months)	[MPa]	5.44 / 5.47	5.49 / 5.57
Moisture content (at the time of testing)	[% by mass]	3.6%	3.9%

TEST SETUP

Thermal Conditions

The setup of the specimens was aimed at assuring one-sided heating from below, so the sides of the specimens were fully insulated. The heating regime was executed according to the requirements of the standard time-temperature curve [6]. During testing, the furnace was instrumented in accordance with European fire test standards [4]; eight standard plate thermometers were positioned inside the furnace. These were used to record and control the temperatures inside the furnace during testing.

Mechanical Conditions

Sustained mechanical loading was applied to simulate an in-service condition for the slabs, in simply-supported four-point bending. The applied load was designed to be sufficient to achieve decompression at the extreme tension fibre within the constant moment region (i.e. $\sigma_{c,bottom} = 0$ [MPa]); this corresponds to a typical design service load condition for a façade element of this type in a real building [5]. Loading was imposed 30 minutes prior to start of heating. Prestressing losses due to elastic shortening, shrinkage and creep of the concrete were considered and calculated based on results from prior experimental studies performed for similar HPSCC mixes [5].

DISCUSSION

Furnace Temperature

Temperature measurements from the eight plate thermometers inside the furnace are shown in Figure 2 along with the objective time-temperature curve. Although compliant with the testing standard [6], the temperature measurements show substantial deviation in the temperature measured inside the furnace, especially during the first 20 minutes (see Figure 3). Due to the obvious technical challenge of precisely controlling the furnace to follow the rapidly growing prescribed time-temperature curve [6] during early stages of the test, most testing standards do not prescribe an allowable deviation during the first 5 minutes (see Figure 3).

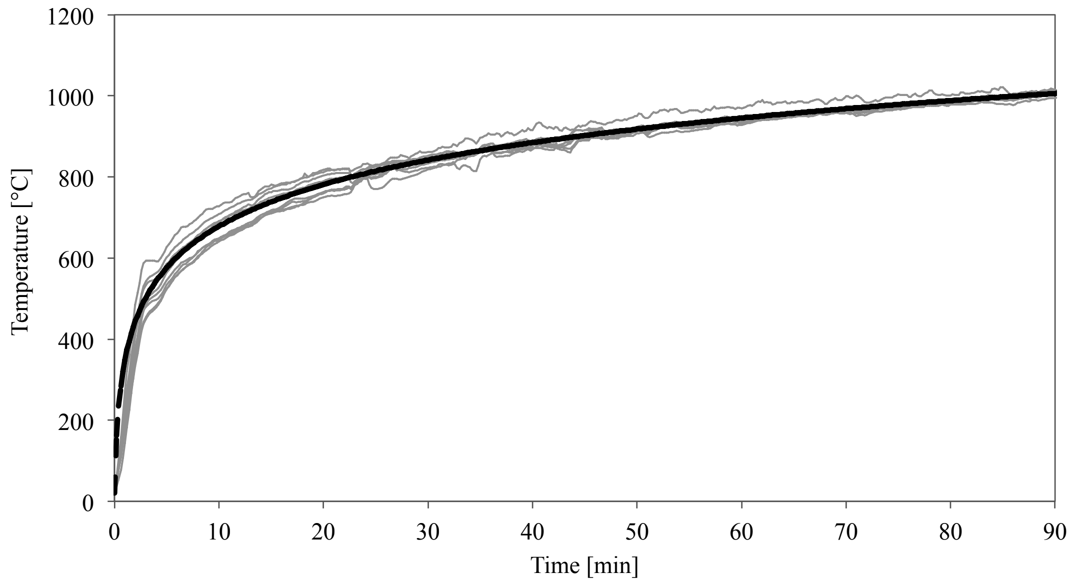

Figure 2. Furnace gas temperatures measured by the plate thermometers along with the objective standard time-temperature curve [6].

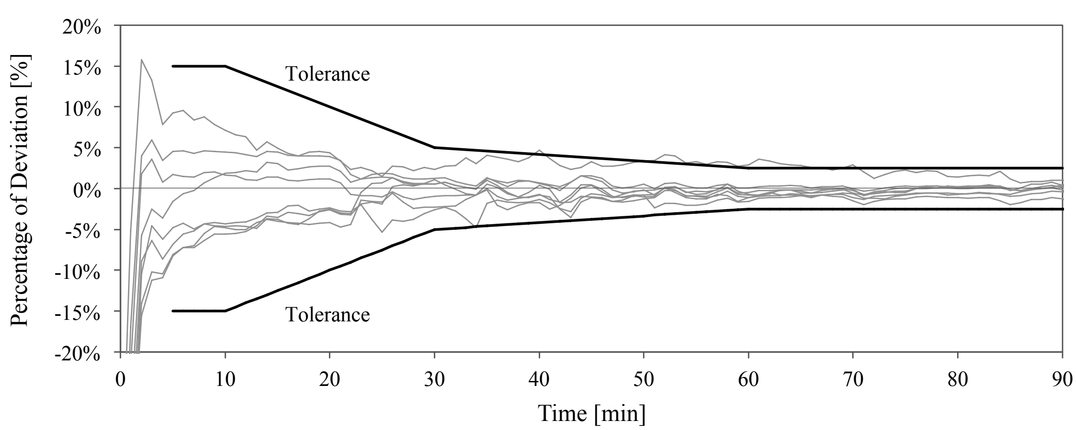

Figure 3. Percentage of deviation of the temperature measured by plate thermometers from that of the objective temperature, and the maximum allowable deviation (tolerance) [6].

Slabs in-depth temperature

In-depth temperature measurements were taken at midspan of the slabs. Temperature was measured in up to eleven positions from the exposed surface of each of the slabs. Special care was taken during the casting process to ensure precise placement of thermocouples at the intended location inside the slabs. A comparison of in-depth temperature distributions measured at midspan is shown in Figures 4. Temperature for the first 12 minutes of a test are shown.

Considerable variation of in-depth temperature distributions was observed for slabs with equivalent thickness, demonstrating poor homogeneity of the thermal exposures for slabs tested simultaneously during a single furnace test; this is despite the temperatures measured by the plate thermometers complying with the test standard (see Figure 3). Slabs with more rapid temperature increase spalled, while slabs with relatively slower temperature increase did not spalled. This suggests the important influence of the thermal exposure, hence transient evolution of thermal gradients, in the occurrence of heat-induced concrete spalling [7].

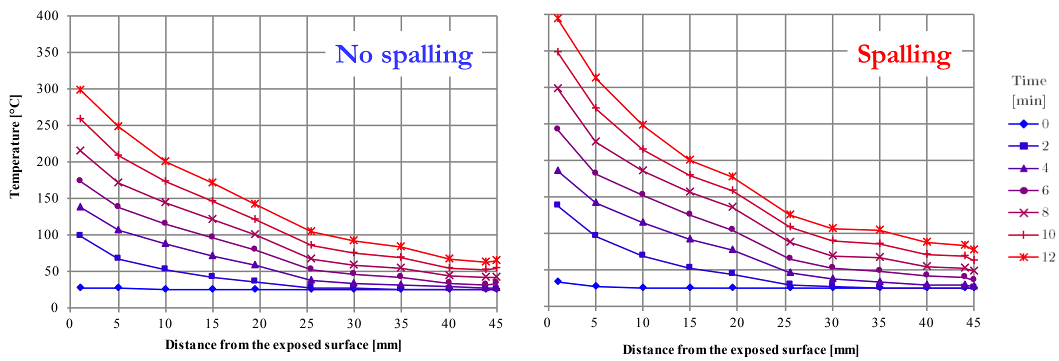

Figure 4. In-depth temperature distribution for identical slabs; Slab #1 (left plot) that did not spalled and Slab #2 (right plot) that spalled 12 minutes from the start of the test (reefer to Table 1).

Failure of slabs #2 and #3 was driven by the occurrence of single explosive concrete spalling events, 12 and 22 minutes from the start of the test, respectively (refer to Table 1). Immediately after spalling, each of these slabs suffered catastrophic failure and collapsed into the furnace. Video stills recorded during testing showed the moment at which spalling occurred (shown for Slab #2 in Figure 19).

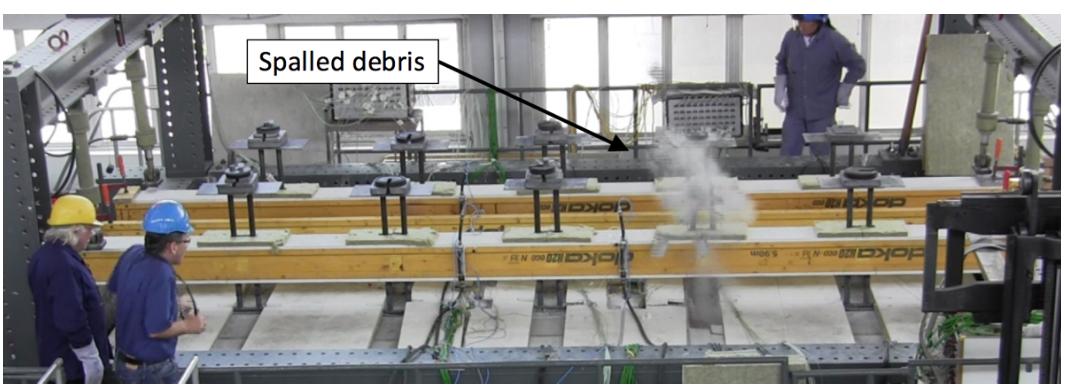

Figure 3. Explosive spalling and immediate collapse of a large-scale slab during a fire resistance test.

Slab #2 failed after 12 minutes, whereas the virtually identical Slab #1 failed due to loss of anchorage after 42 minutes of fire exposure (refer to Table 1); Figure 13 shows that Slab #2 experienced more rapid heating during the early stages of the test. This suggests a possible important influence of the time-history of in-depth temperatures on the occurrence of heat-induced concrete spalling [1]. For instance, Slab #2 spalled when the measured temperature 1 mm from its exposed surface was 400°C, while for Slab #1 the temperature at the same location was only 300°C. The possibility that this was due to misplacement of thermocouples during casting was discarded since equivalent temperature differences between slabs #1 and #2 were observed for temperatures measured at various positions in the slab (e.g. 5, 10, and 15 mm from the exposed surface).

For slabs #4 and #5, both of which were cast from Mix B, no spalling was observed and thus it is not possible to determine whether time-history of in-depth temperatures might influence the occurrence of spalling for this mix. The above demonstrates an inability to properly compare test results for multiple specimens simultaneously tested during a single furnace test when subtle differences in thermal gradients play important roles in the test outcomes.

CONCLUDING REMARKS

Recognizing that it is challenging to draw categorical conclusions on the basis of a limited number of large-scale fire resistance test, the following conclusions can be drawn on the basis of the data and discussion presented herein:

- The fire resistance of CFRP prestressed HPSCC slabs during a standard fire resistance test is influenced by the occurrence of heat-induced concrete spalling, and if no spalling occurs, by loss of anchorage.
- Although all five test specimens were tested simultaneously and exposed to the same notional time-history of temperature inside the furnace, variability was observed in the time-history of in-depth temperatures for essentially identical slabs. This demonstrates the relatively poor, although 'test standard compliant', homogeneity of the thermal loading imposed during a standard furnace test [6]. Interestingly, more rapid in-depth temperature increases were measured for slabs at the centre of furnace, relative to those near its walls.
- Failure of slabs #2 and #3 was driven by the occurrence of a single explosive spalling event leading to sudden failure, while identical slabs did not spalled.
- The occurrence of heat-induced concrete spalling appears to be subtly influenced by the time-history of in-depth temperature within a concrete slab. Comparison of temperature measurements recorded for slabs #1, #2, and #3 (all Mix A) indicated an influence of time-history of in-depth temperatures on the occurrence of heat-induced concrete spalling. More rapid in-depth temperature increases were measured for slabs #2 and #3, which spalled at 12 and 22 minutes, respectively.
- Results suggest that a lower risk of spalling exists for slabs cast with Mix B (containing 1.2 kg/m3 of 6 mm long PP fibres) than for those cast with Mix A (2.0 kg/m3 of 3 mm long PP fibres). This may be related to the short PP fibres (3

mm long) included in Mix A being less effective in mitigating heat-induced concrete spalling. It is noteworthy that existing European (and other) design guidelines for concrete in fire [3] prescribe the inclusion of 2 kg/m3 of monofilament PP fibres to 'avoid' spalling; this is clearly indefensible based on the tests presented herein. Furthermore, these guidelines provide no guidance on the required PP fibre diameter or length.

This work demonstrates the sensitivity of thermal exposure in the occurrence of heat-induced concrete spalling. These findings are based on the comparison of test results from a large-scale fire resistance tests, where it was observed that a 'subtle' differences in thermal gradients can play an important role in the occurrence of spalling; for essentially identical concrete slabs. A proper understanding of the response of these elements is needed before they can be designed and implemented with confidence; this is unlikely to be achieved by performing additional standard fire resistance tests. Conversely, what is needed is scientific understanding of the thermal and mechanical fire behaviour of these elements at the material, member, and system levels; this can be accomplished using a range of conventional and bespoke test methods and procedures, many of which are now being used by the authors (e.g. [1]).

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