Fracture and explosive spalling of concrete slabs subjected to severe fire

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ABSTRACT: The paper presents an experimental investigation on explosive spalling and fracture-induced deformation of 6 full-scale simply supported reinforced concrete slabs subjected to conventional fire curve (BS476) and severe hydrocarbon fire curve, performed at the Fire Research Centre, University of Ulster, UK. Each slab was loaded with 14% of its ultimate load and was heated from the bottom side only. Temperature profile was recorded at 3 depths within the slabs and the moisture content was also measured before and after the tests. The deflection of the slabs was recorded at the middle of the 3 meters span. All slabs suffered from explosive spalling at different degrees. The study showed that explosive spalling took place much earlier and was more violent in slabs subjected to hydrocarbon curve in comparison with BS476. The paper ends with analysis of interaction between the parameters involved in the tests.

1 INTRODUCTION

The majority of the research studies on behaviour of concrete elements which were performed in the last decades have mainly focused on beams and columns. Some of these studies investigated small scale slabs El-Hawary, *et. al.* (1996), Shuttleworth (2001), but a very small number of investigations have involved large scale specimens. Most of these slabs were tested under standard normal heating rates BS476 or ASTME119 (Shirly *et. al*. 1988). However, the effect of more severe fires (hydrocarbon fire curve for example) on the performance of structural elements is gathering momentum following the tragic events of 9/11 in New York. The research performed in the BRE (Cooke (2001)) is among the rare works, which involved the effect of hydrocarbon curve on the fire resistance and deflection of concrete slabs. However, no explosive spalling of concrete was reported in this study. Previous research (Cooke (2001), Ali.*et.al*. (2004), Gamal *et.al*. (1995), Selih, *et.al.* (1991), Chung *et.al.* (2005) and others) has shown that the probability of explosive spalling of concrete increases under higher heating rates. It is well established now that heating a concrete element from one side creates two moving fronts: heat and moisture front. The two fronts move away from the heated face of the concrete towards the cold unheated side. The speed of the two fronts depends on several factors including the heating rate where the two fronts could meet at a specific distance inside the concrete. This causes the water within the moisture clog to transform to vapour. The build up of high vapour pressure which may reach 3 to 5MPa (Chuang *et. al.* 2003) can cause explosions in the concrete. In addition, recent research suggests that the presence of steel reinforcement impedes moisture movement and produces quasi-saturated moisture clog zones that could lead to the development of significant pore pressure (Chuang *et. al.* 2003).

The objective of this paper is to represent the outcomes of an experimental study performed on 6 large simply supported concrete slabs 3300x1200x200mm. The slabs were subjected to conventional (BS476) and hydrocarbon severe heating rates. The temperatures were measured inside the slabs at three depths: - surface, 40mm (steel reinforcement), 100mm. The mid-span deflection of the concrete slabs was also measured is presented. The explosive spalling observed during the tests and an assessment criterion of spalling are discussed. The paper includes also an analysis of the interaction between the parameters involved in the tests.

2 THE EXPERIMENTAL PROGRAMME

The experimental work involved testing 6 large scale 3300x1200x200mm normal-strength reinforced concrete slabs with an average concrete strength of 42 N/mm^2 at 28 days. During the tests the concrete slabs were mounted on the top of the furnace with clear span of 3000mm (see Figure 1). Each slab was reinforced with 6 T12 steel bars, embedded longitudinally along the slab at a spacing of 220mm centre to centre, as illustrated in Figure 1.

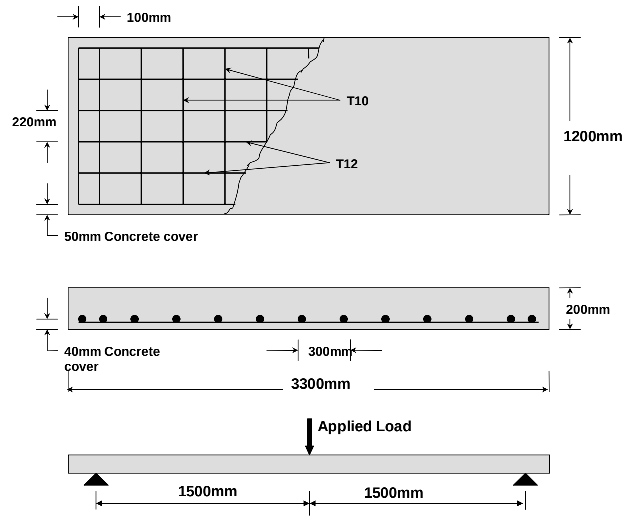

Figure 1. Loading and reinforcement details of concrete slabs

Secondary reinforcement comprising of 13 T10 steel bars were placed perpendicular to the main reinforcement at a spacing of 300mm c/c. The concrete cover of the steel reinforcement was 40mm vertically and 50mm on slab sides (see Figure 1).

2.1 *Test Parameters*

All slabs were tested under the same loading level = 0.14 of the design load of BS8110. This load was applied at the mid-span point of each slab as shown in Figure 1. Two heating regimes were used during the experimental programme, BS476 and hydrocarbon fire curves. Figure 2 shows the average experimental fire curves achieved during the tests. Three slabs S1, S2 and S3 were tested using the standard temperature-time curve BS 476, while the remaining slabs S4, S5 and S6 were tested under the severe hydrocarbon fire curve (see Table 1). All the tests were performed in a 4x3x3m combustion chamber, with the slab specimen situated on top of the furnace and heated from beneath.

Table 1. Tests results

Fire Curve	Slab Ref.	Spalling Degree %	Moisture Content % Top	Moisture Content % Bottom	Max. Defl. mm
BS476	S1	1.0	3.6	5.5	29.7
	S2	2.7	3.7	5.7	32.1
	S3	2.2	3.9	6.0	34.2
Hydro.	S4	2.1	3.7	5.2	44.8
	S5	4.3	3.8	4.9	44.7
	S6	3.2	3.5	4.8	43.9

2.2 *Experimental Data Measurement*

In order to measure the temperature distribution within the specimens, each slab was fitted with five 1.5mm sheathed thermocouples. Three of the thermocouples were used to measure the bottom surface temperature (one located at the mid span of the slab and the other two were located 400mm from both supported ends of the slab). The remaining two thermocouples were cast within the slab. The first one was located at the centre of the slab, while the second was touching the 7th reinforcement bar (mid-span of the slab) at a depth of approximately 40mm from the bottom of the slab surface. Slab deflection was measured using a Linear Variable Differential Transformer (LVDT), located at the mid span of the slab. Temperature distribution and slab deflection data was recorded using a data logging system. The moisture content was measured on both of the top and bottom surfaces of each slab using Tramex CRH concrete moisture content measuring device.

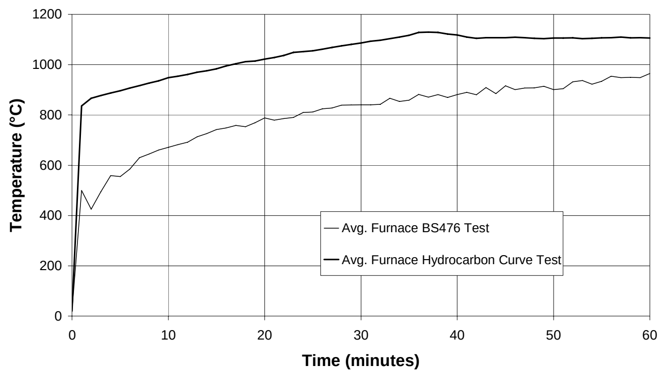

Figure 2. Average temperatures recorded in the furnace.

These measure--ments were then repeated in the same locations following the test process. Audio and visual observations of explosive spalling were made during the tests through the quartz windows situated in the door of the combustion chamber.

2.3 *Test Methodology*

The slabs were set on top of the combustion chamber and the necessary measuring devices were attached. The load was applied at a constant rate until the desired loading level was reached. Then the combustion chamber burners were ignited and controlled to achieve the required time-temperature curve. The applied load was kept at a constant level throughout the test. The duration of each test was 60 minutes.

2.4 *Spalling Assessment*

The primary criterion used to assess spalling was the degree of spalling. Following the test, the concrete lost due to spalling was collected and weighed. The degree of spalling (**S_d**) was then measured using the following formula:

$$S_d = W_L / W_C \tag{1}$$

where **W_L** is the weight of concrete lost due to explosive spalling and **W_C** is the weight of the concrete slab before testing. The depth of spalling and percentage surface area lost due to explosive spalling were approximately measured after the test. This enabled to estimate the volume of concrete that has disintegrated from the slab due to explosive spalling.

3 TESTS RESULTS

The main results from the series of experiments undertaken are shown in Table 1. All slabs were subjected to the same loading level = 0.14 of the design load of BS8110 represented in one concentrated load of 27kN at mid span of the slab as shown in Figure 1. All of the six slabs experienced explosive spalling during testing, with more violent spalling of slabs exposed to the hydrocarbon fire curve where spalling started after 2 minutes of heating. Slabs subjected to the BS476 fire curve did not experience explosive spalling until the 15^{th} minute of heating.

3.1 *Slabs Tested Under BS476 Fire Curve*

3.1.1 *Explosive Spalling*

All slabs have experienced explosive spalling. The spalling was violent with distinctive noises. Figure 3 shows explosive spalling of the three slabs S1, S2 and S3. The degree of spalling experienced by slabs S1-S3 is presented in Table 1. The degree of spalling of the three slabs was reasonably close to each other. The depth of the spalled areas varied along the surface of the slabs, with the greater depths noted towards both ends of the slabs. Slab S2 experienced the largest degree of spalling at 2.7%; with a maximum spalling depth of 25mm. Slabs S1 and S3 had maximum spalling depth of 20mm and 15mm respectively. The first occurrence of explosive spalling was observed approximately after 15 minutes at a slab surface temperature around 750°C. This explosive spalling phase lasted for approximately 20 minutes, after which only minor isolated incidents of explosive spalling were noted.

Figure 3. Explosive spalling of slabs S1-S3

3.1.2 *Temperature Profile along Slab Thickness*

A significant temperature gradient was recorded along the slab thickness during heating. Figure 4 shows the development of temperature of slab S2 at three point:- surface, at reinforcement level and at the mid height of the slab. Figure 4 clearly shows a high thermal gradient of around 880°C between the surface and the center of the slab. It is important to note that slab S2 has experienced the highest degree of spalling when subjected to the BS476 fire curve. Due to violent explosive spalling, the surface thermocouple of slab S1 has dislodged from the slab surface between the 25^{th} and 26^{th} minute. For this reason the surface temperature recorded after the 25^{th} minutes for slab S1 will be disregarded in this analysis. All slabs showed a similar temperature development, with slab 2 achieving a slightly higher maximum temperature of 138°C after 60 minutes. The thermocouple utilized to measure the temperature at the steel reinforcement is situated at a depth of 40mm from the exposed surface of the concrete slab.

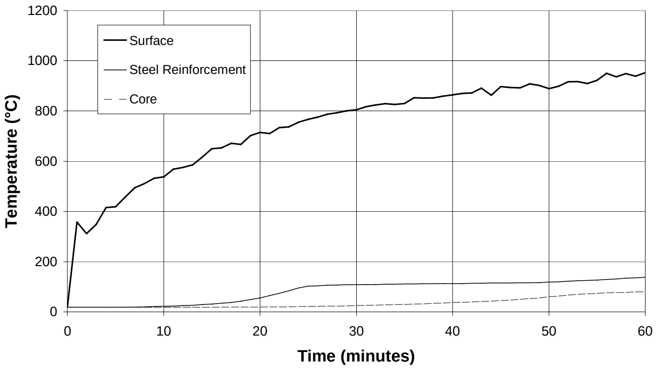

Figure 4. Temperature development within slab S2

3.1.3 *Slab Deflection*

Slab deflection was measured at the central point of the slab span. Figure 5 shows the development of the deflection of slabs S1, S2 and S3 subjected to BS476 fire curve.

It can be seen from Figure 5 that the three slabs have experienced reasonably similar rates and values of deflection (Table 1). From Figure 5 it can also be seen that slab's deflection is relatively small, up to a temperature of approximately 450°C. Beyond this temperature the deflection increases at higher rate up to a temperature of approximately 800°C. After that the rate of deflection increases again until the end of the test. This increase appears to coincide with the onset of severe explosive spalling and the reduction

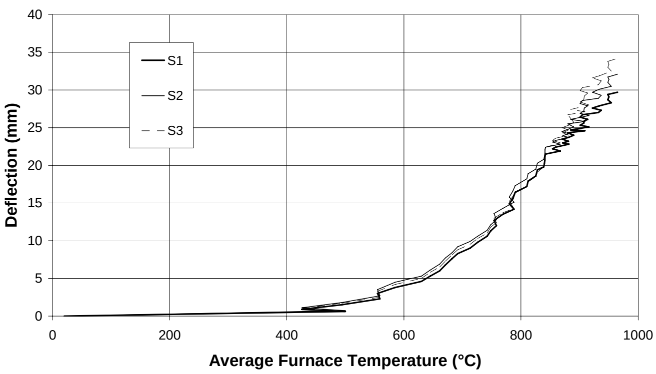

Figure 5. Deflection recorded for slabs S1-S3

in the slabs cross section. In general, slabs have achieved an average maximum displacement of 32mm at a furnace temperature approaching 965°C, with slab S3 showing a marginally greater maximum deflection of 34.2mm.

3.2 *Slabs Tested Under Hydrocarbon Fire Curve*

3.2.1 *Explosive Spalling*

In an apparent difference from BS476 slabs tested under Hydrocarbon fire have experienced more violent explosive spalling which happened on noticeably early time, after 2 minutes of the start of the test. The degree of spalling experienced by slabs S4-S6 is presented in Table 1. Slab S5 experienced the highest degree of spalling of 4.3% with a maximum spalling depth of 20mm. Slabs S4 and S6 both have a maximum spalling depth of approximately 15mm. Also it is important to emphasis that most of the violent explosive spalling occurred within the first 12 minutes. After that only occasional occurrences of mild spalling were noted.

3.2.2 *Temperature Profile along Slab Thickness*

As expected the temperature gradient in slabs subjected to hydrocarbon fire was more evident and higher in values (1020°C). In particular Figure 6 presents the temperature profile of slab S5, which has experienced a degree of spalling of 4.3% (Table 1). From Figure 6, it can be seen that a similar temperature gradient exists within slab S5 to that of slab S2 tested under the BS476 curve. However, the temperatures recorded within slab S5 are higher which indicates the increased severity of the hydrocarbon fire curve. After 30 minutes of fire exposure, the surface of slab S5 has reached a temperature of approximately 1100°C, while temperature at the steel reinforcement was approximately 130°C. Even the centre of the slab has experienced a slight temperature increase to 50°C only. All three slabs showed a very similar temperature profile to that of the hydrocarbon fire curve displayed in Figure 2, reaching a maximum temperature of approximately 1100°C after 60 minutes.

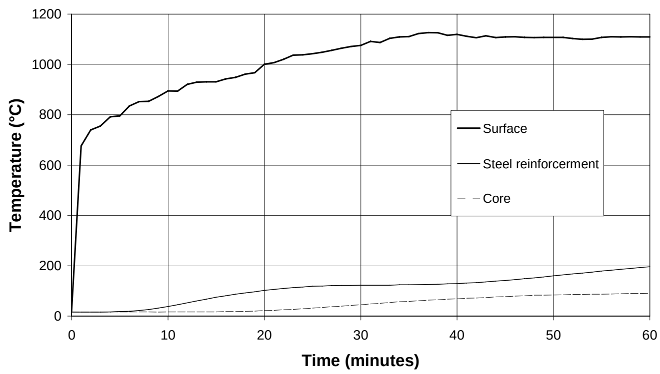

Figure 6. Temperature development within slab S5.

Figure 6 does not only highlight the large temperature gradient that exists in normal strength concrete but also underline the enhanced temperature profile experienced by normal strength concrete when exposed to hydrocarbon fire conditions as opposed to the conventional BS476 time-temperature curve.

3.2.3 *Slabs Deflection*

Figure 7 shows the development of the deflection of slabs S4-S6 when exposed to the hydrocarbon fire curve. All 3 slabs showed almost identical rates of deflection. Initially the slabs deformed at gradual rate, until a temperature of approximately 840°C was reached after 2 minutes. At this point, the gradient of the curves in Figure 7 shows a sudden and sharp increase, indicating a rapid increase in the deflection of the slabs. This point coincides with the moment when explosive spalling has started and caused a reduction in the slab cross section. This increase continues for the remainder of the experiment, with the slabs achieving an average maximum displacement of 44.5mm at a temperature approaching 1100°C. Slab S4 displays the largest deflection of 44.8mm.

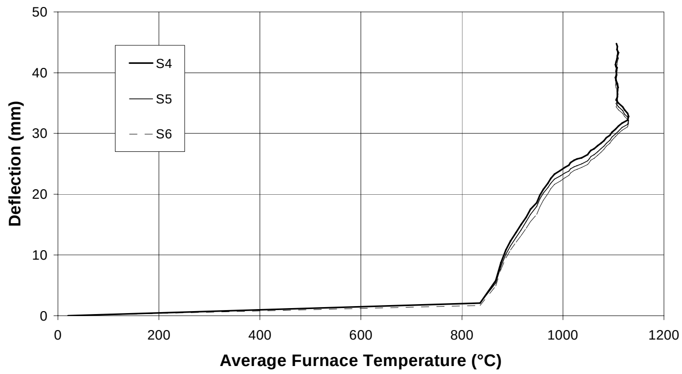

Figure 7. Deflection recorded for slabs S4-S6.

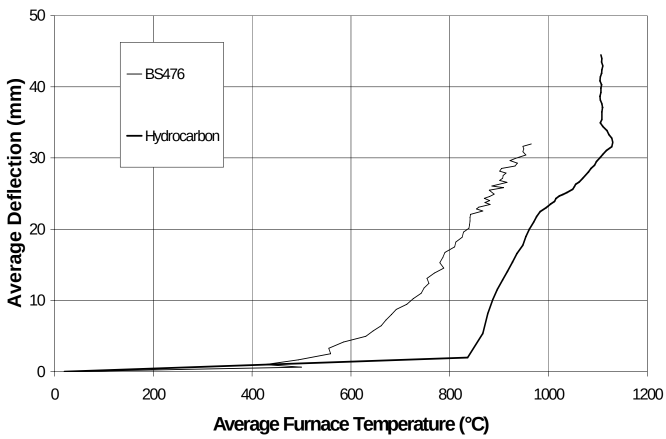

Figure 8. Average deflection of slabs under BS476 and Hydrocarbon fire curves

4 ANALYSIS OF RESULTS

4.1 *Effect of fire severity on slab deflection*

From Figure 8, it can be seen that all slabs showed a slow deformation rate during the early stages of fire exposure. After 2 minutes, at which point the slab deformation is almost negligible, the average furnace temperature under the BS476 and Hydrocarbon fire curves has reached approximately 450°C and 840°C respectively.

At this stage, slabs subjected to both heating regimes showed a sudden and sharp increase in deflection, with the gradient of the curves in Figure 8 indicating that the slabs exposed to the hydrocarbon fire experienced a more rapid rate of deflection.

Under the BS476 curve, the slab deflection increases as the temperature in the furnace (and therefore the surface temperature of the concrete) continues to rise. However, it is noticeable that even when the temperature of the hydrocarbon fire reaches a ‘ceiling’ of approximately 1100°C, the slab deflection continues to increase. In summary, although both heating regimes appear to induce a similar rate of deflection on the concrete slabs, the faster temperature development of the hydrocarbon fire ensures that slabs exposed to the more severe fire conditions will experience a more rapid rate of deflection, and ultimately a greater deformation will be recorded for those slabs.

4.2 *Effect of Fire Severity on Explosive Spalling*

From Table 1, it can be seen that the specimens exposed to the hydrocarbon fire curve experienced a greater degree of explosive spalling. The maximum degree of spalling exhibited by slab S2 under the conventional BS476 fire curve was 2.7%, whereas 4.3% of slab S5 was removed by explosive spalling when exposed to the hydrocarbon fire. Although the slabs subjected to the hydrocarbon fire curve exhibited the greater amount of spalling, the actual depth of the spalling was quite similar for all slabs, measuring between 15mm and 25mm, regardless of the fire severity. Also, while explosive spalling commenced on all slabs in the same temperature range of 750°C - 850°C, the more advanced temperature profile of the hydrocarbon fire ensured that explosive spalling occurred much earlier under hydrocarbon fire conditions than under the BS476 regime. To summarize the analysis, an increase in fire severity resulted in much earlier onset and a greater degree of explosive spalling. However, from the experiments undertaken, the depth of spalling was not noticeably affected by the increase in fire severity but the area affected by spalling was larger under the hydrocarbon fire curve.

4.3 *Effect Of Moisture Content On Slab Deflection And Explosive Spalling*

Figure 9 demonstrates that a relationship appears to exist between the moisture content and the maximum deflection recorded for the slabs. This relationship was more obvious in the slabs exposed to the conventional BS476 time-temperature curve, as the maximum deflection of the normal strength concrete slabs clearly increased with an increase in average moisture content. Although the maximum deflection of the slabs also increased slightly with the increase of moisture content under hydrocarbon fire conditions, this increase was not as marked for hydrocarbon fire as that experienced under the BS476 heating regime.

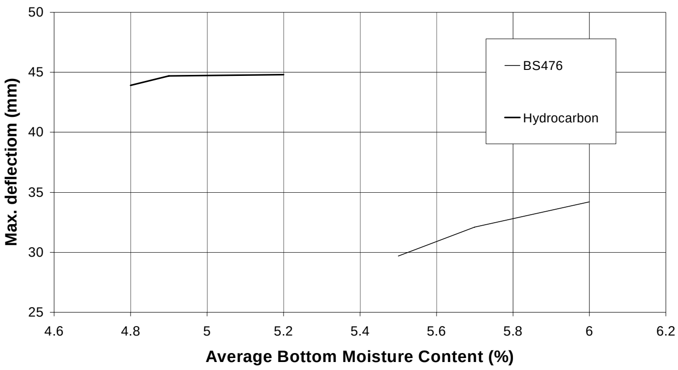

Figure 9. Effect of Average Moisture Content on maximum slab deflection.

4.4 *Evidence Of Moisture Front Movement Through Observation*

Observations were made of the moisture front movement of slab S6, which was exposed to the hydrocarbon fire curve. Prior to testing, the average moisture content of the slab was recorded both on the top surface of the slab and on the bottom surface (Table 1) exposed to the heating regime, with moisture content of 3.5% and 4.8% obtained for the respective surfaces. After 8 minutes of exposure to the hydrocarbon fire curve, water started to appear on the top surface of the slab at the four lifting hooks (embedded for slab lifting). As the temperature within the slab continues to rise throughout the test, the moisture is driven away from the advancing heat front towards the top surface. During the fire test and after 50 minutes, when even the slab core temperature was only 100°C, large pools of expelled water were visible on the surface of the slab (Figure 10). Following the completion of the experiment, the average moisture content of the surface exposed to the fire was measured, and a value of 0% was recorded – as opposed to 4.8% prior to testing.

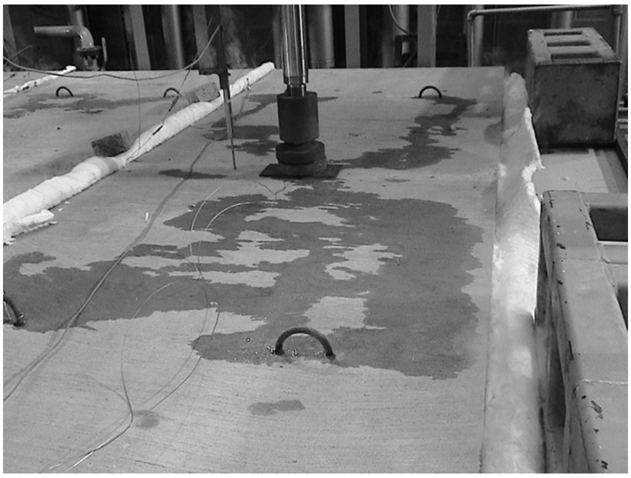

Figure 10. Top surface of slab S6 at minute 50 during the test.

5 CONCLUSIONS

1. All the normal-strength reinforced-concrete slabs experienced explosive spalling, regardless of the heating regime utilised during the experiments.
2. An increase in fire severity resulted in earlier occurrences of explosive spalling, with slabs exposed to the hydrocarbon and BS476 fire curves experiencing explosive spalling after 2 and 15 minutes respectively.
3. It was noticed that all the normal strength reinforced concrete slabs exhibited a large thermal gradient between the slab surface, the steel reinforcement and the slab core.
4. Concrete slabs exposed to more severe fires experienced more rapid deflection rate.
5. Slabs exposed to the severe hydrocarbon fire have experienced a higher degree of explosive spalling; therefore lower heating rates minimized, but did not eliminate, the risk of explosive spalling.
6. From the tests undertaken, the actual depth of explosive spalling was not noticeably affected by an increase in fire severity.
7. The maximum deflection of normal strength reinforced concrete slabs appears to increase with higher moisture content, both under high and low heating rates.
8. From the tests undertaken, the moisture front within the concrete slabs appears to move away from the heated surface during fire exposure. This movement appears to be accelerated with the increase of fire severity.
9. A hard evidence in the form of pictures, confirming the moisture clog movement away from the heated concrete face was obtained.

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