Kinetic energy analysis of fire-induced concrete spalling investigated using ultrahigh-speed photography

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Abstract:

Historically, there's been tremendous efforts towards investigating the variables that drive and govern the occurrence of concrete spalling during fire. To-date, there is no empirical data that has categorically quantify the governing variables and conditions which underpin the scientific nature of the phenomenon. There is relative consensus on certain key variables which influence the occurrence of spalling (for example, internal moisture content of concrete); nevertheless, their influence is not quantify and critical thresholds are currently not very well defined. This study utilized an ultrahigh-speed camera to capture video footage of spalling, aiming to investigate fire-induced concrete spalling. The experiments are conducted using the Heat-Transfer Rate Inducing System (H-TRIS). The captured video footage undergoes further analysis to determine the velocity and acceleration during spalling. Additionally, a comparison of the kinetic energy released during a spalling event and that of the net energy absorbed by concrete due to heating. Multiple experiments were conducted using mid-scale concrete test samples with different compositions and subjected to varying heating conditions. Outcomes of the fire experiments and analysis demonstrated that spalled pieces of concrete can have instantaneous (or initial velocities) ranging between 25-40 [m/s] and a mass 220-340 [g]. Therefore, the kinetic energy released during single spalling events was estimated to be between 68-272 [Joules].

Keywords: concrete spalling, fire, high-speed photography, kinetic energy.

1. Introduction and Background

Fire-induced concrete spalling is a phenomenon where heated concrete detaches or flakes away in a more or less violent manner from the surface (or surfaces) exposed directly to heat during a fire. Spalling is known to occur during growing stages, fully developed stages, or decay stages of a fire. The consequences of spalling are a reduction of the concrete cover to the internal reinforcement and a reduction in the load-bearing cross section of the concrete elements; both having detrimental effects in the structural stability during or after fire.

The current method for evaluating the propensity of fire-induced concrete spalling and the fire resistance of load-bearing concrete structures is centred in the use of a standard fire resistance furnace test; widely used for scientific knowledge growth, although conceived for regulatory approval testing more than a century ago. The fire resistance furnace test is known to have relatively poor repeatability of test outcomes (e.g., time-to-spalling), and comparatively high economic and temporal costs associated with its use [1,2]. Studies in available literature which report the occurrence of concrete spalling during fire resistance tests show a large scatter in test results; such that the research community argues to some extent that fire-induced concrete spalling is an apparently random phenomenon [2].

Based on past research (both experiment and modelling), fire-induced concrete spalling is believed to be driven by a combination of thermal-induced stresses, internal pore pressure build up, and reduction of the mechanical properties of concrete at elevated temperatures [2]. Spalling is known to be influenced to some degree, at least by the following: concrete strength, internal moisture condition, age, aggregate type and grading, certain admixtures, mechanical loads, mechanical restraint, heated area, element thickness, severity of thermal exposure, inclusion of steel and/or polypropylene fibres, and others [3]. The number of factors known to influence spalling make its prediction difficult, if not impossible, in practice. Within scientific and engineering communities, is currently challenging to state with confidence which phenomena or mechanisms primarily influence the occurrence of spalling [4].

Although hundreds of experimental studies have been performed in recent decades, there is yet no empirical data that has been able to categorically quantify the governing variables and conditions which underpin the scientific nature of concrete spalling during a fire. The motivation for this research study is to move knowledge on heat-induced concrete spalling forward in a direction where the governing variables and critical thresholds resulting in concrete spalling during a fire are quantified.

1.1 Aims of this study

The study described herein is part of a larger experimental study on heat-induced concrete spalling. This comprehensive study aims to investigate the spalling propensity and thermo-physical response of concrete (e.g., time-to-spalling, depth of spalling, in-depth temperature). Within the scope of this study, the Heat-Transfer Rate Inducing System (H-TRIS) test method [5] was used to perform fire experiments with high repeatability on identical test sample and conditions – thus, resulting in relatively high statistical confidence on measurements carried during fire testing (e.g., time-to-spalling). This is rarely seen in experimental studies on heat-induced concrete spalling [6].

The aim of this scientific, experimental approach to better understand concrete spalling is that the fundamental phenomenon itself is understood.

2 Materials and Samples Preparation

2.1 Concrete mixes

Concrete mixes were chosen to reflect nominal mixes used in the current Australian construction industry using three types of aggregates. The concrete mix included general purpose cement and fly ash. Concrete mixes were defined by the coarse aggregates included: limestone, granite, and basalt (all of them less than 10mm diameter). Fine aggregate for all mix types contained an even blend of manufactured sand and natural fine sand. Commercially available water reducer was used to obtain the conditions shown in the table below.

The curing conditions remained constant for all concrete test samples; (1) kept in the casting moulds for 24 hours, (2) demoulded, (3) placed under water for 7 days, and then (4) kept in a control environment at 20ºC and 50% RH until before testing. Measured moisture content at the time of testing was between 2.33-2.36% (by mass). Concrete test samples were tested at an age of 2 to 2.5 years

For practical considerations, a concrete mix was chosen to reflect a nominal shotcrete mix used in the current Australian construction industry. Although not detailed herein, the concrete mix included general purpose cement, fly ash, silica fume, 10 mm basalt aggregates, normal and fine sand, and a commercially available water reducer. The concrete mix was designed to achieve a cylindrical compressive strength of 50 MPa at 28 days. The curing conditions remained constant for all concrete test samples; (1) kept in the casting moulds for 36 hours, (2) demoulded, (3) placed under water for 7 days, and then (4) kept in a control environment at 20°C and 50% RH until before testing.

Table 1. Fresh and hardened properties of the concrete mixes.

Concrete Mix	**Properties of fresh concrete**		**Properties of hardened concrete**		
	Slump (mm)	**Air Content (%)**	**Compressive strength at 28 days (MPa)**	**Compressive strength at 284 days * (MPa)**	**Moisture content at 284 days * (mass/mass)**
Plain concrete	220	3.0	54.1	79.5	4.9%

** These tests were completed at the same time as when the spalling tests were performed.*

2.2 Preparation of concrete test samples

Concrete from a single mixing truck containing one concrete mix type was used for casting all test samples prepared within the scope of the research described herein (see Figure 1). Additionally, standard cylindrical concrete samples (100 mm diameter, 200 mm height) were casted for monitoring compressive and tensile strength, and non-standard small cylindrical samples (25 mm diameter, 100 mm height) were casted for monitoring internal moisture content of concrete.

The dimensions of the concrete samples casted for the spalling testing were 300 x 300 mm^2, with a depth of 200 mm. This dimensions of the samples where defined based on past experiments conducted [7] which have demonstrated that, for the expected transient heating conditions, for the concrete sample will behave as a semi-infinite solid. Three samples were casted for each concrete heating condition – therefore, three identical repeat test will be carried for each heating condition. Moulds incorporated thermocouples, precisely placed at thirteen depths from the target exposed surface (2, 5, 10, 15, 20, 25, 50, 75, 100, 150, and 200 mm).

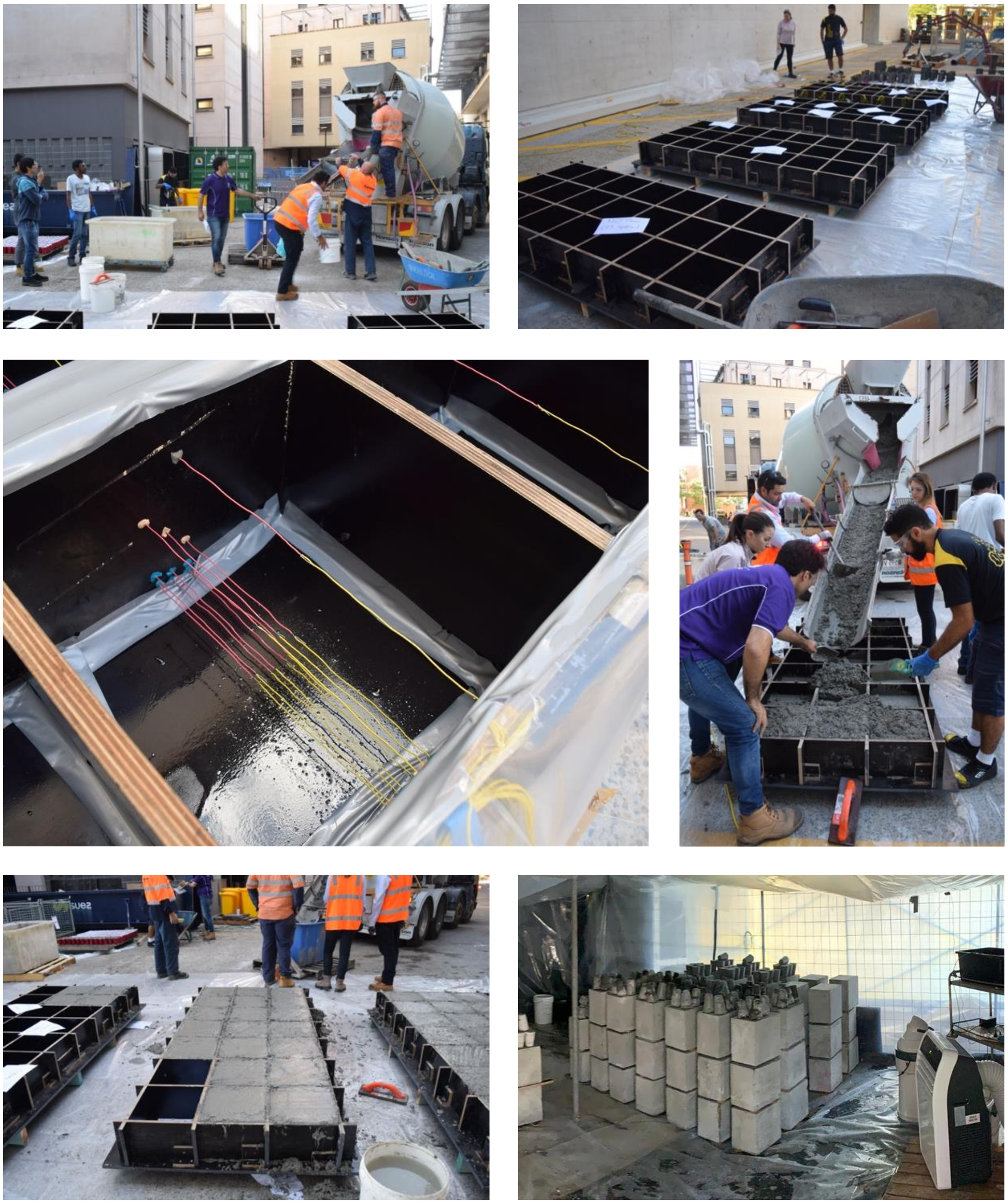


Fig. 1. Photographs of casting setup and concrete moulds prior to concrete casting, close-up view of moulds with thermocouples, pouring of concrete, and concrete sample during curing inside a room conditioned with controlled temperature and humidity.

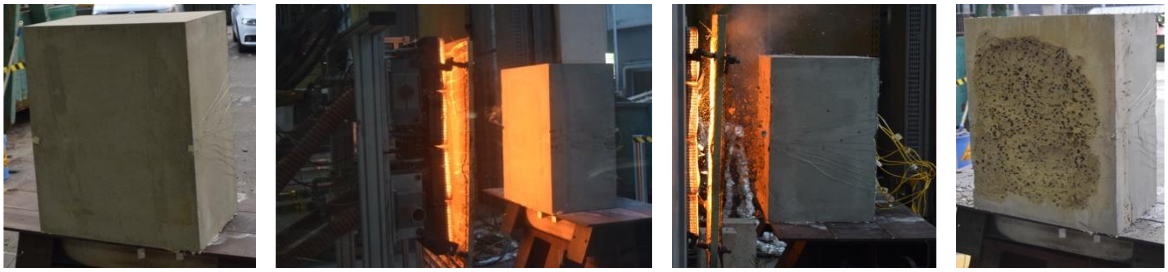
3 Experimental Methodologies

3.1 Test setup

The Heat-Transfer Rate Inducing System (H-TRIS) fire test method was used within the scope of this experimental work. Thoroughly described elsewhere [8-9], H-TRIS carefully quantifies and controls the thermal boundary conditions imposed on the target heated surface of test samples; the time-history of incident radiant heat flux at its exposed surface [10]. The testing equipment controls the relative position between the exposed surface of the test sample and an array of high-performance radiant heaters coupled with a mechanical linear motion system (see Figure 2). Using this test method enables the visual inspection of the test samples during fire testing, which is technically very challenging during a furnace test. Although done in past studies using H-TRIS, within the scope of the study described herein concrete samples where left unloaded and unrestrained; therefore, the influence of sustained external loads or restrain during heating was not investigated.

Fig. 2. H-TRIS test method being used for testing concrete samples (the photograph on the right shows the array of radiant panels).

Sixteen high-performance radiant heaters were mounted on a frame, creating a 600 x 800 mm^2 radiant source of heat. This configuration enables a heating system with a high and stable operational temperature and outstanding thermal homogeneity at the emitting surface. The computer-controlled linear motion system controls the relative position between the array of radiant panels and the exposed surface of the test sample; programmed to impose potentially any time-history of incident radiant heat flux, limited by the maximum proximity to the test sample. The maximum possible incident radiant heat flux that could be achieved using the H-TRIS at The University of Queensland is >250 kW/m2. Essentially, with H-TRIS the time-history of incident radiant heat flux at the exposed surface of test samples can be precisely controlled (refer to Figure 3). Since the main aim of this research study described herein is to examine the fire behaviour (including the potential occurrence of progressive spalling), tests with H-TRIS were continued for a duration of 2 hours.



(a) **(b)** **(c)** **(d)**

Fig. 3. Typical sequence of events for a spalling test; (a) exposed surface of the sample prior to testing, (b) initiation of the heating conditions, (c) snapshot a test sample at the moment of a spalling event, and (d) spalled exposed surface after testing.

3.3 Calculation of heating conditions

There is relative consensus around the scientific and engineering communities that rapid growing fires result in a higher likelihood of concrete spalling – outcomes of work in this remain qualitative in nature, without quantifiable thresholds for a so-called ‘critical’ heating conditions.

Within the scope of this study, the aim of is to investigate the likelihood of concrete spalling for a very wide range of heating scenarios. This comprehensive experimental study will evaluate four different heating conditions experienced by concrete when tested in a fire resistance furnace test (standard, hydrocarbon, modified hydrocarbon, and RABT-Rail). The unique fire testing facilities at The University of Queensland (and currently also in a handful of testing facilities around the world), is essential, where the innovation lays on the precision and wide range in which the heating conditions are controlled when testing with H-TRIS.

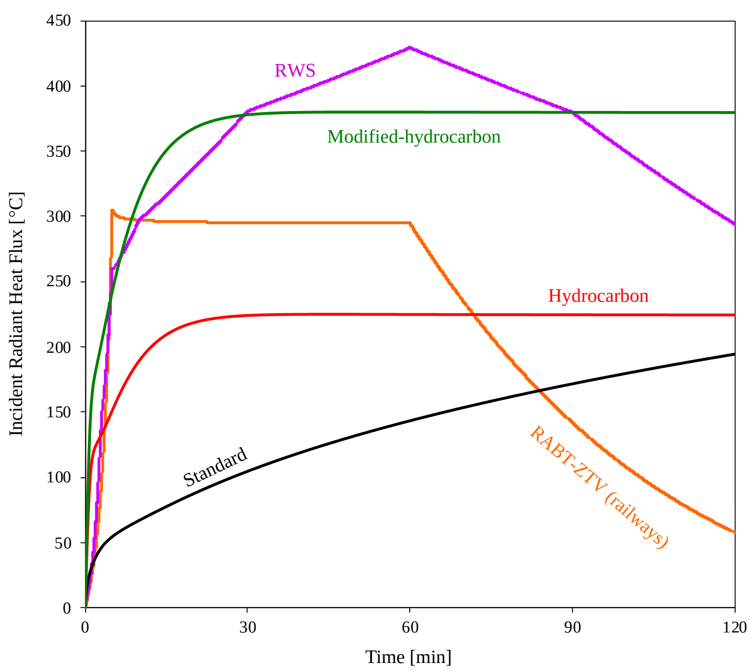


Fig. 4. Temperature vs. time for each heating conditions tested.

To understand the need for the novel fire testing approach described herein, a brief description of key heat transfer principles is shown in this section. Regardless of the design fire selected, the heat transferred from the fire to the exposed surface of a concrete structure (e.g. concrete lining) is normally expressed in terms of a net heat flux, $\dot{q}''_{net}$ [12]:

$$\dot{q}''_{net} = -k_c \cdot \frac{\partial T}{\partial x}\bigg|_{x=0} \tag{1}$$

Where k_c is the thermal conductivity of concrete, and $\frac{\partial T}{\partial x}\big|_{x=0}$ represents the in-depth time dependent temperature distribution at the exposed surface. For simplicity, in the current analysis heat conduction through the surface is taken only in the direction of the principal heat flow.

Within the scope of this study, H-TRIS was programmed to impose a thermal boundary condition equivalent to that experienced by a concrete sample of equivalent depth under idealised conditions during a standard fire resistance tests (controlled to follow the standard Hydrocarbon time-temperature curve). Figure 5 shows the time-history of incident radiant heat flux yielding an equivalent time-history of net heat flux, and hence equivalent in-depth temperature distributions as experienced during the fire resistance tests. Every test lasted for 120 minutes. It is worth highlighting that within the work described herein, incident radiant heat flux refers to the rate of thermal energy imposed (per unit of exposed surface and per unit of time) at the exposed surface of test specimens during testing. All parameters used in the model (e.g. convective heat transfer coefficient) are in accordance for those in the design and test standard using the Hydrocarbon time-temperature curve and European concrete design guidelines.

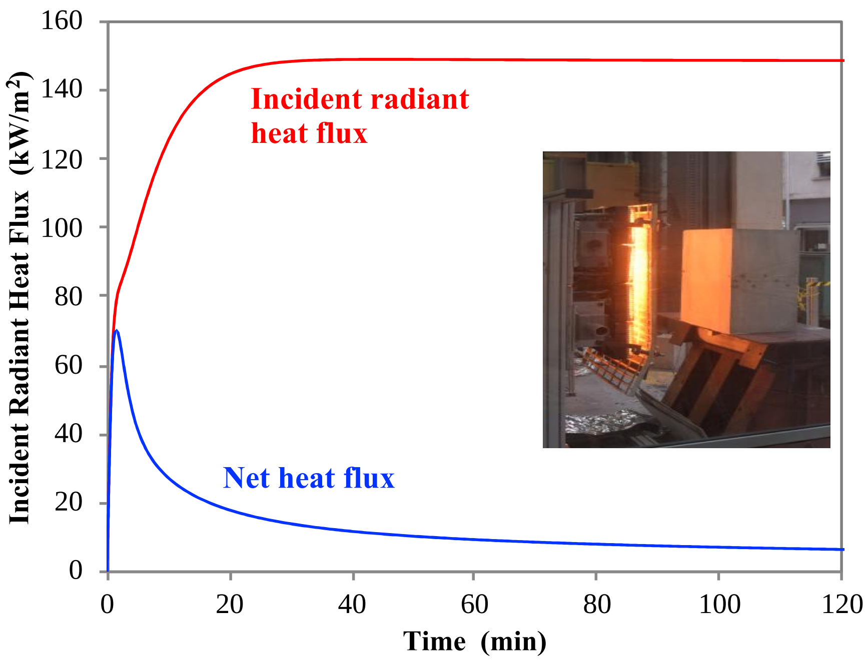


Fig. 5. Time-history of incident radiant and net heat flux imposed using H-TRIS for replicating idealized thermal boundary conditions during the standard fire resistance tests controlled with the Hydrocarbon curve.

4. Test Results

Precisely controlled and repeatable spalling tests were performed at one test per day which in itself demonstrated the low cost and relative ease of using the H-TRIS method. It is noteworthy that contrary to variability expectations based on prior fire-induced concrete spalling experimental studies [13], when spalling occurred for a given mix it occurred for both repeat tests at very similar times from the start of heating (refer to Section 3). When tested, concrete samples had an age between 2 and 2.5 years.

In-depth temperature was measured for each of the samples tested; thermocouples were positioned at 13 locations in moulds prior to casting (using distance to the heated surface as a reference; see Section 2). Temperature was recorded during heating and cooling. The figure below shows the in-depth temperature for each of the heating conditions tested.

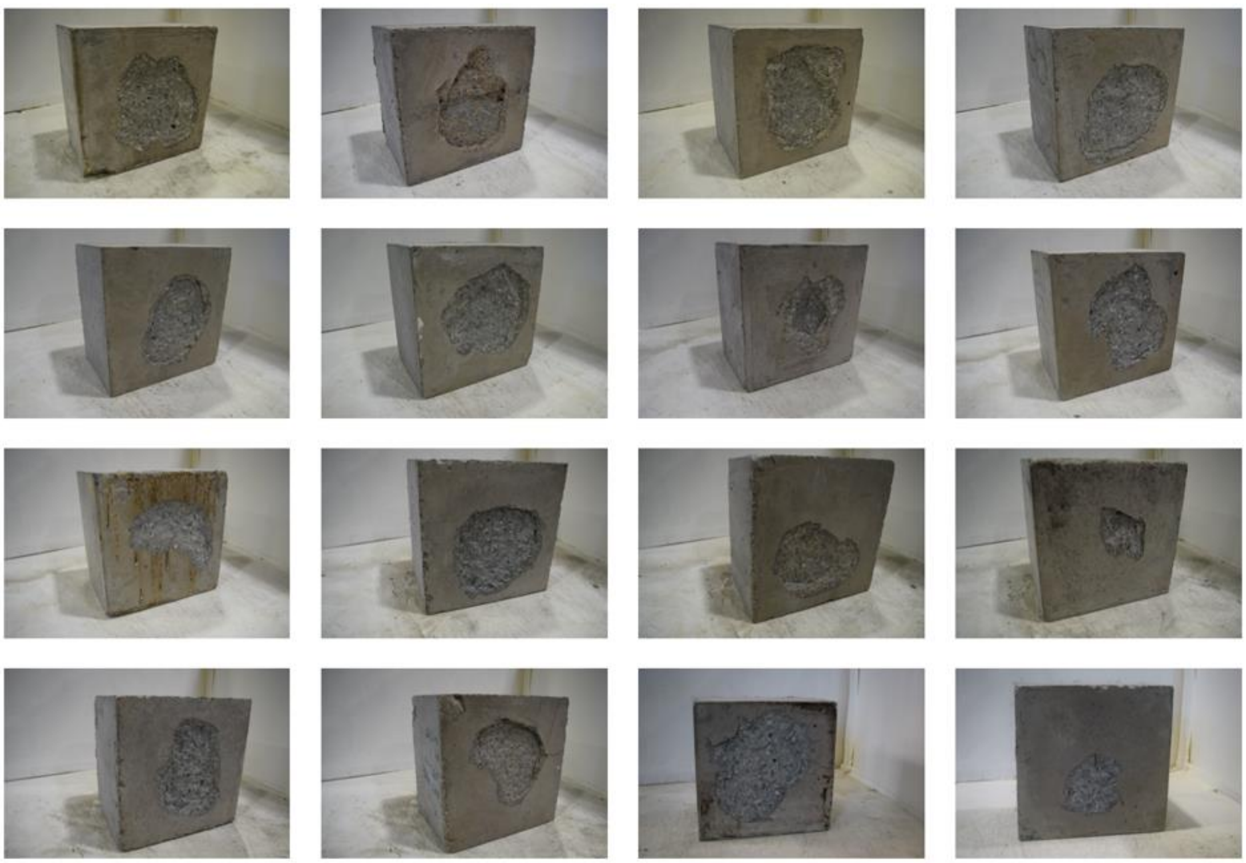


Fig. 6. Photograph for each sample spalled.

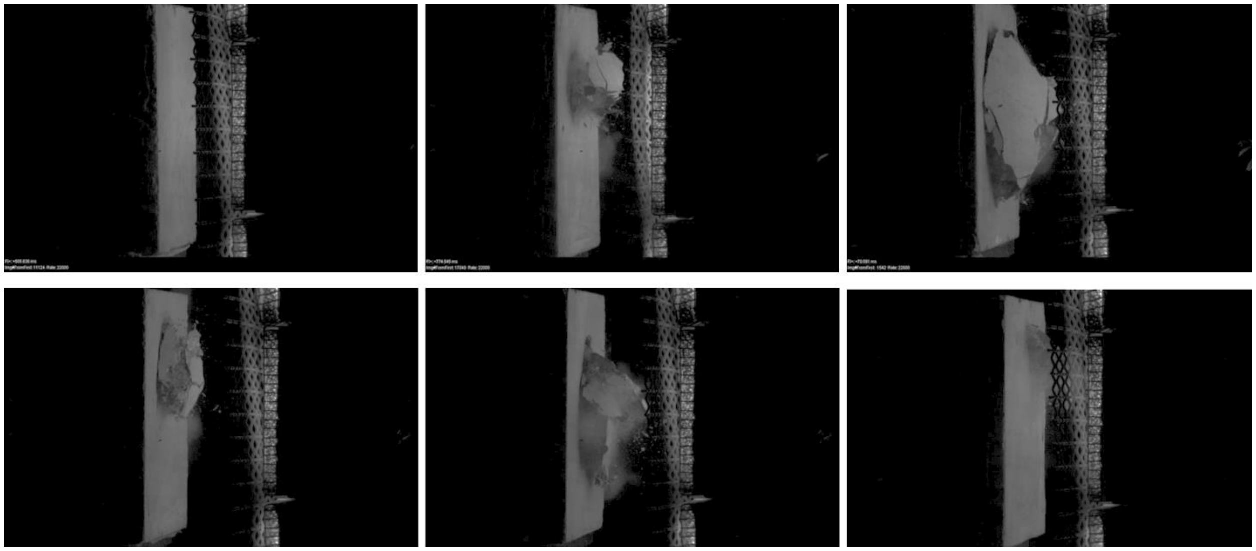


Fig. 7. High-speed camera showing the moment of spalling for various samples.

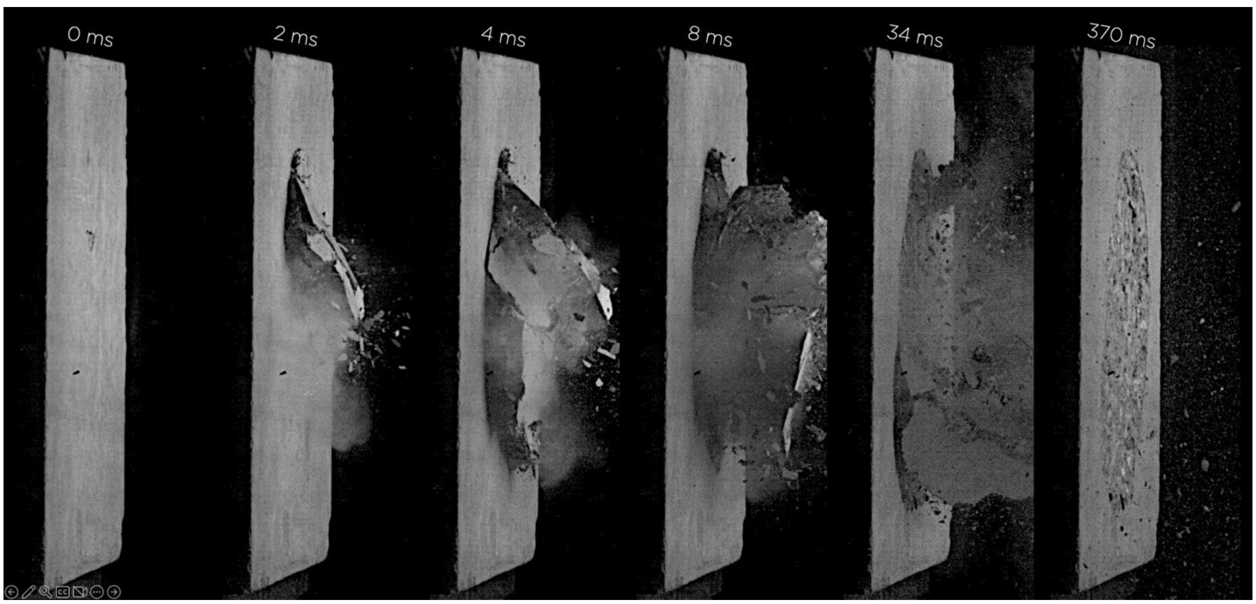


Fig. 8. High-speed camera showing the moment of spalling for a single sample. Time in milli-seconds is shown.

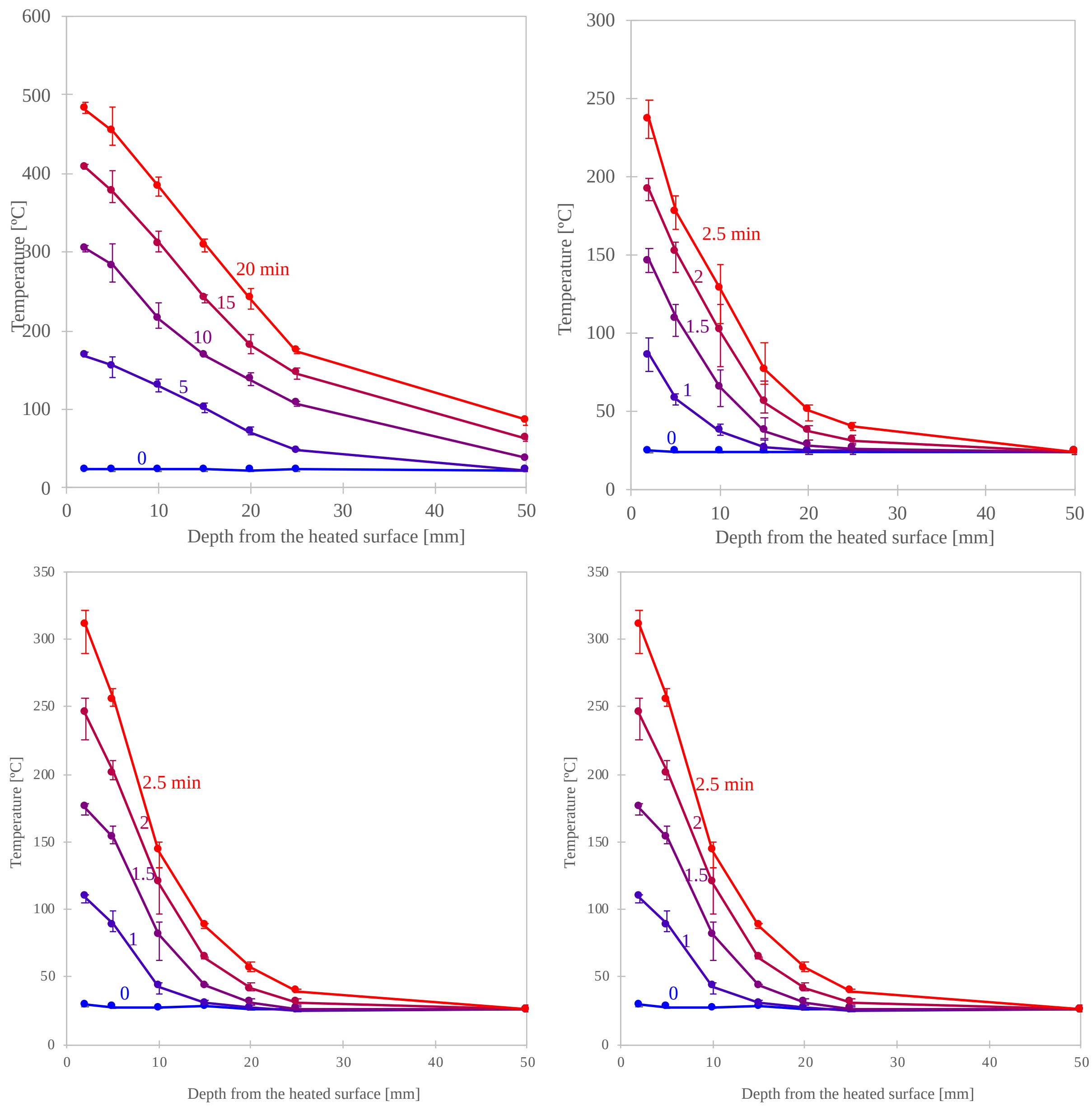


Fig. 9. In-depth temperature for each spalled sample.

5. Analysis and Discussion

Each average temperature result presented in this section were demonstrated with various curve representing the temperature profile with every 30 seconds after the first minute into the test. As such, temperature curves presented in each plot will only display the average temperature profile before time-to-spalling under the corresponding heating condition.

The major differences between the six heating condition curves affecting the temperature of concrete specimens, is primarily due to the heating gradient and magnitude of the imposing heat flux over time. Despite that fact that majority of specimen spalled at 1 – 4 minutes into the test, the average temperature measured from the exposed surface were observed to decrease exponentially as depth towards the opposite side of exposed surface increase. This is due to high-strength concrete consisted with low thermal conductivity and thermal inertia, heat is unlikely to penetrate 200mm depth of concrete specimen thoroughly before spalling occurred. Hence, except for Standard fire curve, the average temperature profile tested under all five remaining heating condition curves were observed to varied only from the heat-exposed surface to typically 25 mm into the specimen, towards the opposite side of exposed surface (Figure 10 to Figure 12).

By combining the temperature profile of each tested result at their corresponding time-to-spalling except for specimens heated under Standard Fire curve, it can be surprisingly found that the temperature at different depth into the concrete specimen, as well as the temperature gradient at their moment of spalling contained with very high likelihood, as illustrated in Figure

Except for specimen heated under Standard Fire curve, all experimental temperature result were displayed in Figure 8 with a typical time-to-spalling range of 1 – 4 minutes into the test. Though, It is believe that this experimental finding has not been verified with any existing literature, it is confident to state that the temperature threshold of plain concrete specimen that exposed under the remaining five heating condition curves was found, as the majority of specimen were observed to spalled when temperature gradient reached approximately 200 [C] at 2mm, 150 [C] at 5mm and 100 [C] at 10mm depth into exposed specimen surface, given the specimen geometric and material condition stated in previous section can further illustrated that due to the short timeframe of specimen has been heated, temperature rise was not considered significant beyond 25mm depth into the heat-exposed surface of specimen. Therefore, it can be summarised that by considering the concrete specimen with 200mm thickness, the influence of heating conditions only affecting temperature profile from the heat-exposed surface to 25mm depth into the concrete specimen by the time-to-spalling, which is 12.5% thickness of the entire specimen at the heat-exposed side.

This experimental result could be valuable for global tunnel fire safety design, as the heating condition presented herein were often studied and referred to when considering tunnel structural safety under threat of fire. However, there are room of potential improvement including numerical correlation to be compute or alternative verification approach in future development.

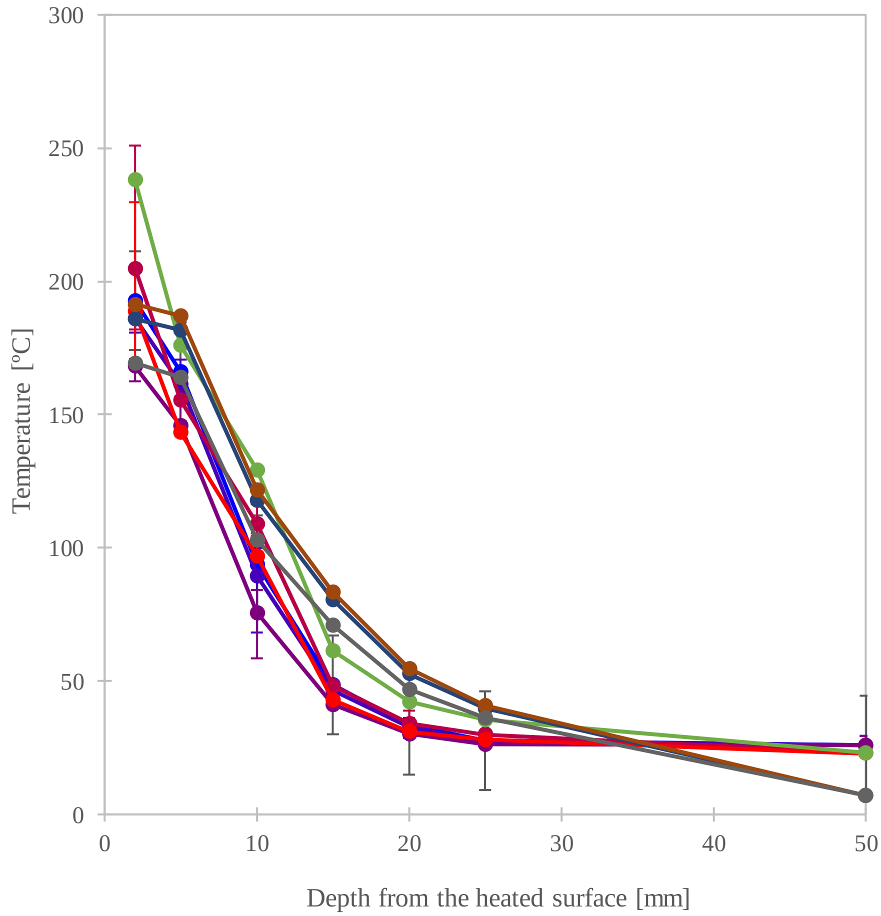


Fig. 10. In-depth temperature for all samples combined in one plot.

5. Conclusions

This paper describes the outcomes of a study investigating the influence of heating conditions on the propensity and severity of concrete spalling during fire. Experiments here conducted for four different heating conditions with varying growth at the beginning of the experiment – with test conducted in triplicate.

Based on the outcomes of the experiments and analysis of the test data, the following may be concluded:

- Regardless of the heating condition and the time-to-spalling, when spalling occurred, the in-depth temperature gradient close to the heated surface (<25 mm) was always very similar – concluding that there is a critical in-depth temperature gradient for which concrete spalling will occur.
- For the concrete type used in this study, the critical in-depth temperature gradient was found to be between -10.1 and -11.7 °C/mm. This in-depth temperature gradient was found to happen

for the Hydrocarbon, Modified-Hydrocarbon, and RABT-Rail heating conditions and therefore spalling occurred for these concrete samples.

- The temperature at the mean depth of spalling measured after the test, at the moment in which spalling occurs, was estimated for each sample, for the mean depth of spalling measured as measured after cooling. For the concrete type used in this study, the temperature was estimated between 111 and 191 °C.

The outcomes of the study described herein is a leap forward in better understanding the likelihood of concrete spalling during a fire. There is still significant work ahead if we (scientific and engineering communities together) are ever to understand the governing variables in the propensity, severity, and consequences of heat-induced concrete spalling.

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Figure captions

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