# Constitutive models of concrete at elevated temperatures: Studying the effect of temperature gradients

**Citation for published version:**
Le, Q, Dao, V, Maluk, C, Bisby, L & Torero, JL 2016, Constitutive models of concrete at elevated temperatures: Studying the effect of temperature gradients. in 9th International Conference on Structures in Fire. Princeton.

**Document Version:**
Peer reviewed version

**Published In:**
9th International Conference on Structures in Fire

**Cover page**

Title: ***Constitutive models of concrete at elevated temperatures: Studying the effect of temperature gradients***

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## ABSTRACT

The outbreak of fire can have serious consequences in the structural performance of a load-bearing concrete structure. To assure adequate fire performance, detailed knowledge of fundamental mechanical properties of concrete at elevated temperatures is crucial. This paper first highlights limitations of existing knowledge regarding the mechanical response of concrete at elevated temperatures, including the inconsistent thermal boundary conditions and intentionally-minimised temperature gradients in "standardized" conventional concrete material testing. Accordingly, it is argued that the effect of temperature gradients within concrete on its fire performance has not been extensively or directly addressed.

On this basis, the paper outlines key features of an ongoing research programme at The University of Queensland aimed at studying the performance of concrete in fire using a novel medium-scale testing method. By heating using radiant panels, well-defined and consistently-controlled heat flux boundary conditions on concrete cylinders ($\phi$100mm x 200mm) have been achieved. The repeatability, consistency, and uniformity of thermal boundary conditions are demonstrated using measurements of heat flux, temperature profile, and compressive strength.

Analysis of initial obtained data shows that the incident heat fluxes, and thus the associated temperature gradients, have potentially significant effects on concrete properties at elevated temperatures. Further research is thus ongoing to quantify such effects and also to develop models for their inclusion into effective performance-based fire design and analysis of concrete structures.

## INTRODUCTION

Despite extensive research over the past decades, current knowledge of fundamental properties of concrete at elevated temperatures remains largely based on data collected from conventional tests in which the thermal loading experienced by concrete specimens is difficult to be consistently controlled [1, 2]. As a result, the effect of

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temperature gradients within concrete on its fire performance has not been well investigated. The influence of processes linked with temperature gradients, including thermal stresses, moisture transport, and pore pressures, has not been directly addressed. This gap of knowledge is potentially important considering the likely steep temperature gradients within concrete structure subjected to real fires.

Realistic structural fire design of concrete structures thus requires detailed knowledge of fundamental properties of concrete at elevated temperatures, taking due account of the effects of temperature gradients. This is especially true in the context of current movements toward performance-based design for fire-related applications. The success of such an approach hinges on the establishment of reliable numerical models; which, in turn requires realistic constitutive models that should:

- reflect the true behaviour of concrete at elevated temperatures and under realistic thermal gradients; and
- be based on reliable and well-documented results from tests carried out under well-defined and well-controlled conditions.

This paper first highlights shortcomings of standardized conventional tests for concrete in fire, and discusses the potentially important limitations in the resulting currently available constitutive models for concrete at elevated temperatures. The paper then briefs details of an ongoing research program that aims to re-examine the fire performance of concrete using a novel testing approach.

## LIMITATIONS IN CONVENTIONAL TESTS AND THEIR EFFECTS

The increase of temperature in a test specimen is directly related to the incident heat flux on the specimen's surface. When a conventional fire testing furnace/oven is used, the temperature evolution of the gases in the furnace is controlled – if thermocouples are used – and the heat-flux to a plate – if a plate thermometer is used. The net heat flux at the specimen's surface results from a combination of radiation and convection between the furnace environment and the test specimen. This complex heat transfer process is sometimes further complicated by the presence of other test specimens within the testing chamber.

Using an energy balance the heat flux at the specimen's surface $q_s^{"}$ can be approximated as:

$$q_s^{"} = \varepsilon . q_{inc}^{"} - \varepsilon . \sigma T_S^4 + h(T_H - T_S) \quad (1)$$

where $\varepsilon$: thermal emissivity; $T_H$, $T_S$: temperature of gas and of specimen surface, respectively; $\sigma$: Stefan-Boltzmann constant; and $q_{inc}^{"}$: incident radiative heat flux (from gases, furnace walls, and other test specimens). The evolution of $q_s^{"}$ in time and space is highly complex and difficult to control accurately or consistently. This has potentially serious implications for concrete samples with a Biot number close to 1, where proper characterisation of thermal boundary conditions is required [2].

Poor definition of $q_s^{"}$ makes it challenging to achieve reliable control of the temperature evolution/gradient in test specimens in furnace tests. This has caused, at least partly, the following issues:

a. Currently available constitutive models for concrete have largely been derived from standardized tests where temperature gradients within the concrete test specimens is intentionally minimized [3, 4], with the aim being to separate, as far as possible, the "material" from the "structural" effects [5]. Limitations of these models include:

- Mass transfer processes affected by heat are different from typical real fire situations (with higher temperature gradients) because the very slow heating rates do not only allow dissipation of heat through the specimen but also slow dissipation of water vapour with minimal pore pressure increase.
- Components of the model linked with temperature gradients have not been explicitly addressed, nor have the couplings between different processes linked to temperature gradients (including moisture transport, vapour pressure, and thermal gradient induced stresses).

b. Significant variation in test results regarding both strength deterioration and spalling of concrete upon heating [3, 5]: Different heating rates result in different heating histories. These are complex and generally undefined due to poor thermocouple/sensor resolution. The undefined different heating histories in turn result in unquantifiable variability in the responses of test specimens. The significant variation in test results is likely also due in part to the inherent variation of concrete properties, and partly to possible experimental errors. In conventional tests, as a result of the limitations in thermal loading highlighted above, it is difficult to assess different sources of errors.

The above-discussed shortcomings can be addressed if known heat fluxes, including those representatives of real fire scenarios, can be consistently applied onto test specimens. A research program is thus underway at The University of Queensland to re-examine the thermal and mechanical performance of concrete at elevated temperatures by establishing well-defined and consistently-controlled thermal boundary conditions. This paper reports initial results of material testing of cylinder specimens, forming the basis for revision of constitutive models to reflect the effects of heat flux and associated temperature gradients.

## EXPERIMENTAL STUDY

### Test specimens and materials

Concrete cylinders of Φ100mmx200mm were adopted due to their common use for establishing uniaxial constitutive models of concrete in compression. The mix design was typical for concrete with 28-day compressive strength of 80 MPa, and is given in Table I. All mixing and casting was done in accordance with relevant Australian standards [6]. To ensure consistent moisture conditions, upon stripping from their moulds one day after casting, test specimens were cured in water at 27°C for four months, and then in air at 27 °C and 70% relative humidity for another three months until testing. The mass loss with time was monitored and found to become negligible after about 40 days. Two series of specimens were prepared:

- Series 1, of 9 specimens with internal thermocouples: Each specimen had 5 thermocouples located on two radial lines at mid-height. Temperatures were measured at three depths (Figure 1): (i) at the specimen's surface and (ii) centreline, and (iii) at 21 mm from the surface; this being the location of the average temperature [7].
- Series 2, of 33 specimens without thermocouples: Specimens were exposed to pre-determined schemes of heat flux boundary condition before testing to failure under

compression. Due to good repeatability of heating and curing, temperature profiles in these specimens are assumed the same as corresponding specimens in Series 1.

TABLE I. CONCRETE MIX DESIGN.

| Constituents | Quantity (/m$^3$) |
|---|---|
| 10mm aggregate | 925 (kg) |
| Manufactured coarse sand | 600 (kg) |
| River fine sand | 140 (kg) |
| Cement | 580 (kg) |
| Water | 193 (l) |
| Superplasticiser | 4.06 (l) |

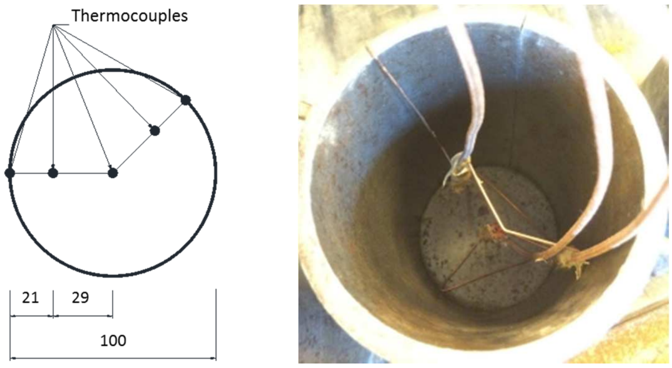

Figure 1. Locations of thermocouples in the cylinder concrete specimen.

## Radiant panel heating setup

The heat flux incident on cylinder test specimens was actively controlled using a system of four high performance radiant heating elements (Figure 3). Calibration of heat flux was performed using a Schmidt-Boelter heat-flux sensor as follows:

- The incident heat flux from each of the four panels was determined as a function of the distance between the panel and the target at the start of the testing, and this was repeated upon completion of the test series. The heat flux profiles produced by the four panels were essentially identical (Figure 2), proving that the consistency between the four panels was maintained throughout the testing.
- Two radiant panels were used to determine the degree of uniformity of incident heat flux intensities on the cylinder specimen surface placed at different offset distances (Figure 2). The measured heat fluxes at the three locations (i.e. A, B and C) varied within by 5% for all distances, giving a homogeneous thermal boundary.

## Imposed heat fluxes

Following the above calibration process, the incident heat flux intensities in this study were chosen as 20, 30, and 40 kW/m$^2$. Concrete specimens were first heated under a given incident heat flux level until the target average temperature, as recorded by thermocouples at 21 mm depth from the specimen surface, was reached. The test specimens were then loaded in compression at a rate of 0.25 mm/min until failure.

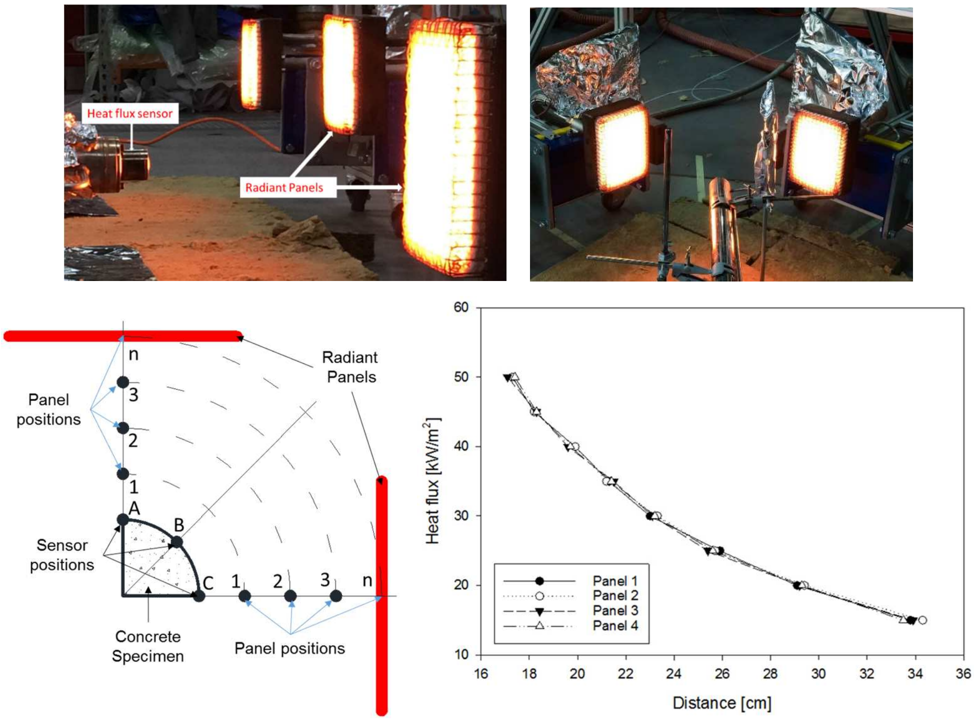

Figure 2. Illustration of heat flux calibration process.

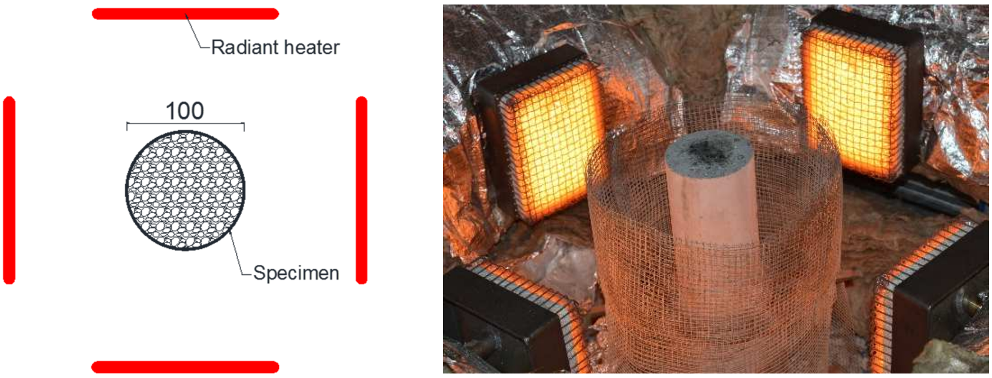

Figure 3. Radiant heaters and specimen.

## Mechanical loading preparation

Figure 4 shows a schematic of the test setup for mechanical and thermal loading. Key features of the test setup include:

- Loading crossheads below and above the test specimen: A water-cooling system was designed to maintain the temperature of the crossheads at less than 40°C during testing. The concrete block, as part of the attachment, was made of 100 MPa concrete, acting as an insulator with similar thermal conductivity to that of test specimens.
- A spherical seat ensured that uniaxial compression load was imposed.
- A steel mesh (of 5mm x 5mm grid) was placed around the test specimens to protect the radiant panels from possible explosive spalling.

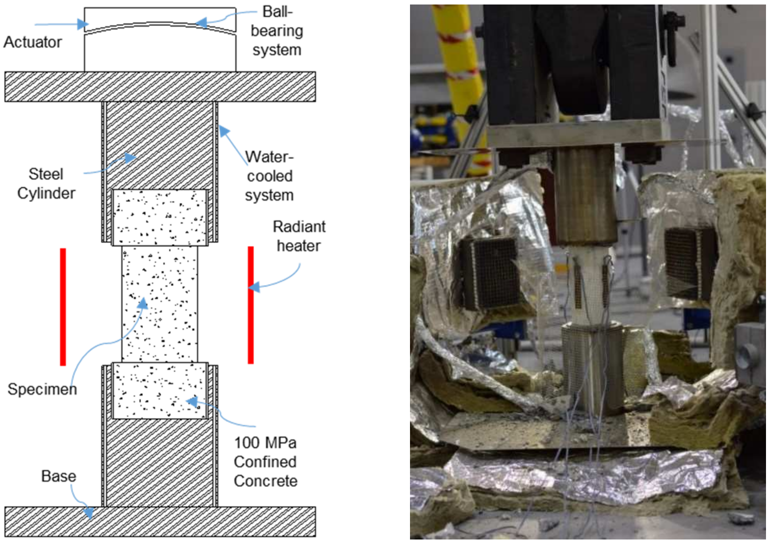

Figure 4. Schematic illustration and photo of test setup.

# EXPERIMENTAL RESULTS AND DISCUSSION

## Spalling

No spalling was observed during testing of all 39 cylinder specimens, despite the high compressive strength of concrete used, which was about 95 MPa at test date, and the relatively high rate of temperature increase for these specimens, which was between 10 and 20°C/min during the initial stages of heating.

## Time evolution of in-depth temperature profiles

The time evolution of in-depth concrete temperature profiles in three test specimens was determined for each of the three incident heat flux levels. A good degree of consistency was observed among the measured temperatures for each heat flux (Figure 5). The recorded temperatures along the two radial lines at corresponding depths (Figure 1) also had good agreement, confirming the uniform heat flux boundary condition.

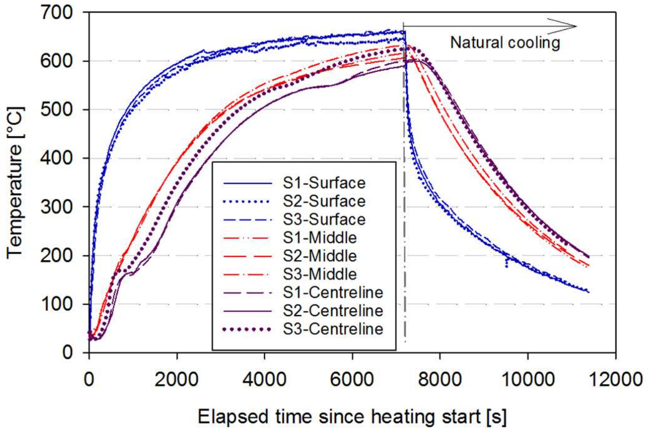

Figure 5. Temperature profiles of 3 specimens subject to HF40.

## Strength of concrete at elevated temperatures

Three cylinder specimens were tested for each combination of incident heat flux and target temperature. The average compressive strengths, normalised against corresponding strengths at ambient temperature, are plotted in Figure 6.

It can be seen from Figure 6 that, at a given average elevated temperature, concrete strengths of test specimens subject to different incident heat fluxes vary over a significant range. Such a difference can be explained by linking temperature gradients, heating time, and corresponding physical-chemical processes within concrete specimens. At an average temperature of 300°C, for instance, the temperature ranges within test specimens due to heat fluxes of 20, 30 and 40 kW/m$^2$ were 233 to 431, 217 to 490, and 212 to 545°C, respectively. As a result, while significant strength recovery was observed in HF20 specimens due to increased surface forces arising from loss of absorbed water [4], such recovery was modest in HF30 and HF40 specimens, possibly due to the counteracting effect of decomposition of $Ca(OH)_2$ [8].

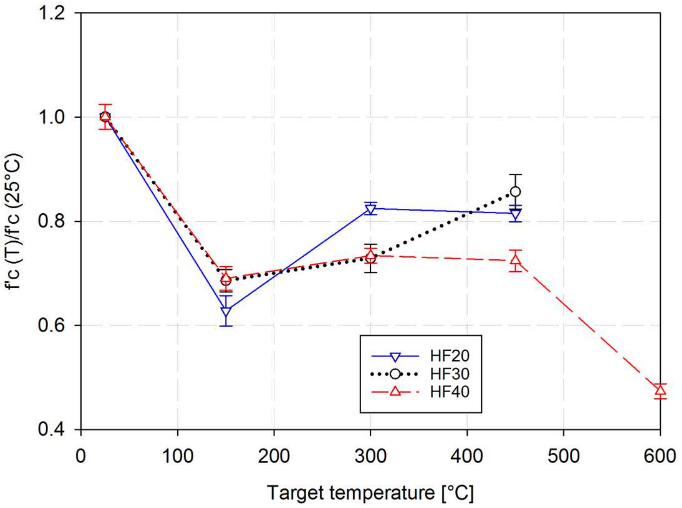

Figure 6. Change of concrete compressive strength at different target temperatures and incident heat fluxes.

Figure 6 thus highlights the potential influence of incident heat fluxes, and thus the associated temperature gradients, on concrete properties at elevated temperatures. The challenging question is to quantify such influence and also to develop methodology to effectively account for it in fire design and analysis of concrete structures.

## SUMMARY AND CONCLUSIONS

This paper has outlined the limitations of inconsistent thermal boundary conditions and intentionally-minimised temperature gradients in conventional materials testing of concrete at elevated temperature. Details of a research program aiming to re-examine the fire performance of concrete structures, taking due account of temperature gradients, are given. The test setup for thermal and mechanical loading, using radiant panels to generate well-defined and reproducible heating regimes, is described. The good repeatability, consistency, and uniformity of the thermal boundary conditions on test cylinder specimens are demonstrated.

Using this novel test setup, the measured compressive strengths of concrete specimens at a given average temperature were observed to be influenced by the incident heat fluxes, implying an observable effect of temperature gradients on concrete properties at identical average elevated temperatures. Further research is required to quantify this effect and also to develop models for its inclusion into structural fire design and analysis.

## ACKNOWLEDGEMENTS

The authors acknowledge the financial support of Australian Research Council's Discovery Projects funding scheme (DP150102354). The first author is also grateful for the financial support of Australia Awards Scholarships.

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