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Citation for published version:

Rickard, I, Bisby, L, Deeny, S & Maluk, C 2016, Predictive testing for heat induced spalling of concrete tunnels – The influence of mechanical loading. in 9th International Conference on Structures in Fire. Princeton.

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

9th International Conference on Structures in Fire

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**Predictive testing for heat induced spalling of concrete tunnels
– The influence of mechanical loading**

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PAPER LENGTH: 8 PAGES

ABSTRACT

This paper describes Phase II of a project being undertaken to develop a predictive test method to investigate heat-induced explosive spalling of concrete, with a specific focus on concrete used in tunneling applications (but obviously applicable to other applications). The test method seeks to allow careful control of the thermal and mechanical transient conditions influencing the occurrence of heat-induced concrete spalling, thus enabling convenient, representative, repeatable, and comparable testing to be carried out on various concrete mixes under various potentially relevant conditions.

Phase I of the project focused on establishing suitable thermal exposures to use for testing based on the thermal exposures which a sample would be exposed to during a standard furnace test (cellulosic or modified hydrocarbon) in the Promethee testing facility at CERIB in France. The work described in this paper deals with establishing suitable mechanical loading conditions for a spalling test, the focus in the current work is to enable provision of a representative test for precast segmental concrete tunnel linings (as opposed to sprayed or cut-and-cover tunnel linings). With small adaptations the spalling test method could be adjusted to suit other applications. This paper focuses on the motivation for developing the testing method and outlines the testing to be carried out. Tests are currently underway, and the full suite of results will be presented at the conference.

INTRODUCTION

Heat-induced concrete spalling poses a serious risk to the design, construction and operation of concrete structures, both above and below ground. In many well-known fires, for instance those in the Channel and Mont Blanc Tunnels, explosive concrete spalling caused considerable damage to the structures of the tunnels and required substantial, costly, and time-consuming repair works. Severe and rapidly growing fires, in combination with the lateral restraint to thermal expansion which may be present in

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some cases, means that all modern concrete structures are potentially susceptible to heat induced concrete spalling, and that tunnel structures have a particularly high risk of spalling in the event of a fire [1].

The project discussed in this paper is motivated primarily by the need for increased knowledge of spalling risk in concrete tunnel projects, and for a convenient and economical testing method to determine the propensity of different concrete mixes for spalling under a range of thermal and mechanical conditions. The work also has relevance to heat-induced concrete spalling building fires, particularly given the current shift toward higher strength, self-consolidating mixes containing silica fume which have shown increase tendency for spalling [2].

Currently there is no validated guidance to enable the design of concrete mixes to prevent spalling, nor is there an established, widely accepted test method available to quantify spalling for a given concrete mix or to demonstrate spalling resistance [2]; even costly and time-consuming large scale furnace testing is performed on an essentially ad-hoc, project-specific basis. As a result, the potential for spalling of candidate concrete mixes continues to pose a serious design risk at all stages of a concrete construction project cycle.

Conventional large-scale fire tests (i.e. ad-hoc standard furnace tests) of concrete structural elements are currently the sole design/compliance method/test for heat induced concrete spalling. Test methods and apparatus typically vary across projects and jurisdictions, thus limiting their usefulness for research and interpretation and their wider international applicability. Coupled with the global growth in infrastructure development, this has created demand from clients, contractors, and designers alike for a convenient predictive test method to quantify spalling risk. Any such test method must be able to accurately and repeatably control the thermal and mechanical exposures, provide known, appropriate loading and restraint conditions, and be cost effective and time efficient.

The project described herein will establish a suitable predictive test method for the explosive spalling of concrete, with a particular focus on tunnel linings. In order to do this, the test method needs to be able to control all the necessary parameters that are known to affect spalling. Defining a suitable thermal exposure and developing a method for accurately and repeatably imposing this thermal exposure on a sample were dealt with in Phase I [3,4]. All tests performed thus far have been carried out on unloaded samples of different sizes and geometries, primarily for the purposes of defining the requisite thermal exposure, however it is well known that mechanical loading and thermal restraint conditions experienced by samples during heating will also significantly influence spalling.

Numerous examples on the influence of loading and restraint in the occurrence of heat-induced concrete spalling are available in current literature [5-8]; based on small and large scale fire tests. The general consensus seems to suggest that increased external compressive loading or increased restraint to thermal expansion (either externally applied, or inherent due to sample thickness) increases the propensity of spalling. To be able to test with relevance to tunnel linings it is necessary to test samples of representative thickness under representative mechanical stresses, and it is therefore necessary to impose large mechanical loads.

FIRE TEST METHODOLOGY

Thermal Boundary Conditions

The testing method is based upon adaptation and extension of a novel testing method and apparatus known as the Heat-Transfer Rate Inducing System (H-TRIS), previously described by Maluk and Bisby [2]. H-TRIS controls the thermal exposure to which a sample is exposed (i.e. the time history of internal thermal gradients within a sample) by varying the incident radiant heat flux imposed at the target exposed surface of the test sample, rather than controlling temperature inside a furnace – as would typically be the case in a standard fire resistance test. The result of this shift in heating method is that the thermal boundary conditions can be more accurately defined, quantified, and reproduced, leading to a more repeatable test method. H-TRIS thus allows multiple repeat tests of candidate concrete mixes under a wide range of potential thermal exposures.

Phase I of the project [3,4], established the appropriate thermal exposure conditions (i.e. time-histories of incident heat flux) for testing under both standard cellulosic (ISO 834) [9] and standard modified hydrocarbon (HCM) [10] fire curves. This was accomplished by testing a large number of heavily instrumented prismatic concrete samples of various sizes and mix designs in the Promethee furnace facility at CERIB, France. The samples varied in surface area from relatively small (350×350 mm in plan) to full scale (4380×1450 mm in plan), and their thickness was either 100 or 250 mm.

Analysis of the in-depth temperature measurements within the samples tested in Promethee allowed the equivalent net heat flux to be determined [2], and this was subsequently converted into an incident heat flux for reproduction within H-TRIS. This thermal characterisation of the thermal exposure was a crucial outcome for the overall project but other insights into spalling behavior were also gained. The testing methodology was verified by testing identical concrete samples using H-TRIS and comparing the in depth thermal profiles against the furnace tests. Figure 1 shows the equivalent time histories of incident heat flux followed by the H-TRIS test apparatus to give an equivalent thermal exposure as experienced during the furnace tests.

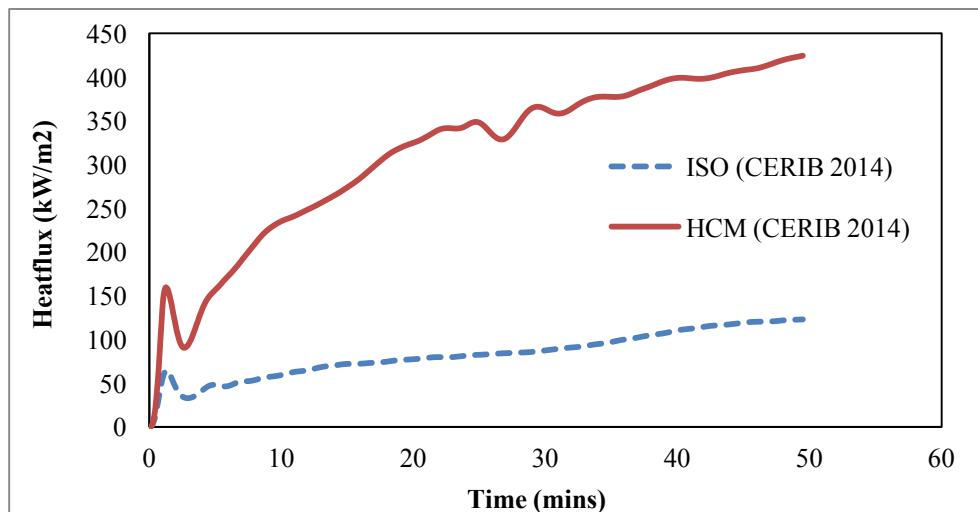


Figure 1. Incident Radiant Heat Flux calculated from in-depth temperature measurements of samples tested during a standard fire resistance test.

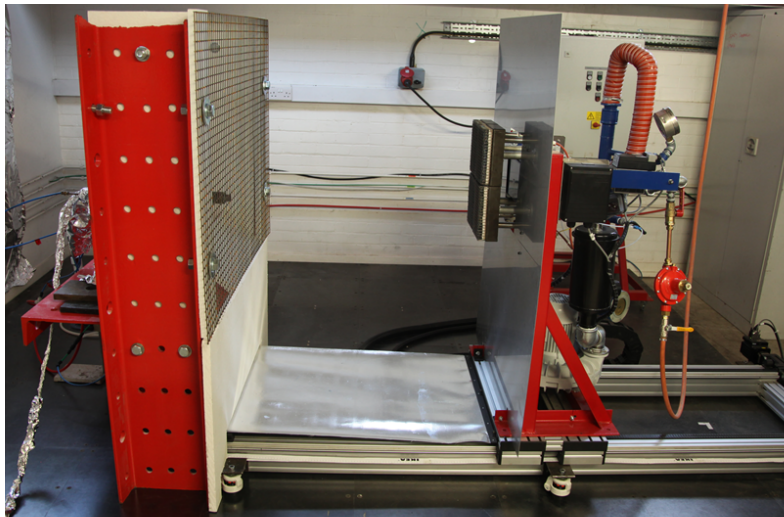


Figure 2. Heat-Transfer Rate Inducing System (H-TRIS) MkII

The current incarnation of the H-TRIS test apparatus (named H-TRIS MkII) is shown in Figure 2. Incident radiant heat flux is varied during testing by varying the standoff distance between the propane fueled radiant panels and the target sample using a computer controlled linear motion system. This method of heating a sample allows superior control and repeatability of the thermal exposure, particularly during the early stages of a test (i.e. within the first five to ten minutes) when standard fire testing furnaces tend to struggle to maintain control (hence the allowable temperature tolerances are much wider, or not existent in available fire resistance testing guidelines). Another advantage the H-TRIS apparatus and methodology is that this method allows for easy, direct observation of spalling times, patterns, and depths.

Loading Conditions

Phase II of the project is being carried out to investigate the influence of sustained compressive loads and localised heating on the propensity for heat-induced concrete spalling. Along with a bespoke 3MN uniaxial loading frame. Figure 3 shows both schematics and photos (during fabrication) of the loading and restraint frame that has been developed. The frame has been designed to allow large concrete samples, with surface areas up to 500×500 mm and depths up to 250 mm, to be loaded to up to a sustained level of 20 MPa (and smaller samples to be loaded to much higher stresses).

When used in conjunction with H-TRIS MkII heating rig, the loading frame enables simultaneous, accurate, heating and uniaxial compressive loading of samples of realistic scale. The loading frame uses two 1500kN hydraulic jacks to apply the load to the samples, and these are operated using load control by control of hydraulic pressure. The load on the samples is held constant during testing, and no increase in load due to thermal expansion is permitted. Such an approach has been taken because attempting to ‘fully’ restrain the samples is impractical and would lead to poorly characterized stress conditions within the concrete (indeed this is a shortcoming of much of the available research to date on spalling).

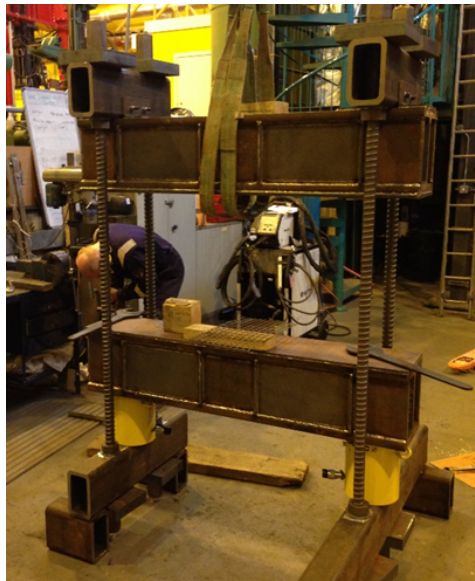
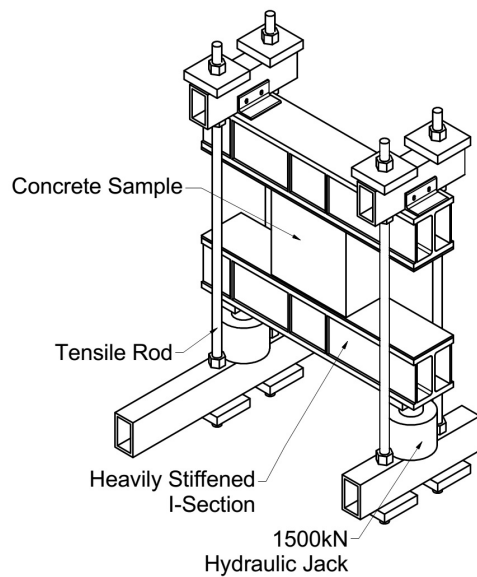


Figure 3. Loading frame design and frame under construction.

PHASE II TESTING PROGRAM

A total of forty-two unreinforced concrete samples, prismatic in shape with plan dimensions of 500 mm square and with various thicknesses (100 mm, 175 mm, and 250 mm), have been cast and conditioned, at room temperature and 50% relative humidity, for more than one year. The samples have been instrumented with thermocouples close to the heat-exposed surface to allow the temperatures within the samples to be monitored and the consistency of heating demonstrated and quantified. The parameters being varied amongst the samples, and the reasons for these choices, are discussed below. The overall testing matrix is shown in Table 1.

Table 1. Test matrix for Phase II testing.

Exposure area (mm)	Heating Curve	Thickness (mm)	Load (% ambient f_c')
400x400	HCM	100	10
400x400	ISO	100	10
400x400	HCM	100	0
400x400	HCM	100	30
400x400	HCM	100	50
400x400	HCM	100	70
400x400	HCM	175	10
400x400	HCM	175	0
400x400	HCM	250	10
400x400	HCM	250	0
100x100	HCM	250	0
150x150	HCM	250	0
200x200	HCM	250	0
300x300	HCM	250	0

* NOTE: Each test to be performed in triplicate

Heating Conditions

The thermal boundary conditions imposed are equivalent to those experienced by concrete test samples during a standard fire resistance test controlled to follow the ISO 834 [9] and HCM [10] time history of temperature inside the furnace. It was observed in Phase I, in agreement with the vast majority of available research on heat-induced concrete spalling, that the more severe HCM fire curve caused more severe spalling; however, tests are being carried out to confirm that this is the case for the Phase II samples. If either no spalling occurs or too much spalling occurs in the initial tests, it may be difficult to determine the influences of the secondary experimental parameters (see discussion below), and it may therefore be necessary to impose a more or less severe heating curve to enable useful comparisons of the influences of additional parameters.

Depth of the Test Sample

Samples with thicknesses of 100 mm, 175 mm, and 250 mm are being testing in Phase II. In Phase I, samples with thicknesses of 100 mm and 250 mm were tested, both in the Promethee furnace and using H-TRIS (MkI). It was observed, particularly during the furnace testing, that when otherwise identical samples that had different depths (thicknesses) were tested together, the 100 mm deep sample experienced almost no spalling, whereas the 250 mm deep sample spalled extensively; regardless of the plan dimensions of the samples. This coincided with the observed thermal bowing of the thinner 100 mm deep samples, and it is therefore hypothesized that thermal bowing allowed restrained differential thermal stresses to be somewhat relieved, resulting in less spalling. In a comparatively thick segmental concrete tunnel lining segment, bowing is highly unlikely to occur in the event of a fire due to both the curvature of the segment and the restraint to deformation provided by the surrounding overburden. Thus, it is important when developing a test method that the concrete be restrained against bowing (to the extent possible). As a result, the loading frame designed and constructed for Phase II imposes uniaxial stress with notional rotationally fixed-fixed end conditions.

Loading Conditions

Previous testing carried out on segments for installation in the Great Belt Tunnel [11] assumed that a realistic in-situ ambient compressive stress of 5MPa was representative of in-service conditions before a fire with relatively little justification. Samples in Phase II are being tested under sustained compressive uniaxial stresses of up to 20MPa. It is well known that the loading/restraint on a concrete sample influences its spalling propensity on heating. It is therefore necessary to determine the relative influence of applied mechanical stress in comparison with other relevant parameters; and to determine the credible worst-case loading to be applied in order to properly test for spalling. In the case of concrete in a precast segmental tunnel lining it is difficult to know the loading state in the tunnel lining (even at ambient temperature) as this depends on a range of uncertain variables, including the ground conditions and factors related to the tunnel's constructability. In the case of fire, the loading in a concrete tunnel segment is likely to depend on, amongst other factors, the in-service ambient loading, the global deformation of the tunnel due to the thermal exposure – which may include the response of the surrounding overburden to tunnel expansion, the tunnel's method of construction – which may influence whether the concrete segments experience biaxial or uniaxial

loading, and the effects of localized, rather than global, heating to buoyancy effects or flame impingement.

It should be noted that it is not the aim of the current project to recreate the thermal and physical realities within a real tunnel, but rather to create a test method which provides a credible worst case for heat-induced spalling, which is representative of the range of conditions which could occur in a fire in a tunnel. The goal is to experimentally unpick the importance of the respective parameters, rather than perform simple compliance testing, and eventually to develop the necessary protocols to show that explosive spalling will not occur for any credible combination of loading and heating in a real tunnel such as is needed to undertake performance based fire design of tunnels and tunnel linings.

It should also be noted that the loading frame developed for Phase II imposes uniaxial versus biaxial loading; this has been a conscious decision taken after consultation with structural designers of segmental concrete tunnel lining systems, who stated that longitudinal restraint is likely to be low in an installed segmental concrete tunnel lining in a fire due to the gasketing materials that are placed between the successive tunnel rings. Biaxial applied stress may, however, be appropriate for other structural scenarios.

Heated Surface of the Test Sample

Samples in Phase II are being exposed to heat areas varied between 100×100 mm and 400×400 mm. Whilst making it difficult to quantify the stress state within a sample, a number of authors have experimented with localized heating of concrete in order for the sample to be subjected to a certain degree (however un-quantified) of self-restraint to thermal expansion [12,13]. Thermal expansion of the heated area is restrained by the cooler surrounding concrete, leading to the development of a complex stress state in the concrete surrounding the heated surface and potentially contributing to (or dominating) explosive spalling. Testing with only localized heating could therefore enable testing that requires no applied loading system, and may also capture the effects of non-uniform/localised heating in a real fire. A comparison of tests using different exposed areas is underway to provide better understanding of how important this parameter might be in practice.

FURTHER OUTCOMES AND OBSERVATIONS

In addition to presenting the details of a novel testing method that can be used to assess the propensity of various candidate concrete mix designs to experience heat induced spalling, the testing described herein will enable a more complete understanding of the relative influences of applied loading and sample restraint/geometry on heat-induced explosive spalling. The results will inform the current project as it moves forward into Phase III to test candidate mixes from actual European tunnel lining projects and compare the results against those from conventional full scale tests undertaken on the same concrete mixes in furnaces. Recommendations for the development of an international industry standard for testing for the spalling propensity of concrete mixes will be proposed based on the work undertaken, via the RILEM committee on spalling of concrete due to fire.

CONCLUDING REMARKS

This paper has presented the current status of a project being undertaken at The University of Edinburgh to develop a predictive test method to investigate heat-induced explosive spalling of concrete, with a specific focus on concrete used in tunneling applications. A brief summary of Phase I has been given and the details of and motivations for phase II of the project have been described. The results of the testing which is currently underway will be presented at the conference.

The test method seeks to allow careful control of the thermal and mechanical conditions influencing the occurrence of heat-induced concrete spalling, thus enabling convenient, representative, repeatable, and comparable testing to be carried out on various concrete mixes under various potentially relevant conditions.

ACKNOWLEDGEMENTS

The work described in this paper would not have been possible without the support of the fire engineering and tunnels engineering teams at Arup and CERIB.

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