Construction and Building Materials 160 (2018) 526–538

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Response of concrete cast in permeable moulds to severe heating

Oliver Richards [a], Ieuan Rickard [b], John Orr [c,*], Luke Bisby [b]

[a] University of Bath, Bath BA2 7AY, United Kingdom
[b] School of Engineering, University of Edinburgh, Edinburgh EH9 3JG, United Kingdom
[c] University Lecturer in Concrete Structures, University of Cambridge, Cambridge CB2 1PZ, United Kingdom

HIGHLIGHTS

- Effects of mould permeability on the spalling behaviour of concrete investigated.
- 6 unrestrained specimens tested by controlling time-history of incident heat flux.
- No significant differences in thermal profile or deflections between mould types.
- Fourfold difference in surface porosity between mould types.
- Additional tests with specimen restraint and applied compression load suggested.

ARTICLE INFO

Article history:
Received 13 October 2017
Received in revised form 16 November 2017
Accepted 17 November 2017

Keywords:
Concrete
Heating
Permeable formwork

ABSTRACT

This paper evaluates the effect that a permeable mould, such as would be used to create fabric-formed concrete, may have on the heat-induced explosive spalling performance of cast concrete, using a novel experimental fire testing method and supported by scanning electron microscopy. Recent research suggests that a concrete cast using fabric formwork will gain durability enhancements at the cast surface that may negatively affect pore-pressure expulsion during severe heating. Six concrete samples were cast using high strength concrete including silica fume and tested using the University of Edinburgh's Heat-Transfer Rate Inducing System (H-TRIS), receiving thermal loading on one surface. Three samples were cast in permeable moulds, formed using a Huesker HaTe PES 70/70 single layer woven geotextile with a characteristic opening size (O_{90}) of 0.1×10^{-3} m. Three samples were cast in conventional impermeable timber moulds. The tests showed no conclusive evidence of differences in thermal profile or differential thermal deflections between the two casting methods; no occurrences of heat-induced explosive spalling were observed for either casting method. However, scanning electron microscopy undertaken on additional samples showed that the test face of samples cast in permeable moulds were over four times less porous compared to their impermeably cast equivalents. This could increase the risk of spalling of samples, particularly in cases where pore-pressure spalling dominates the material response. However, additional fire testing using H-TRIS is needed under a range of heating and loading conditions, before definitive conclusions on the spalling propensity of fabric-formed concrete can be made.

1. Introduction

Detailed structural optimisation of concrete structures can yield material savings in the order of 40% [1]. Such savings can be achieved, for example, by using flexible, permeable, fabric moulds that allow optimised forms to be cast. The permeability of fabric moulds (which are typically made using geotextiles) allows excess water and trapped air to escape, resulting in a more durable surface finish with a denser and more tightly packed microstructure [2]. In addition, fabric formwork is reusable in most cases, with the fabric geometry able to form a different element by an adjustment of its specific tension and clamping [3].

Permeability is widely believed to influence the propensity for heat-induced explosive concrete spalling [4]. Since permeable formwork typically reduces the porosity of the cast face, the extent to which a fabric formed surface layer may alter the tendency for a concrete sample to spall is unknown. Indeed, like-for-like tests performed on the same concrete mix but with differing surface porosity can help to unpick the relative importance of pore-pressure effects versus differential thermal effects as drivers for heat-induced spalling of concrete.

* Corresponding author.
E-mail address: jjo33@cam.ac.uk (J. Orr).

https://doi.org/10.1016/j.conbuildmat.2017.11.097
0950-0618/

Severe thermal exposure testing undertaken at the University of Edinburgh using the bespoke Heat-Transfer Rate Inducing System (H-TRIS) aimed to observe potential differences in propensity for heat induced spalling, whilst also observing internal temperatures and differential thermal displacements to evaluate the effects of casting with a permeable mould on high temperature performance of concrete. Further testing involved a study of the pore structure of fabric and timber-formed cast concrete surfaces using a scanning electron microscope (SEM).

2. Literature review

2.1. Flexible formwork

Fabrics have been an integral part of permeable mould formwork since the 19th century. It wasn't until the late 1980s, however, that research into synthetic fabrics resulted in high strength, tear resistant, and economical materials for this purpose. This led in turn to new methods of concrete construction for offshore, hydraulic, and coastal engineering environments [5]. More recent research into the use of permeable moulds has explored its use for structural optimisation, geometric form finding, and enhanced constructability [6]. Fig. 1 shows an example of a structurally optimised beam designed to minimise material and self-weight whilst maximising flexural strength.

2.1.1. Concrete properties

When cast into permeable formwork, excess water in the concrete in a zone of approximately 0–15 mm from the cast surface can escape [2]. The water to cement ratio in this zone is thereby reduced (by around 35%, depending on the fabric porosity [1,7]). This provides a localised increase in surface strength of as much as 80% [7], a higher density, and lower permeability [2]. Furthermore, any air trapped in the formwork is also able to escape [3]. Combined, these two mechanisms result in a significantly improved quality of the cast face.

The local increase in strength and reduction in permeability at the surface of the cast material also leads to improvements in durability. Orr et al. [2] showed 50% average reductions in carbonation and chloride ingress, for fabric formed concrete, reinforcing similar research carried out by Price [8] on controlled permeability formwork (CPF). If there are smaller pores and a reduced volume of interconnected pores present in the concrete surface layer, it is anticipated to increase the propensity for heat-induced explosive concrete spalling. A reduction in porosity will prevent the expulsion of gases (including pore moisture) through the surface layer at high temperatures, thereby potentially increasing the likelihood of spalling, further exacerbated by high strength concrete which is known to be more susceptible to spalling [9].

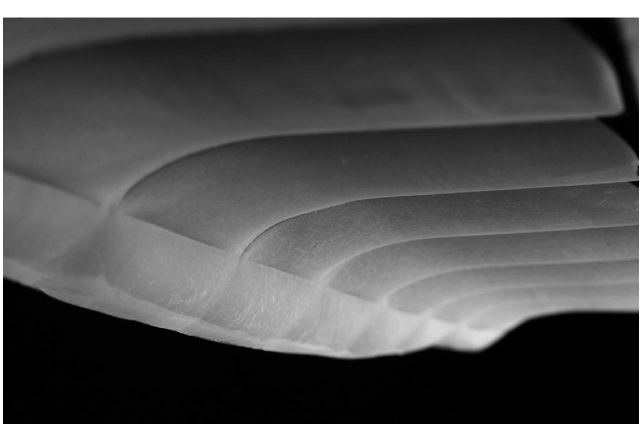

Fig. 1. Fabric formed concrete beam optimised for flexural strength.

2.2. Spalling

Khoury [9] described spalling as the process of concrete breaking off from a structural member, during high temperature states, in a violent or non-violent nature. Although research has been conducted on spalling since at least the 1910s [4], spalling remains an incompletely understood phenomenon within the scientific community – and is currently impossible to predict with confidence. An example of severe heat-induced concrete spalling is shown in Fig. 2, where only the spalled area was exposed to heating during the test. A loss of structural material is evident, which reduces the volume of the element and could result in failure through loss of cross section or loss of thermal protection to the internal steel reinforcement.

According to Jansson [11], prominent researchers in the late 20th Century Meyer-Ottens [12] and Copier [13] hypothesised that the probability of spalling is low if the moisture content of concrete is also low. Mindeguia et al. [14] proposed that free and physically bound water holds the core responsibility over the development of internal pore pressures from elevated temperatures. Considering moisture as an important factor affecting the propensity for concrete spalling, it is therefore clearly detrimental to have a large amount of free water within a sample.

The Moisture Clog Model originally developed by Harmathy [15] describes one of two widely accepted theoretical mechanisms for spalling. At elevated temperatures, a plane of fully saturated concrete is expected to form within the concrete specimen, as a result of vaporisation of pore water within the concrete, restricting the movement of steam out of the sample. This causes pore pressures within the concrete to rise. Once the tensile strength of the concrete is exceeded locally, spalling may occur [16]. By cutting specimens shortly after they been tested at high temperature [16] demonstrated that a moisture clog layer was visible, which partly validated this explanation of pore pressure as a factor influencing spalling. Although the mechanism has not been definitively proven and the research community has put forward various alternative mechanisms [9], the Moisture Clog theory is still regarded as relevant to explaining the phenomenon of spalling. The other key mechanism involves differential thermal stresses which are generated as the concrete surface heats and tries to expand, whereas the cooler concrete within the core remains cool;

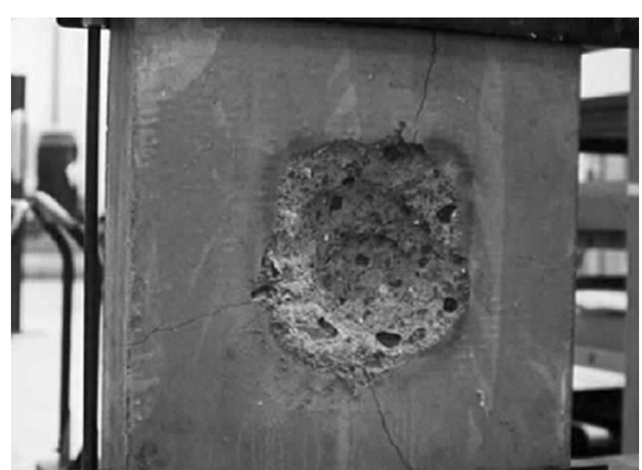

Fig. 2. Severe heat-induced explosive spalling of a concrete sample locally exposed to elevated temperature [10].