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Analysis of the early-age cracking in concrete made from rapid hardening cement

Análisis de la fisuración a edades tempranas de un hormigón fabricado con cemento de endurecimiento rápido

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Abstract

This paper investigates the use of concrete containing ultra-rapid hardening cement for rapid repairs in confined spaces where the repaired element has to sustain dynamic loading within a short time after repair. The study focuses on the early-age strength development and structural integrity of the repaired element. The study is divided in two parts. The first part is devoted to the compressive and split cylinder strengths, and to the temperature rise under adiabatic conditions in the concrete repair material from early-age (1 h after casting) to 7 days of age. The second part of the study focuses on the finite element thermal and thermo-mechanical analysis of three repair options of a damaged concrete element in a confined space using simplified pseudo-static loading characteristics for the repaired element.

Keywords: Cracking behaviour; Ultra-rapid hardening cement; Concrete; Maintenance; Numerical modelling

Resumen

En este artículo se analiza la utilización de un hormigón fabricado mediante cemento de endurecimiento ultra-rápido para la reparación urgente en espacios confinados, donde los elementos reparados son sometidos a cargas dinámicas poco tiempo después de su reparación. La investigación se centra principalmente en el estudio del desarrollo de la resistencia del material a edades tempranas, así como de la integridad estructural del elemento reparado. El trabajo se ha dividido en 2 partes. En la primera parte se analiza la resistencia a compresión, la resistencia a tracción indirecta y el aumento de temperatura bajo condiciones adiabáticas del hormigón de reparación desde una edad muy temprana (1 h después del hormigonado) hasta una edad de 7 días. En la segunda parte de la investigación se realiza un análisis térmico y termo-mecánico mediante elementos finitos de 3 opciones de reparación de un elemento de hormigón dañado y confinado en un espacio, utilizando cargas seudoestáticas simplificadas para el estudio del elemento reparado.

Palabras clave: Comportamiento en fisuración; Cemento de endurecimiento ultra-rápido; Hormigón; Mantenimiento; Modelización numérica

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1. Introduction

In some structural applications, the curing time of concrete must be reduced since there is an imperative need, in terms of reducing operational costs, of accelerating the strength gain of the material. In such applications, the utilisation of standard Portland cement is not convenient and the rapid hardening cements (also called ultra-high early strength cement) must be used in the concrete. Rapid-hardening hydraulic cement based concrete mix can attain the 28-day strength of an equivalent Portland cement mix [1] in less than six hours. Usually, this type of cement has high alumina and calcium sulfate content and a minor amount of reactive lime than Portland cements [2,3].

Rapid-hardening hydraulic cement has a chemical reaction different from Portland cement [3]. The reaction product is composed primarily of hydraulic tetracalcium trialuminate sulphate (CSA) and dicalcium silicate (C_2S). Hydration of CSA leads to ettringite, which is a strong needle-like crystal that develops rapidly and gives the hydraulic cement a rapid hardening at early age [4]. It achieves strength much faster than Portland cement and many installations can be put into service in as little time as one hour. Another important aspect of this kind of cement is the absence of tricalcium aluminate (C_3A), which provides a high durability of this material in sulfate environments [5].

Rapid-hardening hydraulic cement has been used for both concrete repair [6,7] and new construction [8], especially in concrete pavements [9], i.e. wherever superior durability and rapid strength gain are required. One relevant application where this kind of rapid hardening cement composite is very appropriate is as filling materials for 3-D concrete printers [10], where the setting of concrete must be precisely controlled.

In this paper, we investigate the use of a commercial concrete mix containing ultra-rapid hardening cement for rapid repairs in confined spaces where the repaired element has to be put into service within a short time after repair. The investigation focuses on the early age strength development and structural integrity of the repaired element. The investigation is divided in two parts. The first part is devoted to the determination of the compressive and split cylinder strengths, and to the temperature rise under adiabatic conditions in the commercial concrete repair material from early age (1 h after casting) to 7 days of age. The second part of the investigation focuses on the finite element thermal and thermo-mechanical analysis of three repair options of a damaged concrete element in a confined space using simplified pseudo-static loading characteristic for the element application. The first part of the investigation which is a kind of forensic investigation was made necessary because the supplier of the ready-mix concrete repair material was reluctant for commercial reasons to reveal any information on the proportions of cement blend used in the ready-mix concrete material. From the results of the two investigations, it was possible to identify the origin of premature cracking in the repaired element and to suggest a solution to avoid this problem.

Table 1
Ratio of the mass of the components of cement classes I and II to the total cement mass.

Class	C_3S	C_2S	C_3A	C_4AF	FreeCaO	SO_3	MgO
I	0.565	0.140	0.100	0.080	0.029	0.035	0.013
II	0.510	0.240	0.053	0.166	0.004	0.025	0.009

2. Theoretical background. Heat of hydration of cement based materials

Since the early age behaviour of the rapid hardening cement is crucial and as no information about the cement blend in the concrete mix was supplied, a thermo-mechanical model for the analysis of the heat of hydration of the different cement blends and solutions had to be used as a forensic tool. The model used to predict the evolution of the heat of hydration is that proposed by Schindler and Folliard [11] (see also [12]).

The model of Schindler and Folliard considers the heat of hydration flux of the cement transferred to the concrete mix. According to this model, the total heat of hydration of a Portland cement class is a function of that provided by its components:

$$H_{cem} = 500\, p_{C_3S} + 260\, p_{C_2S} + 866\, p_{C_3A} + 420\, p_{C_4AF} + 624\, p_{SO_3} + 1186\, p_{FreeCaO} + 850\, p_{MgO} \quad (1)$$

where H_{cem} is the total heat of hydration of the Portland cement (J/g) considering fully-hydrated cement and p_i is the ratio of the mass of the ith component to the total cement mass. Table 1 shows the components of cement classes I and II [13].

The evolution of the hydration of the Portland cement can be evaluated by means of the degree of hydration, δ, which varies from 0 to 1 (1 means complete hydration). This variable is stated as the ratio of the heat of hydration generated at a given time t, $H(t)$ in J/g, to the total heat produced in the reaction [14]:

$$\delta(t) = \frac{H(t)}{H_u} \quad (2)$$

H_u is the total heat available for the hydration reaction, $H_u = H_{cem}$.

The degree of hydration is usually considered as an exponential function as follows:

$$\delta(t_e) = \delta_u e^{-(\tau/t_e)^{\beta}} \quad (3)$$

where δ_u is the total degree of hydration, β the hydration shape parameter, τ the hydration time parameter (in hours), and t_e the equivalent age (in hours) at the reference temperature, T_r (K), which is given by:

$$t_e(t) = \sum_{0}^{y} e^{\left[-\frac{E_a}{R}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right]} \Delta t \quad (4)$$

Here, Δt is the time interval (in hours), T is the average temperature of the concrete mix (in K), R is the universal gas constant