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Thermo-mechanical assessment of concrete microcracking damage due to early-age temperature rise

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HIGHLIGHTS

- Early-age time–temperature cycles damage observed on a variety of concrete mixtures.
- Mismatch between strain in concrete phases as main cause of cracking due to interfacial restraint gradients.
- Simplified two-phase micromechanical model proposed to assess thermal stresses.
- Detailed thermo-mechanical characterization of elastic modulus and CTE of phases.
- Interaction pressure (P) selected as indicator of thermal cracking damage level.

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ABSTRACT

The pursuit of high early-age strength concrete has led to mixtures with higher heat of hydration rates at early ages which produces higher temperatures and an overall increased risk of cracking. This study uses a two-phase micromechanical model to compute thermal stresses based on both coefficient of thermal expansion (CTE) and elastic Young's modulus (E) mismatches between aggregates and the cementitious matrix. Concrete specimens were prepared using four types of coarse aggregates (different CTE and E), and subjected to temperature cycles to generate thermal cracking. Fluorescence microscopy, compressive strength, dynamic elastic Young's modulus, and electrical resistivity were used to characterize the effect of this induced thermal cracking. Experimental results were in agreement with the two-phase model and it was concluded that the interaction pressure (P) between phases could be used to estimate the impact on the mechanical and transportation properties of a temperature gradient at early age.

1. Introduction

The main driving force in concrete construction over the last few decades has been construction speed, which has pushed the industry to develop high early-age strength concrete. These mixture designs promote the use of high cement contents, a low water-to-cement ratio (w/c), finer cements, and high-C_3A, contents, among others [1]. The resulting materials are commonly referred to as high-strength concretes [2]. Unfortunately, these mixtures are more prone to cracking [3] mainly because they tend to contain a higher paste fraction and exhibit more pronounced self-desiccation, chemical shrinkage [4], and autogenous shrinkage [2,5].

In addition, the higher cement content per unit volume and the use of finer cements increase both the initial rate and the total released heat of hydration, which can lead to an increase in temperature gradients inside the material. Differential thermal expansion of the concrete constituents may produce stresses and cracking that negatively affect the mechanical properties and durability of concrete [6–9]. These stresses occur in the early stages of

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the concrete, when it is more vulnerable to cracking [5,10]. Furthermore, the increased temperature that accelerates cement hydration [11], produces lower quality and more porous calcium silicate hydrates (CSH) [12]. Moreover, concrete temperatures greater than 70 °C can induce chemical modifications of the hardened phases and lead to expansion due to delayed ettringite formation (DEF) [13–15].

The ACI committee 207 defines two types of thermal gradients that can lead to thermal stress development: a "*surface gradient*", which is the difference in temperature between two locations in the concrete element, and a "*mass gradient*", which is the difference in temperature between two periods of time, usually between the internal peak temperature and the annual average ambient temperature [16].

The surface gradient usually generates cracking due to differential expansion between the center and the edges of the structural elements due to differences in temperature at a certain instant [16,17]. The mass gradients usually generates cracking due to external restraint to thermal volume change, leading to thermal stresses [16].

A third kind of thermal cracking phenomena has its origin on the multi-phase nature of concrete and can be denoted as "*interfacial restraint gradient*". This interfacial restraint gradient originates in the thermo-mechanical mismatches between concrete constituents, i.e., aggregates and cementitious matrix [18–21], which lead to generation of internal restraint and thermal stresses. These stresses occur at early ages in the interfacial transition zone (ITZ), which exhibits lower strength and higher porosity compared with those of the bulk matrix [22–24].

Although several studies and efforts have been carried out in order to control and mitigate surface gradient [25–27] and mass gradient [28,29] effects, less information is available on interfacial restraint gradient effects. Moreover, a lack of knowledge of the effects of internal restraint and thermo-mechanical mismatches between concrete phases on key design parameters (i.e., compressive strength and elastic Young's modulus), leads to uncertainty in the actual load-bearing capacity of concrete subjected to high temperatures at early age. Few studies exist in the assessment of permeability of damaged concrete [30–32], which further affects durability, but still not directly related to thermal cracking by interfacial restraint gradient. Understanding how the aggregate and cementitious matrix properties affect the thermo-mechanical mismatches is crucial in assessment and design of concrete mixtures with reduced microcracking risk for the purpose of ensuring mechanical and durability performance.

2. Objective

The aim of this research is assess the impact of aggregate and matrix thermo-mechanical properties (CTE and elastic Young's modulus) mismatches on thermal stresses and potential cracking of concrete by using a micromechanical model.

3. Proposed two-phase micromechanical model

It is widely accepted that concrete is most accurately represented as a three-phase material [23], including the aggregates, cement paste, and the ITZ between them. The ITZ has been described as the explanation for the quasi-ductile behavior of concrete [24], and several studies attempted to characterize and understand this particular phase [33–36]. Despite the recognized relevance of the ITZ in explaining concrete behavior, the inherent difficulties in measuring the mechanical and thermal properties at a micro-scale makes it impractical to fully incorporate the ITZ in models. Advances have been made in this matter using nano-indentation, which consistently shows that the ITZ has higher porosity and lower modulus of elasticity than the bulk matrix. However, most of these studies also verify the high variability of elastic properties of the ITZ, turning the selection of a specific value for modeling less representative and highly inaccurate [33–35,37,38]. For this reason, a widely adopted approach considers concrete as a two-phase material: the coarse aggregates and the bulk matrix of mortar surrounding them. This simplification has been successfully used to model and predict relevant properties of concrete, i.e., elastic Young's modulus and coefficient of thermal expansion [21,39–41].

Another assumption of the model is that the cementitious matrix exhibits an elastic behavior. In reality, creep and stress relaxation are relevant phenomena occurring early ages [1,42–44], that are not represented in the model. Since the inelastic behavior decrease stresses [1] at the ITZ, the stresses computed with the model are higher than the exact thermal stresses, giving a conservative approach.

Due to the composite nature of concrete, understanding the elastic and thermal compatibility of its components is crucial for predicting and modeling concrete behavior with reasonable accuracy [19]. In particular, temperature fluctuations in concrete during cement hydration produce differential strains between the concrete phases and thus the thermally induced stresses that generate microcracking [19,45]. Assuming a uniform temperature distribution in all concrete phases, the main thermo-mechanical variables that control the magnitude of these stresses are the differences in elastic Young's modulus (E) and the coefficient of thermal expansion (CTE) of the aggregates and the matrix [20,21]. The occurrence of differential strains is well explained by the mismatch between the thermo-mechanical parameters of the aggregates and the matrix.

Based on the general formulation presented by Zhou et al. [21], a two-phase model is proposed in this work to assess the thermal stresses between concrete composites in different thermo-mechanical mismatch scenarios. As shown in Fig. 1, the micromechanical model consists of a spherical aggregate particle of radius a surrounded by an infinite thickness spherical shell matrix. This model applies a temperature change from T_0 to T_1, which will be denoted as ΔT. This parameter represents the temperature variation of a particular place at two different time periods.

Properties and values related to the aggregate and matrix phase will be denoted with the subscripts 1 and 2, respectively. The radial strain (ε_r) and the tangential strain (ε_t) generated in the interface between the aggregate and the bulk matrix are given by [46]:

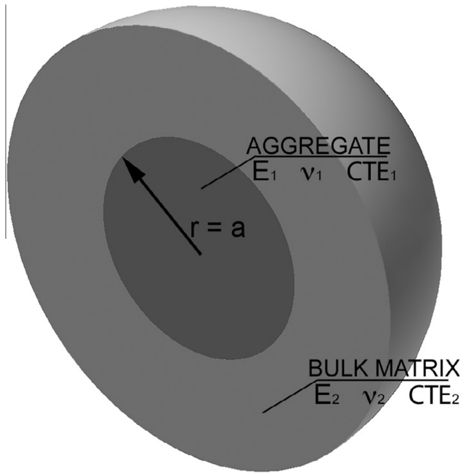

Fig. 1. Two-phase model of concrete consisting of an aggregate particle surrounded by an infinite mortar matrix.