Engineering Failure Analysis 85 (2018) 167–188

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Meso-scale response of concrete under high temperature based on coupled thermo-mechanical and pore-pressure interface modeling

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ARTICLE INFO

Keywords:
Thermal damage
Fracture
Discrete crack approach
Meso-scale
Pore-pressure

ABSTRACT

This work proposes a meso-scale approach for modeling the failure behavior of concrete exposed at elevated temperature inducing thermal damage. The procedure accounts for a thermo-mechanical and pore-pressure based interface constitutive rule. More specifically, the model represents a straightforward extension of a coupled thermo-mechanical fracture energy-based interface formulation, accounting now for damage induced by the temperature dependent pore-pressure effects in concrete. The nonlinear response of the proposed fully coupled interface model for porous cohesive-frictional composites, like concrete, is activated under kinematic, temperature and/or hydraulic increments (with or without jumps). A simplified procedure is proposed to consider the temperature dependent pore-pressure action. After describing the updated version of the interface model, this work focuses on numerical analyses of concrete failure response under high temperature tests. Particularly, meso-scale analyses demonstrate the predictive capabilities of the proposed formulation.

1. Introduction

High temperature in concrete members represents a field of great interest due to its crucial influence in terms of induced thermal damage, affecting strength, durability and serviceability conditions of structural components. Specifically, exposure to high temperature and/or fire represents one of the most destructive events that concrete constructions and structures can suffer [1,2]. The most relevant mechanical properties of concrete and cementitious mortar composites such as cohesion, friction, stiffness and strength show severe degradation under long term exposure to these critical conditions [3,4].

Experimental evidence shows that above 300 °C, the chemical, the micro- and mesoscopic physical compositions, as well as the moisture content (through the inner open porosity) of concrete change drastically [5,6]. This is due to both the dehydration process of the hardened cement paste and the conversion of calcium hydroxide into calcium oxide [7]. As a consequence, during and after long term exposure to high temperature, the most important mechanical features of concrete such as cohesion, tensile and compressive strengths, Young's modulus and Poisson's ratio show dramatic and radical decreases [8,9].

When temperature rises, particularly in the range 20–200 °C, cementitious materials quickly diminish their mass per unit volume because of the loss of evaporable water. In the range between 200 and 600 °C the mass loss rate continuously and monotonically

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https://doi.org/10.1016/j.engfailanal.2017.11.016
Received 12 September 2017; Received in revised form 27 November 2017; Accepted 28 November 2017
Available online 05 December 2017
1350-6307/

decreases. This is mainly due to the loss of water chemically combined to the calcium silicate hydrates. Beyond 600 °C the decomposition of magnesium and calcium carbonates, constituting the concrete matrix, causes further weight loss, which may reach up to 10% of its original value [10–12].

Plenty of the available scientific articles, related to experimental studies on concrete, deal with the evaluation of its mechanical properties variations when subjected to increasing temperature, with special attention on durability aspects. The study of pore size distribution in concrete exposed to thermal action (up to 800 °C) has been addressed by Janotka and Bagel [13]. This work confirmed that under increasing temperatures, the pore size mainly grows and its distribution becomes more and more homogeneous throughout the concrete bulk. Porosity of concrete subjected to high temperatures may increase up to 40% of its initial value. It is worth mentioning that porosity's rise is not only due to the evaporable water loss, but also to the dehydration of the gel structure formed by the calcium-silicate hydration products [14].

One of the crucial and most investigated phenomena in concrete components subjected to fire or high temperature is the so-called "spalling effect". Such a phenomenon has been analyzed both experimentally [15,16] and theoretically [17,18]. The spalling is quite a complex process and the literature on this matter underlines that it mainly depends on several coupling actions: i.e., the porosity of the cement matrix, the amount of water content and the stress state either due to thermal gradients and/or applied mechanical loads. During heating, water within concrete is transformed into steam and tends to migrate to colder areas of the matrix. Once the vapor flux reaches the coldest zones it condenses again, forming a fully saturated water layer. This process typically occurs in regions of the concrete components located near the heated surface. These regions, where this phenomenon develops, are commonly called "moisture clog". These are characterized by a low permeability, generating an impermeable barrier to gases flux. Thus, the continuous temperature rise, with the subsequent generation of further vapor gases, which cannot escape to colder areas due to the presence of the water barrier, generates pore-pressure. Such increase in the pore-pressure, added to the stresses induced by thermal strains, mainly activates the spalling mechanism. It is important to remark that pore-pressure mainly acts as a trigger of this mechanism. Once the cracking process starts, and despite the quick pore-pressure release, the spalling mechanism further develops due to the already generated strong localization of failure and the increasing of thermo-mechanical stresses [19,20].

In this paper the discrete-crack approach is followed to simulate, at the mesoscopic level of observation, the failure behavior of porous materials, such as concrete, when subjected to long term exposure to high temperature. To this end, a zero-thickness interface constitutive theory for thermo-poroinelastic cementitious composites is formulated, which is based on a further extension of the temperature dependent interface model for non-porous materials by Caggiano and Etse [21]. The proposed interface theory includes a novel pressure-dependent dehydration rule accounting for the porosity features of concrete and thermal conditions. The thermo-poroinelastic interface model, as shown in this work, allows accurate mesoscopic simulations of concrete failure process when subjected to arbitrary combinations of high temperature or fire and mechanical loading.

After the abovementioned brief literature review, Section 2 summarizes the modeling assumptions based on a meso-mechanical approach for the coupled thermo-mechanical problem. In Section 3 the temperature dependent interface theory is formulated, which is used for numerical analyses of cracking behavior of quasi-brittle porous materials such as cementitious mortar and concrete in the framework of the discrete crack approach. Section 4 presents the validation of the proposed interface model. The considered finite element approach for the evaluation of concrete failure processes at the mesoscopic level of observation, under different temperatures and mechanical loading, clearly demonstrates the soundness and capability of the numerical tools. Some concluding remarks are finally drawn out in Section 5.

2. Mesoscopic thermo-mesomechanical problem

A mesoscopic procedure for the numerical analysis of concrete specimens subjected to arbitrary combined effects of temperature and mechanical actions is presented in this section. Particularly, concrete is represented as a 2D composite material characterized by large aggregates embedded in a surrounding cementitious matrix (which represents the mortar paste plus fine aggregates).

The meso-scale modeling procedure accounts for the following assumptions:

- A convex polygonal representation is adopted for both large aggregates and the surrounding mortar matrix. They are numerically generated through standard Voronoi/Delaunay tessellation procedure [22] starting from a regularly distributed array of points. These are then slightly perturbed (Fig. 1a) with the aim of obtaining the so-called Voronoi diagram (Fig. 1b). Once this diagram is obtained the explicit mesoscopic structure can be obtained by resizing and randomly rotating the Voronoi polygons (Fig. 1c). It is worth mentioning that the explicit meso-geometry of a concrete specimen can be also obtained by advanced scanning tomographic procedures, i.e. by means of "CT scan" techniques (computer-processed combinations of X-Ray images), as employed in real specimens [40,41].
- 2D Finite Element (FE) mesh is generated through the discretization of each mesoscopic polyhedron particle into iso-parametric 4-nodes elements as schematically indicated in Fig. 2. Particularly, thermoelastic FEs are considered for both aggregate and mortar continuum elements, being temperature and displacements the node variables. Elastic properties of concrete play a key role in its overall temperature-dependent response. Based on several experimental results [6,25,26] the dependency of the concrete elasticity modulus E and of the Poisson's ratio ν on the temperature rise can be approximated by means of the following temperature-based rules $E = E_0(1 - \alpha_E\theta)$ and $\nu = \nu_0(1 - \alpha_\nu\theta)$, where $\theta = T - T_0$ is the temperature rise (being T and T_0 the actual and reference temperatures, respectively), E_0 and ν_0 are the elastic modulus and Poisson's ratio at a reference temperature T_0, respectively, and lastly α_E and α_ν are degradation parameters to be calibrated (suggested values by the authors for normal strength concrete are $\alpha_E = 0.0014$ and $\alpha_\nu = 0.0010$).