International Journal of Heat and Mass Transfer 98 (2016) 493–507

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

On the thermal spalling mechanism of reactive powder concrete exposed to high temperature: Numerical and experimental studies

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ARTICLE INFO

Article history:
Received 28 June 2015
Received in revised form 6 February 2016
Accepted 8 March 2016

Keywords:
Reactive powder concrete (RPC)
Thermal spalling
High temperature
Distortion energy density
Numerical simulation
Spalling experiments

ABSTRACT

Concrete spalling at high temperature seriously jeopardizes the integrity of the entire structure. Many explanations for the spalling risk exist, but few models can accurately predict it. A numerical approach to quantitatively characterizing the intrinsic mechanism that governs the devastating spalling of RPC at high temperature is presented. The proposed model is implemented in COMSOL MULTIPHYSICS, and the finite element method is employed as the basic stress analysis tool. The maximum tensile stress criterion and the distortion energy density theory are utilized as the spalling failure thresholds. The interior temperature field, stress field, spalling distribution and evolution of RPC are analyzed accordingly. It is shown that the numerical simulation results are in good agreement with the experimental observations of RPC's spalling. A conceptual model is proposed to elucidate the mechanism that induces the progressive spalling failure of RPC based on the numerical and experimental results.

1. Introduction

Reactive powder concrete (RPC), a novel type of high-strength concrete (HSC) developed in the late 1990s, is characterized by ultra-high strength, remarkable deformability and outstanding durability. Since the advent of RPC, it has attracted great attention for both academic and engineering aspects and has been widely used in a variety of engineering applications, such as skyscrapers, pavements, bridges, runways, nuclear containments, underground tunnels, etc. [1–20].

In spite of the outstanding mechanical performance, RPC used to suffer a severe failure known as thermal spalling when exposed to elevated temperatures higher than 300 °C [21–24], which often causes a devastating explosion. Accurate knowledge and description of the spalling mechanism and its influencing factors are of critical significance to prevent RPC from suffering this devastating disaster.

Indeed, according to pioneer investigations, it is shown that various factors, such as the physical and/or mechanical properties of fibers [25–28] and concrete matrices [29–31], fiber fractions [32,33,22], specimen preparation and curing methods [34,35], heating procedures [36,37], temperature ranges [1,38], specimen sizes [33,39], etc., influence the thermal spalling performance of concrete in different ways. However, few analytical studies are available for quantitatively elaborating the governing mechanism of concrete spalling through which the aforementioned influencing factors take effect. Early research has shown that there are three primary hypotheses for the spalling mechanism of regular high-strength concrete (HSC): vapor pressure, thermal stress, and thermal cracking due to the structural deformation of aggregates. Among these assumptions, the thermal stress mechanism postulates that the temperature gradient in the media, which is caused by uneven thermal conduction due to the thermal inertia effects when raising the temperature, leads to thermal stresses and induces thermal damage. When the thermal stress reaches the tensile strength of concrete, explosive spalling occurs [40–45]. Bazant [42] stated that the main driving force of explosive thermal spalling is the release of stored energy due to the thermal stresses. De Moraisde [40] noted that a tensile stress greater than the tensile strength of concrete is responsible for its explosive spalling. According to the basic principles of heat transfer, Mirza and Li [46,47] derived the components of the temperature field of concrete under fire by means of finite difference methods. Additionally, a variety of experiments have been conducted to test the influences of different factors, including heating rate [36], aggregates [48,49], cement fraction [50], moisture rate [51], admixture [52], and temperature

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.033
0017-9310/

Nomenclature

T	temperature
P	porosity
C_P	specific heat capacity of the fluid at constant pressure
$C_{p,p}$	specific heat capacity of solid at constant pressure
k	thermal conductivity of fluid
k_{eq}	equivalent thermal conductivity of fluid–solid material
Q	heat source
q_0	heat flow
h_C	heat transfer coefficient
h_f	heat radiation coefficient
T_f	furnace temperature
T_s	surface temperature of specimens
T_{ref}	strain reference temperature
ξ	Stefan–Boltzmann constant, 5.67×10^{-8}
E	modulus of elasticity
F_v	volume force
u	solid phase displacement
f_f	ultimate tensile strength of concrete at room temperature
f_{fT}	ultimate tensile strength of concrete at the relevant temperature
ρ	fluid density
ρ_p	solid density
v	poisson's ratio
$(\rho C_P)_{eq}$	equivalent heat capacity per volume at constant pressure
Θ_p	solid volume fraction
Θ_L	fluid volume fraction
σ	stress
$\mathcal{E}$	strain
α	coefficient of thermal expansion
u	fluid velocity per unit cross section
σ_0	initial stress
$\mathcal{E}_0$	initial strain
ρ_v	volumetric fraction of steel fibers
σ_{eq}	Von-Mises equivalent stress
σ_1	first principal stress
σ_2	second principal stress
σ_3	third principal stress
ε_1	first principal strain
ε_2	second principal strain
ε_3	third principal strain
θ	volume strain
σ_t	uniaxial tensile strength of material
v_d	distortion energy density

elevation [53,49], on the thermophysical properties of concrete. In recent years, various researchers have implemented experimental tests and numerical simulations [54,40,55–66] to probe the relationships between the temperature-induced stress field and the explosive spalling of both HSC (high-strength concrete) and HPC (high-performance concrete) during heating processes. Fumie [67] carried out experiments and mathematical calculations and captured the concrete crack sound before spalling. The maximum thermal stress was found to be approximately 10% of the compressive strength of concrete. Zhang etc. [68] employed a mathematical model to describe the coupled hygro-thermal–mechanical-damage behavior of concrete exposed to high temperature. The results showed that the induced stress is the primary factor causing thermal failure and spalling in concrete, while the pore pressure, at most, plays a secondary role. Zhao et al. [69] calculated the temperature field, thermal decomposition of cement paste, vapor pressure, moisture transport, and distribution and evolution of thermal stresses in concrete through numerical simulations. It was concluded that the explosive spalling of HPC specimens under exposure to fire was mainly attributed to the temperature gradient-induced thermal stress.

Although more and more attentions have been paid to the effects of interior thermal stress on the spalling failure of HSC, few studies are available to elucidate the spalling mechanism of ultra-high strength RPC. Both the understanding of the thermophysical properties and spalling mechanism of RPC and the attempts to improve its performance are far behind the requirements of engineering applications.

The purpose of this study is therefore to investigate the role of internal thermal stress in governing the devastating spalling of RPC by means of numerical simulations and experimental tests. The multiphysics software COMSOL was employed to determine and analyze the internal temperature distribution, the thermal stress field and the mechanism triggering the spalling of RPC. Differing from previous numerical attempts, the thermophysical parameters of RPC adopted in the governing equations for determining the heat transfer and stress field in this study were acquired from preliminary tests of RPC specimens exposed to elevated temperatures. A conceptual model was proposed to elucidate the intrinsic mechanism that causes the progressive spalling failure of RPC under elevated temperatures.

The remainder of the paper is structured as follows: In Section 2, the numerical method to determine the thermal stress and the spalling characteristics of RPC is developed. A three-dimensional coupled thermo-mechanical failure model is established. In Section 3, the simulation results of thermal properties of RPC are presented, including interior temperature field, deformation field, stress field, spalling distribution and evolution, when exposed to the elevated temperature based on the proposed failure model and methodology. The numerical predictions are verified by comparison with the experimental observation of the RPC specimens' spalling. In Section 4, a conceptual model is developed to elucidate the mechanism that induces the progressive spalling failure of RPC based on the numerical and experimental results. The concluding remarks are made in Section 5.

2. Methodology and models

2.1. Experimental observation of the spalling of RPC

The thermal spalling of concrete refers to the phenomenon of concrete outburst or explosion that first occurs on outer surfaces and gradually moves inward to the center of the specimen when exposed to high temperature. To understand the spalling characteristics of RPC and to gain the thermophysical parameters that are needed to determine the interior temperature distribution and the stress field of the material, we conducted a series of experiments on RPC specimens. Fig. 1 demonstrates the experimental setup and instruments adopted for recording the spalling process of RPC subjected to high temperature of up to 500 °C. According to our preliminary tests [1,29,28], when the RPC specimen was heated from room temperature to approximately 380 °C, explosive spalling occurred and the specimen spalled into two parts. With continuous elevation of the ambient temperature, the spalled parts of the specimen gradually burst into a pile of small debris. As the temperature continuously rose and approached 450 °C, almost all