Sci. Bull. (2015) 60(23):2022–2040
DOI 10.1007/s11434-015-0939-0

CrossMark

www.scibull.com
www.springer.com/scp

Article

Engineering Sciences

An experimental investigation of the thermal spalling of polypropylene-fibered reactive powder concrete exposed to elevated temperatures

Yang Ju · Li Wang · Hongbin Liu · Kaipei Tian

Received: 4 September 2015 / Accepted: 12 October 2015 / Published online: 18 November 2015

Abstract Polypropylene fibers are embedded to prevent reactive powder concrete (RPC) from spalling failure under high temperatures. This paper probes the influence of embedded fibers at various volumetric dosages on the thermomechanical properties of polypropylene-fibered reactive powder concrete (PPRPC) exposed to high temperatures up to 350 °C and on the spalling performance and characteristics up to 600 °C. The thermomechanical properties include the characteristic temperature for spalling, and residual strengths, such as the compressive strength, split tensile strength, and flexural tensile strength. A high-definition charge-coupled device camera and scanning electron microscope technology were employed to capture the spalling processes and to detect the microstructural changes in the materials with various fiber dosages. To understand and characterize the mechanism by which polypropylene fibers influence the thermal spalling of RPC, a numerical model to determine the moisture migration and vapor pressure transmission during spalling was developed in this paper. It showed that there was an optimal volumetric dosage of fibers to prevent PPRPC from explosive spalling. The relationships between the mechanical characteristics of PPRPC and the fiber dosages were derived based on experimental data.

Keywords Polypropylene reactive powder concrete (PPRPC) · Thermal spalling · Vapor pressure mechanism · Polypropylene fibers · Elevated temperatures

Y. Ju (✉) · H. Liu
State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing 100083, China
e-mail: juy@cumtb.edu.cn

Y. Ju
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China

Y. Ju
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

L. Wang
School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing 100083, China

K. Tian
Institute of Construction Materials, University of Stuttgart, Stuttgart 70569, Germany

1 Introduction

Reactive powder concrete (RPC) has drawn worldwide attention for its ultra-high strength, remarkable deformability, and outstanding durability. To date, it has found many applications in diverse engineering fields, such as transportation, infrastructure, protective construction, and underground tunneling [1–6]. Pioneering studies reported that RPC is vulnerable to explosive spalling when exposed to high temperature, which has raised great safety concerns [7–12]. Thus, it is of critical significance to understand the mechanisms that induce material degradation and trigger explosive spalling to prevent RPC from devastating failure.

Previous work has suggested three hypotheses for understanding and interpreting the spalling mechanisms of regular high-strength concrete (HSC): the vapor pressure mechanism [13–19], the thermal stress mechanism [20], and the thermal cracking mechanism [21]. Many investigations have focus on the vapor pressure spalling [15, 18, 22–24]. The hypothesis, however, may not fit RPC, which has a much more compacted microstructure, without passageways through which water vapor can migrate and escape from tight matrices at elevated temperatures. Recent studies of the thermal and mechanical properties of 200 MPa level RPC by means of MIP and scanning electron microscopy (SEM) technology have proven that the highly compacted microstructure is the major factor leading to a rapid rise in the interior vapor pressure and the subsequent devastating explosion when the RPC is heated over a characteristic temperature level [9, 12, 24].

Studies have indicated that the explosive spalling of regular HSC could be noticeably alleviated by embedding an appropriate volume of strong, flexile polypropylene fibers [25–31]. This improvement is supposedly attributed to the difference in the thermal expansion capability between polypropylene fibers and cement pastes, which can introduce micro-fractures to release the vapor pressure [32, 33]. High temperatures cause the disordered distributed polypropylene fibers to melt down and evaporate, leaving voids of the equivalent volume of the fibers when heated over the melting temperature of the fibers (approximately 171 °C). This process generates a well-developed, interconnected passageway network, through which the internal water vapor and heat can diffuse out of the matrix, alleviating the occurrence of destructive spalling [34–41].

Nonetheless, the mechanism by which polypropylene fibers improve the thermal resistance of RPC could differ from that of HSC because RPC achieves much better cement hydration and greater matrix compactness by removing coarse aggregates, adding active silica fume, and curing under high temperature than conventional HSC [2, 42–46]. Experiments indicate that, despite the positive effects of polypropylene fibers in enhancing the residual strength of the heated HSC, an overdose of fibers could have an adverse influence on the HSC's thermomechanical properties [34–36, 47–50]. A proper dosage of the fibers to improve the spalling resistance of HSC depends on the mixture proportions and the geometry of the fibers [35].

However, neither experiments nor analytical models are available to interpret and characterize the effects of polypropylene fibers on the thermal spalling of ultra-high-strength RPC. It is unknown whether adding polypropylene fibers could generate a similar network for releasing vapor pressure as in HSC when RPC is heated over the melting temperature of the fibers. It is imperative to probe the mechanisms by which polypropylene fibers modify the microstructure, water vapor migration, vapor pressure distribution, and thermophysical properties of RPC to prevent devastating failure.

In this study, the laboratory tests investigate the influence of the fiber content on the mechanical properties and spalling performances of fibered RPC subjected to elevated temperatures ranging from 20 to 600 °C. To identify the improvement functions of polypropylene fibers, the entire spalling process of PPRPC under elevated temperature was monitored by a high-definition CCD camera and the microstructural changes in PPRPC were detected via SEM technology. Five fiber dosages with volumetric fractions ranging from 0 % to 1.2 % are considered. To interpret the fiber mechanism that resists the thermal spalling of RPC, this paper incorporates experimental measurements and a conceptual model to elucidate the evolution of the internal vapor pressure and moisture migration during the spalling failure. A relationship between the thermal mechanical properties of PPRPC and the fiber dosage was formulated based on the experimental data. The purpose of this research is to study the effects of polypropylene fibers on RPC's spalling properties when the material is exposed to high temperatures, aiming to provide a reference for better elucidating the intrinsic mechanism of RPC's thermal explosive spalling. Our study is a preliminary work for full-scale tests of PRC specimens under fire and practical applications.

2 Materials and methods

2.1 Material preparation

Local Portland cement P. O. 42.5 with a 28-d static compressive strength of 59.3 MPa, fine quartz sand with a particle size of 0.15–0.63 mm, quartz powder with a granular diameter of 45 μm, EBS-S silica fly ash with a diameter of 0.1–0.2 μm, and Sika superplasticizer with a water reducing rate of more than 30 % and a solid content fraction of 37.2 % were adopted to manufacture RPC mortar. 9-mm-long polypropylene fibers with five different volumetric fractions, 0 %, 0.3 %, 0.6 %, 0.9 %, and 1.2 %, were mixed into the mortar, and the PPRPC specimens were categorized into five series, P0, P0.3, P0.6, P0.9, and P1.2, respectively. Tables 1 and 2 show the mixture proportions of the raw materials and the specifications of the polypropylene fibers used for the specimens.

To manufacture PPRPC, the raw materials, i.e., cement, sand, quartz powder, silica fume, and polypropylene fibers, were first mixed and blended for 6 min to obtain a uniform mixture. Then, half of the total amount of water along with the superplasticizer was added, and the mixture was blended for 3 min, followed by the addition of the other half of the total amount of water and superplasticizer and 3 min more of mixing. Afterward, the mixture was cast into stainless steel cubic molds and prism molds of dimensions 100 mm × 100 mm × 100 mm and 40 mm × 40 mm × 160 mm, respectively, to produce