Construction and Building Materials 155 (2017) 571–583

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental investigation of the effect of silica fume on the thermal spalling of reactive powder concrete

Yang Ju [a,b,*], Kaipei Tian [c], Hongbin Liu [a], Hans-Wolf Reinhardt [c], Li Wang [d]

[a] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology at Beijing, Beijing 100083, China
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou 221008, China
[c] Institute of Construction Materials, University of Stuttgart, Pfaffenwaldring 4, 70569 Stuttgart, Germany
[d] School of Mechanics and Civil Engineering, China University of Mining & Technology, 100083 Beijing, China

HIGHLIGHTS

- The effects of silica fume (SF) on the thermal spalling of RPC were investigated.
- The RPC achieved the largest compressive strength with 16% SF replacement.
- The RPC presented the best high-temperature resistance with 8% SF replacement.
- Microstructural phases of C-S-H gels and the mechanical properties were analysed.
- A conceptual model was used to interpret the effect of SF on RPC's spalling.

ARTICLE INFO

Article history:
Received 23 March 2017
Received in revised form 26 July 2017
Accepted 16 August 2017

Keywords:
Reactive powder concrete (RPC)
Thermal spalling
High temperature
Silica fume
Microstructure
Pore structure
Experimental characterization

ABSTRACT

The distinct spalling performances of reactive powder concrete (RPC) specimens with various silica fume (SF) contents exposed to high temperatures were observed via high-resolution photography. The RPC microstructures and pore structures after high-temperature exposure were characterized using scanning electron microscopy and mercury intrusion porosimetry. The results provide experimental evidence of the high-temperature spalling mechanism of RPC. Increasing the SF content in RPC increases its compressive strength and compactness, offering greater mitigation of devastating spalling behaviour, but also producing more pulverized spalling remnants. This is attributed to the post-heating cracked microstructure and refined pores, which promote localized rather than entirely explosive spalling.

1. Introduction

Reactive powder concrete (RPC), a type of high-strength concrete (HSC) developed in the 1990s [1], is characterized by ultra-high strength [2,3], high fracture toughness [4–6], excellent dynamic mechanical properties [7–9], and outstanding durability [10,11]. RPC has attracted attention from both academia and engineering fields, with wide applications in the construction of municipal works [12], highways [13], railway [14], bridges [15,16], nuclear containment and military shelters [17,18].

Despite its outstanding room-temperature mechanical performance, RPC experiences severe spalling when exposed to high temperatures. Spalled RPC has been characterized as completely pulverized, presenting a powder-like morphology, which differs from the partial surface failure or cracking experienced by conventional HSC at high temperatures [19–23]. However, RPC spalling has remained a poorly understood phenomenon, and the associated risk is difficult to predict by modelling. Until now, the spalling risk of HSC has been commonly explained by three different mechanisms: vapour pressure, thermal stress, and thermal cracking due to the structural transformation of aggregates [20,24,25]. Based on these primary mechanisms, most researchers have focused on the inner vapour content, moisture transportation, or thermal stress on the heated surface of concrete, which may characterize the most important mechanisms of HSC spalling, especially for severe and

* Corresponding author at: China University of Mining & Technology at Beijing, D11 Xueyuan Road, Beijing 100083, China.
E-mail addresses: yju@icloud.com, juy@cumtb.edu.cn (Y. Ju).

http://dx.doi.org/10.1016/j.conbuildmat.2017.08.086
0950-0618/

explosive spalling. Mindeguia et al. [25] and Bažant [26] showed that large compressive stresses, particularly within a few centimetres of the heated surface, are induced by high temperature gradients and the high pore pressure produced by vapour and moisture migration in concrete; these effects can cause spalling. An experimental device used to measure pore pressure, developed by Kalifa et al., and nuclear magnetic resonance (NMR) technology used to test the mobility of moisture within concrete subjected to elevated temperatures may uncover the spalling mechanism in concrete [27–30]. Based on these mechanisms for RPC spalling, the accumulation of pore pressure in heated RPC was measured in our laboratory and a thin-wall spherical pore model was developed to illustrate the performance of the vapour. The model implied that the stress generated by vapour pressure could exceed the tensile strength of the matrix and thereby cause a spalling outburst [31]. A numerical model was also proposed to replicate the progressive spalling of RPC from the perspective of the thermal stress mechanism and the theory of energy release [23].

RPC contains a high amount of silica fume (SF), which is believed to strongly influence the spalling of concrete. It is therefore necessary to investigate the influence of SF content on the spalling of RPC. At room temperature, SF is known to enhance the performance of concrete through the micro-aggregate filling effect and pozzolanic reactions [32–34]. SF is a very reactive material because it is extremely fine with a high content of amorphous SiO_2. Chatterji et al. [35] showed that approximately 100,000 grains of SF surrounded each cement particle in conventional concrete. SF accelerates and improves the cement hydration process, thus allowing the production of significant pozzolanic calcium silicate hydrate (C-S-H), and improving the concrete performance by enhancing cementation and refining the pore structure, strengthening the cement paste aggregate bonds, and forming more homogenous microstructures in concrete [36,37]. Regarding the properties of RPC at room temperature, several studies have reported that SF improves the compressive, tensile, and flexural strength, as well as the pore structure and steel fibre bonding characteristics [32,38,39].

Explosive spalling in dense concrete made with SF was first observed at high temperatures by Hertz [40]. In particular, spalling occurred at just 300 °C and the heating rate of 1 °C/min; the specimen was dried thoroughly under these conditions. Thus Hertz suggested an upper limit of 10% SF replacement of cement by mass to avoid spalling [41]. This limit was lowered to 5% by Poon et al. [42]. Furthermore, Peng et al. [43] reported spalling when concrete specimens with SF were dried in an oven at a temperature of 105 °C for two days. In contrast, for concrete without SF, a previous study on the spalling behaviour of HSC exposed to high temperatures reported that spalling was unlikely to occur for concrete with free water contents of less than 3–4% by weight [44,45]. RPC has a SF content of more than 20% of the total binder materials (cement + SF) by weight. So et al. [46] studied the effect of SF dosage on the sensitivity of RPC specimens mixed with steel fibres and polypropylene fibres under the standard fire test curve. They concluded that RPC became more susceptible to explosive spalling as the SF addition was increased, even though the specimens were mixed with polypropylene fibres and steel fibres, which are normally effective in preventing concrete spalling.

Until now, experimental research on the effects of SF on the spalling of RPC has been scarce. Therefore, it is of great importance to perform a parametric study to investigate the influence of SF content on the spalling phenomenon of conventional RPC without fibre reinforcement.

This study focuses on the influence of the SF contents on the explosive spalling of RPC. To better understand and characterize this effect, the following methods were used: (1) recording of the spalling of RPCs with different SF ratios, (2) scanning electron microscope (SEM) analysis of the microstructures of RPC samples before and after exposure to high temperatures, and (3) mercury intrusion porosimetry (MIP) measurements of the pore characteristics of RPCs with different SF ratios.

2. RPC compositions and mix proportions

The RPC samples were prepared with the following ingredients: Chinese standard ordinary Portland cement (PO 42.5) [47]; fine quartz sand with grain sizes of 0.15–0.63 mm (mix ratio of grain sizes 0.15–0.315 mm and 0.315–0.63 mm of 1:2; SiO_2 content exceeds 90%); quartz powder with particle diameters of 45 μm; SF (average diameter of approximately 0.2 μm) with SiO_2 content exceeding 98%; and Sika superplasticizer (SP) with a water-reducing rate of 30%, a solid content of 37.2%, and a bulk density of 1.08 g/cm^3. Table 1 lists the chemical, physical, and mechanical properties of the cement and SF as well.

The mixing proportions of the concrete were designed based on a RPC control mixture SF22 shown in Table 2, which has a compressive strength of about 150 MPa after a 3-day steam curing period and is often studied in our laboratory. A series of concrete mixtures with the water/binder ratio of 0.19 and 2% SP by mass were prepared, as shown in Table 2, to produce plain and SF-incorporating RPCs. Mixtures containing SF replaced cement with SF by volume. The SF-containing mixtures, corresponding to mass percentages SF/(C + SF) of 0%, 8%, 12%, 16%, and 22%, are denoted as SF0, SF8, SF12, SF16, and SF22, respectively. Thus, five types of RPCs were produced. For each SF ratio, six cubes of 100 × 100 × 100 mm (three for compressive strength testing, two for spalling phenomena observation, and one for SEM investigation) and one specimen the size of a conventional brick (240 × 115 × 53 mm) (for the core drilling of a sample for porosity testing) were prepared, for a total of 35 specimens.

All components of RPC were mixed, cast, and vibrated in the same sequence in the laboratory. For each mixture design, the aggregates and powders were first dry-mixed for 3 min. Then, half of the combined solution of water and SP was added and mixed for approximately another 3 min. Subsequently, the rest of the water and SP was added and mixed for approximately 3 min. The mixture was then cast into steel moulds, and the specimens were vibrated to release any entrapped air bubbles. All moulded specimens were

Table 1
Chemical, physical, and mechanical properties of cement and SF.

	Cement	SF
Chemical composition (%)		
SiO_2	21.00	98.48
Al_2O_3	5.02	0.40
Fe_2O_3	3.51	0.03
CaO	62.47	0.44
MgO	3.90	0.40
K_2O	0.85	0.72
Na_2O	0.18	0.25
SO_3	2.69	0.42
Physical and mechanical properties		
Density (g/cm^3)	3.10	2.23
Loss on ignition	2.26	0.90
Fineness (m^2/g)	0.3–0.5	30.1
Mean size (μm)	–	0.2
Initial setting time (min)	197	–
Final setting time (min)	247	–
Compressive strength (MPa)		
3 d	27	–
28 d	56	–
Flexural strength (MPa)		
3 d	6	–
28 d	9	–