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Study on high-performance concrete at high temperatures in China (2004–2016) - An updated overview

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ABSTRACT

High-performance concrete (HPC) has gained a worldwide utilization; however, it may encounter a larger risk of fire exposure which can jeopardize its behavior. Both Chinese and overseas researchers have conducted numerous investigations to reveal the influence of high temperatures on the properties of HPC. As a continuous work, this paper presents the progress in the behavior of HPC exposed to high temperatures in China since 2004. Experimental data are compiled on both thermal and mechanical properties of HPC. They are compared with those from remarkable studies and current code provisions. Introductions and discussions are first made to the thermal properties of HPC, including thermal conductivity, specific heat, and thermal expansion. The paper then summarizes the spalling behavior of HPC under high temperatures. Critical factors are analyzed about their influences on the spalling of HPC. Spalling mechanisms are also presented and discussed. Afterwards, the paper systematically compiles the mechanical properties of HPC under and after elevated temperatures. Finally, some suggestions are put forward with respect to the fire safety of HPC structures.

1. Introduction

High-performance concrete (HPC) has gained a worldwide application in the structural engineering because of its favorable workability, strength and durability [1]. In line with the sustainability of the building industry, policies have been made to promote the use of HPC with C60 (i.e. the cube compressive strength is greater than 60 MPa) or higher strength grade in China. HPC will undoubtedly account for more share of concrete in use. However, there is a growing concern about the performance of HPC in fire, because HPC shows a relatively inferior behavior at elevated temperatures especially when the spalling is considered [2].

Behavior of concrete exposed to high temperatures has been attracting the interest of researchers in China since 1960s [3]. Besides the organizations mentioned in an early review paper [3], more key laboratories have been established to investigate the fire performance of structures, such as the Fire Safety of Engineering Structures Testing Division in 2008 under the State Key Laboratory of Disaster Reduction in Civil Engineering, the State Key Laboratory of Building Safety and Built Environment in 2008, and the Institute of Fire Science and Engineering in 2009. These institutes involve hundreds of researchers devoting themselves to the study on the effect of high temperatures on building materials and structures. They have made significant achievements. Fig. 1 shows the annual number of papers about the research on heated concrete materials and structures in China. It is compared with the number of accident fires (excluding forest fire, mine fire) each year in China. Given the tens of thousands of building fires causing countless property loss and disastrous damage to the structures, this kind of continuous and intensive study is essential to guarantee the safety of concrete structures in/after fire.

Following Xiao and König [3], the authors compile the experimental data of fire tests on HPC materials from 2004 to present, sharing the efforts of Chinese scholars and providing suggestions regarding the fire safety of HPC structures. This paper starts with the thermal properties of HPC, i.e. thermal conductivity, specific heat capacity, and thermal expansion. Afterwards, the paper presents the spalling behavior of HPC exposed to high temperatures, mainly by introducing the influence of critical factors on spalling of concrete and the spalling mechanisms. Then the paper compiles the mechanical properties of heated HPC. They include six categories: residual compressive strength, residual elastic modulus, residual tensile strength, residual flexural strength, residual fracture energy, and stress-strain curves. At last, conclusions are drawn according to the collected data and intensive analyses.

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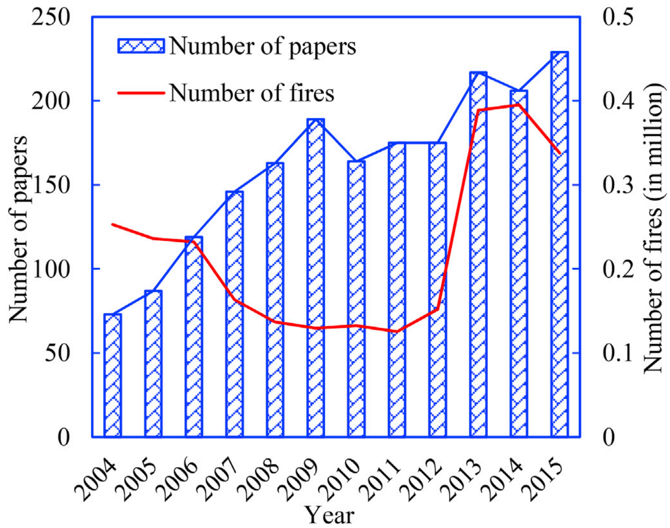


Fig. 1. Number of papers and fires over years.
(Data source: www.cnki.net and www.fdmps.gov.cn)

2. Thermal properties of HPC

Temperature development within reinforced concrete components mainly depends on the thermal properties of concrete and steel. These properties include thermal conductivity, specific heat capacity, thermal diffusivity, thermal expansion, and mass loss. The Eurocode [4] presents the thermal properties of conventional concrete with a notice that high strength concrete (HSC) may have a higher thermal conductivity than conventional concrete. These data are often adopted by the code for fire resistance design of concrete structures in China [5]. However, the thermal properties may not be applicable for HPC, which includes HSC, reactive powder concrete (RPC) and self-consolidating concrete (SCC). This is mainly because HPC components demonstrate a stronger fire response than conventional concrete members [6,7]. Therefore, data about thermal properties of HPC under high temperatures are needed to reveal the underlying mechanism.

2.1. Thermal conductivity

The Chinese experimental data about the thermal conductivity of HPC are presented in Fig. 2, where they are compared with those observed by Kodur [7,8] and the recommended values of conventional concrete in Eurocode [4]. The data show a significant difference and only a little overlap between the thermal conductivity of HPC and that of conventional concrete.

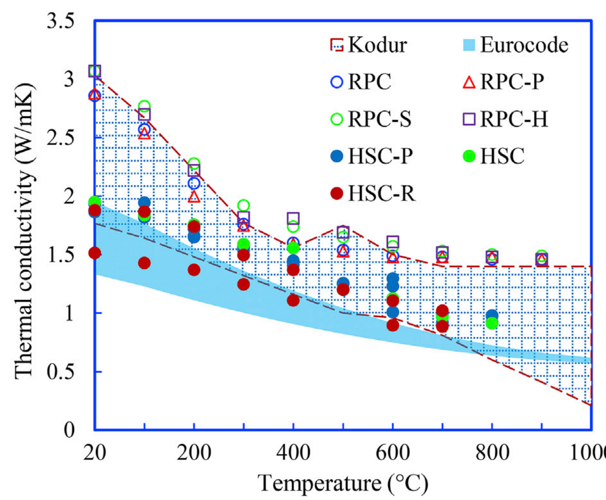
RPC generally possesses super high strength, extreme durability and superior toughness. Therefore it has been extensively applied in civil facilities [9] and special prestressed and precast concrete members [10]. Via a hot wire method, Zheng et al. [11] tested the thermal conductivity of RPC with and without fibers under high temperatures. The results are presented in Fig. 2(a) where the values stay at the upper bound of those provided by Kodur [7,8]. Statistically, the thermal conductivity shows no remarkable difference among various types of RPC, including plain RPC, RPC with polypropylene (PP) fibers (RPC-P), RPC with steel fibers (RPC-S) and RPC with hybrid fibers (RPC-H).

Using a guarded hot plate method, Zhang [12] measured the thermal conductivity of cooled HSC with PP fibers (HSC-P). Within the range of data observed by Kodur in Fig. 2(a), the values of HSC with 1.8 kg/m^3 PP fibers are close to the lower bound. When the amount of fibers remains the same, the length and diameter of PP fibers have a negligible influence on the thermal conductivity of HSC. With the same method, Wang et al. [13] also obtained the thermal conductivity of HSC-P after the specimens cooled down to the room temperature. They concluded that PP fibers slightly decreased the thermal conductivity of HSC.

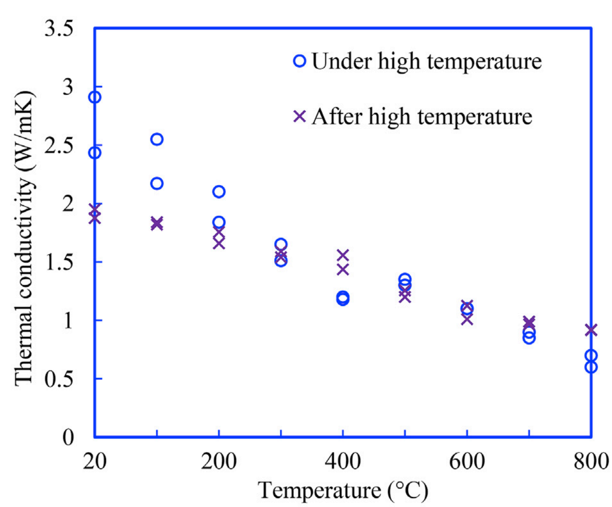
To improve the ductility of concrete and to deal with the growing amount of wasted rubber tire, ground rubber powder has been mixed into concrete and gained a wide application. Using the guarded hot plate method, Cheng [14] measured the thermal conductivity of cooled HSC mixed with rubber powder (HSC-R). The results in Fig. 2(a) show that HSC-R possesses a relatively small thermal conductivity compared with other types of HPC. The value would fall into the data range of conventional concrete in Eurocode [4] when the amount of rubber is larger than 3% of the volume of sand.

Based on measured temperatures and the heat transfer theory, Xiao and Li [15] calculated the thermal conductivity of plain HSC under elevated temperatures using the finite difference method. The results are validated with other experiments. This calculation can be a reasonable option when actual thermal property values of HSC cannot be obtained.

Fig. 2(b) compares the results from two different methods of measuring the thermal conductivity of HSC. The values under high temperatures are from Ref. [7] using the hot wire method, and those after



(a) Thermal conductivity of various HPC



(b) Thermal conductivity of HSC under and after high temperatures.

Fig. 2. Thermal conductivity of HPC.