Construction and Building Materials 71 (2014) 472–483

Contents lists available at ScienceDirect

Construction and Building Materials

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

Shear transfer across a crack in high-strength concrete after elevated temperatures

Jianzhuang Xiao [a,*], Zhiwei Li [a], Jiabin Li [a,b]

[a] *Department of Structural Engineering, Tongji University, Shanghai 200092, PR China*
[b] *Institute for Structural Concrete, Graz University of Technology, Graz A8010, Austria*

HIGHLIGHTS

- High temperature tests on two grades of HSC specimens were carried out.
- Push-off test on HSC specimens after elevated temperatures was firstly performed.
- Effect of elevated temperatures on shear transfer behavior of HSC was revealed.
- Relationships between HSC shear strength and exposed temperature were proposed.

ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 15 August 2014
Accepted 24 August 2014
Available online 19 September 2014

Keywords:
High-strength concrete (HSC)
Elevated temperature
Shear transfer
Crack deformation
Push-off

ABSTRACT

This paper experimentally investigated the shear transfer behavior of high-strength concrete (HSC) across a crack after elevated temperatures. The compressive strength of concrete and the experienced temperature were the two main parameters in this study. Twenty-two uncracked push-off specimens were casted and heated in an electrical furnace. Push-off tests were then conducted to study the shear strength and the crack formulation and deformation of the concrete after elevated temperatures. The elevated temperature test results indicate that the heating process of HSC is related to the furnace chamber temperature, the thermal convection and the thermal radiation. The heating process can be divided into 3 stages based on the heating time. Except for an exposed temperature of 200 °C, the ultimate shear strength of HSC reduces and the corresponding crack deformation (crack slip and crack width) increases with the increase of the temperature. The shear brittleness of HSC decreases as the exposed temperature increases. The higher the strength of concrete is, the more brittle the shear transfer characteristics becomes. Finally, the equation for estimating the residual shear strength of HSC after elevated temperatures are proposed based on the statistical analysis of the test data.

1. Introduction

In recent years, high-strength concrete (HSC) is increasingly popular in civil engineering practice due to its higher strength and better durability in comparison with conventional normal strength concrete (NSC) [1]. HSC with a compressive strength of 62 MPa was applied for Water Tower Place in Chicago in 1974, and the compressive strength of the concrete used in Burj Dubai reached 80 MPa [2]. However, with the increasing engineering applications and the deepening of related research activities, it was noticed that HSC can be inferior to NSC in the aspects of some mechanical properties after elevated temperatures [3]. The elevated temperature, as one of the most severe environments, should be taken into account in the design of HSC elements and structures [1]. The properties of NSC and HSC at elevated temperatures have been widely studied, and a literature review indicates that concrete can experience drastic physical and chemical changes when the exposed temperature increases. The changes of the microcosmic structure of concrete have a great influence on its macroscopic mechanical properties. For example, the interface between the aggregate and the cement paste can form micro cracks due to different thermal expansions once the temperature exceeds 100 °C. Consequently, the bonding force between the aggregate and the cement paste reduces, and the concrete strength decreases [4]. The calcium silicate hydrate (C–S–H), which provides the strength of the cement paste, decomposes further when the exposed temperature is beyond 600 °C. This can result in a great reduction of the compressive strength of concrete [5]. At a temperature of 800 °C, the $CaCO_3$ decompose into CO_2 and CaO, and the concrete

---

[*] Corresponding author. Tel.: +86 21 65982787; fax: +86 21 65986345.
E-mail address: jzx@tongji.edu.cn (J. Xiao).

http://dx.doi.org/10.1016/j.conbuildmat.2014.08.074

compressive strength reduces to 20–30% of that at room temperature, and the material loses its strength greatly [6]. The microcosmic diversification of concrete can not only result in the degradation of the compressive strength, but also reduce the tensile strength, the flexural strength and the elastic modulus [7]. Due to the effect of the high temperature on the material properties, the load bearing characteristics of HSC structural members exposed to elevated temperatures are different from that at room temperature [8–10]. Up to now, however, there is only few published work that examined the shear transfer behavior of HSC across a crack after elevated temperatures although it is an important mechanical property of this material in structural members to resist the lateral force and self-weight.

Since Birkeland and Birkeland [11] published their work in 1966, a lot of studies have been undertaken to investigate the shear transfer behavior and mechanism of concrete at room temperature. Loov and Patnaik [12] proposed an equation of the concrete shear strength. The equation was proved to be able to provide a good prediction of the shear strength of HSC [13]. Loov and Peng [14] further studied the effect of the concrete strength, the number and length of the stirrups, the angle between the longitudinal axis of the beam and the shear plane on the shear transfer characteristics of concrete. Detailed equations for estimating the shear strength of both NSC and HSC have been developed by Kahn and Mitchell [15] based on fifty push-off specimens. The equations indicate that the higher compressive strength and reinforcement ratio lead to an improvement of the shear strength of concrete. However, the shear strength of concrete is no higher than 0.2 f'_c, where f'_c is the cylinder compressive strength. Based on the truss model and a softened compressive stress–strain relation along the concrete struts. Hsu et al. [16] proposed a theory for predicting the shear strength of concrete. Their theory took into account the fact that the reinforcement parallel to and near the shear plane can have a significant contribution to the shear strength of concrete when the longitudinal reinforcement ratio is relatively low. This fact was ignored in most of the shear transfer theories. Equations for the shear strength of a full range of concrete strengths were proposed by Ali and White [17] based on the contact density model. These purely analytical equations were approximated for design purposes. In addition to macroscopic investigations on the shear transfer behavior of concrete across a crack, studies on the shear transfer mechanism have also been carried out at the submicroscopic level. Martin-Perez and Pantazopoulou [18] concluded that the shear strength of concrete consists of the dowel action, the bond between the reinforcement and the concrete as well as the aggregate interlock. The flexure of the bars makes a principal contribution to the dowel action. The bond between the reinforcement and the concrete is affected by the reinforcement type and the concrete strength. Aggregate interlock occurs because the protruding aggregates on one side of the shear surface squeeze the cement pastes on the other side to resist the shear deformation. The primary source of the shear transfer of concrete is due to the aggregate interlock, as demonstrated by many investigators [19,20].

The characteristics of the aggregate interlock vary with the concrete compressive strength. The aggregate particles in NSC can be pushed out from the cement paste through the crack propagation [19]. However, the cement paste in HSC has a higher strength than the aggregate, which results in the aggregate fracture and the crack across aggregate particles. Consequently, the shear strength starts to reduce due to the serious fracture of the aggregate particles when the concrete compressive strength reaches a certain value [21]. Hence, there is a complex relation between the aggregate interlock and the compressive strength of concrete. Xiao et al. [22] investigated the shear transfer performance of recycled aggregate concrete (RAC). The results have showed that the aggregate interlock in RAC is weakened because of a layer of old and weak mortar wrapping the recycled coarse aggregate. It was observed that concrete containing river gravel exhibited more favorable aggregate interlock behavior compared to that mixed with limestone aggregate. In addition, the volume of aggregate was also found to be an influencing factor of the shear strength of concrete [23].

As described above, the elevated temperatures can result in a deterioration of the cement paste, which is much stronger than the aggregates in HSC at room temperature. The aggregate even decomposes beyond 800 °C. It is assumed that the aggregate interlock characteristics may change when the exposed temperature increases. Thus the shear transfer of HSC across a crack can change and degrade. However, no detailed studies on the shear transfer of HSC after elevated temperatures have been reported in literature. Therefore, a comprehensive study is required to investigate the shear transfer and the degradation mechanism of HSC after elevated temperatures. This paper presents such an experimental investigation on the shear transfer characteristics of HSC across a crack after elevated temperatures.

2. Research significance

The shear transfer behavior of HSC after a fire is an important indicator for the fire resistance requirement of HSC elements and structures. The change of the aggregate interlock is the main reason characterizing the shear transfer behavior of HSC at room and elevated temperature. Elevated temperatures have adverse effect on the cement paste and aggregate, hence the corresponding characteristics of the aggregate interlock can be changed. This paper aims to study the shear transfer behavior and mechanism of HSC after elevated temperatures. This study may provide useful data for the assessment of some mechanical performance of HSC elements after a fire.

3. Test programme

3.1. Materials

The specimens consisted of two concrete types, labeled as L (lower strength)-series and H (higher strength)-series. PO42.5 and PO52.5 Portland cement were used for L-series and H-series specimens, respectively. Slag powder was used for both series, and silica fume was only mixed into H-series. The maximum aggregate sizes of the siliceous crushed stones with continuous grading were 25 mm and 20 mm for L- and H-series, respectively. The fine aggregate for both series was river sand with a fineness modulus of 2.70. Table 1 describes the chemical composition of HSC mixture. The mixture proportions of HSC are presented in Table 2.

3.2. Specimen preparation

The specimens for both L- and H-series were similar to those used in the push-off tests recently conducted by Xiao et al. on RAC [22]. The dimensions of all push-off specimens were 150 × 400 × 600 mm^3, as shown in Fig. 1. Four closed stirrups (diameter 8 mm) with a spacing of 70 mm across the shear plane were used to simulate the lateral constraint for the shear plane. The yield strength of the stirrups is 325 MPa at room temperature. All specimens had eight steel bars with a diameter of 14 mm as longitudinal reinforcements (parallel to the shear plane). The reinforcement cages were assembled carefully, and were then placed inside of wooden moulds, as shown in Fig. 2.

Each series of specimens was subdivided into four groups, designated as 20, 200, 400 and 800. These numbers represent the scheduled exposed highest temperature. The group 20 included 2 specimens and the other groups consisted of 3 ones. Therefore, the specimens were designated by the series name followed by the group number and a letter. For example, L-200-a indicated the first specimen of lower strength concrete, which was exposed the highest temperature of 200 °C. In total, there were 8 groups of specimens.

The specimens were compacted by a poker vibrator. Three cubes of 150 × 150 × 150 mm^3 for L- and H-series were respectively casted, for determining the cube compressive strength of the concrete. Three K-type thermocouples were installed into one of every three specimens of group 200, 400 and 800 before the setting of the HSC specimens. Fig. 3 displays the thermocouple locations with an X-designation and a reference number. Thermocouples 1, 2 and 3 recorded the