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Splitting strength of GGBFS concrete incorporating with steel fiber and polypropylene fiber after exposure to elevated temperatures

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ABSTRACT

Experiments were carried out to investigate the splitting properties of fiber reinforced ground granulated blast furnace slag (GGBFS) concrete after exposure to elevated temperatures. Based on experimental observation, the effect of GGBFS content, steel fiber dosage, polypropylene (PP) fiber dosage and strength grade of concrete on the residual splitting strength of the concrete after being subjected to high temperature was systematically analyzed. Test data indicated that high temperature caused significant deterioration in the splitting strength of concrete; the addition of GGBFS, PP fiber and steel fiber could all effectively improve the residual splitting properties of concrete; the optimum amount of GGBFS, PP fiber and steel fiber were identified, respectively; the degree of strength loss of concrete with different strength grades was very close to each other. A set of theoretical equations was proposed to predict the residual splitting strength of concrete after being heated to temperatures up to 800 °C.

1. Introduction

In general, high performance concrete is a pozzolanic concrete which meets special performance requirements with regard to workability, strength and durability that cannot always be obtained with techniques and materials typically used for producing conventional cement concrete. It has been demonstrated by many investigators that the fire performance of high strength concrete is different from that of normal strength concrete and may not exhibit same level of performance as normal strength concrete in fire. An effective approach to this problem is to add fibers into the mixture, e.g., PP fiber or steel fiber. As a mineral admixture, GGBFS has become a common constituent of concrete. There is a large amount of literature data available on the fire resistance of high-strength concrete. However, there is still a necessity to quantify the effect of GGBFS content, PP fiber dosage, steel fiber dosage and strength grade of concrete matrix on the residual mechanical properties of concrete after exposure to high temperature.

1.1. *Fire performance of high strength concrete*

Nowadays, high performance concrete has been gradually replacing normal strength concrete. The advantages of high performance concrete stem from the improvement of internal structure of the materials as compared with that of normal concrete. Densification of the concrete microstructures ensures a high strength and a very low permeability [1]. However, the dense structure of high performance concrete has been found to be detrimental to performance in fire. The absence of voids, which could relieve the continuous pressure build-up as a consequence of vaporization of evaporable water, may cause serious damage or even spalling to the concrete. There are many factors involved in the occurrence of spalling in concrete from fire. These include strength grade of concrete, rate of temperature increase, type of aggregate and size of specimen etc. [2]. The danger of spalling of concrete in relation to fire is not only the loss of section, but also the possibility of early yield of the steel reinforcement as it becomes directly exposed to the high temperature.

1.2. *Fire performance of GGBFS concrete*

GGBFS is an industrial by-product from the iron and steel industry. Because of the technological, economic, and environmental benefits, GGBFS has been gradually replacing cement in concrete in recently years. In high performance concrete, partial replacement of cement with GGBFS has been proven to be able to improve workability, lower the amount of hydration heat, increase resistance to sulfate attack, reduce shrinkage, permeability, chloride-ion diffusion into concrete, the likelihood of deterioration due to alkali-silica reaction and thus improve the durability of concrete [3]. Additionally, the replacement of cement with GGBFS will improve the fire resistance of concrete as well. Wang [4] studied the effect of elevated temperature on cement

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paste containing GGBFS and found that an increase of GGBFS content to 20% or above greatly improved the fire resistance at a water–binder ratio of 0.23. Poon et al. [5] studied the strength and durability performance of normal- and high-strength pozzolanic concretes at elevated temperatures and found that pozzolanic concretes containing blast furnace slag had better performance than the pure cement concrete.

1.3. Fire performance of PP fiber and steel fiber reinforced concrete

The inclusion of PP fiber in the concrete mix has been proposed as a method of improving the performance of high grade concrete, especially reducing or eliminating the spalling in fire by all of the researchers [6,7]. The results by Abdul-Hamid et al. [8] indicated that the addition of PP fiber effectively retarded the deterioration process of surface skin of the concrete specimens cured in hot weather environments. Xiao and Falkner [9] tested concrete specimens with and without PP fibers and found no explosive spalling on specimens with PP fiber while some spalling on specimens without PP fiber. The test data by Kodur [10] indicated that the addition of PP fibers improved fire resistance of concrete. PP fiber can effectively improve the compressive strength, splitting strength, bonding strength, dynamic performance and fatigue life of concrete. A PP fiber dosage of 0.9 kg/m^3 was proved to have the optimum concrete performance output [11].

Steel fiber reinforced concrete possesses many superior performances to plain concrete such as improved strength and toughness [12,13], hindrance of macrocracks' development, delay in microcracks' propagation to macroscopic level, improved ductility after microcracks' formatting [14,15], and improved resistance to explosion and penetration [16]. However, the addition of steel fiber can hardly contribute to the fire resistance of concrete. Based on experimental data, Hertz [17] concluded that the presence of steel fibers did not reduce the risk of explosion and specimens with the highest fiber dosage were most likely to explode. Aydin et al. [18] also observed that steel fiber did not improve the high temperature resistance of concrete.

To reduce the risk of spalling of concrete exposed to high temperature and take advantage of the abundant benefits of adding steel fiber, a feasible technique is to add a cocktail of PP fibers and steel fibers into the concrete mixture [19]. From the test conducted by Ali and Nadjai [19], it was found that columns containing both PP fiber (1 kg/m^3) and steel fiber (80 kg/m^3) had a higher fire resistance by an average factor of 1.76 compared to columns containing PP fiber only. Peng et al. [20] studied the effect of hybrid fiber (PP fiber and steel fiber) and concluded that incorporating hybrid fiber seemed to be a promising way to enhance resistance to explosive spalling Han et al. [21] studied the spalling resistance of high performance concrete with PP fiber and metal fabric subjected to fire and concluded that spalling did not occur in all specimens in which PP fibers and metal fabric were both applied. Chen and Liu [22] studied the residual strength of hybrid-fiber-reinforced high-strength concrete and concluded that the properties of HSC after exposure to high temperatures were greatly improved by mixing high melting point fiber (i.e., carbon or steel fiber) with low melting point fiber (i.e., PP fiber).

The review of literature indicates that there is still a lack of database on the residual mechanical properties of GGBFS high-strength concrete containing both PP fiber and steel fiber after exposure to elevated temperatures.

1.4. Research objective of this study

The objective of the ensuing experimental investigation is to assess the influence of the GGBFS content, steel fiber dosage, PP fiber dosage and the strength grade of concrete on the splitting characteristics of concrete after being subjected to high temperatures. This paper contributes to the literature by supplying very unique data to understand the compound concrete materials incorporated GGBFS and a cocktail of steel fiber and PP fiber. The raw data are presented for future reference and proposed equations may be adopted in the design codes.

2. Materials and experiment parameters

A locally manufactured ordinary Portland cement complying with ASTM Type I was used in this study. The coarse aggregate was crushed limestone with a maximum size of 20 mm. The fine aggregate was river sand with a fineness modulus of 2.4. The steel fiber had a length of 32.6 mm, an equivalent diameter of 0.95 mm and a tensile strength of 808.6 MPa. PP fiber was 19.0 mm long, with a relative gravity of 0.91, a tensile strength of 276 MPa, an elastic modulus of 3793 MPa, a melting point of 160 °C and a burning point of 580 °C. Type JKH-1 super plasticizer was used in the concrete mixtures. The chemical compositions and physical properties of the GGBFS are listed in Table 1. In all, 17 different concrete mixtures were investigated, as listed in Table 2.

Totally five variables were examined in the following experimental program: temperature, GGFBS content, steel fiber dosage, PP fiber dosage and strength grade of concrete matrix. That is, (a) Five types of temperatures: 20 °C, 200 °C, 400 °C, 600 °C, 800 °C; (b) Four GGBFS contents: 0, 30%, 40% and 50%. (c) Five steel fiber dosages: 0, 0.5%, 1%, 1.5%, and 2% (by volume); (d) Four

Table 1
Chemical and physical properties of GGBFS.

Chemical composition	Percentage (%)
SiO_2	38.1
SiO_3	0.58
MgO	9.3
Na_2O	0.32
Al_2O_3	11.63
K_2O	0.41
Fe_2O_3	3.35
CaO	35.12
Loss on ignition	0.05
Density (g/cm^3)	2.85
Specific surface area (m^2/kg)	415
Activity index after 7 day (%)	76

Table 2
Mix proportion (kg/m^3).

Group	Water	GGBFS	Cement	Sand	CA	SP	S	P
BIK	150	0	500	612	1188	7.5	0	0
BIIK	150	150	350	612	1188	7.5	0	0
BIIIK	150	200	300	612	1188	7.5	0	0
BIVK	150	250	250	612	1188	7.5	0	0
BIP2S2	164	0	547	696	1044	8.2	78	0.9
BIIP2S2	164	164	383	696	1044	8.2	78	0.9
BIIIP2S2	164	219	328	696	1044	8.2	78	0.9
BIVP2S2	164	273	273	696	1044	8.2	78	0.9
BIIIP2S0	150	200	300	612	1188	7.5	0	0.9
BIIIP2S1	156	208	312	710	1064	7.8	39	0.9
BIIIP2S3	172	229	344	682	1023	8.6	117	0.9
BIIIP2S4	180	240	360	668	1002	9	156	0.9
BIIIP0S2	164	219	328	696	1044	8.2	78	0
BIIIP1S2	164	219	328	696	1044	8.2	78	0.6
BIIIP3S2	164	219	328	696	1044	8.2	78	1.2
AIIIP2S2	176	190	286	719	1079	0	78	0.9
CIIIP2S2	167	247	371	666	999	9.3	78	0.9

W—Water; CA—Coarse aggregate; SP—Super plasticizer; S—Steel fiber; P—PP fiber.