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Experimental study on flexural behaviour of inorganic polymer concrete beams reinforced with basalt rebar

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ABSTRACT

Corrosion of reinforcing steel and the severe degradation of mechanical properties with temperature and fire conditions are the weakest points of steel-reinforced concrete structures and fibre reinforced polymer (FRP) system, respectively. In this paper, the basalt reinforced inorganic polymer concrete (IPC) beam which combines the specific characteristics of IPC and basalt reinforcement such as good corrosion resistance and fire resistance was proposed. The inorganic polymer binder was made of fly ash, ground granulated blast-furnace slag and alkaline activating solution. The mechanical properties of IPC were measured and compared with those of reference ordinary Portland cement (OPC) concrete. The flexural behaviour of basalt reinforced IPC beam was investigated and compared to control steel-reinforced OPC concrete beam. The measured ultimate flexural capacity of basalt reinforced IPC beam was compared with the predicted value obtained using the guidelines for FRP-reinforced OPC concrete beam. Results indicated that the elastic modulus of IPC was very close to OPC, while the compressive strength and flexural strength of IPC were around 80% of those of OPC. The IPC beam reinforced with basalt rebar exhibited a two-stage load-midspan deflection response that was different from control concrete beam due to the different mechanical properties of basalt and steel rebars. The crack patterns in basalt reinforced IPC beam were found to be similar to control beam, however, the maximum crack width of basalt reinforced beam was approximately 2 times that of control beam. The guidelines for FRP-reinforced concrete beam were adequate for predicting the flexural strength of basalt reinforced IPC beams.

1. Introduction

Concrete is the most widely used man-made material in the world. The sustainability has become an increasingly important characteristic for concrete infrastructure, as the manufacture of Portland cement accounts for a significant proportion of raw material consumption and nearly 7% of global CO_2 emissions [1]. Inorganic polymers, also called geopolymers, are conventionally produced by synthesizing pozzolanic compounds or aluminosilicate source materials with highly alkaline hydroxide and/or alkaline silicate. Over the last two decades, inorganic polymer concretes (IPC) have emerged as novel engineering materials with the potential to become a substantial element in an environmentally sustainable construction and building products industry [2,3]. Industrial by-products, such as fly ash (FA) and ground granulated blast-furnace slag (GGBFS) are commonly used as the source of IPC due to the low cost and wide availability of these materials. It has been shown that compared to ordinary Portland cement (OPC) concrete, IPC has many attractive properties, such as good fire resistance, good resistance to chloride penetration, acid attack, freeze-thaw cycles, etc. and can help reduce embodied energy and carbon footprint by up to 80% [4–6].

Corrosion of reinforcing steel is the leading cause of deterioration of reinforced concrete (RC) structures. In recent years, an increasing attention has been paid towards the replacement of traditional steel bars with fibre reinforced polymer (FRP) as internal concrete reinforcement to solve the problem of rebar corrosion in RC structures. The most commonly used FRP reinforcing bars for concrete structures are made from glass (GFRP), carbon (CFRP) and aramid (AFRP). However, the performance of GRRP and AFRP would be significantly affected by the alkaline environment within concrete [7]. CFRP reinforcing bars are too expensive to be

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implemented in normal civil engineering structures [8]. A new type of reinforcing bars made from basalt fibre (BFRP) has recently gathered attention as an alternative to other FRPs because of its cost effectiveness, ease of manufacture, high temperature resistance, freeze-thaw performance and good resistance to vibration and impact loading, corrosion and acids [9–12]. In addition, BFRP has better durability in alkaline conditions compared to GFRP [13]. Because of these outstanding characteristics, BFRP fibres have been used either as internal reinforcement for new concrete structures or as external strengthening for existing concrete structures [14].

Over the past few years, many efforts have been made to investigate the mechanical behaviour of steel- and FRP-reinforced inorganic polymer (geopolymer) concrete, and BFRP reinforced concrete in order to offer a solid theoretical basis for the use of geopolymer concrete and BFRP in concrete structures. With respect to the interaction between reinforcement and geopolymer concrete, Songpiriyakij et al. [15] experimentally studied the bonding strength between the embedded steel rebar and substrate geopolymer concrete made of fly ash, rice husk and bark ash and silica fume, and showed that the bond strength of rebar and geopolymer was slightly higher than that of control OPC concrete (1.05–1.12 times). Sarker [16] used the beam-end test method to measure the bond strength of low calcium fly ash-based geopolymer concrete with deformed steel rebars and compared with the equivalent OPC concrete system. The geopolymer concrete was observed to have higher bond strength than OPC concrete, which was attributed to the higher splitting tensile strength of geopolymer concrete relative to OPC concrete of the same compressive strength. Castel and Foster [17] carried out the standard RILEM pull-out test to investigate the bond between geopolymer and deformed and smooth steel rebars. The used geopolymer binder was composed of 85.2% of low calcium fly ash and 14.8% of GGBFS. The 28-day bond strength and the overall bond stress-slip behaviour of the geopolymer concrete were found to be similar to those of OPC concrete. Menna et al. [18] studied the flexural behaviour of reinforced geopolymer concrete beams strengthened with high strength steel cord and CFRP to evaluate the effectiveness of strengthening. Results indicated that geopolymer matrix provided a very good adhesion to concrete substrate and to reinforcement. With respect to BFRP reinforced concrete, Tomlinson and Fam [19] evaluated the flexural and shear performances of concrete beams reinforced with BFRP rebar and stirrups, and found that the beams with BFRP had significantly higher strengths than control steel-reinforced counterparts with the same reinforcement ratio. Ge et al. [20] carried out a series of experiments including tensile test, standard pull-out test of BFRP bars and static flexural test on hybrid concrete beams reinforced with BFRP bars and steel bars, and observed that the bond strength between BFRP rebar and concrete is similar to that of steel rebar and concrete. These previous studies have shown that the systems of steel rebar and geopolymer concrete, and BFRP rebar and OPC concrete have a similar bond behaviour and mechanical performance to control steel-reinforced OPC concrete, which leads to the idea in this study of combing BFRP rebar and IPC (geopolymer concrete) in a composite system to improve the durability and sustainability of concrete structures. According to authors' knowledge, the mechanical behaviour of IPC beam reinforced with BFRP reinforcement has not been extensively investigated elsewhere.

In this work, the mechanical properties including compressive strength, flexural strength and elastic modulus of IPC are studied and compared to reference OPC concrete. The inorganic polymer binder is composed of both fly ash and GGBFS. Afterwards, the flexural behaviour of IPC beam reinforced with BFRP rebar in terms of ultimate flexural strength and cracking patterns and development is investigated in detail and compared with that of control steel-reinforced OPC concrete beam to understand the failure mechanisms of BFRP reinforced IPC beam. A comparison between the theoretical previsions of the flexural behaviour of the tested beams calculated according to the recommendations for FRP-reinforced OPC concrete beam and experimental data for BFRP reinforced IPC beam was carried out to estimate whether the guidelines for FRP-reinforced concrete system are adequate for predicting the flexural strength of IPC beams with BFRP reinforcement.

2. Materials and methods

2.1. Inorganic polymer concrete

The inorganic polymer concrete used for experiments was made of a mixture of inorganic polymer binder composed of FA, GGBFS and alkaline activating solution, fine and coarse aggregates. FA and GGBFS used in this study were produced by Qingshan Power Station and Wuhan Iron and Steel Company Limited in Wuhan in Hubei Province of China, respectively. The chemical compositions of FA and GGBFS are given in Table 1. The scanning electron microscope (SEM) images of FA and GGBFS morphology are shown in Fig. 1. The alkaline activating solution was obtained by dissolving solid sodium hydroxide (NaOH) into sodium silicate (Na_2SiO_3) solution with the Na_2SiO_3/NaOH ratio of 1.53. Fifteen series of inorganic polymer binder were prepared and tested in order to determine the optimal composition of the mixture accounting for both early-age properties and durability, which was presented in detail in a previous work [11]. The medium-sized sand with fineness modulus of 2.72 was used as fine aggregate. The coarse aggregate was 13 mm nominal size crushed stone. The particle size distributions of fine and coarse aggregates are presented in Tables 2 and 3, respectively.

The mix proportion of raw materials in inorganic polymer concrete is given in Table 4. The fine and coarse aggregates were firstly mixed for 2 min. Afterwards, the inorganic polymer binder was mixed together with fine and coarse aggregates for about 3 min followed by a gradual addition of free water. The inorganic polymer concrete was then placed in the moulds and compacted using a poker vibrator. The concrete specimens were prepared for compressive and flexural tests.

2.2. Basalt rebar

Fig. 2 shows the used BFRP reinforcing bar for inorganic polymer concrete beams. It was supplied by Shenzhen Academy of Aerospace Technology. According to the manufacturer the Young's modulus, yield strength and ultimate tensile strength of BFRP rebar are 50 GPa, 600 MPa and 650–1000 MPa, respectively. In order to study the mechanical behaviour of IPC beams reinforced with basalt rebar, it is necessary to examine the stress–strain

Table 1
Chemical compositions of fly ash and GGBFS (wt.%).

Oxide	FA	GGBFS
Silicon dioxide, SiO_2	51.12	33.20
Aluminium oxide, Al_2O_3	29.53	14.63
Iron oxide, Fe_2O_3	5.57	0.34
Calcium oxide, CaO	2.99	37.13
Potassium oxide, K_2O	2.38	0.33
Sulphur trioxide, SO_3	1.34	2.97
Magnesium oxide, MgO	1.03	9.18
Sodium oxide, Na_2O	0.5	0.32
Barium oxide, BaO	0.06	0.36
Others	2.42	1.20
Loss of ignition (LOI)	3.06	0.34