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Impact response of concrete reinforced with hybrid basalt-polypropylene fibers

Qiang Fu *, Ditao Niu *, Jian Zhang, Daguan Huang, Mengshu Hong

Department of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, PR China

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ABSTRACT

The impact-resistance behaviour of concrete reinforced with hybrid basalt–polypropylene fibers (HBPRC) was experimentally investigated at strain rates of 10^1–10^2 s^{-1}, using a ϕ75 mm split-Hopkinson pressure bar. The strain-rate effect of the dynamic compressive strength, dynamic elastic modulus, critical strain, specific energy absorption and characteristic length of HBPRC was analyzed in detail. The results showed that all mechanical indices of HBPRC increased with increasing strain rate. The dynamic increase factor of compressive strength and elastic modulus increased linearly with the decimal logarithm of strain rate, and the critical strain and characteristic length increased linearly with strain rate. The addition of basalt fiber (BF) and polypropylene fiber (PF) yielded a significant increase in the strain-rate sensitivity of dynamic mechanical behaviour of HBPRC, while PF had a more significant effect compared to BF. Hybridization of BF and PF resulted in various influences on the strain-rate sensitivity of dynamic mechanical behaviour of HBPRC, but there was a significant positive correlation between the hybrid content of fibers and the strain-rate sensitivity of dynamic mechanical behaviour of HBPRC. The variation in specific energy absorption and characteristic length with strain rate and fiber content was consistent, and both could characterise the impact toughness of HBPRC.

1. Introduction

Concrete is widely used in various buildings, both civilian and military, and is the most important construction material worldwide. However, because of the relatively low tensile strength and weak resistance to cracking, concrete exhibits brittle characteristics, which seriously limits its use under high strain-rate loadings, such as earthquakes, blasts, impacts, etc. [1–3].

The addition of fibers to concrete can effectively prevent the creation and propagation of cracks in concrete by bridging, as well as increase the toughness, specifically the impact-resistance behaviour under high strain-rate loading [4]. According to their elastic moduli, fibers are classified as flexible fibers (polypropylene fiber and nylon fiber), or stiff fibers (steel fiber, carbon fiber, and basalt fiber). Flexible fibers can improve the crack- and impact-resistance of concrete due to their high ductility, whereas stiff fibers contribute partly to the strength of concrete. Hybridization of flexible and stiff fibers is widely used to obtain a strengthened and toughened concrete. An example of this is the hybrid steel-polypropylene fibers, which is commonly used, and has been proven to be effective in fiber-reinforced concrete. With appropriate size and hybridization ratios of fibers, the hybrid steel-polypropylene fibers can significantly improve the strength, ductility, and impact-resistance of concrete, by acting at different scales [5–8]. However, because of the same chemical component as rebar, the steel fibers rust easily. This is especially true in a marine chlorine environment, where the addition of steel fibers severely reduces the durability of concrete structures. Further, the addition of steel fibers will reduce the workability of concrete, and increase the weight of structure [9,10]. Basalt fiber (BF), produced by melting and wire drawing from natural volcanic basalt rock, possesses excellent physical and mechanical properties, including high temperature stability, good acid alkali-resistance, high tensile strength, and superior plastic-deformation capacity. It is a cost-effective, environmentally friendly, and inorganic fiber [9–14]. BF can be used as a substitute for steel fiber to some extent and improve the impact-resistance behaviour of concrete as a reinforcing material by combining with polypropylene fiber (PF). This can further expand the application range of hybrid fiber-reinforced concrete, especially for marine and offshore structures that require high durability, and are prone to impact loading.

There exist numerous research reports of the impact-resistance behaviour of concrete-like materials under high strain rate loading. The compressive strength, elastic modulus, and energy absorption capability of concrete-like materials increase with increasing strain rate, and the strain-rate sensitivity of elastic modulus is usually less than that of compressive strength. However, there is no consensus on the strain-rate sensitivity of peak strain [15–19]. Due to the addition of fibers, the mechanical properties of concrete reinforced with hybrid basalt–polypropylene fibers are significantly different to those of normal concrete, especially under high strain-rate impact loading.

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* Corresponding authors.
E-mail addresses: fuqiangcsu@163.com (Q. Fu), niuditao@163.com (D. Niu).

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However, there are few reports on the impact-resistance behaviour of BF and PF reinforced concrete. Li and Xu [20–22] investigated the impact toughness of BF reinforced normal concrete and geopolymeric concrete at high strain rates, and reported that the compressive strength, critical strain, and energy absorbing capability of the two types of concrete increased consistently with increasing strain rate. The addition of BF to concrete with a content of 0.1%, by the volume of concrete, could markedly improve the deformability and energy absorbing capacity of both concretes. Hu et al. [23] reported that the impact toughness of PF-reinforced concrete increased with increasing strain rate, and the optimum content of PF is 1.5 kg/m^3. Zhang et al. [24] concluded that the dynamic mechanical properties, compressive strength, and toughness of PF-reinforced concrete increased with strain rates under high strain-rate loading, which showed a parabolic development with increasing fiber content. The suggested optimal PF content is 1.5 kg/m^3, which was consistent with the findings of Hu et al. [23]. As mentioned above, there is a lack of research on the impact-resistance behaviour of BF and PF reinforced concrete. However, no study on the impact-resistance behaviour of hybrid basalt–polypropylene fibers reinforced concrete has been conducted.

With the addition of mineral additives, the performance of concrete has changed dramatically [6,25]. Mineral additives influence the dispersion of fibers in concrete and the bonding properties between fibers and the concrete matrix, which is the cause for the difference in impact-resistance behaviour between fiber-reinforced concrete containing mineral additives and normal concrete. Therefore, the impact-resistance behaviour of concrete reinforced with hybrid basalt–polypropylene fibers containing mineral additives (HBPRC) under high strain-rate loading should be investigated, in order to increase its scope for application.

The primary aim of this study is to investigate the dynamic mechanical behaviour of HBPRC at strain rates ranging from 10^1–10^2 s^{-1}. The variation in dynamic compressive strength, dynamic elastic modulus, critical strain, specific energy absorption and characteristic length with strain rate was analyzed. The influence mechanism of strain rate, single or hybrid addition and addition content of fibers on the impact-resistance behaviour of HBPRC was explored. The results presented in this study are useful in enhancing the understanding of the impact-resistance behaviour of HBPRC under high strain-rate loading.

2. Experimental program

2.1. Materials and mix proportions

The binder used in this study mainly includes P.O. 42.5R Portland cement (C), silica fume (SF), fine grade fly ash (FA), and S95 grade ground granulated blast furnace slag (GGBS). SF, FA and GGBS are shown in Fig. 1. Tables 1–3 summarize the chemical composition and physical properties of the binder. A polycarboxylic-based superplasticiser (PBS) with a water-reducing rate of 30% was used. River sand (S) with a maximum particle size of 4.75 mm and a fineness modulus of 2.8 was used. A coarse aggregate (CA) of limestone with a particle size of 5–20 mm was prepared, and tap water (W) was used for mixing. BF and PF were shown in Fig. 2. The physical and mechanical properties of BF and PF are presented in Table 4.

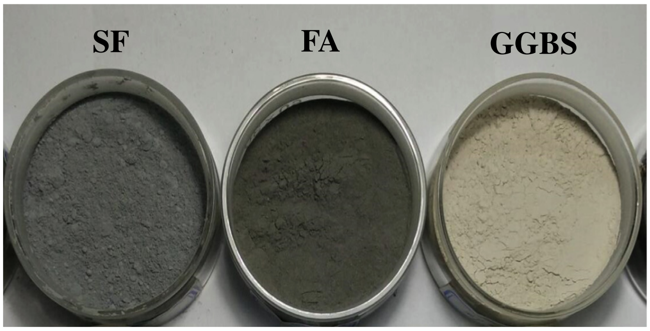

Fig. 1. Mineral additives.

Table 1
Chemical properties of cementitious materials.

Composition (wt%)	C	SF	FA	GABS
SiO_2	21.18	85.04	35.71	34.65
Al_2O_3	5.02	0.97	16.57	14.21
Fe_2O_3	3.14	1.04	8.92	0.49
CaO	63.42	1.63	21.14	34.11
MgO	3.12	0.32	1.41	11.15
SO_3	2.3	–	1.94	1
Other	1.82	10	12.49	3.74

To investigate the hybridization effect of BF and PF on the impact-resistance behaviour of HBPRC, a reference mixture without fibers (NC) and four mixtures with single or hybrid fibers were used in this study. The four mixtures with fiber contents of 0.1% (BF), 0.1% (PF), 0.1% (0.05%BF + 0.05%PF) and 0.2% (0.1%BF + 0.1%PF) by volume of concrete, were named BC-0.1, PC-0.1, BPC-0.1 and BPC-0.2, respectively. BC-0.1, PC-0.1 and BPC-0.1 were used to investigate the impact-resistance behaviour of HBPRC with the same fiber content and different hybridization of fibers, and BPC-0.1 and BPC-0.2 were used to investigate the behaviour of HBPRC with the same hybridization of fibers and different fiber contents. The mix proportions are shown in Table 5.

2.2. Sample preparation and curing

During mixing, S and CA were first mixed for 30 s. The binder was then added and mixed for a further 2 min. The PF and BF were successively added, and mixed for 3 min and 2 min, respectively. Then, 90% of the water was added, and mixed for 3 min. Finally, the remaining water and PBS were added, and mixing continued for a further 2 min to achieve a uniform distribution. The mixtures were cast into the prepared moulds and compacted on a vibrating table for 15 s. The specimens were covered with a plastic film to prevent the moisture from evaporating, and de-moulded after 24 h. They were then cured at a constant temperature (20 ± 2 °C) and relative humidity (greater than 95%) for 28 d.

To minimize the influence of the end-friction confinement effect between the specimens and bars, and the transverse inertial effect of specimens on the test results during the dynamic compressive test of concrete-like materials, the optimal slenderness of specimens should be 0.5 [26,27]. Therefore, specimens with dimensions of $\phi 75 \times 37.5$ mm were used for dynamic compressive testing in this study. After curing for 15 d, the specimens for the dynamic compressive test were drilled and ground, to make the two ends parallel so as to ensure the reliability of the results. Then, the specimens continued to be cured to 28 d for testing.

2.3. Quasi-static compressive test

The compressive strength and elastic modulus of HBPRC specimens, with dimensions of 100 × 100 × 300 mm, under quasi-static

Table 2
Physical and mechanical properties of cement.

Water content for standard consistency (%)	Specific area surface (m^2/kg)	Soundness	Ignition loss (%)	Setting time (h)		Compressive strength (MPa)		Flexural strength (MPa)	
				Initial	Final	3 d	28 d	3 d	28 d
25.8	334	Satisfied	2.79	2.3	3.4	28.8	48.6	6.4	8.6