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Original Research Article

Dynamic compressive mechanical behaviour and modelling of basalt–polypropylene fibre-reinforced concrete

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ABSTRACT

Dynamic compressive behaviour of basalt–polypropylene fibre-reinforced concrete (BPFRC) was experimentally investigated using a 75-mm-diameter split-Hopkinson pressure bar. The results showed that the addition of basalt fibre (BF) and polypropylene fibre (PF) is effective at improving the impact-resistance behaviour of concrete. The dynamic compressive strength, critical strain, and energy absorption capacity of BPFRC increased with increasing strain rate. At strain rates of 20–140 s^{-1}, the addition of BF and PF significantly increased the dynamic compressive strength, critical strain, and energy absorption capacity of concrete. The dynamic increase factor of BPFRC increased linearly with the decimal logarithm of strain rate. The hybrid addition of BF and PF significantly improved the strain rate effect of the dynamic compressive strength. The strengthening and toughening mechanisms of BF and PF are discussed in detail. The proposed dynamic damage constitutive model can be used to accurately describe the dynamic stress–strain relationship of BPFRC.

1. Introduction

Concrete, used in a variety of civil and military infrastructures, is presently the most widely used construction materials. However, in addition to the static loading, concrete structures will inevitably suffer the dynamic loading from events such as earthquake, explosion and impact during their periods of service; moreover, a variety of protective structures are vulnerable to artillery attacks and explosions [1,2]. The airport pavements are subjected to the impact caused by landing aircraft, while the marine and offshore engineering structures are vulnerable to wave impact, hydrodynamic pressure, and wind load. However, the normal concrete exhibits typical brittleness because of its weak resistance to cracking. Under impact loading, the normal concrete usually exhibits a failure

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mode of collapsibility, which results in further serious safety problems in normal concrete structures. Therefore, improving the impact-resistance behaviour of concrete and studying the evolution of its dynamic mechanical behaviour under impact loading are the basis for ensuring the safe service of modern concrete structures.

Effective measures that improve the impact-resistance behaviour of concrete usually involve the addition of fibres to the concrete. These dispersed fibres in concrete can effectively prevent the formation and propagation of cracks through bridging and significantly increase the toughness of concrete, thereby improving the impact-resistance behaviour of concrete [3–5]. In general, the synergy between stiff and flexible fibres can be achieved by their hybridization, which imparts better strength and toughness to the concrete. Basalt fibre (BF) is produced by the melting and wire-drawing of natural volcanic basalt rock. Because of the wide availability of raw materials and the absence of any additives during the production process, the cost of BF is very low. BF, an inorganic fibre, has high tensile strength and elastic modulus, and distinct advantages that include temperature and chemical stability, sound- and heat-insulating properties, cost effectiveness, and environmental friendliness [6–8]. Polypropylene fibre (PF), the most typical synthetic fibre, has good ductility, good chemical stability, and a low elastic modulus. The addition of PF can significantly improve the crack-resistance behaviour and ductility of concrete [9,10]. The hybridization of BF and PF can improve the impact-resistance behaviour of concrete through the crack-resistance and toughening actions of BF and PF at different deformation stages of concrete.

The dispersion uniformity of fibres in concrete and the bonding strength between the fibres and the concrete matrix are the main factors affecting the mechanical properties of fibre-reinforced concrete. The mineral admixtures (silica fume, fly ash, and slag) can significantly improve the dispersion of fibres in concrete and help to increase the bonding strength between the fibres and the matrix. Qian and Stroeven [11] pointed out that a certain content of fly ash is conducive to the dispersion of fibres. Nili and Afroughsabet [12] found that the addition of silica fume led to an increased compressive strength for fibre reinforced concrete. Yoo and Banthia [13] reviewed the mechanical properties of ultra-high-performance fibre-reinforced concrete, and found that silica fume is beneficial to increasing the bond strength between fibres and the matrix, and using fly ash and slag positively affected the flexural strength concrete. Hence, the addition of mineral admixtures not only improves the durability of BF- and PF-reinforced concrete, but also contributes to the crack-resistance and toughening actions of BF and PF.

Numerous research papers have reported on the dynamic compressive mechanical behaviour of concrete-like materials under impact loading [14,15]. However, only a few studies on the dynamic compressive mechanical behaviour of single BF- or PF-reinforced concrete have been conducted. Li and Xu [16] indicated that BF can improve the impact-resistance behaviour of concrete. The size of BF reinforced concrete fragment is larger compared to normal concrete. In addition, Li and Xu [17] obtained that BF significantly increased the dynamic compressive strength and energy-absorption capacity. Li and Xu [18] further investigated the effect of BF on the impact-resistance behaviour of geopolymeric concrete (GC), and reported that BF can improve the energy absorption properties of GC, while there is no notable enhancement in dynamic compressive strength. Li et al. [19] reported that the addition of BF increased the impact-resistance behaviour of concrete, and pointed out that BF with 0.1% volume can improve the impact-resistance behaviour of concrete to the maximum extent. Zhang et al. [20] found that the dynamic compressive strength and toughness index of PF-reinforced concrete varied parabolically with increasing PF content. Hu et al. [21] reported that PF can significantly improve the toughness of concrete when the content of PF is 1.5 kg/m^3. After the hybrid addition of BF and PF to the concrete, differences between the effects of the hybrid and single fibres on the dynamic compressive mechanical behaviour of concrete are observed. Particularly, when the mineral admixtures is added to the concrete, the improvements in fibre dispersion and the bonding strength will also affect the effect of the fibres on the dynamic compressive mechanical behaviour of concrete.

The dynamic constitutive model for concrete is the basis of the structural design and dynamic safety analysis of concrete structures. However, only a few studies have been conducted on the dynamic constitutive model for concrete-like materials, which dramatically limits the applications of the existing research results of dynamic mechanical behaviour to the practical structural design and dynamic analysis. Lai and Sun [4] improved the ZWT model by introducing a damage factor and established a viscoelastic damage constitutive model for the ultra-high performance cementitious composite. Li and Xu [17] employed the ZWT model to describe the dynamic stress–strain relationship of BF-reinforced concrete. Su et al. [22] established a dynamic constitutive model for ceramic fibre-reinforced concrete based on the improved parallel-bar system model. The fitted results of the three aforementioned models are in good agreement with the experimental results before the peak stress. However, these reports do not provide the fitted results after the peak stress [4,17,22]. Zhou and Chen [23] proposed a dynamic statistical damage model for cement mortar using the statistical damage theory. In addition, Chen et al. [24] proposed a dynamic constitutive model for cement paste, cement mortar, and concrete based on Lemaitre's strain equivalence hypothesis. The models proposed by Zhou and Chen [23] and Chen et al. [24] can accurately describe the dynamic stress–strain relationships of concrete-like materials.

Up to now, the research on the dynamic compressive mechanical behaviour of basalt–polypropylene fibre-reinforced concrete containing mineral admixtures (BPFRC) have, to the best of our knowledge, not been reported. In addition, the lacking dynamic constitutive model for BPFRC is necessary to promote its application in building structures. Hence, a systematic study on the dynamic compressive mechanical behaviour and the establishment of the dynamic constitutive model for BPFRC will help to promote its application in the engineering structures those are prone to impact loading.

In this study, the dynamic compressive mechanical behaviour of BPFRC was experimentally investigated under the strain rates corresponding to the impact and blast load. The effects of BF, PF, and strain rate on the dynamic compressive mechanical behaviour of concrete were analyzed and discussed. Based on the standard solid model and