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Transient dynamic behavior of polypropylene fiber reinforced mortar under compressive impact loading

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HIGHLIGHTS

- The dynamic characteristics of polypropylene fiber reinforced mortar (PFRM) are investigated under compressive impact loading.
- The effects of water–cement ratios, fiber contents and strain rates, on the blast resistance performance of PFRM are studied.
- The dynamic performance of PFRM is significantly affected by strain rates.
- A dynamic constitutive law is derived for PFRM considering material damage.

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ABSTRACT

The dynamic characteristics and the constitutive relationship, of polypropylene fiber reinforced mortar (PFRM) materials, were investigated under compressive impact loading. The impact tests were carried out using an improved Split Hopkinson Pressure Bar (SHPB) equipment installed with confining pressure device. Both the static tests and SHPB impact experiments of PFRM were conducted to study the effect of water–cement ratios, fiber volume fractions, and strain rates, on the blast resistance performance of PFRM. The compressive strength, the dynamic elastic modulus, the toughness as well as the ductility of PFRM were analyzed. Experimental results show that the dynamic performance of PFRM materials is significantly affected by strain rates. Nevertheless, the strain rate effect decreases as the strength of mortar increases. Polypropylene fibers are able to improve the impact toughness. The dynamic constitutive law of PFRM was finally derived based on an improved Zhu–Wang–Tang (ZWT) dynamic constitutive model taking into account the material damage. The dynamic stress–strain curves from experiments can be well predicted by the proposed constitutive law which, consequently, can be used to describe the dynamic properties of PFRM materials.

1. Introduction

Polypropylene fiber reinforced concrete (PFRC) belongs to the category of multiphase heterogeneous composite materials composed of fine aggregates, coarse aggregates, cement and polypropylene fibers. Because polypropylene fibers possess a good strengthening and toughening feature, which are able to improve plain concrete's mechanical performance, PFRC has been widely used and in engineering construction (e.g., applied in aqueduct structures to prevent cracks causing water leakage [1].

In real-life applications, many concrete structures are designed to withstand normal design loads as well as uncertain dynamic loads such as impact, explosion, earthquake, etc. Therefore, the study on the dynamic properties of PFRC under high strain rate impact is practically significant in dynamic analyses of concrete structures. The dynamic characteristics of concrete under high strain rates are different from that in the case of static loads. At present, the physical properties and static responses of PFRC have been well studied in practical structural design. Nevertheless, due to the limitation of current experimental methods, studies on the dynamic properties of PFRC, especially under high strain rate loading conditions, are limited. Since cement mortar, as a major component and a typical form of concrete, has the closely homogenous property, we study the dynamic characteristics of PFRM instead of concrete so as to obtain a stable control of the experiments. The dynamic experiments on cement mortar as well as PFRM are able to provide an insightful reference for PFRC design and analysis.

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The Split Hopkinson Pressure Bar (SHPB) equipment is often used to study the mechanical properties of materials under high strain rate loading. Large diameter bars, with diameters such as Ø51 mm, Ø76 mm, Ø100 mm, are usually used to study dynamic properties of concrete [2–6]. For instance, Ross and Tedesco [7] studied the dynamic properties of concrete by means of an Ø51 mm SHPB device and concluded that the strength of concrete increases linearly as the strain rate increases. Zhao et al. [8,9] employed SHPB techniques to determine the dynamic behavior of materials in the range of small strains and presented a new two-gauge measure method taking into account the correction of wave dispersion. Investigators also employed the SHPB equipment to study the dynamic characteristics of cement and concrete composites. For example, Hao et al. [10,11] studied the dynamic compressive behavior of spiral steel fiber reinforced concrete in SHPB tests as well as the influence of end friction confinement [12]. Su and Xu [13] investigated the dynamic properties of ceramic fiber reinforced concrete under impact loads via SHPB tests. Behnood et al. [14] have done an extensive experimental study on the compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers after exposure to 600 °C. The experimental study by Cao et al. [15] shows that the impact resistance of PFRC increases by 4–6 times when the volume fraction of polypropylene fibers is 0.1–0.2%. In addition, Alhozaimy et al. [16] proposed that the polypropylene fiber can increase the static and dynamic strength of concrete with low fiber contents (e.g., volume content is 0.05–0.1%).

In Ref. [17], the physical and mechanical properties of PFRC under both static and low strain rate compression loads were obtained respectively. In order to characterize the strain–stress relationship of cementitious materials under compressive impact loading, Chen et al. [18,19] established a rate type damage evolution law applicable to cement and mortar, according to the basis of Zhu–Wang–Tang (ZWT) nonlinear viscoelastic constitutive equation. Other constitutive damage models can be found in [18,20]. Nevertheless, the experiments on PFRC reported in literature are mainly focused on the material physical properties either under the low velocity impact or quasi-static loading. As a matter of fact, studies under high strain rates are limited. What is more, the dynamic constitutive relationship of PFRC or PFRM materials considering the strain rate effects have not been sufficiently studied.

In the present work, we investigate the dynamic performance of PFRM under compressive impact loading. We carried out both the quasi-static and the dynamic impact tests. The impact test was realized by using the SHPB equipment with a large diameter bar (e.g., Ø74 mm). The effect of water–cement ratios, fiber volumes and impact strain rates were studied through analyzing the peak compressive stress and strain, the dynamic elastic modulus, the toughness as well as the ductility of PFRM. Finally, a dynamic constitutive damage law was established for PFRM materials under impact/blast loading.

2. Experiment framework

2.1. Description of specimens

Since the dynamic mechanical properties of PFRM are highly related to the material parameters and the test device, we carried out a parametric study considering the effects due to several influence factors such as the water–cement ratios, fiber contents and impact strain rates. Ordinary Portland cement with the strength grade of 32.5 was used. The river sand, after sieving control of the particle size (e.g., smaller than 3 mm), was employed as the fine aggregate. Three different water–cement ratios were considered, namely, 0.4, 0.5 and 0.6. The mixtures of cement, water and sand are given in Table 1. The polypropylene fibers added in the mortar mixtures are shown in Fig. 1 and their property parameters are presented in Table 2. Five sets of polypropylene fiber contents were used, which are 0 (plain mortar), 0.9, 1.2, 1.5 and 1.8 kg/m^3, respectively. Three batches of specimens were prepared and thus tested, given the identical mixture portion of PFRM.

As shown in [21], the specimen size is also an important factor. To reduce the dispersion effect of strain signals and to obtain more accurate experimental results, the optimal ratio between specimen

Table 1
Different water–cement ratios of cement mortar mixtures.

Water–cement ratio	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)
0.4	240	600	1200
0.5	300	600	1200
0.6	360	600	1200

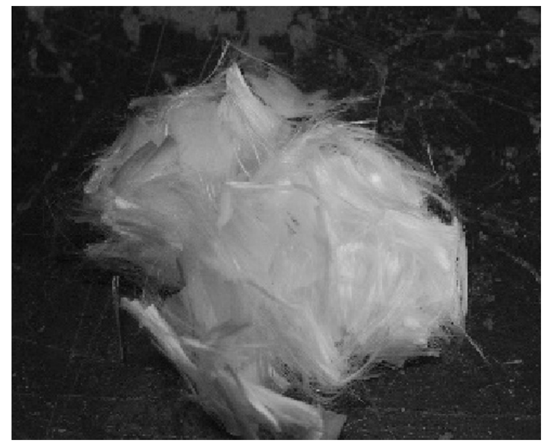

Fig. 1. Polypropylene fibers.

Table 2
The main parameters of polypropylene fibers.

Material name	Modified polypropylene	Fiber type	Wispy monofilament
Diameter	20–48 μm	Density	0.91 g/cm^3
Tensile strength	⩾350 MPa	Modulus of elasticity	⩾3500 MPa
Fiber length	12 mm	Elongation	15–25%
Melting point	⩾165 °C	Fire point	⩾590 °C

Fig. 2. PFRM specimen.