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Dynamic compressive behavior of ceramic fiber reinforced concrete under impact load

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HIGHLIGHTS

- The dynamic compressive strength and impact toughness of CRFRC increase with strain-rate.
- The observed dynamic enhancement of DIFs can truly reflect the strain-rate effect.
- Ceramic fiber can improve the dynamic strength and elastic modulus of concrete.
- 0.2% is the relatively optimum volume fraction of ceramic fiber
- The constitutive model can well describe the dynamic mechanical behavior of CRFRC.

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ABSTRACT

Dynamic properties of ceramic fiber reinforced concrete (CRFRC) are investigated using a 100-mm-diameter split Hopkinson pressure bar (SHPB) system. Different ways of choosing strain rate were adopted to express the strain rate effects on dynamic compressive stress, elastic modulus and impact toughness of CRFRC. The results show that the dynamic compressive strength and impact toughness increase with strain rate, while the elastic modulus decrease with strain rate. The addition of ceramic fiber can significantly improve the dynamic strength and elastic modulus of concrete. 0.1% and 0.2% volume fraction of ceramic fiber improve the impact toughness at higher strain rate. And the optimum volume fraction of ceramic fiber is 0.2%. The dynamic damage model was established based on the improved parallel bar system (IPBS) model. The result reveals that the model can well describe the relation between stress and strain of CRFRC.

1. Introduction

Concrete constructions, such as buildings, bridges and dam, inevitably endure the dynamic loads. In recent years, terrorist attack occurs frequently, which greatly threaten the security of common life. Adding fibers into concrete can enhance the compressive, tensile and shear strengths, flexural toughness, durability and resistance to impact [1–3]. The mechanical properties of fiber reinforced concrete depend on the type and the content of the added fibers. Consequently, the dynamic response of fiber reinforced concrete under impact loads has aroused much concern. Xu [4] researched the impact characterization of basalt fiber reinforced geopolymeric concrete, which reveals that the addition of basalt fiber can significantly improve deformation and energy absorption properties of GC, while there is no notable enhancement in dynamic compressive strength. Nili and Afroughsabet [5] researched the effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete, which indicates that the increase of polypropylene fiber in the mixtures from 0.2% to 0.5%, generally increased the compressive strength. Giner et al. [6] studied the effect of steel and carbon fiber additions on the dynamic properties of concrete and found that the addition of carbon fiber slightly increases the resonant frequencies of concrete specimens in the three modes of vibration, while they tend to decrease when the amount of steel fiber increases.

Ceramic fiber, as a new high-strength and high-modulus of elastic, has been widely used in areas of mechanism, metallurgy, chemical and engineering, oil, electronics and so on. It is praised as the fifth energy source product and has a good application prospect incorporated into concrete as reinforcement. Ma and Tan [7] studied mechanical property and durability of ceramic fiber reinforced cementitious composites. The results show that incorporating ceramic fibers at volume fraction of 5% into cement mortar can increase the flexural strength by 40% and the ratio rises up to 100% when adding silica fume. However, relatively few studies have

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Table 1
Physical and mechanical properties of ceramic fiber.

Chemical components	Diameter (μm)	Length (mm)	Density (g/cm^3)	Tensile modulus (GPa)	Tensile strength (MPa)	Temperature (°C)
>99%Al_2O_3	10–12	12.7	3.88	380	3000	1204

been conducted to study the anti-impact characteristics of ceramic fiber reinforced concrete (CRFRC). 0.1%, 0.2% and 0.3% volume fraction of ceramic fiber was incorporated into concrete and the strain-rate effects and fiber effects of CRFRC were investigated in the present paper. A dynamic damage constitutive model was built to describe its dynamic behavior.

2. Experimental program

2.1. Materials

The following materials are used in the fabrication of CRFRC specimens: P.O 42.5R cement, fly ash, silica fume (average grain diameter: 0.1–0.15 μm, SiO_2: 92%), limestone rubble (5–10 mm: 15%, 10–20 mm: 85%), river sand (river sand/limestone rubble = 0.67) with a fineness modulus of 2.8, high efficient water reducing agent FDN, tap water and ceramic fiber. Table 1 presents the physical and mechanical property of ceramic fiber and Table 2 shows the mix proportions of CRFRC.

2.2. Specimen preparation

Different mixing processes for plain concrete and CRFRC are adopted to make the plain concrete compact and obtain uniform fiber distribution. The former can be described as follows: partial mixture of water and FDN and total sand (30 s), limestone rubble (30 s), cement, fly ash and silica fume (30 s), residual mixture of water and FDN (60 s). The latter is: limestone rubble and ceramic fiber (30 s), sand (30 s), cement, fly ash, silica fume (30 s), mixture of water and FDN (120 s).

After the mixing procedure, cylindrical specimens were casted. Cylindrical specimens of $\Phi 100 \times 50$ mm dimensions were used for dynamic properties tests. Thereafter, the specimens were left in their molds for 24 h, and finally cured in the standard conditions of 20 ± 2 °C and >95% relative humidity for 28 days until tested.

2.3. SHPB test

A 100-mm-diameter SHPB was used to test the mechanical properties of CRFRC. This apparatus consists of main body, energy source and measurement systems. Main body mainly contains launch tube, projectile, incident bar, transmission bar and energy absorbing setup; energy source system mainly contains air compressor, pressure vessel; measurement system contains velocity and dynamic strain measurement setup. The projectile, incident and transmission bars are made of 48CrMoA and have Young's modulus of 210 GPa, density of 7850 kg/m^3, and wave velocity of 5172 m/s.

The fundamental of SHPB test is the propagation theory of elastic stress-wave [8] in thin and long bar, which is based on two assumption [9]: (1) plane assumption, that is, every cross section of elastic bar remains plane during the propagation process and (2) stress equality assumption, that is, stresses are the same in the bar everywhere after two or three come-and-go. According to three-wave method, stress, strain rate and strain histories of specimen can be expressed, respectively, as below:

$$\left.\begin{array}{l} \sigma_s(t) = \frac{E[\varepsilon_i(t)+\varepsilon_r(t+\tau_1)+\varepsilon_t(t+\tau_2)]A}{2A_s}. \\ \dot{\varepsilon}_s(t) = \frac{[\varepsilon_i(t)-\varepsilon_r(t+\tau_1)-\varepsilon_t(t+\tau_2)]c}{l_s}. \\ \varepsilon_s(t) = \int_0^t \dot{\varepsilon}_s(\tau)d\tau. \end{array}\right\} \quad (1)$$

where E is Young's modulus of bars, c is wave velocity in bars, A and A_s are cross-sectional areas of bars and specimen, respectively; l_s is original length of specimen, ε_i, ε_r, ε_t are incident, reflected and transmitted strain, respectively; τ_1 and τ_2 are time delays of reflected and transmitted pulses, respectively.

3. Results and discussion

Table 3 shows the SHPB test results for CRFRC.

Table 2
Mix proportions of CRFRC (kg/m^3).

Cement	Tap water	River sand	Limestone rubble	FDN	Fly ash	Silica fume	Ceramic fiber		
							0.1%	0.2%	0.3%
371	180	672	1008	5	99	25	3.88	7.76	11.64

Table 3
SHPB tests results.

Concrete materials	Specimen No.	Average strain rate $\bar{\dot{\varepsilon}}_s/(s^{-1})$	Dynamic compressive strength $f_{c,d}$/(MPa)	Elastic modulus E/(GPa)	Impact toughness U/(kJ m^{-3})
Plain concrete	1	26.5	86.5	38.4	476
	2	37.7	100.6	33.5	617
	3	47.9	104.6	26.8	856
	4	69.9	106.5	24.2	1176
	5	98.6	122.5	17.4	1452
0.1%CRFRC	1	35.0	82.2	30.5	375
	2	47.3	86.5	28.1	763
	3	66.6	103.3	26.5	1161
	4	77.6	106.8	23.8	1246
	5	94.6	115.8	22.3	1412
0.2%CRFRC	1	28.3	92.1	32.1	384
	2	49.6	101.2	28.9	926
	3	61.7	106.5	26.3	1073
	4	73.6	110.2	24.5	1203
	5	91.4	134.3	23.7	1671
0.3%CRFRC	1	28.6	89.7	35.9	233
	2	39.0	100.9	38.8	351
	3	51.1	107.0	29.7	833
	4	60.6	114.8	25.2	891
	5	75.5	115.6	23.3	1254