Engineering Structures 169 (2018) 119–130

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental study on dynamic compressive properties of fiber-reinforced reactive powder concrete at high strain rates

Xiaomeng Hou[a,b,*], Shaojun Cao[a,b], Wenzhong Zheng[a,b], Qin Rong[a], Gang Li[a,b]

[a] Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China
[b] Key Lab of the Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 150090, China

ARTICLE INFO

Keywords:
Reactive powder concrete
Split Hopkinson pressure bar
Energy absorption
Dynamic stress–strain responses
Dynamic increase factor

ABSTRACT

Dynamic compression tests were performed on reactive powder concrete (RPC) using split Hopkinson pressure bar (SHPB) apparatus. A total of 102 RPC samples including plain RPC (PRPC), steel fiber-reinforced RPC (SFRPC) with 2% and 5% volumetric fractions of steel fiber, and hybrid fiber reinforced RPC (SPFRPC) with 0.2% polypropylene (PP) fiber and 2% steel fiber were characterized at high strain rate of 72–317 s^{-1}. The characteristics of wave transmission, dynamic compressive strength, compressive deformation, energy absorption ability, and dynamic increase factor (DIF) of RPC under high strain rate impact were systematically investigated. Results revealed that the dynamic compressive strength of PRPC was more sensitive than that of SFRPC. With the addition of 0.2% PP fiber, the dynamic compressive strength of SFRPC exhibited a slight decrease. The critical strain increased with increasing strain rate. In all cases of RPC, the critical damage variable decreased with increasing fiber content subjected to same strain rate impact. The energy absorption of RPC increased with increasing content of steel fiber, which was found to be higher than normal strength concrete and high strength concrete. It was observed that application of CEB formula to calculate DIF of RPC was not safe. Thus, an empirical formula for DIF of RPC was proposed based on test data of this study and existing literature results.

1. Introduction

Reactive powder concrete (RPC) is a type of cement-based material with ultra-high strength, excellent durability, and high fracture capacity, which is one of the primary used ultra-high performance concrete (UHPC). Compared to normal strength concrete (NSC) and high strength concrete (HSC), RPC exhibits excellent mechanical properties attributed to the utilization of some novel technologies including removal of coarse aggregates, mixing of cementitious materials, and addition of fibers [1]. RPC shows a great application potential in nuclear facilities, military engineering, long-span bridges and high-rise buildings, etc. [2]. As a consequence, RPC has gained increasing attention in both academic and engineering areas. In the last few decades, a variety of researchers have paid their interests in investigating the mechanical properties of RPC [3–9].

It is of critical importance to make the behavior of RPC at high strain rate clear for its application and popularization. Available test data on the performance and application of RPC mainly focused on its static behavior, while experimental studies and theoretical analyses on its dynamic mechanical properties are still limited [10–17] and require a lot more systematic explorations.

Ren et al. [10] conducted dynamic compression tests on steel fiber-reinforced RPC (SFRPC) using a split Hopkinson pressure bar (SHPB) apparatus with 74 mm diameter. The dynamic behaviors of RPC containing 2.0% steel fibers in volume were studied at the strain rates of $1–10^2\ s^{-1}$. Results revealed the absence of an obvious strain rate effect on the dynamic compressive properties of RPC. Based on SHPB tests, Wang et al. [11] investigated effects of the strain rate and hydrostatic stress on the dynamic compressive strength of RPC with steel fiber volumes of 0%, 1.5%, and 2.0% when the strain rate was 40–145 s^{-1}. The SHPB test was performed by Rong et al. [12] on UHPC specimens containing 0, 3%, and 4% steel fibers in volume at the strain rate ranging from 25.9 to 93.4 s^{-1}. Results indicated that the impact resistance capacity of UHPC improved with increasing steel fiber content.

Zhang et al. [13] conducted test on UHPC with steel fiber volumes of 0, 1%, 2%, 3%, and 4% at the strain rate ranging from 10 to 114.7 s^{-1} using SHPB apparatus. Test results showed that UHPC obviously presented an enhancement in the dynamic strength. The peak stress increased rapidly with increasing strain rate. Addition of steel fibers improved the static strength, dynamic strength, and energy absorption

* Corresponding author at: Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China.
E-mail address: houxiaomeng@gmail.com (X. Hou).

https://doi.org/10.1016/j.engstruct.2018.05.036
Received 21 October 2017; Received in revised form 9 May 2018; Accepted 12 May 2018
0141-0296/

ability. Jiao et al. [14] studied the impact behavior of three types of RPC with steel fiber volume fractions of 0%, 3%, and 4% using SHPB apparatus at the strain rate of 30–95 s^{-1}. Results indicated that the strain rate sensitivity threshold value was 50 s^{-1}. Moreover, the dynamic increase factor (DIF) of compressive strength for SFRPC was smaller than that for plain RPC (PRPC).

Ju et al. [15] reported the mechanical performances of RPC with five steel fiber volumetric fractions of 0, 1%, 1.5%, 2%, and 3% respectively under the strain rates of 20–105 s^{-1} by SHPB apparatus. Results revealed that under a constant strain rate, the dynamic compressive strength increased with increasing fiber proportion when the fiber volume fraction was less than 1.75%. In contrast, the dynamic compressive strength had a tendency to decrease with increasing fiber volume beyond 1.75%. For the comprehensive understanding of dynamic behaviors of UHPC, SHPB tests were conducted by Su et al. [16]. Effects of nanomaterials on performances of UHPC were evaluated through comparison. The values of DIF for both the compressive strength and tensile strength were generated. Results showed that the strength of UHPC increased with increasing strain rate.

Nevertheless, it is noted from previous researches that there is still a lack of comprehension of dynamic performances of RPC involving higher strain rate. In the first place, the existing researches related to SHPB tests performed on RPC focused more on the dynamic behaviors of RPC at strain rates of 10–100 s^{-1}, while the strain rate produced by explosion is usually in the range of 10^1–10^3 s^{-1}. Therefore, it is necessary to make certain whether RPC samples meet with the similar regularity of the dynamic properties when subjected to strain-rate overrides 10^2 s^{-1}. Tai et al. [17] studied the dynamic compressive strength and stress–strain response of RPC containing steel fibers in 0, 1%, 2%, and 3% volume fraction under impact of strain rates within 78.5–1.23×10^3 s^{-1}. However, existing literatures do not provide enough information on energy absorption efficiency, which is one of the most important factors to evaluate the impact resistance of RPC with different fiber types and contents. Moreover, a typical DIF formula suitable for different types of RPC at a wider range of strain rate has not been proposed yet.

To overcome some of the above mentioned current limitations, a series of SHPB tests performed on RPC cylindrical specimens without fibers, with steel fibers in 0, 2%, and 5% volume fraction, and with hybrid fibers containing 0.2% polypropylene (PP) fiber and 2% steel fiber in volume was conducted at high strain rates of 72–317 s^{-1}. The characteristics of wave transmission, dynamic compressive strength, compressive deformation, damage level, energy absorption, and DIF of RPC under impact were systematically investigated. The effects of strain rate and fiber contents and types on the dynamic properties of RPC are underlined. This study attempts to provide a better approach for understanding the dynamic performance of RPC subjected to impact with high strain rate overriding 10^2 s^{-1}, which would accelerate the application and popularization of RPC.

2. Specimen preparation

The ingredients and mixing ratio of RPC specimens for both static and dynamic tests are listed in Table 1. Ordinary Portland cement (OPC) with strength grade of 42.5, fine quartz sand with diameter of 0.18–0.6 mm and the SiO_2 content of more than 99.6%, and silica fume (SF) with diameter ranging from 0.1 to 0.2 μm and the SiO_2 content of 95% were used in this study. Details of chemical contents of cement, silica fume, and ground granulated blast furnace slag (GGBS) are listed in Table 2. Brass-coated steel fibers with diameter of 0.22 mm and length of 13 mm on an average were incorporated to improve mechanical strength of RPC. The elastic modulus and tensile strength of steel fibers were 200 GPa and 2250 MPa, respectively. Besides, PP fibers with average diameter of 45 μm and length of 18–20 mm were used. The elastic modulus and tensile strength of the PP fibers were 3.85 GPa and 500 MPa, respectively. The PP fibers had a density of 0.91 g cm^{-2} and melting point of 165 °C. Particle size analysis on raw materials of RPC including cement, slag, and silica fume was operated using Laser Particle Size Analyzers by dry method. The particle size distributions of the raw materials of RPC are shown in Table 3.

Table 1
Mixing proportion of RPC.

Specimen	Binders (kg/m^3)			Quartz sand (kg/m^3)	Superplasticizer (kg/m^3)	Water (kg/m^3)
	OPC	SF	GGBS			
RPC	800.5	240.2	120.1	960.6	46.4	232.2

Table 2
Details of chemical contents of cement, silica fume and slag (%).

Binders	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
OPC	21.40	5.45	3.50	64.48	1.46
SF	94.50	0.50	0.45	0.60	0.70
GGBS	34.90	14.66	1.36	37.57	9.13

RPC specimens were produced by the following procedure. First, cement, quartz sand, silica fume, and slag were mixed for 3 min in a designated mixing ratio mentioned in Table 1. Then, water and superplasticizer were added and mixed for 6 min. Further, fibers (steel fibers or PP fibers) were mixed and stirred uniformly (only for the fiber-reinforced RPC) and mixed for another 6 min. Finally, the mixture was poured into a cubic mold with the side length of 100 mm and vibrated. The so-obtained RPC samples were first cured at ambient temperature for 24 h and then cured under 90 °C heated vapor for additional three days.

RPC samples were trimmed to specific dimension to meet the requirements of SHPB tests. 12 RPC cylindrical samples with the size of Φ36 mm × 36 mm (diameter by length) were divided into three groups on an average for quasi-static test, and 102 RPC cylindrical samples with the size of Φ36 mm × 17.5 mm were prepared for the dynamic compression test.

3. Quasi-static compression experiments

For comparative analysis, 12 RPC cylindrical specimens were tested under the condition of uniaxial stress to obtain their static compressive strength. Specimen design and test results which provide a baseline level for the dynamic compressive strength are listed in Table 4. The dimension of RPC samples in quasi-static compression tests was Φ36 mm × 36 mm (diameter by length). The coefficients of variation (COV) of static compressive strength for Φ36 mm × 36 mm specimens are presented in Table 4.

Table 4 summarizes that the static compressive strength of RPC increases with increasing content of steel fiber. The static compressive strength of SFRPC2 and SFRPC5, compared to PRPC, increases by 26% and 46%, respectively. This is attributed to the fact that the crisscrossed network structures of steel fibers restrain the lateral deformation and delay the generation and expansion of lateral cracks in RPC specimens. The bonding between RPC matrix and steel fiber is tight, and the transition region is dense and integral. Therefore, the existence of steel fiber can obviously lead to improvement of the RPC compressive strength, and the same conclusion was reported by El-Dieb [18].

The comparative analysis of the test results of SFRPC2 and SPFRPC indicates that after the addition of PP fiber, compressive strength of RPC specimens gets reduced, which is in well agreement with the research of Aydın et al. [19]. This is ascribed to the low elastic modulus of PP fiber [20].