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Effects of steel fiber and strain rate on the dynamic compressive stress-strain relationship in reactive powder concrete

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HIGHLIGHTS

- A damage-softening statistical constitutive model for SFRPC is proposed.
- With a constant steel fiber content, E_d/E_s increases with increasing strain rate.
- Given same strain rate, E_d/E_s decreases with increasing steel fiber content.

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ABSTRACT

Three types of steel fiber-reinforced reactive powder concrete (SFRPC) with steel fiber contents of 0%, 2%, and 5% by volume are tested under dynamic compression by using a 40-mm-diameter split Hopkinson pressure bar (SHPB) apparatus. Data from SHPB experiments are employed to analyze the influence of critical parameters on the dynamic compressive stress-strain relationship of SFRPC at high strain rates. Test results show that steel fiber has a significant effect on the stress-strain relationship and energy absorption of RPC. Peak strain and peak stress increase with the increasing steel fiber content at the identical strain rates. A dynamic compressive damage-softening model for SFRPC at high strain rates is put forward on the basis of the Weibull distribution of SFRPC strength. A theoretical formula for E_d was established in order to ascertain E_d for the proposed constitutive model. The ratio of E_d to static elastic modulus E_s increases with increasing strain rate and decreasing steel fiber content. The proposed constitutive model captures the dynamic compressive stress-strain relationship of SFRPC, and theoretical results are in agreement with measured data.

1. Introduction

Reactive powder concrete (RPC) is a kind of cementitious composite material, which is one of the primary used ultra-high performance concrete (UHPC) [1]. Compared with normal strength concrete (NSC), high strength concrete (HSC), and high performance concrete (HPC), technologies such as removing coarse aggregates, mixing active fly ash, adding fibers, and curing under particular pressure and high temperature are utilized. RPC has an ultra-high strength, high fracture capacity, and excellent durability [2–5]. Adding steel fiber to the RPC matrix yields steel fiber-reinforced RPC (SFRPC).

Strain rate is applied to characterize the deformation speed of material. Different materials exhibit different mechanical responses with the change of strain rate [6]. Strain rate can be classified according to its amplitude: low strain rates (10^{-5}–10^{-2} s^{-1}), intermediate strain rates (10^{-1}–10^{2} s^{-1}), and high strain rates (10^{2}–10^{4} s^{-1}) [6,7]. Comparison of failure modes between plain RPC and SFRPC with 5% steel fiber at the strain rate of 100 s^{-1} is illustrated in Fig. 1. It is obvious by comparing Fig. 1(a) and Fig. 1(b) that steel fiber can significantly improve the dynamic performances of RPC.

Understanding the mechanical performance of RPC under high strain rates is of critical importance to its application and popularization [8]. As a consequence, RPC has gained notoriety in both the academic and engineering fields. Test results on the dynamic properties of RPC are limited [9–18]. Wang et al. [9] studied the effect of hydrostatic stress and strain rates on the dynamic strength of RPC with different steel fiber volumes of 0%, 1.5%, and 2.0% at strain

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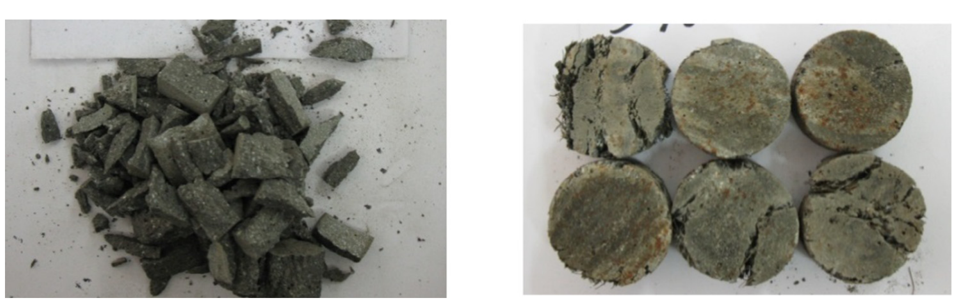
Nomenclature

V_f	the volume fraction of steel fiber	η	the energy absorption efficiency parameter
σ_s	the average axial stress	σ_{max}	the maximum stress at the strain ranging from 0 to ε
E_b	the elastic modulus	D	the cumulative probability parameter (namely damage variable)
A_s	the sectional area of RPC samples	A_c	the area of discontinuities
A_b	the sectional area of Hopkinson bars	A_0	the area of cross-section
ε_s	the calculated average axial strain	n	the number of broken elements
L_s	the original length of RPC specimen	N	the number of total elements
c	the wave pulse velocity	E_d	dynamic elastic modulus
ε_R	axial strain of the reflected pulse	ε	the strain of the surviving SFRPC
ε_T	transmitted pulse	a, b	the point of $0.4\sigma_m$ and $0.6\sigma_m$ in the stress-strain curve
ε_f	final ultimate strain	m	the shape parameter of Weibull distribution parameter
ε_m	the peak strain	F_0	the scale parameter of Weibull distribution parameter
$\dot{\varepsilon}$	the strain rate	C_n	one of Weibull distribution parameter
$\bar{\dot{\varepsilon}}$	the average strain rate for each RPC specimen group	E_s	the static elastic modulus
σ_m	the peak stress		
W	the energy absorption		

rates ranging from 40 s^{-1} to 145 s^{-1} using a split Hopkinson pressure bar (SHPB) apparatus. The cylindrical samples with 50 mm in diameter and 25 mm in thickness are obtained by mechanical drilling, cutting and grinding and used to impact test. The stress-strain behaviors of RPC with multiple steel fibers at various strain rates were obtained. Ren et al. [10] conducted dynamic compression tests for SFRPC samples with 60 mm in diameter and 30 mm in thickness by using a 74-mm-diameter SHPB apparatus. The dynamic behavior of SFRPC containing 2.0% steel fibers by volume was investigated at strain rates ranging from 1 s^{-1} to 100 s^{-1}. Results show that with increasing strain rate, dynamic compressive strength, strain, and elastic modulus increase. Rong et al. [11] investigated the dynamic compressive property of UHPC. The SHPB test was performed on specimens with 0.0%, 3.0%, and 4.0% steel fibers by volume and with 70 mm in diameter and 35 mm in thickness at strain rates between 25.9 s^{-1} and 93.4 s^{-1}. Results show that with increasing steel fiber content, the impact resistance of UHPC increase. Analysis and design of SFRPC structures under dynamic load are mainly dependent upon the behavior of the dynamic stress-strain relationship. Ju et al. [12] studied the dynamic properties of RPC with five steel fiber contents of 0, 1%, 1.5%, 2%, and 3% respectively and with 56 mm in diameter and 26 mm in thickness at strain rates between 20 s^{-1} and 105 s^{-1}. Four generalized shapes of stress-strain relationships of SFRPC under dynamic compression were proposed. Zhang et al. [13] conducted tests on UHPC with various volume fractions of steel fibers (0, 1%, 2%, 3% and 4%) and with 75 mm in diameter and 35 mm in thickness at the strain rate ranging from 10 s^{-1} to 114.7 s^{-1}. Results showed that UHPC obviously presented a dynamic strength enhancement. The addition of steel fibers improved the static strength, dynamic strength and the energy absorption ability. Jiao et al. [14] studied the impact behavior of three types RPC with steel fiber volume fraction of 0%, 3%, and 4% and with 70 mm in diameter and 35 mm in thickness at the strain rate ranging from 30 s^{-1} to 95 s^{-1}. Results indicated that the strain rate sensitivity threshold value is 50 s^{-1}. Moreover, the DIF of compressive strength for steel fiber reinforced RPC is littler than that of plain RPC. Wang et al. [16] studied the impact behavior of PRPC with 36.5 mm in diameter and 23 mm in thickness at the strain rate ranging from 76 s^{-1} to 138 s^{-1}. Huang et al. [15] and Wang et al. [17] conducted dynamic compression tests for SFRPC samples with 30 mm in diameter and 10 mm in thickness. The dynamic behavior of PRPC and SFRPC containing 2.0% steel fibers was investigated at strain rates ranging from 76 s^{-1} to 200 s^{-1}.

In this paper, all available literatures [9–17] concerning the dynamic compressive properties of steel fiber reinforced RPC and plain RPC at high strain rates have been reviewed extensively. Stress-strain relationship underlies analysis and simulation of the dynamic responses of RPC structures [12]. All these literatures related to RPC compression impact tests had paid attention to dynamic stress-strain curves of RPC under varying strain rates. Failure patterns of RPC with varying steel fiber content under impact tests had been reported by some of these researchers [9–14]. As an important variable and a reflection of dynamic property of RPC, the dynamic increase factors (DIFs) of RPC compressive strength were commonly investigated [9,10,13–17]. Nevertheless, there is seldom efficient stress-strain model for the dynamic compressive properties of SFRPC at high strain rates to make these test results applicable to finite element analysis.

Based on test results, Ju et al. [12] proposed four basic models for stress-strain relationship of RPC by taking account of the effect of strain rate and steel fiber content. These models are multi-lined



a) Plain RPC b) SFRPC(5% steel fiber)

Fig. 1. Failure modes of RPC at strain rate of 100 s^{-1}.