Research Article

Journal of Applied Material Science & Engineering Research

Dynamic Constitutive Model for Reactive Powder Concrete with Standard Curing

B Sun* and C J Jiao

School of Civil Engineering, Guangzhou University, No. 230, Outer Ring West Road, Panyu District, Guangzhou 510006, China

***Corresponding author**
B Sun, School of Civil Engineering, Guangzhou University, No. 230, Outer Ring West Road, Panyu District, Guangzhou 510006, China, E-mail: sunbeimlj@126.com

Submitted: 23 Jan 2018; **Accepted**: 31 Jan 2018; **Published**: 10 Feb 2018

Abstract
In view of the disadvantages of steam curing of reactive powder concrete (RPC), RPC with standard curing (SC-RPC) is proposed. SC-RPC is an ultra-high strength concrete material prepared with high strength cement, silica fume, and gypsum by standard curing. In this study, quasi-static and impact compression tests were performed to investigate the mechanical properties of SC-RPC. The results show that steel fiber and the strain rate significantly affect the compression performance. Nevertheless, the Holmquist–Johnson–Cook (HJC) constitutive model is mainly used to analyze the dynamic response of brittle materials, such as common concrete, under shock and impact. Therefore, based on the quasi-staticand impact compression tests and the HJC constitutive model for concrete, by analyzing the steel fiber strengthening effect under quasi-static uniaxial compression, strain rate hardening, and the damage softening effect under SHPB impact compression, the steel fiber strengthening factor K_f, dynamic increase factor DIF, and revised damage variable D are introduced, and a modified HJC constitutive model for RPC with standard curing is proposed.

Keywords: Standard curing, Reactive powder concrete, Dynamic constitutive model, Steel fibers, Strain rate

Introduction
Reactive powder concrete (RPC) is a cement-based material developed by the French Bouygues Company in the 1990s that has ultra-high strength, high toughness, high durability, and wide application prospects. From research of RPC, the drawbacks of steam curing and the knock-on effects, such as high costs, restrict application of RPC [1]. To meet the requirements of construction industry development and overcome the disadvantages of RPC, RPC with standard curing (SC-RPC) has been proposed, which removes the need for steaming equipment, pre-fabrication and its production equipment investment, and transportation costs, reducing the production costs. Thus, research on SC-RPC will overcome the technology bottlenecks of steam curing. Research on the mechanical properties and development of a constitutive model for SC-RPC under dynamic loading will benefit its application and popularization in civil engineering.

Research on the dynamic mechanical properties of concrete materials began in the 1980s, but strain rate characterization of the dynamic mechanical properties was narrow because of the limitations of the test machines. For example, Menzies, et al., Takeda, et al. and Dong, et al. investigated the dynamic mechanical properties of concrete using a hydraulic system testing machine, where the strain rate was generally not more than 10^{-1} s^{-1} [2-4]. Hughes, et al. and Watstein performed the dynamic mechanical test by the dropping hammer method and the strain rate improved to $10^{0}s^{-1}$ [5,6]. With introduction of the split Hopkinson pressure bar (SHPB), the strain rate improves to 10^{1}–10^{2} s^{-1}, which has greatly promoted research on the dynamic mechanical properties of concrete [7-10]. Dynamic constitutive models related to the strain rate have been proposed, for example, the Kelven, Maxwell, and Zhu–Wang–Tang (ZWT) viscoelastic models, the widely used Perzyna consistent viscous-plastic model, the Drucker–Prager viscous-plastic model, and the Holmquist–Johnson-Cook (HJC), RHT, and TCK dynamic constitutive models based on damage theory [11-13]. Although the HJC model shows the best performance for simulation of the mechanical properties of concrete materials under impact compression conditions, this area has not been extensively investigated. Most studies have investigated brittle materials, such as common concrete, or ignored the effect of the strain rate. For example, Cao established the HJC model for SFRC where larger aggregates increase the experimental error. Ren, et al. and Li simulated $C60V_0$ series concretes by SHPB compressive tests ignoring the strengthening effect of the steel fibers. Similarly, Polanco-Loria, et al. proposed the modified HJC modelbut did not consider the effect of steel fibers. Wang, et al. simulated the impact mechanical properties of RPC, but only the effect of a single strain rate on the compressive strength was considered [14-18].

In this study, the influence of steel fibers and the strain rate on the compressive strength of SC-RPCwas investigated by quasi-static and impact compression tests. Based on damage theory and the original HJC dynamic constitutive model, by decoupling the strain rate hardening effect and damage softening effect, the steel fiber strengthening factor, dynamic increase factor , and revised damage variable were considered, and a modified HJC constitutive model for SC-RPC is proposed.

Experimental materials and methods

After removing the coarse aggregates, SC-RPC includes ordinary Portland cement (density 3150 kg/m^3, specific surface area 448 m^2/kg), a high strength admixture with a specific surface area of 13,050 m^2/kg, silicon sand in the size range 40–300 mesh, quartz sand with fineness modulus of 2.4, steel fibers (density 7800 kg/m^3, length 15 mm, diameter 0.22 mm), and polycarboxylic water-reducing agent powder. The mix proportions of SC-RPCV$_0$ are given in Table 1.

SC-RPC with steel fiber volume fractions of 0%, 1%, 2%, 3%, 4%, and 5% were selected for the mechanical tests, which are called SC-RPCV$_0$, SC-RPCV$_1$, SC-RPCV$_2$, SC-RPCV$_3$, SC-RPCV$_4$, and SC-RPCV$_5$, respectively. The SC-RPC samples were molded by casting. After casting, the specimens were kept in a curing room at 20 and 100% RH for 90 days before the mechanical tests.The quasi-static uniaxial compressive tests were performed using 100 mm × 100 mm × 300 mm prism specimens using a servo-controlled MTS test machine (Matest Company, Treviolo, Italy) with a capacity of 500 kN. The impact compression tests were performedfor cylindrical specimens with a diameter of 70 mm and a thickness of 35 mm using the SHPB setup with 74 mm diameter. Fig. 1 shows the SHPBsetup of impact compression used in the tests. It is composed of three parts: (1) a velocity testing system, (2) an intelligent measuring analyzer, and (3) a data acquisition system.

Table 1: Mix proportions of SC-RPCV$_0$ (kg/m^3).

Cement	High strength admixture	Silicon sand	Quartzes sand	Water	Water-reducing agent
977	246	747	271	220.2	7.34

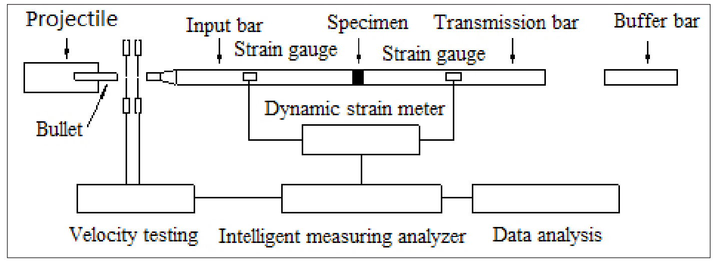


Figure 1: Schematic diagram of the SHPB experimental setup.

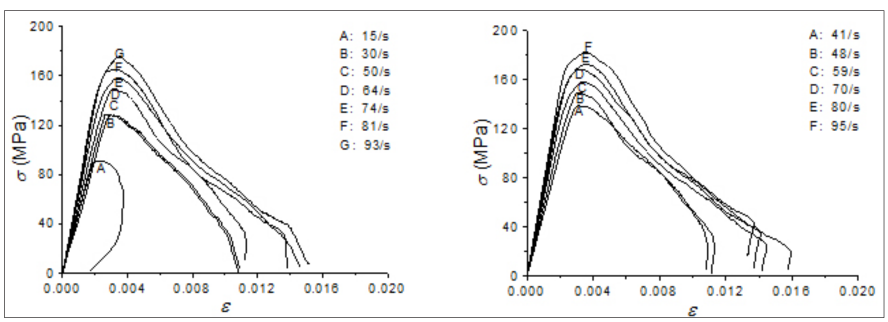
Experimental mechanical properties

In the concrete structure design code, the axial compression strength is an important factor to determine the bearing capacity of the component. Table 2 shows the axial compressive strengths of SC-RPC with fiber volume fractions of 0%, 1%, 2%, 3%, 4%, and 5% from quasi-static uniaxial compression tests. The results indicate that addition of steel fibers significantly increases the SC-RPC axial compressive strength.

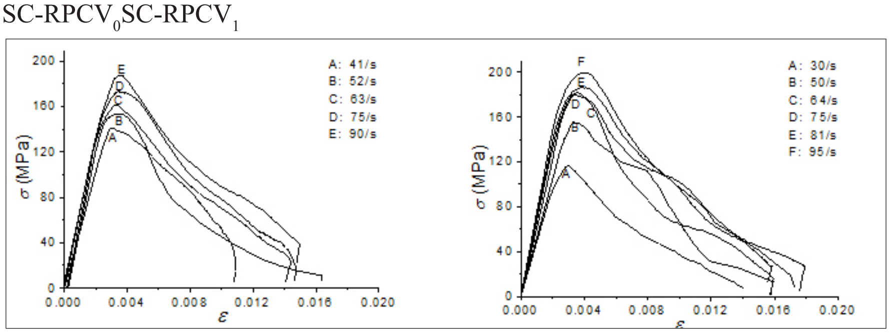
Table 2: Axial compressive strengths of the SC-RPC samples.

No.	Axial compressive strength (MPa)	No.	Axial compressive strength (MPa)
SC-RPCV$_0$	83.13	SC-RPCV$_3$	116.80
SC-RPCV$_1$	101.25	SC-RPCV$_4$	121.70
SC-RPCV$_2$	110.91	SC-RPCV$_5$	125.43

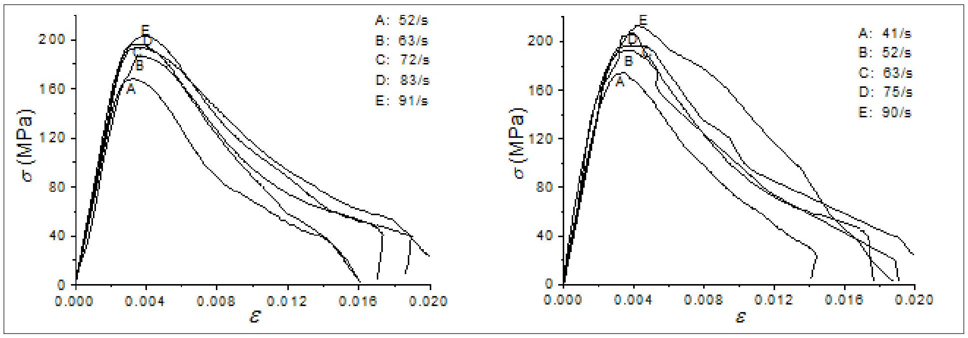
The impact compression tests of all of the SC-RPC specimens were performed with the SHPB setup, and dynamic stress–strain curves at different strain rates were obtained. As examples, Fig. 2 shows the change of the dynamic stress–strain curves with the impact strain rate for SC-RPC specimens. There is a noticeable increase in the strain corresponding to the peak stress and a significant increase in the ductility, as described by the descending portion of the stress–strain curve.



SC-RPCV$_0$SC-RPCV$_1$



SC-RPCV$_2$SC-RPCV$_3$



SC-RPCV$_4$SC-RPCV$_5$

Figure 2: Stress-strain curves of SC-RPCV$_0$ and SC-RPCV$_4$.

Modified HJC dynamic constitutive model

Original HJC model analysis

The HJC constitutive model is a damage constitutive model related to the strain rate based on the Ottosen model [19]. It was originally developed for impact calculations of concrete where the material experiences large strains, high strain rates, and high pressures [19]. In the HJC model, the equivalent yield pressure is related to the stress, strain rate, and damage. The pressure is a function of the volume strain. The damage accumulation is the function of the pressure, equivalent plastic strain, and plastic volumetric strain. The HJC model includes the yield surface equation, state equation, and damage evolution equation. Here, only the yield surface equation and damage evolution equation are involved.

In the HJC model, the yield surface equation is expressed as

$$\sigma^* = [A(1-D) + Bp^{*N}][1 + C\ln(\dot{\varepsilon}^*)] \le S_{\max} \tag{1a}$$

$$\begin{cases} \sigma^* = \sigma_{eq}/f_c \\ p^* = p/f_c \end{cases} \tag{1b}$$

$$\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0 \tag{1c}$$

Where σ*is the normalized equivalent stress, p* is the normalized pressure, σeq is the equivalent stress, p is the hydrostatic pressure, $\dot{\varepsilon}^*$is the normalized strain rate, is the equivalent deviatoric strain rate, and D is the damage variable. The quasi-static compressive strength fc and reference strain rate $\dot{\varepsilon}_0$ = 1 s^{-1} are the normalizing parameters. In addition, A is the cohesion parameter, B is the pressure hardening coefficient, C is the strain rate sensitivity coefficient, N is the pressure hardening exponent, and S_{max} is the normalized maximum strength.

In the HJC model, the damage is described by the accumulation of the equivalent plastic strain and plastic volumetric strain, and the damage variable D increases with increasing plastic strain accumulation. The damage evolution is expressed as

$$D = \sum \frac{\Delta\varepsilon_p + \Delta\mu_p}{\varepsilon_p^f + \mu_p^f} \tag{2a}$$

$$f(P) = \varepsilon_p^f + \mu_p^f = D_1(P^* + T^*)^{D_2} \tag{2b}$$

$$T^* = T / f_c \tag{2c}$$

where $\Delta\varepsilon_p$ is the equivalent plastic strain increment, $\Delta\mu_p$ is the equivalent plastic volumetric strain increment, ε^f_p is the equivalent plastic strain to fracture, μ^f_p is the equivalent plastic volumetric strain to fracture, T is the maximum hydrostatic tension, T* is the normalized hydrostatic tension, and D_1 and D_2 are the concrete damage constants.

The HJC model can reflect the dynamic response of concrete, namely, the damage, cracking, failure, and so forth when the material experiences large strains, high strain rates, and high pressures. However, it is only suitable for brittle materials, such as common concrete. From the results of quasi-static and impact compression tests of SC-RPC, the steel fiber strengthening effect, strain rate hardening effect, and damage softening effect are significant. However, these three mechanisms are not included in the original HJC model. Therefore, it is necessary to take these three mechanisms into account and develop a modified HJCmodel suitable for SC-RPC.

Parameters of the HJC model

Steel fiber strengthening effect

In the strength equation of the HJC model, the stress and pressure are the ratios of the actual equivalent stress and hydrostatic pressure to the quasi-static compressive strength f_c, respectively. Therefore, the accuracy of f_c in the quasi-static uniaxial compression test is particularly important. According to the results of the quasi-static compression tests of SC-RPC and previous results, V_f and l_f/d_f can increase the quasi-static compressive strength of SC-RPC. The product of Vf and lf/df is defined as the steel fiber characteristic parameter $V_f l_f/d_f$. The steel fiber strengthening factor K_f is introduced to describe the strengthening effect of steel fibers:

$$K_f = \frac{f_c}{f_{c0}} - 1 \tag{3}$$

Where f_c is the quasi-static compressive strength of the SC-RPC specimenmixed with steel fibers and f_{c0} is the quasi-static compressive strength of the SC-RPCV$_0$ specimen.

Fig. 3 shows the relationships between K_f and $V_f l_f/d_f$ for the SC-RPC specimens tested with quasi-static compression. K_f initially rapidly increases and then gradually increases with increasing $V_f l_f/d_f$. By fitting to the experimental data of K_f and $V_f l_f/d_f$, the strengthening equation of the K_f can be expressed as

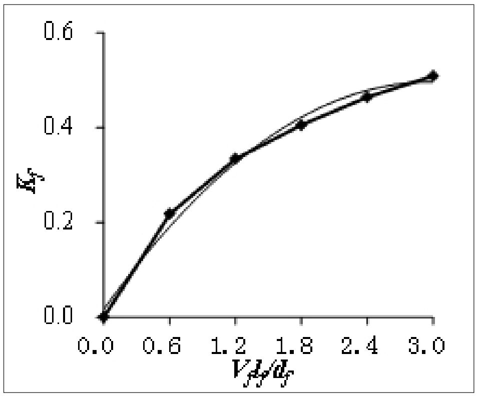


Figure 3: Relationship between Kf and Vflf/df.

$$K_f = -0.0543\left(\frac{V_f l_f}{d_f}\right)^2 + 0.3226\frac{V_f l_f}{d_f} + 0.017 \tag{4}$$

Strain rate hardening effect

The HJC constitutive model shows the influence of the strain rate on the strength. The strain-rate sensitivity coefficient C is less than 0.01, namely, the effect of the strain rate on the strength can be ignored. However, the dynamic stress–strain curves of SC-RPC show that the peak stress rapidly increases with increasing dynamic strain rate. The variation in the peak stress with the strain rate can be described using the dynamic increase factor (DIF), which is defined as the ratio of the peak stress of the dynamic stress–strain curve to the quasi-static compression strength. Thus, the DIF is defined as

$$DIF = \sigma_d / \sigma_s \tag{5}$$

Where σ_d and σ_s are the dynamic compressive strength and quasi-static compression strength, respectively.

The variation of the DIF of SC-RPC under different dynamic strain rates and the logarithm of the strain rate log $\dot{\varepsilon}$ are shown in Fig. 4. The DIFof SC-RPC rapidly increases with increasing strain rate, which verifies the strain rate hardening effect of steel fiber reinforced concrete. There is a difference between SC-RPCV_0 and SC-RPC mixed with steel fibers: the increasing rate of the DIFof SC-RPCV_0 is slightly greater than that of SC-RPC mixed with steel fibers. However, the increasing rates of DIFof SC-RPC mixed with different steel fiber contents are similar. The same phenomenon was found by Lok et al. using SHPB to investigate the dynamic behaviour of SFRC. This can be explained by the following two factors [20]. First, when the SC-RPC specimen is subjected to impact loading, the dynamic strength increasing rate of the material increases with increasing specimen brittleness. SC-RPCV_0 is brittle whereas SC-RPC mixed with steel fibers is ductile. Second, the strain rate hardening effect of steel fibers is not significant, and the strain rate hardening effect of SC-RPC decreases after mixing. Therefore, the DIF of SC-RPCV0 is greater than that of SC-RPC mixed with steel fibers.

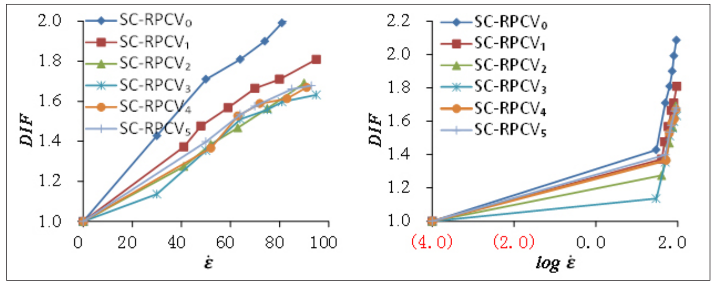


Figure 4: Relationships between the DIF and $\dot{\varepsilon}$ and log $\dot{\varepsilon}$.

From the relationship between the DIF and log $\dot{\varepsilon}$, there is a threshold value of the strain rate sensitivity. When the strain rate is less than the threshold value, the DIF of SC-RPC gradually increases with increasing log $\dot{\varepsilon}$. Conversely, when the strain rate is greater than the threshold value, the DIF of SC-RPC rapidly increases, which is known as the strain rate hardening effect. A similar phenomenon was reported by Ross using SHPB to investigate the dynamic behaviour of C40 concrete, where the dynamic compressive strength linearly increased with increasing log $\dot{\varepsilon}$ when the strain rate was greater than a certain value [21]. By fitting to the experimental data of DIF and log $\dot{\varepsilon}$, the relationship between DIF and log $\dot{\varepsilon}$ can be expressed as

$$DIF = a \lg \dot{\varepsilon} + b \tag{6}$$

In Eq. (6), it is assumed that theparameters a andb are only related to $V_f l_f/d_f$. According to the DIFand log $\dot{\varepsilon}$ values of SC-RPC, the relationships between a, b, and $V_f l_f/d_f$ obtained by fittingcan be expressed as

$$a = -0.0573\frac{V_f l_f}{d_f} + 1.2472 \quad b = 0.012\frac{V_f l_f}{d_f} - 0.5397 \tag{7}$$

Damage softening effect

Damage softening is the weakening of the macroscale mechanical properties of SC-RPC materials under impact compression, which the complex damage caused by crack initiation and growth on the surface and inside the material, interlayer glide, steel fibers being pulled out, and so forth.

Concrete materials are considered to be composed of many microscale units. Under external loading, the internal concrete units will undergo different degrees of damage. Continuous damage accumulation of the microscale units leads to deterioration of the concrete at the macroscale. The damage degree of SC-RPC can be described using damage variable D, which is related to the defect quantity of each microscale unit.

Xu et al. found that the nonlinear behavior in the stress–strain curve of a Kevlar fiber reinforced composite can be well described by the Weibull distribution [22]. It is assumed that the strength of the microscale units of SC-RPC obeys the Weibull distribution. Thus, the probability function of the strain $\varphi(\varepsilon)$, which represents the internal damage of each micro unit of concrete, can be expressed as

$$\varphi(\varepsilon) = \frac{m}{\alpha}\left(\frac{\varepsilon - \varepsilon^*}{\alpha}\right)^{m-1} \exp\left[-\left(\frac{\varepsilon - \varepsilon^*}{\alpha}\right)^m\right] \tag{8}$$

Where ε is the strain, α is a parameter related to the strain rate, m is the strain rate coefficient, and ε* is the threshold strain, which represents the beginning of damage accumulation and generally ε* is equal to 0.7 times the peak strain. When $\varepsilon \le \varepsilon^*$, D = 0 and it is considered that no damage occurs inside the concrete.

Owing to the randomness of the microscale unit damage, D can be expressed as

$$D=\int_0^{\varepsilon}\varphi(\varepsilon)\,dx=1-\exp\left[-\left(\frac{\varepsilon-\varepsilon^*}{\alpha}\right)^m\right] \quad (9)$$

Based on fitting to the experimental data of SC-RPC from quasi-static and impact compression tests, the parameters α and m can be determined. It is assumed that αand mare only related to $V_f l_f/d_f$. The fitting curves and relationships between α, m, and $V_f l_f/d_f$ obtained by fitting (Fig. 5) can be expressed as

$$\begin{cases} m=-0.7078\dfrac{V_f l_f}{d_f}+4.0384 \\ \alpha=-0.2459\left(\dfrac{V_f l_f}{d_f}\right)^2+0.7297\dfrac{V_f l_f}{d_f}+1.1622 \end{cases} \quad (10)$$

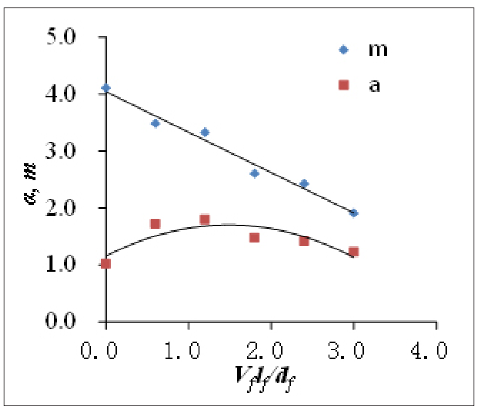


Figure 5: Relationships between α, m, and $V_f l_f/d_f$.

Modified HJC dynamic constitutive model

K_f, the DIF, and revised damage variable D are introduced into the original HJC model. Thus, by rewriting the yield surface (Eq. (1)), we propose a modified HJC model for SC-RPC:

$$\sigma^*=\underbrace{(1+K_f)}_{\text{Steel fiber's strengthening effect}}\underbrace{\left\{A\exp\left[-\left(\frac{\varepsilon-\varepsilon^*}{\alpha}\right)^m\right]+Bp^{*N}\right\}}_{\text{Damage softening effect}}\underbrace{[a\lg\dot{\varepsilon}+b]}_{\text{Strain rate hardening effect}}$$

The yield surface equation in the modified HJC model includes three parts: the steel fiber strengthening effect, the strain rate hardening effect, and the damage softening effect.

Conclusions

The mechanical properties of SC-RPC under quasi-static and impact compression have been investigated, and the constitutive model for SC-RPC is discussed. The main conclusions of this study are as follows.

1. Addition of steel fibers significantly increases the SC-RPC compressive strength under quasi-static uniaxial compression of SC-RPC. Strain rate hardening and the damage softening effect occur under SHPB impact compression of SC-RPC.
2. Based on systematic investigation of the steel fiber strengthening effect under quasi-static uniaxial compression, strain rate hardening, and the damage softening effect underSHPB impact compression of SC-RPC, the relationships of the steel fiber strengthening factor K_f, dynamic increase factor DIF, and revised damage variable D with the steel fiber characteristic parameter $V_f l_f/d_f$ have been determined.
3. Based on damage theory and the original HJC dynamic constitutive model, a modified HJC constitutive model for SC-RPC based on K_f, the DIF, and D is proposed.

Acknowledgments

This study is funded by the National Natural Science Foundation of China (Nos. 51778158, 51478128 and 51278135), the Scientific and Research Developing Project of Ministry of Housing and Urban-Rural Development of China (Nos. 2010-K3-27 and 2010-K4-18), the Guangzhou Government technical innovation key Project (2017-32), and the key technical project and Fostering project of Guangzhou University (40-253101). The authors gratefully acknowledge to the Guangzhou University.

References

1. P Richard and M Cheyrezy (1994) “Reactive powder concretes with high ductility and 200-800 MPa compressive strength.” Aci Special Publication 114: 507-518.
2. JB Menzies and PR Sparks (1973) “The effect of rate of loading upon the static and fatigue strengths of plain concrete in compression.” Magazine of Concrete Research 24: 73-80.
3. J Takeda, H Tachikawa and K Fujimoto (1974) “Mechanical behavior of concrete under higher rate loading than in static test.” Mechanical Behaviour of Materials 2: 479-486.
4. YL Dong, HP Xie and P Zhao (1997) “Experimental study and constitutive model on concrete under compression with different strain rate.” Shuili Xue bao 7: 72-77.
5. BP Hughes and R Gregory (1972) “Concrete subjected to high rates of loading in compression.” Magazine of Concrete Research 24: 25-36.
6. D Watstein (1953) “Effect of straining rate on the compressive strength and elastic properties of concrete.” ACI Materials Journal 49: 729-744.
7. CA Ross, DM Jerome, JW Tedesco and ML Hughes (1996) “Moisture and Strain Rate Effects on Concrete Strength.” ACI Materials Journal 93: 293-300.
8. P Forquin, K Safa and G Gary (2010) “Influence of free water on the quasi-static and dynamic strength of concrete in confined compression tests.” Cement and Concrete Research 40: 321-333.
9. SS Hu, DR Wang and JF Liu (2001) “Experimental study of dynamic mechanical behavior of concrete.” Engineering Mechanics 18: 115-118.
10. Z Cui (2016) Dynamic constitutive model and finite element analysis of steel-PVA hybrid fiber concrete, M.S. thesis, South China University of Technology, Guangzhou, China.
11. FH Zhou, LL Wang and SS Hu (1992) “A damage-modified nonlinear visco-elastic constitutive relation and failure criterion of PMMA at high strain-rates.” Explosion and Shock 4: 47-56.

12. P Perzyna (1966) "Fundamental Problems in Viscoplasticity." Advances in Applied Mechanics 9: 243-377.
13. LM Taylor, EP Chen and JS Kuszmaul (1985) "Microcrack-Induced Damage Accumulation in Brittle Rock under Dynamic Loading." Computer Methods in Applied Mechanics & Engineering 55: 301-320.
14. JX Cao (2011) Dynamic constitutive model of steel fiber reinforced concrete and its finite element method, Ph.D. thesis, Southwest Jiaotong University, Chengdu, China.
15. GM Ren, H Wu, Q Fang, JW Zhou, ZM Gong, (2016) "Determinations of HJC constitutive model parameters for normal strength concrete." Journal of Vibration and Shock 35: 9-16.
16. Y Li (2009) Researches on HJC dynamic constitutive model for concrete, M.S. thesis, Hefei University of Technology, Hefei, China.
17. M Polanco-Loria, OS Hopperstad, T Børvik and T Berstad, (2008) "Numerical predictions of ballistic limits for concrete slabs using a modified version of the HJC concrete model." International Journal of Impact Engineering 35 290-303.
18. YH Wang and YJ Juan, (2007) "Numerical Simulation and Analysis of RPC Material Hopkinson Pressure Bar shock Compression test." Architectural and Structural Design 8: 34-38.
19. TJ Holmquist and GR Johnson, (2011) "A Computational Constitutive Model for Glass Subjected to Large Strains, High Strain Rates and High Pressures." Journal of Applied Mechanics 78: 051003.
20. PJ Zhao, TS Lok and G Lu, (2003) "Using the split Hopkinson pressure bar to investigate the dynamic behaviour of SFRC."Magazine of Concrete Research 55: 183-191.
21. CA Ross, JW Tedesco and ST Kuennen, (1995) "Effects of strain rate on concrete strength." ACI Materials Journal 92: 37-47.
22. SH Xu, XJ Wang, GM Zhang, JW Chen and ZY Zhang, (2001) "Experimental investigation on the dynamic compression properties of Kevlar fiber-rain forced composite laminates." Journal of experimental mechanics 16: 26-33.