Dynamic Compressive Behavior of Concrete with Different Polyvinyl Alcohol Fiber Content

Jun Wu, Guilin Jiang, Zhenghong Tian, Hao Lu and Hengrui Liu

ABSTRACT

The compressive behavior of concrete with different polyvinyl alcohol (PVA) contents and strain rates was studied by using Split Hopkinson Pressure Bar. The result showed that the compressive strength of fiber concrete, peak strain, ultimate strain and specific energy absorption increased with the enhanced strain rate and the raise of fiber content. The simplified constitutive model of fiber-reinforced concrete is proposed, based on the viscoelastic damage theory, which can simulate the relationship effectively between the compressive stress and strain of fiber concrete under impact loading.\(^1\)

INTRODUCTION

The fiber-reinforced cement-based composite materials, which are subjected to the dynamic load, are common engineering materials. Several studies have proved that they have a series of great characteristic such as toughening, strengthening and crack resistance [1-3]. However, the main research about performance of this kind of material is concentrated on carbon fiber and steel fiber under dynamic loading [4-6]. Research on dynamic mechanical properties of PVA cement-based composite is few, and hasn’t got the consistent and credible conclusion [7-8].

In this paper, a simplified nonlinear and viscoelastic constitutive model, based on macroscopic damage factor, is proposed and verified. Moreover, the influence of parameter on the properties of fiber concrete is also analyzed, while there are few,

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theoretical researches about the mechanical properties of fiber-reinforced concrete under impact loading.

EXPERIMENTAL PROGRAM

Specimens Preparation

The materials include the ordinary Portland cement P.O 42.5, the river sand with fineness modulus 2.8 as fine aggregate, portable water, the crushed limestone whose size is from 5mm to 10 mm as coarse aggregate and the high-strength and high-elastic PVA fiber with 42Gpa. The proportion for specimens was Water: Cement: Sand: Gravel= 1:1.91:2.70:4.78. The contents of PVA fiber are 0.6Kg/m3, 1.2Kg/m3, 1.8Kg/m3, 2.4Kg/m3 respectively. Firstly, the specimens are molded by plastic cylinder with 74mm diameter, secondly vibrate fresh concrete until it’s dense, and then cure green concrete under moist environment by covering plastic wrap during 28 days, lastly, cut the specimens into height of 37mm.

Experimental Setup

The SHPB apparatus is given in figure1. It’s composed of three major components: a loading device, the bar components, and the data acquisition system. The specimens are set between the incident bar and transmission bar. The different stress waves [9] are produce by hitting incident bar at the different speeds from bullet which are controlled by air pressure.

![Figure 1. The major components of a compression SHPB apparatus.](image)

The test of Hopkinson bar is based on two assumptions: (1) the equation of one-dimensional stress wave propagation; (2) the propagation of stress wave is axial inside, and the stress distribution is uniform in the specimen. The time histories of strain $\varepsilon(t)$, strain rate $\dot{\varepsilon}(t)$, and stress $\sigma(t)$ in the specimen at any time $t$ can be obtained from the following equations.

$$\sigma_s(t) = E_s \frac{A_4}{A_3} \varepsilon_s(t)$$  \hspace{1cm} (1)

$$\varepsilon_s(t) = \frac{2C_0}{l} \int_0^t \varepsilon_s(t) \, dt$$  \hspace{1cm} (2)
\[ \dot{e} = \frac{dE_e(t)}{dt} \quad (3) \]

Where \( A_h, E_h, C_0 \) are the cross sectional area of Hopkinson bars, the modulus of elasticity of Hopkinson bars and the velocity of wave velocity in Hopkinson bars respectively; \( l \) is the length of specimen. \( A_s \) is the cross sectional area of specimen.

In this paper, the strain rate at the peak stress is taken as the representative value of the strain rate under dynamic loading. Each group of fiber concrete was loaded with five different air pressures such as 0.30MPa, 0.35MPa, 0.40MPa, 0.45MPa and 0.50MPa, and is repeated five times under the same experimental conditions.

RESULTS AND DISCUSSION

Failure Mode

Figure 2 shows the damage pattern in selected test specimens, retrieved after SHPB testing, for different strain rate ranges. The label "0" means plain concrete and the label "P-1.2" means that the specimens were mixed the amount of 1.2Kg/m3 PVA fiber.

![Image of failure modes](image)

Figure 2. Failure modes of concrete specimens under different strain rates.

In general, it can be seen from the figure that the specimen containing more fibers sustain comparatively lower degree of with damage with certain ductile fracture and the degree of damage has increased with the increase of strain rate. The
experimental result shows that the toughness of concrete can be improved by adding fibers, which is beneficial to increasing the resistance of impact loading. When subjected to impact loading, the rising time of internal stress inside concrete is so short that internal cracks can’t extend follow the path with minimum resistance. At this moment, the stress has reached a peak of through the coarse aggregate. According to the law of energy conversation, the deformation resulting from the high-speed impact loading, with the further increase of strain rate, breaks specimen into more fragments to dissipate the external energy [10,11]. Moreover, the bridging effect of fiber inside the concrete can not only restrict crack propagation and its width, but can increase the lateral restraint during the course of damage.

**Stress-Strain Curve**

The stress-strain curves of fiber-reinforced concrete are as shown in Figure 3.

![Stress-Strain Curves](image-url)

Figure 3. Stress-strain curves of concrete in each group.
The slope and strain rate in the ascending phrase of stress-strain curve have a positive correlation from figure 3, and the compressive strength, peak strain and ultimate strain of fiber concrete rise with the increase of strain rate. With the increase of fiber content, the slope and ultimate strain of fiber concrete also have a positive correlation, but the increasing extent is obviously less than the effect of strain rate. In fact, the compressive strength and ultimate strain of fiber concrete are higher than plain concrete.

**Specific Energy Absorption**

Specific energy absorption [12] (SEA), which is expressed as the energy absorbing per unit volume of material, is used to describe dynamic energy absorption property of fiber-reinforced concrete and can be obtained from equation [13] as below:

$$\text{SEA} = \frac{A_p}{A_f} \int_0^t \left[ \dot{\varepsilon}_t(t)^2 - \dot{\varepsilon}_s(t)^2 - \dot{\varepsilon}(t)^2 \right]$$  \hspace{1cm} (4)

The relationship between SEA and strain rate with fiber contents is shown in figure 4.

![Figure 4. Relationship between strain rate and specific energy absorption of fiber.](image)

From the above picture, we can get that the specific energy absorption rises with increase of strain rate, while the increasing extent is getting to decrease. In addition, the specific energy absorption also has a positive correlation with the content of fiber. Due to the free surface on the side of SHPB uniaxial compression specimen, the lateral deformation will occur under the impact loading, and the effect of bridging fiber can delay the propagation of lateral cracks. Therefore, the energy absorption of PVA fiber-reinforced concrete rises gradually with the increase of fiber content, and its SEA is also increasing.
DYNAMIC DAMAGE CONSTITUTIVE MODEL

Constitutive Model

The ZWT constitutive model is composed of a nonlinear spring and two Maxwell bodies with different characteristic times in parallel, the equation as follows.

\[
\sigma_r = E_0 \epsilon + \alpha \epsilon^2 + \beta \epsilon^3 + E_1 \int_0^t \dot{\epsilon} \exp\left(-\frac{t - \tau}{\theta_1}\right) d \tau + E_2 \int_0^t \dot{\epsilon} \exp\left(-\frac{t - \tau}{\theta_2}\right) d \tau
\]  

(5)

Which \(E_0, \alpha\) and \(\beta\) are related elastic constants. Two integral formulas are used to calculate viscoelastic behaviors at low strain rate and high strain rate, respectively. \(E_1\) and \(\theta_1\) are the elastic modulus and characteristic time at low frequent Maxwell body, respectively. \(E_2\) and \(\theta_2\) are the elastic constant and characteristic time at high frequency of Maxwell body, respectively. According to Chen et al [14], the Maxwell unit at low frequency will not have sufficient time to relax on the time scale of 10-6 ~ 10-4s under impact loading, with low frequency Maxwell \(\theta_1\) unit relaxation time will not have sufficient time to relax. So the Maxwell unit at low frequency is translated to the spring with elastic constant \(E_1\), the ZWT equation as follows.

\[
\sigma_r = E_0 \epsilon + \alpha \epsilon^2 + \beta \epsilon^3 + E_1 \int_0^t \dot{\epsilon} \exp\left(-\frac{t - \tau}{\theta_1}\right) d \tau
\]

(6)

Hu [15] improved the constitutive equation by considering the smaller deformation of concrete material, the equation as follows.

\[
\sigma = \sigma_r (1 - D) = (1 - D) \cdot [(E_0 + E_1) \epsilon + E_2 \int_0^t \dot{\epsilon} \exp\left(-\frac{t - \tau}{\theta_2}\right) d \tau] \]

(7)

Where \(\sigma\) is the real stress inside concrete and \(\sigma_r\) is the stress when the concrete material has no damage.

A Simplified-rate Constitutive Model

According to the damage evolution rate of Wang [16], the damage rate can be calculated as follows.

\[
\dot{D}(t) = D_0 |\dot{\epsilon}|^{\delta}
\]

(8)

Integrating time \(t\):

\[
D = D_0 (\dot{\epsilon})^{\delta-1} \epsilon + D_i
\]

(9)
Considering the boundary conditions: 

\[ D|_{\varepsilon=0} = 0 \]  

(10)

So \( D_1 = 0 \), Therefore:

\[ D = D_0 (\dot{\varepsilon})^{\delta-1} \varepsilon \]  

(11)

Due to \( k = \delta - 1 \), then

\[ D = D_0 (\dot{\varepsilon})^k \varepsilon \]  

(12)

Substitute the damage factor \( D \) into eq.7, and considerate the SHPB test is similar to the test with constant strain rate. Therefore the ultimate constitutive equation of dynamic compression as follows.

\[ \sigma = (1 - D_1 \varepsilon) \cdot [E_1 \varepsilon + E_2 \theta_2 (1 - e^{-\frac{\varepsilon}{\theta_2}})] \]  

(13)

Where \( E_3 = E_1 + E_2 \), \( D_c \) is a damage evolution factor; \( E_3 \) is an elastic modulus which is independent of strain rate, \( E_2 \) is an elastic modulus of Maxwell body at high frequency, \( \theta_2 \) is characteristic time. In this paper, the fiber-reinforced concretes with two different contents 1.2Kg/m3 and 2.4Kg/m3 are simulated, and the specific results are shown in table I.

**TABLE I. PARAMETER FITTING RESULTS OF CONCRETE CONSTITUTIVE MODEL OF EACH GROUP.**

<table>
<thead>
<tr>
<th>Group number</th>
<th>Strain rate/( \text{s}^{-1} )</th>
<th>( D_c )</th>
<th>( E_3 / \text{GPa} )</th>
<th>( E_2 / \text{GPa} )</th>
<th>( \theta_2 )</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>38.8 $$\text{v}$$</td>
<td>89.05$$\text{v}$$</td>
<td>15.26$$\text{v}$$</td>
<td>40.14$$\text{v}$$</td>
<td>3.29$$\text{v}$$</td>
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<td>2</td>
<td>54.4 $$\text{v}$$</td>
<td>75.38$$\text{v}$$</td>
<td>16.99$$\text{v}$$</td>
<td>51.25$$\text{v}$$</td>
<td>5.70$$\text{v}$$</td>
</tr>
<tr>
<td>0</td>
<td>70.5 $$\text{v}$$</td>
<td>68.08$$\text{v}$$</td>
<td>16.95$$\text{v}$$</td>
<td>57.56$$\text{v}$$</td>
<td>5.14$$\text{v}$$</td>
</tr>
<tr>
<td></td>
<td>88.6 $$\text{v}$$</td>
<td>55.39$$\text{v}$$</td>
<td>14.71$$\text{v}$$</td>
<td>46.08$$\text{v}$$</td>
<td>9.10$$\text{v}$$</td>
</tr>
<tr>
<td></td>
<td>105.9 $$\text{v}$$</td>
<td>44.83$$\text{v}$$</td>
<td>10.58$$\text{v}$$</td>
<td>32.67$$\text{v}$$</td>
<td>14.50$$\text{v}$$</td>
</tr>
<tr>
<td>P-1.2 $$\text{v}$$</td>
<td>37.5 $$\text{v}$$</td>
<td>81.72$$\text{v}$$</td>
<td>16.03$$\text{v}$$</td>
<td>38.21$$\text{v}$$</td>
<td>4.45$$\text{v}$$</td>
</tr>
<tr>
<td></td>
<td>52.8 $$\text{v}$$</td>
<td>69.88$$\text{v}$$</td>
<td>18.58$$\text{v}$$</td>
<td>45.26$$\text{v}$$</td>
<td>7.01$$\text{v}$$</td>
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<tr>
<td>P-1.2 $$\text{v}$$</td>
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<td>56.73$$\text{v}$$</td>
<td>17.86$$\text{v}$$</td>
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<td></td>
<td>84.3 $$\text{v}$$</td>
<td>48.26$$\text{v}$$</td>
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<td>46.30$$\text{v}$$</td>
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</tr>
<tr>
<td></td>
<td>100.4 $$\text{v}$$</td>
<td>42.38$$\text{v}$$</td>
<td>13.98$$\text{v}$$</td>
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<td></td>
<td>36.1 $$\text{v}$$</td>
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<td>50.7 $$\text{v}$$</td>
<td>62.88$$\text{v}$$</td>
<td>14.28$$\text{v}$$</td>
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<td>9.75$$\text{v}$$</td>
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<td>P-2.4 $$\text{v}$$</td>
<td>65.8 $$\text{v}$$</td>
<td>51.18$$\text{v}$$</td>
<td>19.38$$\text{v}$$</td>
<td>41.33$$\text{v}$$</td>
<td>12.11$$\text{v}$$</td>
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<tr>
<td></td>
<td>82.2 $$\text{v}$$</td>
<td>44.05$$\text{v}$$</td>
<td>15.66$$\text{v}$$</td>
<td>35.41$$\text{v}$$</td>
<td>19.25$$\text{v}$$</td>
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<tr>
<td></td>
<td>96.9 $$\text{v}$$</td>
<td>39.53$$\text{v}$$</td>
<td>11.35$$\text{v}$$</td>
<td>28.10$$\text{v}$$</td>
<td>27.34$$\text{v}$$</td>
</tr>
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</table>
As shown in Table I, with the increase of strain rate, the damage evolution rate $Dc$ of each group of fiber concrete is getting to decrease, which is corresponded to the theory that the cracks with high strain rate of crack expansion have no time to extend themselves. The $Dc$ value decreases gradually as the increase of fiber content, which shows that the fiber can restrict the propagation of cracks. In the same way, with the increase of strain rate, the elastic modulus $E3$ which is independent to strain rate tends to increase gradually at first, and then is getting to decrease. The elastic modulus $E2$ of Maxwell body at high frequency also tends to increase at first and then decrease. However, the characteristic time $\theta_2$ is gradually rising with the increase of strain rate, which has verified a conclusion that the toughening effect of PVA fiber is enhanced and effect from strain rate is weaker.

The comparison of stress-strain curves between experiment and simulation, as shown in Figure 5, shows that the simplified constitutive model can well simulate the dynamic stress-strain relationship of each fiber-reinforced concrete in the whole process.

Figure 5. The comparison of stress-strain curves between experiment and simulation.
CONCLUSIONS

(1) PVA fiber concrete has the strain rate effect but less than plain concrete;
(2) The dynamic compressive strength, ultimate strain, peak strain and specific energy of fiber reinforced concrete increase with the acceleration of reaction rate.
(3) The simplified constitutive model can simulate the compressive stress strain relationship very well of PVA fiber cementitious materials under impact load.

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