Research Article

Dynamic Compressive and Tensile Characteristics of a New Type of Ultra-High-Molecular Weight Polyethylene (UHMWPE) and Polyvinyl Alcohol (PVA) Fibers Reinforced Concrete

Bashir H. Osman, 1,2 Xiao Sun, 1 Zhenghong Tian, 1,3 Hao Lu, 1 and Guilin Jiang 1

1 College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China
2 Civil Engineering Department, College of Engineering, University of Sinnar, Sinnar, Sudan
3 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China

Correspondence should be addressed to Xiao Sun; xiaos@hhu.edu.cn

Received 10 November 2018; Accepted 17 December 2018; Published 23 January 2019

Abstract

The dynamic mechanical properties of concrete materials are important parameters for evaluating the safety performance of concrete structures under dynamic loads. Fiber cement-based materials have been widely used in the construction projects due to their strength, toughening, and cracking resistance. In this study, we conducted experimental and theoretical studies on dynamic compression and tensile mechanical properties of different proportions of new-type fiber concrete. A Split-Hopkinson pressure bar equipment was used to determine the concrete behavior at different strain rates. The effect of strain rate and fiber content on the strength of the specimen, dynamic increase factor, and ultimate strain were analyzed. Based on the macrodamage factor, the traditional nonlinear viscoelastic constitutive model was simplified and improved. The four-parameter constitutive model was obtained, and the influence of these parameters on the performance of fiber concrete was analyzed. The experimental results were compared with those predicted from the available equations, and results were in accordance. Finally, an analytical equation for predicting the dynamic compression and tensile properties of these new-type fibers was proposed.

1. Introduction

Concrete as a common construction material used in the industry may often be subjected to dynamic loads during service, and concrete compression and tensile performances are important parameters for evaluating structures and building safety and stability. Tensile properties of the concrete material are significantly lower than the compression resistance, resulting in the structure being prone to tensile damage, and the dynamic direct tensile properties are difficult to measure directly by the test. Most researchers [1–3] have shown that the tensile test with Brazilian disc specimens yields the closest tensile strength value to the actual tensile value. Addition of fiber to concrete can effectively reduce cracks from rising and propagating, thus improving its strength and enhances its toughness and anti-impact properties [4].

Fiber cement-based composites have good reinforcement and toughening effects and have been widely used in civil engineering construction. Most of the mechanical properties of fiber-reinforced concrete under impact load are based on the experimental analysis [5, 6]. Due to the strain rate effect, the performance of concrete structures under static loading is different from those subjected to high strain rate loading conditions. Most research on properties of concrete subjected to high strain rate loadings has focused on compressive strength. It is generally accepted that there is a strength increase with the increase in strain rate [7–9]. Mindess [10] found that an increase in the strain rate leads the elastic modulus to increase. Ultra-high-molecular weight polyethylene (UHMWPE) fiber is a new type of ultra-high-performance manufacturing industrial material, but there is little research on the dynamic tensile
properties of UHMWPE fiber-based composites. Although the conclusions on the dynamic tensile properties of fiber cement-based materials are basically the same, the theoretical analysis needs to be further studied [11–14].

Research on polyvinyl alcohol (PVA) fiber cement composite material and its dynamic mechanical properties have not yet been agreed with credible conclusions, and the use of ultra-high-molecular weight polyethylene (UHMWPE) on the mechanical properties of fiber-reinforced concrete under impact load is almost blank. Therefore, in this study, the dynamic tensile test of UHMWPE and PVA fiber concrete is carried out by a Split-Hopkinson pressure bar (SHPB) impact device, and the dynamic tensile effect of fiber concrete with different strain rates were obtained. Furthermore, dynamic compressive and tensile characteristics of UHMWPE and PVA fibers reinforced concrete in terms of failure mode of fiber concrete, the evaluation of the antisliding ability of the above fiber concrete, the influence of strain rate on the tensile strength, dynamic increase factor and dissipative energy of the test piece, and the establishment of uniformity between dynamic and static tensile strain and strain rate model are studied.

2. Experimental Study

2.1. Test Materials. The experimental materials are specified as follows: P.O 42.5 cement; natural river sand (MX = 2.8); tap water; coarse aggregate is limestone, in order to ensure that the size of the test specimen is greater than 3 times the maximum aggregate size. The aggregates before construction are screened to ensure the coarse aggregate size in the range of 5–10 mm; UHMWPE fiber is produced by Shanghai DISMAN Company, which is in the form of the white fiber bundle, as shown in Figure 1(a); the PVA fiber is in the form of a yellowish fiber bundle, as shown in Figure 1(b). The properties of the fibers are shown in Table 1.

2.2. Test Mixture Proportion. The concrete quality of each group is shown in Table 2, where group No. 0 represents plain concrete as a control group, P-0.6 and U-0.6 represent a content of 0.6 kg/m³ for PVA and UHMWPE fibers concrete, respectively, and the same for other groups. The ratios of 230, 440, 620, and 1100 for water, cement, sand, and aggregate were used, respectively. The proportions of the fibers are shown in Table 2.

2.3. Compression Test

2.3.1. Samples Preparation. The test was carried out by using a 75 mm diameter PVC pipe. After the concrete was compacted using a vibrating table, the surface of the samples was covered with a plastic film to cover the moisturizing and curing. After 48 hours, the mold was removed and the sample was cured by the saturated water method. After 28 days, the cutting was polished to a height of 74 mm for the static compression test, and an additional height of 37 mm test was carried out for the dynamic compression test. The samples with a thickness of 37 mm are shown in Figure 2.

2.3.2. Static Compression Test. The concrete test specimens were statically loaded with a universal testing machine, with the maximum capacity of 1000 kN. The samples dimensions of 74 mm diameter and 148 mm height were tested. Loading and test procedure were carried out in accordance with ASTM C192 specification, and the static compressive strength of each group of fiber concrete is shown in Table 3.

2.3.3. SHPB Dynamic Compression Test. The SHPB device consists of a launching system, striker, incident bar, transmitted bar, shock absorber, and a data acquisition system. During the test, the striker was launched by compressed gas towards the incident bar. The schematic of the device is shown in Figure 3. Adjust the impact air pressure load, where striker impacts the incident rod at different speeds, thus generating the corresponding stress wave [15]. Figure 4 shows a three-wavelength map obtained from the impact test. The SHPB test principle shows that the reflected stress wave can be unique. The strain rate of the sample is determined, and a “platform zone” appears on the reflected wave curve in the figure. At this time, the constant strain rate loading is realized inside the test [16]. The SHPB test is based on two assumptions: (1) calculation based on one-dimensional stress wave propagation; and (2) stress wave propagation in the specimen is axial and the stress is evenly distributed. The stress, strain, and strain rate of the specimens can be calculated from Equations (1)–(3) [17]. The schematic of the strain rate determination is shown in Figure 5.

\[
\sigma_s(t) = E_b \left( \frac{A_s}{A_b} \right) \varepsilon_T(t),
\]

\[
\varepsilon_s(t) = -2C_0 \int_0^t \varepsilon_R(t) dt,
\]

\[
\dot{\varepsilon} = \frac{d\varepsilon_s(t)}{dt},
\]

where \( A_b \), \( E_b \), and \( C_0 \) are the cross-sectional area of the pressure bar, the elastic modulus, and the propagation velocity of the waveform, respectively; \( l \) and \( A_s \) are the thickness and cross-sectional area of the specimens, respectively.

Each group of fiber concrete was loaded with five different (0.30 MPa, 0.35 MPa, 0.40 MPa, 0.45 MPa, and 0.50 MPa) impact air pressures, and each group was repeatedly tested in the same working condition for five times. The strain rate was considered to be approximately constant during the test loading [16].

2.4. Tensile Test

2.4.1. Samples Preparation. The sample preparation of the tensile test is the same as that of the compression test. The
Table 1: Fiber physical parameters.

<table>
<thead>
<tr>
<th>Fiber species</th>
<th>Length (mm)</th>
<th>Density (g/cm³)</th>
<th>Diameter (μm)</th>
<th>Elastic modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation at failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVA fiber</td>
<td>12</td>
<td>1.30</td>
<td>29</td>
<td>37.2</td>
<td>1.3</td>
<td>6.15</td>
</tr>
<tr>
<td>UHMWP fiber</td>
<td>12</td>
<td>0.91</td>
<td>25</td>
<td>121</td>
<td>3.1</td>
<td>2–3</td>
</tr>
</tbody>
</table>

Table 2: Mix proportion of fiber concrete in each group (measured in m³).

<table>
<thead>
<tr>
<th>Group no.</th>
<th>0</th>
<th>P-0.6</th>
<th>P-1.2</th>
<th>P-1.8</th>
<th>P-2.4</th>
<th>U-0.6</th>
<th>U-1.2</th>
<th>U-1.8</th>
<th>U-2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber content (kg)</td>
<td>0</td>
<td>0.6</td>
<td>1.2</td>
<td>1.8</td>
<td>2.4</td>
<td>0.6</td>
<td>1.2</td>
<td>1.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 3: Compressive strength (MPa) of each group of fiber concrete.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Concrete</th>
<th>PVA fiber concrete</th>
<th>UHMWPE fiber concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount (kg/m³)</td>
<td>0</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>30.4</td>
<td>30.8</td>
<td>31.1</td>
</tr>
<tr>
<td>Differences %</td>
<td>—</td>
<td>0.013</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Figure 1: Fiber morphology.

Figure 2: Test samples with 37 mm thickness.
test was carried out by using a 75 mm diameter PVC pipe. After the concrete was compacted using a vibrating table, the surface of the samples was covered with a plastic film to cover the moisturizing and curing. After 48 hours, the mold was removed and the sample was cured by the saturated water method. After 28 days, the cutting was polished to a height of 74 mm for the static Brazilian disc test, and an additional height of 37 mm test was carried out for the dynamic Brazilian disc test.

2.4.2. Static Brazilian Disc Test. The static Brazilian disc test was carried out using a universal testing machine. According to the ASTM specifications [18], the specimen sizes were 74 mm and 37 mm for diameter and thickness, respectively. The principle of the Brazilian disc test is shown in Figure 6.

Based on the theory of elasticity, the Brazilian condition of the diameter-compressed disk specimen is expressed in Equation (4) [19], while Equation (5) showed the stress at the center of the disc:

\[
\sigma_x = \frac{2F}{\pi LD}
\]

\[
\sigma_y = \frac{2F}{\pi LD} \left[ \frac{D^2}{y(D-y)} - 1 \right],
\]

\[
\sigma_x = \frac{2F}{\pi LD}
\]

\[
\sigma_y = \frac{6F}{\pi LD}
\]

where \(L\) and \(D\) are the thickness and diameter of the sample, respectively, while \(\sigma_y\) is the tensile strength in the normal direction, and \(\sigma_x\) is the tensile strength.

It can be seen from Equation (5), the compressive stress at the center of the circle is three times the tensile stress. Generally, the tensile strength of cement-based materials is 1/20–1/10 of the compressive pressure.

2.4.3. Dynamic Brazilian Disc Test. For the dynamic Brazilian disc test, each group of fiber concrete was carried out by five kinds of air pressure (0.20 MPa, 0.25 MPa, 0.30 MPa, 0.35 MPa, and 0.40 MPa), and the impact test was carried out for 5 times in the same working condition.

For dynamic Brazilian disc test, a 74 mm diameter variable cross section SHPB pressure bar device is used, and the test sample is sandwiched between the incident bar and the transmitted bar, as shown in Figure 7. By controlling the impact air pressure, the striker produces different impact velocities and strikes the incident bar, thereby generating corresponding stress waves. The time course of the incident wave, reflected wave, and transmitted wave is shown in Figure 8.
According to [20], the test tensile strength can be expressed by using Equation (6):

$$\sigma_t = \frac{2P_{\text{max}}}{{\pi}L} \frac{A\epsilon_{t\text{max}}}{{\pi}L D}$$  \hspace{1cm} (6)

where $\sigma_t$ is the dynamic tensile strength and $\epsilon_{t\text{max}}$ is the maximum strain measured on the transmitted bar. The dynamic tensile strain rate of cement-based materials can be defined as in Equation (7) [21]:

$$\dot{\epsilon} = \frac{\sigma_t}{E_t t}$$  \hspace{1cm} (7)

where $E_t$ is a static tensile modulus and $t$ is the duration of the transmitted wave from the beginning to the climax.

3. Test Results and Discussion

3.1. Compressive Characteristics

3.1.1. Failure Mode. Figure 9 shows the failure modes samples of each group under static load, while the damage pattern of typical fiber concrete under dynamic loading is shown in Figure 10.

It can be seen from Figure 9 that the surface of the ordinary concrete is seriously damaged, and a large number of microcracks are formed on the surface of the fiber concrete. There is no wide crack, and the surface of the 2.4 kg/m$^3$ UHMWPE fiber concrete specimen showed tinier cracks. Generally, the concrete expands outward from the top portion or the middle portion at ultimate. When the tensile stress of the outward expansion reaches the peak tensile stress of the concrete material, the concrete specimen is damaged; the concrete crack is weakened from the joint by the matrix. At the same place, the addition of fibers increases the bonding strength of the matrix and increases the path of concrete cracking. There is a negative correlation between crack width and fiber content during fiber concrete failure.

The fiber and bridging and lateral restraint can effectively suppress the deformation of the specimen when it is compressed under pressure, so that the fiber concrete specimen can maintain good integrity when subjected to large damage, thus UHMWPE and PVA fiber restraint effects are gradually enhanced. From the crack width and its surface damage morphology, the compressive performance of the equivalent UHMWPE fiber concrete is better than that of PVA fiber, because the UHMWPE fiber elastic modulus and tensile strength are higher than PVA fiber, but the density is lower than that of PVA fiber, so the UHMWPE fiber concrete specimens has better integrity and surface microcracks, and UHMWPE antistatic compression ability is stronger.

As the strain rate increased (Figure 10), the damage degree of each group of concrete specimens is increased, and the plain concrete starts breaking; and with the increase of fiber content, the strength of the fiber concrete specimens improved and showed a certain ductile damage. The UHMWPE fiber concrete showed better performance compared with the same amount of PVA fiber. It indicates that the fiber bridging effect and lateral restraint function increase the path of crack development and can effectively inhibit the crack propagation in the impact process, thereby improving the concrete compression resistance.

Under the impact load, the failure mode of the concrete specimen and fiber cracking are shown in Figure 11. At the lower strain rate, the crack expands along the joint surface of the cement mortar matrix and the coarse aggregate and finally failed as shown in Figure 11(a). The impact time of the high strain rate is very short, the internal crack is not extended by the path with the least resistance, and the stress has reached the critical stress throughout the coarse aggregate. The expansion path is basically linear, which leads to an increase in the amount of coarse aggregate fracture of concrete on the failure surface than in the static test, as shown in Figure 11(b). As the strain rate continues to increase, the concrete material cannot be dissipated and absorb excess energy. According to the principle of energy conservation, at this time, the material must generate more strain energy; this means, the damage degree of the test specimens will be further aggravated and will break into more fragments [22, 23], as shown in Figure 11(c). The schematic of fiber cracking in concrete materials is shown in Figure 11(d). The bridging effect of fiber can inhibit the expansion of cracks during impact and restrain the crack width to develop. Furthermore, it can enhance the lateral restraint performance of concrete when it is damaged. Impact damage occurs under pressure conditions, which can improve the dynamic compressive strength of the concrete; in addition, the fiber can dissipate and absorb a large amount of impact energy and improve the threshold value of the energy dissipation of the concrete material at a high strain rate to generate strain energy. Therefore, the integrity of fiber concrete is stronger than that of plain concrete under impact compression, while the compressive strength and elastic modulus of UHMWPE fiber are higher than those of PVA fiber. The bridging and limiting effect of the equivalent UHMWPE fiber is stronger. Also, UHMWPE fiber is better.
than PVA fiber concrete in terms of energy absorption, reinforcing the concrete, toughening and crack-resisting effect, and dynamic compressive performance.

3.1.2. Stress-Strain Curve. Figure 12 shows that the dynamic elastic modulus of fiber concrete increases with the strain rate increasing. With the increase of fiber content, the ultimate strain of concrete is also positively correlated, but the increase under the same working condition is obviously smaller than the strain rate effect. Ultimate stress and ultimate strain of fiber concrete is larger than that of plain concrete, and the increasing amplitude of UHMWPE fiber concrete is larger than that of PVA fiber. UHMWPE fiber can increase the compressive strength and ultimate strain up to 23%, and 17.5%, respectively; thus, the addition of fiber can effectively enhance the concrete performance.

3.1.3. Dynamic Increase Factor. The dynamic increase factor (DIF) can be determined by Equation (8). Based on existing researches [24, 25] and experimental results, the logarithmic relationship is used to characterize the relationship between strain rate and DIF, as shown in Equation (9). The obtained results using equation (9) are shown in Table 4:

$$DIF = \frac{\sigma_d}{\sigma_s},$$  \hspace{1cm} (8)

where $\sigma_d$ and $\sigma_s$ are the dynamic strength and static strength of concrete materials, respectively.

$$DIF = m \log \dot{\varepsilon} + n.$$  \hspace{1cm} (9)

As shown in Table 4, the logarithmic function relationship can well fit the relationship between the DIF of the UHMWPE and PVA fiber concrete and the strain rate. Positive values of $m$ indicate that the dynamic compressive strength of the fiber concrete has positive correlation rate effect. With the increase of fiber content, $m$ value led the concrete to fail gradually. The $m$ value of the same amount of UHMWPE fiber concrete is larger than that of PVA fiber, indicating that UHMWPE fiber improves the concrete performance. Furthermore, higher strength proves that UHMWPE fiber is better in strengthening, toughening, and delaying the failure point.

3.1.4. Energy Absorption. The energy absorption of fiber cement-based composites can be characterized by specific energy absorption (SEA), determined by the strength and degree of deformation of the material [26], and SEA can be expressed by Equation (10) [27]:

$$SEA = \frac{\sigma_d \varepsilon_s}{\sigma_s},$$  \hspace{1cm} (10)
Figure 10: Failure modes of concrete specimens of different groups at different strain rates.

Figure 11: Schematic of the failure mode of concrete specimens and fiber cracking in concrete materials at different strain rates.
Figure 12: Continued.
\[ \text{SEA} = \frac{A_s E c_0}{A f} \int_0^t [\epsilon_i(t)^2 - \epsilon_r(t)^2 - \epsilon_i(t)^2]. \]  

The relationship between SEA and strain rate of different PVA and UHMWPE fibers concrete at different strain rates is shown in Figure 13.

Figure 13 shows that the SEA of each group of fiber-reinforced concrete increases gradually with the increase of strain rate, indicating that there is an upper limit threshold for the energy absorption of fiber concrete. The SEA of concrete with an equal amount of UHMWPE fiber is greater than that of PVA fiber, indicating that UHMWPE fiber is better than PVA fiber in improving the impact compression performance of concrete. Since the side surface of the SHPB uniaxial compression test left free, lateral deformation occurs under impact load, and the bridging and lateral limitation of the fiber can delay the expansion of the crack and suppress the lateral shape of the cracks. UHMWPE fiber concrete can absorb and dissipate more impact energy, so its SEA is greater than PVA fiber.

3.1.5. Dynamic Damage Constitutive Model. The Zhu–Wang–Tang (ZWT) [28] constitutive model was originally a constitutive relationship proposed for polymer materials. Because cement-based materials have rate sensitivity and the test curve under impact load exhibits hysteresis viscoelasticity, this model is also commonly used to describe the rate constitutive of fiber-reinforced concrete materials [29].

The ZWT constitutive model consists of a nonlinear spring and two Maxwell bodies with different characteristic
The constitutive equation is given as follows:

$$\sigma = E_0 \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_1 \int_0^t \varepsilon \exp\left(-\frac{t-\tau}{\theta_1}\right) d\tau + E_2 \int_0^t \varepsilon \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau,$$

where $E_0$, $\alpha$, and $\beta$ are the corresponding elastic constants and $E_1$ and $\theta_1$ represent the low-frequency Maxwell elastic modulus and characteristic time, respectively. Two integral expressions were used to characterize the viscoelastic behavior of cement-based materials at low and high strain rates. According to research conducted by [30], the low-frequency Maxwell unit can be equivalently converted into an $E_1$ spring, as shown in Figure 14(b). Then the ZWT constitutive model can be simplified to the following equation:

$$\sigma = E_0 \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_1 \varepsilon + E_2 \int_0^t \varepsilon \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau,$$

$$\sigma = \varepsilon_0 (1 - D) = \left[ (E_0 + E_1) \varepsilon + E_2 \int_0^t \varepsilon \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau \right],$$

where $\sigma$ is the true stress in the test specimen and $\sigma_r$ is the stress when the material is not damaged.

According to the damage evolution rate of cement-based materials by [32], the rate of damage change can be expressed by Equation (14) (simplified rate constitutive model):

$$\dot{D}(t) = D_0 |\dot{\varepsilon}|^k. \quad (14)$$

Integrate the time $t$ to

$$D = D_0 (\dot{\varepsilon})^{k-1} \varepsilon + D_1. \quad (15)$$

Consider the actual boundary condition:

$$D|_{\varepsilon=0} = 0, \quad (16)$$

one gets $D_1 = 0$, therefore

$$D = D_0 (\dot{\varepsilon})^{k-1} \varepsilon. \quad (17)$$

With $k = \sigma - 1$ and substituting the damage factor into Equation (13) and considering the SHPB test approximate constant strain rate test, let $D_c = D_0 (\dot{\varepsilon})^k$, then the final dynamic compression constitutive equation of fiber concrete is expressed as

$$\sigma = (1 - D_c) \left[ E_3 \varepsilon + E_2 \theta_2 \varepsilon \left(1 - e^{\theta_2 t}\right) \right], \quad (18)$$

where $E_3 = E_1 + E_2$; $D_c$ is the damage evolution factor; $E_3$ is the elastic modulus independent of strain rate; $E_2$ is the high-frequency Maxwell elastic modulus; and $\theta_2$ is the characteristic time. The fitting results for each group of fiber concrete are shown in Table 5.

As shown in Table 5, the strain rate increases, the damage evolution rate ($D_c$) value of each group of fiber concrete decreases gradually. Under the impact load, the internal stress of the specimen rises rapidly and the crack does not expand enough. With stress increasing, the critical strength throughout the coarse aggregate is reached; as the fiber content increases, the $D_c$ value decreases gradually. This revealed that the bridging and confinement of the fiber can effectively increase the stress threshold required for the coagulation crack initiation and reduces the crack propagation. The damage evolution rate ($D_c$) of the UHMWPE fiber-concrete with same working conditions is smaller than that of the PVA fiber.
which indicates that the UHMWPE fiber is better than the PVA fiber in strengthening, toughening, and crack resistance. In addition, with the increase of the strain rate, the fiber-reinforced concrete specimens and strains of each group and rate-independent elastic modulus $E_3$ basically increases first and then decreases. Similarly, the elastic modulus $E_2$ of the high-frequency Maxwell body also increases first and then decreases. The characteristic time $\theta_2$ is positively correlated with strain rate and fiber content. The characteristic time $\theta_2$ of the equivalent UHMWPE fiber concrete specimen is larger than that of the PVA fiber, and the characteristic time $\theta_2$ of the 2.4 kg/m$^3$ UHMWPE fiber concrete is the largest.

The comparison between the experimental values of various groups of fiber concrete and the theoretical values are shown in Figure 15. It can be seen from Figure 15, the simplified four-parameter constitutive model is simple in form and clear in physical meaning and can effectively simulate the stress-strain relationship of the dynamic compression process of each group of fiber-reinforced concrete specimens.

### 3.2. Tensile Characteristics

#### 3.2.1. Failure Mode

Figure 16 shows that the crack width of each group of fiber concrete is smaller than that of plain concrete, and the crack width decreases with the increase of fiber content of the concrete specimens. Due to fiber bridging and lateral restraint, it not only increases the stress threshold required for cracking of concrete specimens but also prolongs the path of concrete failure and effectively reduces the crack growth rate, thus inhibiting crack propagation of specimens. With the increase of the dosage, the inhibition effect is gradually enhanced, while the UHMWPE fiber elastic modulus and tensile strength are higher than those of PVA fiber. So, the limitation and inhibition effect is obviously stronger than that of the equivalent PVA fiber. The typical dynamic tensile failure modes of each group of fiber concrete are shown in Figure 17.

Figure 17 shows that the failure of each group of fiber-reinforced concrete specimens is caused by the central penetrating crack, and the splitting damage occurs along the loading direction. The degree of cracking of the fiber concrete of each group gradually increases with the increase of the strain rate, with partial cracking failures in the triangular region at both ends. This is because the specimens are partially broken at both ends of the specimen when the stress is greater than the compressive strength before the center crack penetrates. As the strain rate increases, the degree of fracture in the central region is aggravated (from the splitting into two pieces and gradually becoming part of the fracture in the test specimen) and the degree is more serious than the static tensile failure of the plain concrete.
Figure 15: Comparison of the experimental values and the fitted values of each group of fiber concrete.
Figure 16: Static collapse behavior of each group of concrete.

Figure 17: Dynamic collapse of fiber-reinforced concrete in each group.
impact time of the impact load is very short because the internal stress of the test specimen rises very quickly, the specimen cannot be destroyed by the minimum path resistance, and the stress has reached the critical stress required to penetrate the coarse aggregate. As the strain rate continues to increase, the concrete specimen cannot absorb and dissipate excess energy. According to the principle of conservation of energy, the specimen must offset the additional impact energy in the form of greater strain energy.

The failure modes of UHMWPE and PVA fiber concrete are mainly center cracks, but UHMWPE fiber concrete can maintain better relative integrity than PVA fiber, which indicates that UHMWPE fiber with equal volume fiber has better crack resistance, reinforcement, and toughening effect. Verification of fiber elastic modulus and tensile strength are the main factors affecting fiber toughening and cracking resistance, while elongation at break is a secondary factor [33]. Since the fiber itself can absorb more energy, the strain energy of the test specimen is greatly reduced to offset the threshold of excess energy. The dynamic antipull ability of UHMWPE fiber concrete is obviously better than that of PVA fiber concrete.

3.2.2. Static and Dynamic Tensile Strength. The static tensile properties of each group of fiber concrete are shown in Table 6, and the relationship between fiber content and static tensile strength of concrete is shown in Figure 18.

The results from Table 6 and Figure 18 show that, as the dosage increases, the tensile strength increases gradually, but the increasing amplitude decreases gradually. According to Table 6, the elastic modulus and fiber content of concrete was a negative correlation. The bridging and lateral restraint of the fiber can effectively restrain the lateral deformation of the specimen during the tension, thereby improving the tensile properties of the fiber concrete. The dynamic tensile performance parameters of each group of fiber concrete are shown in Table 7.

It can be seen from Table 7 the tensile strength of the equivalent UHMWPE fiber concrete is larger than that of the PVA fiber concrete; the dynamic tensile strength of UHMWPE fiber concrete can be increased by at least 10% compared to that of PVA concrete. Because under the impact load, the internal stress rise time of the test specimen is very short and the material does not have sufficient time to deform, showing a viscous mechanism. According to the functional principle, the test specimen can only offset the excess impact energy by increasing the stress [34]. The fiber bridging and lateral restraint function can not only prolong the crack development path of the test specimen but also limit the lateral deformation when it is damaged, so it can effectively delay the crack growth rate and improve the toughness of the test specimen.

3.2.3. Relationship between Tensile Strength and Strain Rate. The fiber concrete DIF can be calculated from the ratio of dynamic to static tensile strength. Some researchers have used a piecewise function to express the relationship between strain rate and dynamic tensile strength. For example, [35] proposed that the relationship between cement-based material DIF and strain rate can be expressed by the following equation:

\[
\text{DIF} = \begin{cases} 
0.0225 \log \frac{\epsilon_d}{\epsilon_s} + 1.12, & \epsilon_d \leq 10^{-1}, \\
0.2713(\log \epsilon_d)^2 - 0.3563 \log \epsilon_d + 1.2275, & \epsilon_d > 10^{-1}.
\end{cases}
\]

In Equation (19), \(\epsilon_d\) is a dynamic strain rate. CEB [36] proposed a concrete DIF relation (Equation (20)) for the highest strain rate of 300 s\(^{-1}\):

\[
\text{DIF} = \begin{cases} 
(\epsilon_d/\epsilon_s)^{1.026a}, & \epsilon_d \leq 30 \text{ s}^{-1}, \\
(\epsilon_d/\epsilon_s)^{0.33}, & \epsilon_d > 30 \text{ s}^{-1},
\end{cases}
\]

where \(a = 1/(10 + 6 f_s/10)(f_c\) is static compressive strength, MPa), and \(\epsilon_s = 3 \times 10^{-6} \text{ s}^{-1}\).

Equations (19) and (20) are complex in the current form, have segmentation points, and the physical meaning is not clear enough. So, based on previous studies and combined with experimental results, a new equation for calculating the dynamic and static uniform strain rate and tensile strength of cement-based materials is proposed in this paper:

\[
\sigma = p + q \left( \frac{\epsilon_d}{\epsilon_s} \right)^r,
\]

where \(\epsilon_s\) is a static strain rate and \(\epsilon_d = 3 \times 10^{-6} \text{ s}^{-1}\), and \(p, q, \) and \(r\) are all undetermined coefficients.
Table 7: Performance parameters of fiber concrete of different groups under different strain rates.

<table>
<thead>
<tr>
<th>Group no.</th>
<th>Air pressure (MPa)</th>
<th>Strain rate (s⁻¹)</th>
<th>Dynamic tensile strength (MPa)</th>
<th>Static compressive strength (MPa)</th>
<th>DIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.20</td>
<td>7.84</td>
<td>8.21</td>
<td>2.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>12.43</td>
<td>11.13</td>
<td>2.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>18.32</td>
<td>13.54</td>
<td>3.84</td>
<td>3.53</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>24.25</td>
<td>15.43</td>
<td>4.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>29.67</td>
<td>17.05</td>
<td>4.14</td>
<td></td>
</tr>
<tr>
<td>P-0.6</td>
<td>0.20</td>
<td>7.66</td>
<td>8.78</td>
<td>2.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>12.24</td>
<td>11.92</td>
<td>2.97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>17.83</td>
<td>14.52</td>
<td>4.01</td>
<td>3.62</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>23.76</td>
<td>16.58</td>
<td>4.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>29.27</td>
<td>18.37</td>
<td>4.58</td>
<td></td>
</tr>
<tr>
<td>U-0.6</td>
<td>0.20</td>
<td>7.42</td>
<td>8.97</td>
<td>2.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>12.08</td>
<td>12.18</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>17.58</td>
<td>14.84</td>
<td>4.06</td>
<td>3.66</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>23.49</td>
<td>16.95</td>
<td>4.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>28.96</td>
<td>18.77</td>
<td>4.62</td>
<td></td>
</tr>
<tr>
<td>P-1.2</td>
<td>0.20</td>
<td>7.26</td>
<td>9.17</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>11.95</td>
<td>12.46</td>
<td>3.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>17.42</td>
<td>15.19</td>
<td>4.09</td>
<td>3.71</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>23.20</td>
<td>17.36</td>
<td>4.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>28.72</td>
<td>19.24</td>
<td>4.70</td>
<td></td>
</tr>
<tr>
<td>U-1.2</td>
<td>0.20</td>
<td>7.15</td>
<td>9.44</td>
<td>2.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>11.83</td>
<td>12.82</td>
<td>3.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>17.27</td>
<td>15.63</td>
<td>4.14</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>22.98</td>
<td>17.86</td>
<td>4.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>28.43</td>
<td>19.78</td>
<td>4.78</td>
<td></td>
</tr>
<tr>
<td>P-1.8</td>
<td>0.20</td>
<td>7.09</td>
<td>9.52</td>
<td>2.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>11.71</td>
<td>12.92</td>
<td>3.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>17.13</td>
<td>15.73</td>
<td>4.16</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>22.82</td>
<td>17.84</td>
<td>4.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>28.21</td>
<td>19.69</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td>U-1.8</td>
<td>0.20</td>
<td>6.97</td>
<td>9.69</td>
<td>2.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>11.48</td>
<td>13.18</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>16.74</td>
<td>16.10</td>
<td>4.20</td>
<td>3.83</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>22.37</td>
<td>18.39</td>
<td>4.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>27.62</td>
<td>20.38</td>
<td>4.85</td>
<td></td>
</tr>
<tr>
<td>P-2.4</td>
<td>0.20</td>
<td>6.89</td>
<td>9.61</td>
<td>2.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>11.36</td>
<td>13.07</td>
<td>3.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>16.58</td>
<td>15.95</td>
<td>4.21</td>
<td>3.79</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>22.13</td>
<td>18.24</td>
<td>4.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>27.35</td>
<td>20.19</td>
<td>4.80</td>
<td></td>
</tr>
<tr>
<td>U-2.4</td>
<td>0.20</td>
<td>6.75</td>
<td>9.87</td>
<td>2.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>11.27</td>
<td>13.42</td>
<td>3.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>16.34</td>
<td>16.38</td>
<td>4.26</td>
<td>3.85</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>21.98</td>
<td>18.71</td>
<td>4.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>27.06</td>
<td>20.70</td>
<td>4.86</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Results of fitting parameters of each group of fiber concrete using the proposed equation.

<table>
<thead>
<tr>
<th>Group no.</th>
<th>p</th>
<th>q × 10⁻⁵</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.76</td>
<td>7.84</td>
<td>0.75</td>
</tr>
<tr>
<td>P-0.6</td>
<td>3.92</td>
<td>9.44</td>
<td>0.74</td>
</tr>
<tr>
<td>U-0.6</td>
<td>3.97</td>
<td>11.39</td>
<td>0.73</td>
</tr>
<tr>
<td>P-1.2</td>
<td>4.00</td>
<td>12.91</td>
<td>0.73</td>
</tr>
<tr>
<td>U-1.2</td>
<td>4.06</td>
<td>14.98</td>
<td>0.72</td>
</tr>
<tr>
<td>P-1.8</td>
<td>4.07</td>
<td>15.68</td>
<td>0.71</td>
</tr>
<tr>
<td>U-1.8</td>
<td>4.11</td>
<td>16.09</td>
<td>0.72</td>
</tr>
<tr>
<td>P-2.4</td>
<td>4.12</td>
<td>15.45</td>
<td>0.72</td>
</tr>
<tr>
<td>U-2.4</td>
<td>4.17</td>
<td>18.62</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Figure 19 shows that the empirical fitting equation proposed in this paper has clear physical meaning and simple form. Furthermore, it can easily be used to simulate the relationship between dynamic and static tensile strength and strain rate of each group. According to Equation (21), the tensile strength of the test specimen is composed of two parts: static and rate type effect enhancement part. In Table 8, the parameter p is close to the static compressive strength of concrete. Under static conditions, the strain rate changes very little. At this time, the tensile strength of the specimen depends mainly on the static tensile strength; the parameter q indicates an increase with the strain rate. The degree of tensile strength increases the q value, which is positive, indicating that the tensile strength of each group of fiber concrete is positively correlated with the impact strain rate and fiber content. The positive correlation of the equivalent amount of UHMWPE fiber is higher than PVA fiber which indicates that the reinforcement effect of UHWMPE fiber is stronger; the parameter r characterizes the degree of strength-type effect of fiber concrete of each group.

3.2.4. Energy Dissipation. The energy principle is used to study the mechanical properties of fiber concrete during dynamic tensioning. The input, reflected, and transmitted waves energies are defined by Equations (22)–(24), respectively [37]:

\[ W_i(t) = EAC \int_0^t \epsilon_i^2(t), \]  
\[ W_r(t) = EAC \int_0^t \epsilon_r^2(t), \]  
\[ W_t(t) = EAC \int_0^t \epsilon_t^2(t). \]

According to the principle of energy conservation, the energy dissipation \( W_s(t) \) can be obtained by the following equation:

\[ W_s(t) = W_i(t) - W_r(t) - W_t(t). \]  

The time-history relationship of four energy changes of plain concrete with an impact load of 0.30 MPa using Equations (22)–(25) is shown in Figure 20(a). The time-history

Correlation was applied to each group of fiber concrete, the abscissa was measured by logarithmic coordinates, and the ordinate was linear. Taking the relative strain rate \( \epsilon/d\epsilon \) as the horizontal axis variable, the fitting parameter results are shown in Table 8. The comparison between the experimental and the theoretical values is shown in Figure 19.
curve of $W_s(t)$ of each group of fiber concrete under the impact pressure of 0.30 Mpa is shown in Figure 20(b); the relationship between the maximum energy consumption and strain rate of fiber concrete with different contents is shown in Figure 20(c).

As shown in Figure 20(b), the dissipative energy of all specimens shows the same tensile failure threshold time period: initial a-section ($0–50\mu s$), the fiber concrete specimen is in the compaction stage, and no damage effect has been produced; accumulating b-segment ($50–275\mu s$), the dissipative energy of different fiber concrete specimens increases linearly with time. With the increase of the dosage, the energy dissipation rate of fiber concrete is gradually increased, and the energy consumption rate of the equivalent UHMWPE concrete is faster than that of PVA fiber concrete; stable c-section (after 275\mu s) at this time, the fiber concrete specimen has been destroyed, and the peak dissipated energy has stabilized and will not continue to grow. The above three-stage characteristics show whether the dynamic tensile energy consumption of fiber-reinforced concrete has a small difference in duration, reflecting that the fiber is effective for improving the concrete failure mode but has little effect in preventing the crack-tip opening.

Figure 20(c) shows that the maximum dissipative energy of the fiber concrete specimen is positively correlated with the dosage. Similarly, the maximum dissipative energy of the specimen also increases nonlinearly with the increase of the strain rate, and there is an upper threshold; the equivalent amount of UHMWPE fiber concrete dissipates more than PVA fibers. After the strain rate exceeds $25 \text{ s}^{-1}$, the maximum dissipative energy of fiber concrete tends to be rough and basically no longer increases. The fiber’s maximum energy dissipation performance is no longer significant, and the fiber has reached the dissipation and energy absorption. At the same time, it is verified that the strength of the concrete material is enhanced under the impact load due to the addition of fiber, and the degree of reinforcement is positively correlated with the dosage. Compared with plain concrete, UHMWPE fiber-concrete with 2.4 kg/m$^3$ can increase the maximum dissipative energy $W_s$, by up to 50%.

4. Conclusion

In this study, the experimental and theoretical studies on dynamic compression and tensile mechanical properties of different proportions of new-type fiber concrete (UHMWPE and PVA) were carried out by using 74 mm variable cross section SHPB pressure bar device. The main conclusions are as follows:

1. The reinforcing, toughening, and crack-resisting effects of UHMWPE fiber are better than those of PVA fiber concrete. UHMWPE fiber concrete can increase the compressive strength by up to 23% and increase the ultimate strain to at least 17.5%. Furthermore, the semilogarithmic function relationship can well characterize the relationship between the strain rate of UHMWPE and PVA fiber concrete and DIF.

2. The simplified four-parameter constitutive models which is proposed in this paper has a simple form and clear physical meaning, which can easily be used to simulate the stress-strain, dynamic and static tensile strength, and the strain rate relationship of each group of fiber-reinforced concrete materials. Thus, it can be used as an alternative to experimental test which is typically costly and time-consuming.
The contents of the fiber have great effect on the concrete properties such as dynamic compressive strength, ultimate strain, and the specific energy of fiber-concrete.

The dynamic tensile strength, DIF, and dissipative energy of each group increase nonlinearly with the increase of strain rate and fiber content, and there was an attenuation of increase, but the strain rate had stronger effect than fiber content.

UHMWPE fiber concrete has the highest tensile strength, which increased by at least 10% compared with the plain concrete. Furthermore, blending 2.4 kg/m³ UHMWPE fiber concrete can increase the maximum dissipative energy ($W_s$) approximately 50% compared with the plain mortar concrete.

The logarithmic function expression can be used to simulate the relationship between DIF and the strain rate of each group of fiber concrete.

**Data Availability**

The data used to support the findings of this research are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This study is financially supported by the National Natural Science Foundation of China (No. 51879094) and by the
References


