Study on constitutive relationship of acicular wollastonite polypropylene hybrid fiber concrete under uniaxial compression

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Abstract—In order to study the influence of fiber parameters on the performance of ordinary hybrid fiber concrete, the corresponding constitutive relationship of hybrid fiber concrete is proposed. The test data are obtained by adding steel tubes to increase the stiffness of the press, and the constitutive relationship of C40 hybrid fiber concrete is proposed. The constitutive relationship is polynomial in the rising section and rational in the falling section.

1. Introduction
Hybrid fiber reinforced concrete is a new composite material formed by the interactive combination of two or more fiber reinforced materials.[1] Considering the uniaxial compression constitutive relationship of their composites, the research is of great significance in the field of civil engineering.

2. Test scheme
2.1 Test materials and test parameters
Referring to the official version of code for mix proportion design of ordinary concrete JGJ55-2011[2] and technical code for fiber reinforced concrete structures CECS38-2004[3], the volume ratio of acicular wollastonite fiber in this paper is 0%, 5%, 7% and 9%, which are represented by letters W0, W1, W2 and W3 respectively. The volume ratio of polypropylene fiber is 0%, 0.25%, 0.35% and 0.45%, which are represented by the letters P0, P1, P2 and P3. The specific coordination is shown in Table 1.

Table 1. C40 light aggregate hybrid fiber concrete mix ratio

| Test piece No | Cement/kg | River sand/kg | Crushed stone/kg | Water/kg | Acicular wollastonite fiber/kg | Polypropylene fiber/kg |
|---------------|-----------|---------------|------------------|----------|-------------------------------|-----------------------|
| W1P0-C1       | 408.6     | 746.7         | 986.2            | 169.1    | 37.6                          | 0                     |
| W1P1-C2       | 408.6     | 746.7         | 986.2            | 169.1    | 37.6                          | 2.3                   |
| W1P2-C3       | 408.6     | 746.7         | 986.2            | 169.1    | 37.6                          | 4.2                   |
| W2P0-C4       | 404.9     | 725.5         | 948.7            | 166.6    | 53.2                          | 3.2                   |
| W2P1-C5       | 401.4     | 720.5         | 927.9            | 168.7    | 68.4                          | 0                     |
| W2P2-C6       | 401.4     | 720.5         | 927.9            | 168.7    | 68.4                          | 2.3                   |
| W2P3-C7       | 401.4     | 720.5         | 927.9            | 168.7    | 68.4                          | 4.1                   |
| W2P4-C8       | 410.0     | 783.0         | 1082.0           | 156.0    | 68.4                          | 4.3                   |
| W2P5-C9       | 410.0     | 783.0         | 1082.0           | 156.0    | 68.4                          | 0                     |

2.2 Test process
According to the test method proposed by P.T. Wang and ye Liangsheng[8], a 500t press is used for the
test, and a steel pipe with an outer diameter of 180 mm and an inner diameter of 160 mm is added to the test piece. The loading steps are as follows:
(1) Preload the specimen, and take 40% of the failure load as the preloaded load to make the two sides of the specimen under uniform stress.
(2) After the preloading is completed, the C40 hybrid fiber concrete is formally loaded and uniformly loaded with a loading speed of 0.7mpa/s.

3. Constitutive relationship of needle wollastonite polypropylene hybrid fiber concrete under uniaxial compression

3.1 Constitutive formula of needle shaped wollastonite polypropylene hybrid fiber concrete

The specific fitting results of the uniaxial compression constitutive relationship curve of hybrid fiber concrete in this paper are shown in Table 2:

Table 2 Axial compression stress-strain curve fitting of each test piece

| Test piece | Curve expression | Rising section parameters | Descending section parameters |
|------------|------------------|---------------------------|------------------------------|
| WiP0-C1    | $y = 2.053x - 1.106x^2 + 0.253x^4$, $R^2=0.960$ | 2.253 | 2.750 |
| WiP1-C2    | $y = x/\left[2.750(x-1)^2 + x\right]$, $R^2=0.989$ | 2.251 | 2.391 |
| WiP3-C3    | $y = 2.285x - 1.57x^2 + 0.285x^3$, $R^2=0.981$ | 2.285 | 2.237 |
| WiP2-C4    | $y = x/\left[2.237(x-1)^2 + x\right]$, $R^2=0.945$ | 2.334 | 2.394 |
| WiP0-C5    | $y = 2.332x - 1.664x^2 + 0.332x^3$, $R^2=0.948$ | 2.332 | 2.406 |
| WiP1-C6    | $y = x/\left[2.394(x-1)^2 + x\right]$, $R^2=0.985$ | 2.387 | 2.272 |
| WiP2-C7    | $y = 2.360x - 1.088x^2 + 0.404x^4$, $R^2=0.972$ | 2.404 | 2.607 |
| WiP3-C8    | $y = x/\left[2.607(x-1)^2 + x\right]$, $R^2=0.988$ | 2.018 | 2.953 |
| WiP0-C9    | $y = x/\left[3.376(x-1)^2 + x\right]$, $R^2=0.952$ | 1.992 | 3.376 |

3.2 Comparison of rising section between test curve and fitting result ($0 \leq x \leq 1$)
The rising section of the stress-strain curve of needle wollastonite polypropylene fiber hybrid fiber concrete under uniaxial compression is adopted \( y = ax + (3 - 2a)x^2 - (2 - a)x^3 \). The comparison between the test curve and the fitting curve of the rising section \((0 \leq x \leq 1)\) of the specimen is shown in Figure 1.

Fig. 1 Comparison of the test curve and the fitting curve of the rising section

Calculate the average value of each parameter \( a \) according to different fiber volume ratio to obtain Figure 2.

Fig. 2 Relationship between fiber content and parameter \( a \)

It can be seen from the above figure that with the increase of needle wollastonite fiber content, the rising section parameter \( a \) shows an increasing trend, but the growth rate gradually decreases. With the
increase of polypropylene fiber content, the rising section parameter $a$ first increases and then decreases.

3.3 Comparison of falling section of test curve and fitting result curve ($x > 1$)

The descending section ($x > 1$) of the stress-strain curve of needle wollastonite polypropylene fiber hybrid fiber concrete under uniaxial compression is adopted $y = x/[b(x-1)^2 + x]$ The comparison between the test curve and the fitting curve of the falling section ($x > 1$) of the specimen is shown in Fig. 3.

![Comparison of the test curve and the fitting curve of the falling section](image)

(a) $W_1P_0$ Descending section (b) $W_1P_1$ Descending section (c) $W_1P_3$ Descending section
(d) $W_2P_2$ Descending section (e) $W_1P_2$ Descending section (f) $W_3P_1$ Descending section
(g) $W_3P_3$ Descending section (h) $W_0P_1$ Descending section (i) $W_0P_0$ Descending section

Fig. 3 Comparison of the test curve and the fitting curve of the falling section

Calculate the average value of each group parameter $b$ according to different fiber volume rate to obtain Figure 4.
Fig. 4 Relationship between fiber content and parameter b

It can be seen from the figure that with the increase of the content of acicular wollastonite fiber, the parameter b in the falling section roughly shows a decreasing trend. With the increase of polypropylene fiber content, the lower riser parameter B first decreases and then increases.

4. Conclusion
Based on the above analysis, the results are as follows:

(1) The specific constitutive relationship expression of needle wollastonite polypropylene hybrid fiber concrete under uniaxial compression is as follows:

\[
y = \begin{cases} 
  ax + (3-2a) x^2 + (a-2) x^3 & 0 \leq x < 1 \\
  \frac{x}{b(x-1)^3 + x} & x \geq 1
\end{cases}
\]

Of which: \( x = \varepsilon / \varepsilon_0 \), \( y = \sigma / \sigma_0 \) (\( \sigma_0 \) is the peak stress of the curve, i.e. axial compressive strength, \( \varepsilon_0 \) is the strain corresponding to the peak stress of the curve).

(2) With the increase of needle wollastonite fiber content, the parameters of the rising section show an upward trend, but the growth rate decreases gradually. With the increase of polypropylene fiber content, the parameters of the rising section first increase and then decrease.

(3) With the increase of the content of acicular wollastonite fiber, the parameters in the falling section show a downward trend, and with the increase of the content of polypropylene fiber, they show a change trend of first decreasing and then increasing.

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References
[1] Nguyen DL, Kim DJ, Ryu GS, et al. Size effect on flexural behavior of ultra-high-performance hybrid fiber-reinforced concrete[J]. Composites Part B—ENGINEERING, 2004, 45 (1): 1104—1116.
[2] Chinese Academy of Building Sciences. JGJ 55-2011 code for mix proportion design of ordinary concrete [S]. Beijing: China Construction Industry Press, 2011.
[3] China Engineering Construction Standardization Association. CECS 38-2004, technical specification for fiber reinforced concrete structures [S]. Beijing: China Planning Press, 2004.
[4] Deng Zongcai, Li Jianhui, Fu Zhi. Experimental study on direct tensile properties of polypropylene fiber concrete [J]. Highway traffic science and technology. 2005, 22 (7): 45-48.