Compression constitutive relationship of RPC with different steel fiber content

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Abstract—Uniaxial compression tests were carried out on RPC with different steel fiber contents. The mechanical properties of RPC and the compressive-stress-strain curves of RPC with different steel fiber contents were studied. The results show that under the same mixture proportions, compressive strength increase with the increase of steel fiber content. When the steel fiber content is 3.5%, the compressive strength of RPC cubes is the largest; under the same mixture proportions, the compressive strength of RPC cube is approximately linear with the compression strength of prism, and the peak compressive strain and elastic modulus ratio of RPC cubes increase with the increase of steel fiber content. In this paper, the equation of the rising and descending sections of the stress-strain curves of different steel fiber volume admixtures is derived. According to the results of this test, the relationship between rising section, descending section coefficient and steel fiber content is obtained.

1. INTRODUCTION
Reactive Powder Concrete (RPC) is an cement-based composite with ultra-high performance[1, 2]. Halit Yazıcı [3] studied the compressive strength of RPC specimens under different curing conditions. The results showed that the early strength of RPC reached 100MPa, the strength of standard curing under 2 days reached 160Mpa, and the strength exceeded 200Mpa after 28 days of standard curing. Wang[4] investigated the mechanical properties of RPC reinforced with basalt fiber polypropylene fibers, Roux[5] found that the carbonation coefficient of ordinary concrete is 50mm/yr0.5, while the carbonation depth of RPC placed in a carbon dioxide content of 100% is 0. RPC has excellent resistance to freezing and thawing, Cwirzen[6] experimentally obtained multiple cycles of freeze-thaw cycles of RPC in 3% NaCl solution, and the loss rate of stone surface quality did not exceed 300 g/m2. RPC has a certain high temperature performance, Graybeal[7] think that RPC's chloride ion permeability is negligible. Ju[8] investigated bonding behavior between RPC and normal strength concrete (NSC), and proposed a NSC-RPC shear strength formula. Yoo[9] found that RPC beam has excellent bending performance, and RPC beams have higher load carrying capacity after cracking and have soft post-peak softening behavior. Wang[10-12] investigated shear bearing capacity and crack resistance properties of RPC beam-column joints, experimental results showed that the role of steel fiber through cracks is similar to reinforcement bars in the truss mechanism, it improves shear bearing capacity and crack strength of beam-column joints.

In summary, RPC has very superior mechanical properties, durability structural property. In addition, the ductility of RPC incorporating steel fiber has been significantly improved. Due to the great difference of mechanical properties between RPC and ordinary concrete, the stress-strain curve of RPC
under uniaxial compression cannot be calculated by ordinary concrete. So far, there are few studies on the constitutive relation of different steel fiber content RPC. To a certain degree, this limits the extensive application of RPC in engineering. Based on this, in order to study the rule of influence of steel fiber content on RPC constitutive equation and make RPC better applied in engineering, the mechanical properties of steel fiber RPC and the axial compressive stress-strain relationship of different steel fiber RPC content were studied. In this paper, a uniaxial compression test for RPC specimens of different steel fibers is carried out to study its mechanical properties and stress-strain relations.

2. EXPERIMENTAL PROGRAM

2.1 Materials
Portland cement used ordinary cement, production label 42.5, fineness of 3400cm²/ g; Silica gray to white powder, the largest particle size of 2μm, density of 2.214kg / m³; Quartz sand produced by a sand plant, particle size range of 0.16 ~ 1.25mm; Using a company's production of thin round surface, copper-plated steel fiber, length 13 ~ 15mm, diameter 0.2 ~ 0.3mm; The use of high performance water reducer AN3000, dark purple transparent liquid, solid content 30%, water reduction rate of 29%.

In order to study the influence of different steel fiber content on RPC mechanical properties and axial compressive stress-strain curve, five different mixture was designed in this study. Among them, the water-cement ratio of different groups was 0.20, the ratio of silica fume cement was 0.30, and the ratio of mortar to cement was 1.30. The volume fractions of the steel fiber were 1.0, 1.3, 2.0, 3.5 and 5.0 respectively.

2.2 Specimen and test method
The cube specimen size is 100 × 100 × 100mm. The intensity average of the three specimens in the same group was used to reflect the relationship between steel fiber content and RPC compression strength. The prismatic specimen size is 100×100×308mm, and three specimens are also taken from each mixture. The prismatic compressive strength of RPC under the standard curing conditions is recorded. The average values of the three specimens are recorded.

This test uses 5000 KN of computer-controlled electro-hydraulic servo pressure testing machine, the size of the cube specimen is 100×100×100mm, and the size of the prism specimen is 100×100×308mm. Based on the experience of compressive strength tests of reactive powder concrete made by Mechanics Laboratory of Northeast Dianli University in the past, the loading speed is taken as 0.8 MPa/s.

3. RESULTS AND DISCUSSION

3.1 Compression strength of RPC
The relationship between compression strength and steel fiber content of RPC is shown in Table 1. As we can be seen from the table, the RPC compression strength under standard curing conditions is above 115MPa, which is much higher than that of steel fiber high strength concrete. With the increase of steel fiber content, RPC compressive strength also increased, and the compressive strength of RPC cube with 3.5% steel fiber content increased by 20.24% compared with that of 1.0%. However, the RPC strength of 5% steel fiber content decreased by 1.6% compared with 3.5% steel fiber content. The compressive strength of RPC prism increases with the increase of steel fiber, the compressive strength of RPC prism with 3.5% steel fiber content increases by 29.12% than 1.0%, which is higher than the compressive strength of cube obvious.

| Group   | Steel fiber content(kg/m³) (Volume content) | Average cubic compression strength (MPa) | Average compression strength of prism specimens (MPa) |
|---------|-------------------------------------------|----------------------------------------|------------------------------------------------------|
| RPCS1.0 | 78.50 (1.0%)                               | 115.35                                 | 88.23                                                 |
The conversion formula of compression strength and cube compression strength of RPC prism is: $f_c = 0.8319 f_{cu}$, $f_{cu}$ is cube compression strength of RPC, $f_c$ is RPC prism compression strength of RPC.

3.2 Compression peak strain of RPC

The relationship between compression peak strain and steel fiber content of RPC is shown in Table II.

It can be seen that the compressive peak strain of steel fiber RPC is between 3000 and 5000, far greater than the compressive peak strain of ordinary concrete. With the increase of steel fiber content, the peak compressive strain of RPC also increases, and the compressive peak compressive strain of 5% steel fiber increases by 47.0% compared with 1.0% RPC, this is because the addition of steel fibers greatly improves the toughness of RPC.

| Group   | Steel fiber content(kg/m³) (Volume content) | Average compression peak strain (x10⁶) |
|---------|-------------------------------------------|-------------------------------------|
| RPCS1.0 | 78.50 (1.0%)                               | 3102.4                              |
| RPCS1.3 | 102.05 (1.3%)                              | 3919.4                              |
| RPCS2.0 | 157.00 (2.0%)                              | 4130.1                              |
| RPCS3.5 | 274.75 (3.5%)                              | 4309.4                              |
| RPCS5.0 | 392.50 (5.0%)                              | 4561.1                              |

4. Constitutive relationship

The opinions of many scholars can be divided into two kinds: one is to describe the rising section and the descending section of the reactive powder concrete by a unified equation; the other is to describe the ascending section and the descending section of the stress-strain curve by using the piecewise equation respectively. The former is simple in form and convenient in calculation, but the equation and the test result cannot be well fitted. In this paper, we refer to a large number of literatures, adopt the piecewise equation, the ascending section curve adopts the polynomial equation, and the descending section adopts the rational fractional equation.

4.1 Rising section constitutive equation

The rise segment of the constitutive equation of the compressive strain curve of RPC is in the form of equation $y = c_1 x + c_2 x^2 + c_4 x^4$, according to the boundary condition of the whole curve of stress-strain relation, $x=0$, $y=0$; $x=1$, $y=1$, $dy/dx=1$; we simplify the equation as $y = cx + (2 - 1.5c)x^2 + (0.5c - 1)x^4$.

Among them, the relationship between steel fiber content and coefficient $c$ of RPC compressive stress-strain full curve rising section is shown in Table III.

| Steel fiber content (%) | 1   | 1.3  | 3.5 | 5   |
|------------------------|-----|------|-----|-----|
| Coefficient $c$        | 1.36| 1.40 | 1.79| 1.99|
It can be seen that with the increasing of the steel fiber content, the value of the coefficient $c$ of the constitutive equation of the RPC pressure rise section is also increasing. The steel fiber content recorded as $V_s$, we can get the relationship between $c$ and $V_s$ approximate a linear relationship, the equation is $c=16.113V_s+1.1999$.

### 4.2 Decrease constitutive equation

The descending equation of this paper adopts the form of equation of $y=(A_1x+B_1x^2)/(1+A_2x+B_2x^2)$, according to the boundary condition of the whole curve of stress-strain relation, $x=1, y=1, \frac{dy}{dx}=0$; $x\to\infty, y\to\infty$; we simplify the equation as $y=Ax/(1+(A—2)x+x^2)$.

The relationship between steel fiber content and coefficient $A$ of RPC compressive stress-strain full curve drop section is shown in Table IV.

### Table IV. The relationship between steel fiber content and coefficient $A$

| Steel fiber content (%) | 1     | 1.3   | 3.5   | 5     |
|-------------------------|-------|-------|-------|-------|
| Coefficient A           | 0.62  | 0.68  | 0.80  | 0.85  |

It can be seen that with the increase of steel fiber content, the coefficient of decline of RPC pressure is also increasing, the relationship between coefficient $A$ and the steel fiber content $V_s$ is expressed as $A=13112V_s^3-1342.3V_s^2+45.642V_s+0.2847$, see in Figure 1.
5. CONCLUSION

In this paper, the compression test of RPC prism specimens with different steel fiber content is carried out and the following conclusions are obtained:

5.1 Under the same mixture proportions and curing conditions, the compression strength of RPC prism specimen increased with the increase of steel fiber content. However, the RPC strength of 5% steel fiber content decreased by 1.6% compared with 3.5% steel fiber content.

5.2 We found that the peak strain of RPC spiked with steel fiber is more than $3000 \times 10^{-6}$, which is much higher than that of ordinary concrete $1800 \times 10^{-6}$ - $2000 \times 10^{-6}$. And the compressive peak strain can reach $4500 \times 10^{-6}$ with the increase of steel fiber volume.

5.3 In this paper, the ascending and descending equations of the RPC compressive stress-strain full-curve constitutive equation of steel fiber doped steel are obtained. In the equation, there are coefficients related to the volume content of steel fiber. We have obtained a concrete expression of this coefficient and the volume of steel fiber. The constitutive equation of the stress-strain full curve under the uniaxial compression of steel fiber doped RPC is obtained.
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