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Finite Element Analysis on Flexural Performances of Reactive Powder Concrete Beams with Different Admixtures

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Abstract. In this paper, the flexural performances of reactive powder concrete beams with different admixtures are studied by the finite element analysis. The paper analyzes the cracking loads, the yield loads, the mid-span deflections and the equivalent stress cloud charts of reactive powder concrete beams. The results show that the different influence of admixtures on flexural performances of RPC beam is as follows: fly ash> ganister sand> powder mixed with fly ash and quartz powder> quartz powder, the influence of admixture content on flexural performance of RPC beams is larger. When the content of fly ash is 40%, the flexural performance of reactive powder concrete beam is better. By the finite element analysis, the formulas on cross-section flexural capacity of RPC beams with different admixtures are deduced.

1. Introduction
Modern society requires higher mechanical properties and durability of concrete materials, compared with ordinary concrete, reactive powder concrete (RPC) has higher strength, higher toughness and better durability [1], so it has a good application prospect. Xueyuan Lv [2] proposed the division method of reactive powder concrete strength grade, and obtained the conversion relations of RPC’s correlation mechanical performance index. Mingke Deng [3] found that water-binder ratio had a greater influence on the compressive strength of RPC. Mingzhe An [4] tested the splitting tensile strength, the axial tensile strength and the tensile stress-strain curves of RPC by changing the amount of steel fiber. Zongcai Deng [5] studied the bonding properties of high strength steel and RPC by drawing test. On the basis of existing researches, Yue Wang [6] comprehensively discussed the durability of RPC. Ziruo Yu [7] studied fatigue properties of RPC by uniaxial compression fatigue test. Juanhong Liu [8] studied the high temperature performance of RPC and found that the initial time and temperature of RPC high temperature burst decrease with the increase of mineral powder admixture content. At present, there are many researches on the properties of RPC materials, but there are less studies on structural members. And the application of RPC in engineering is still in the initial stage, there is lack of a complete set of technical specification.

Therefore, this paper uses RPC beams as the research model and analyzes the flexural performance of RPC beams with different mixing methods and different contents of fly ash and quartz powder by using the finite element analysis, and it provides a theoretical basis for the practical application of RPC beams.
2. Research project design

2.1 Research project
In this paper, 10 sets of reactive powder concrete beams are designed with different mixing methods and different contents of fly ash and quartz powder. The loads and mid-span deflections of RPC beams under the initial cracking and the yield moment are studied. The length of the beams is 1500mm, the span is 1200mm, the section size is 150mm×250mm. The longitudinal tensile steel bar adopts 4#18 (HRB400 grade steel), the reinforcement ratio is 3.57%, the frame reinforcement adopts 2Φ10 (HPB300 grade steel), and the stirrup adopts Φ10@100 (HPB300 grade steel, double limb hoop). The design scheme is shown in table 1, and the structural diagram of the beam is shown in figure 1.

Table 1 Details of RPC Specimens

| test sequence number | specimen number | ganister sand | fly ash | quartz powder | prism compressive strength/MPa | tensile strength/MPa | Modulus of elasticity /GPa |
|----------------------|-----------------|---------------|---------|---------------|-----------------------------|---------------------|---------------------------|
| 1                    | S0              | 0.35          | 0       | 0             | 110.8                       | 10.6                | 43.9                      |
| 2                    | A20             | 0.28          | 0.07    | -             | 108.9                       | 10.4                | 43.5                      |
| 3                    | A40             | 0.21          | 0.14    | -             | 111.6                       | 10.6                | 44.2                      |
| 4                    | A60             | 0.14          | 0.21    | -             | 107.8                       | 10.3                | 42.8                      |
| 5                    | B20             | 0.28          | -       | 0.07          | 104.0                       | 9.9                 | 42.8                      |
| 6                    | B40             | 0.21          | -       | 0.14          | 99.8                        | 9.5                 | 42.6                      |
| 7                    | B60             | 0.14          | -       | 0.21          | 99.5                        | 9.5                 | 41.0                      |
| 8                    | C20             | 0.28          | 0       | 0.07          | 104.1                       | 9.9                 | 42.5                      |
| 9                    | C40             | 0.21          | 0.07    | 0.07          | 107.2                       | 10.2                | 42.4                      |
| 10                   | C60             | 0.14          | 0.14    | 0.07          | 100.2                       | 9.5                 | 42.3                      |

Note:
1) S,A,B,C: Admixtures of replacing ganister sand, in turn, it is not replaced, single fly ash, single quartz powder, double mixing fly ash and quartz powder;
2) 0,20,40,60: Mass fractions of admixture are 0%,20%,40%,60% respectively;
3) The contents of admixtures are mass ratios of admixtures to cement content.

2.2 Modeling process
Because the mechanical properties of the reinforcement and concrete are different, in order to better simulate the flexural performance of RPC beam, the separated model is used to simulate the finite element [9], that is, the reinforcement and concrete are regarded as two different units respectively. The reactive powder concrete is analyzed by SOLID65 element, and the longitudinal tensile steel bar, the frame reinforcement and the stirrup are selected by LINK8 unit. In order to prevent the stress...
concentration, four rigid plates with 50mm×150mm are simulated at the top and the bottom of the beam. The finite element model of RPC beam is shown in figure 2, and the element model of reinforcement is shown in figure 3.

The Poisson's ratio of reactive powder concrete is 0.20, and the Poisson's ratio of reinforcement is 0.30. The finite element analysis of the reinforcement in the beam use bilinear kinematic model (Bkin) and Von Mises yield criterion. In the process of solving, the shear transfer coefficients of concrete opening crack and closed crack are 0.5 and 0.95 respectively, and the uniaxial compressive strength is -1, that is, the crushing function is closed. The number of loading step iterations is set to 60, the output frequency is set to write every substep, the maximum cycle number is set to 20 in the Nolinear option. The displacement convergence criterion is used to analyze, and the convergence accuracy is set to 1.5%.

3. Results and analysis of finite element simulation

3.1 Loads and mid-span deflections of RPC beams under the initial cracking moment

Figure 4 are the cracking loads of RPC beams with different admixtures under the initial cracking moment. It can be seen from the figure that the cracking load of group S0 with 100% ganister sand content is 52.9kN. For the RPC beams with single fly ash (group A), the cracking load of group A40 is 53.7kN, which is 1.5% higher than that of group S0, but the cracking loads of group A20 and A60 are reduced. This is because the particle size of fly ash is smaller than that of cement particles, and the surface of the particles is smooth and spherical. In the mixing process, fly ash produces ball effect and fills the gaps of particles, thus the fluidity and compactness of RPC paste are improved. And the second hydration reaction of fly ash produces a large amount of gel that fill in the gaps of aggregates, the particle size distribution is further improved, so the strength of concrete is improved. However,
when the content of fly ash is small, the activity of fly ash is less. When the content of fly ash is large, the hydration product of cement is not enough to excite the activity of fly ash, and the strength of concrete caused by fly ash is less than that caused by the decrease of ganister sand. For the RPC beams with single quartz powder (group B), the cracking loads are lower than that of group S0. This is because the particles of quartz powder have many edges, while the particles of ganister sand are spherical. Under the same conditions, the RPC paste with quartz powder has poor fluidity, and the pozzolanic effect of quartz powder is difficult to play under normal temperature, thus the strength of concrete is reduced. For the RPC beams with double fly ash and quartz powder (group C), the cracking loads are lower than that of group S0, but group C40 has the least reduction. This is because the pozzolanic effect of fly ash is better, and the addition of quartz powder improves the particle size distribution, thus the strength of concrete is less reduced. When the content of fly ash is 40%, the cracking load of RPC beam is the highest, and the cracking load of RPC beam is the lowest when the content of quartz powder is 60%.

Figure 5 are the mid-span deflections of RPC beams with different admixtures under the initial cracking moment. It can be seen from the figure that the mid-span deflections of RPC beams with different mixing methods and different contents of fly ash and quartz powder are similar, so it can be considered that different mixing methods and different contents of admixtures have little influence on the mid-span deflections of RPC beams under the initial cracking moment.

3.2 Equivalent cracking stress cloud charts
Figure 6 are the equivalent cracking stress cloud charts of RPC beams with different admixtures. It can be seen from the figure that the maximum compressive stress occurs in the compression zone of the middle and upper part of the RPC beam under the initial cracking moment. The maximum compressive stress of group S0 is 6.43MPa. For group A, the maximum compressive stress of group A40 is 6.53MPa, which is 1.6% higher than that of group S0, but the maximum compressive stresses of group A20 and A60 decrease. For group B, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0, but group C40 has the least reduction. When the content of fly ash is 40%, the maximum compressive stress of RPC beam is maximum, and the maximum compressive stress of RPC beam is minimum when the content of quartz powder is 60%.

3.3 Loads and mid-span deflections of RPC beams under the yield moment
Figure 7 are the yield loads of RPC beams with different admixtures under the yield moment. It can be seen from the figure that the yield load of group S0 is 309.9kN. For group A, the yield loads of RPC beams are both higher than that of group S0, and the maximum yield load of group A40 is 314.7kN, which is 1.5% higher than that of group S0. This is because a proper amount of fly ash can improve
the strength of concrete, but when the amount of fly ash is large, the activity of fly ash is not fully played, and the strength is increased a little. For group B, the yield loads are lower than that of group S0. For group C, the yield loads are lower than that of group S0, but group C40 has the least reduction. When the content of fly ash is 40%, the yield load of RPC beam is the highest, and the yield load of RPC beam is the lowest when the content of quartz powder is 60%.

![Figure 7 The yield load of RPC beams](image1)

![Figure 8 The yield mid-span deflection of RPC beams](image2)

Figure 8 are the mid-span deflections of RPC beams with different admixtures under the yield moment. It can be seen from the figure that the mid-span deflection of group S0 is 34.5mm. For group A, the mid-span deflections of RPC beams are both higher than that of group S0, and the maximum mid-span deflection of group A40 is 37.5mm, which is 8.7% higher than that of group S0. For group B, the mid-span deflections are lower than that of group S0. For group C, the mid-span deflection of group C40 is higher than that of group S0, while the mid-span deflections of group C20 and C60 are lower than that of group S0. This is because the stiffness of RPC beams with different admixtures has no distinct difference, so the greater the yield loads are, the greater the deflections are.

3.4 Equivalent yield stress cloud charts

Figure 9 are the equivalent yield stress cloud charts of RPC beams with different admixtures. It can be seen from the figure that the maximum compressive stress occurs in the compression zone of the middle and upper part of the RPC beam under the yield moment. The maximum compressive stress of group S0 is 70.23MPa. For group A, the maximum compressive stresses are higher than that of group S0, and the maximum compressive stress of group A40 is 73.57MPa, which is 4.8% higher than that of group S0. For group B, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0. For group C, the maximum compressive stresses are lower than that of group S0.
3.5 Load-deflection curves

Figure 10 are the load-deflection curves of RPC beams with different admixtures. It can be seen from the figure that the changing trends of curves are basically the same, and it indicates that the mixing methods and contents of admixtures have little influence on the rigidity of the beams. Therefore, the deflections of the beams have little difference under the same load.

4. Simulation formulas of cross-section flexural capacity of RPC beams

4.1 Calculation formulas of cross-section flexural capacity of RPC beams

Because of the high tensile strength of RPC, it is necessary to consider the contribution of concrete in tension zone when calculating the flexural capacity of RPC beams. In this paper, Wenzhong Zheng's calculation formula [10] of cross-section flexural capacity is taken as the basic formula:

\[ M_u = \alpha f_c b x \left( h_0 - \frac{h}{2} \right) - k f_y b \left( h - \frac{x}{\beta} \right) \left[ 0.5 \left( h - \frac{x}{\beta} \right) - a_s \right] \]

\[ M_u = \alpha f_c b x \left( h_0 - \frac{h}{2} \right) - k f_y b \left( h - \frac{x}{\beta} \right) \left[ 0.5 \left( h - \frac{x}{\beta} \right) - a_s \right] \]  

(1) 

(2)

Where: \( M_u \) is cross-section flexural capacity of RPC beam, \( f_c \) is design value of RPC axial compressive strength, \( f_y \) is design value of RPC axial tensile strength, \( f_y \) is tensile strength design value of longitudinal reinforcement, \( A_s \) is sectional area of longitudinal tensile reinforcement, \( a_s \) is the distance between the center of longitudinal tensile reinforcement and the tensile edge of section, \( \alpha \), \( \beta \)
are equivalent rectangular stress diagram coefficients in compression zone, \( \alpha = 0.9 \), \( \beta = 0.77 \), \( k \) is equivalent rectangular stress diagram coefficient in tensile zone, \( k = 0.25 \), \( x \) is height of compression zone, \( b \) is section width, \( h \) is section height, \( h_0 \) is effective height of cross section.

Considering the influence of different mixing methods and different contents of fly ash and quartz powder on the cross-section flexural capacity of RPC beams, the formula (2) is modified:

\[
M_{u1} = (1 + a\lambda)M_u
\]  

(3)

Where: \( M_{u1} \) is cross-section flexural capacity of RPC beam with different admixtures, \( a \) is coefficient related to admixture, \( \lambda \) is characteristic value of admixture content.

Taking group A40 as an example, according to the physical performance index, the specific surface area of fly ash is 0.34m\(^2\)/g, and the specific surface area of quartz powder is 20m\(^2\)/g, 
\[
\lambda = \rho_s = 0.34 \times 0.14 / 1.35 = 0.035,
\]
where: \( \rho \) is specific surface area of admixture, \( s \) is admixture content, that is, the ratio of admixture to cementitious material. \( M_u = 69.78 \text{kN} \cdot \text{m} \), \( M_{u1} = 70.6 \text{kN} \cdot \text{m} \), substituting into the formula (3) and obtaining \( a = 0.3338 \). Similarly, group A20’s \( a = -1.1397 \) and group A60’s \( a = -0.4562 \), the average of 3 groups is \( a = -0.4207 \). Therefore, the calculation formula of flexural capacity of the RPC beams with single fly ash can be obtained:

\[
M_{u1} = (1 - 0.4207\lambda)M_u
\]  

(4)

Similarly, the calculation formula of flexural capacity of the RPC beams with single quartz powder can be obtained:

\[
M_{u2} = (1 - 0.0091\lambda)M_u
\]  

(5)

The calculation formula of flexural capacity of the RPC beams with fly ash and quartz powder can be obtained:

\[
M_{u3} = (1 - 0.0173\lambda)M_u
\]  

(6)

4.2 Comparison between the calculated values and the simulated values

Table 2 are the results of comparison between the calculated values and the simulated values on cross-section flexural capacity of RPC beams. It can be seen from the table that the average value of the calculated values / simulated values is 0.999, the standard deviation is 0.009, the coefficient of variation is 0.009. It shows that the calculated values are in good agreements with the simulated values. The formulas can be used to calculate the flexural capacity of RPC beams with different mixing methods and different contents of fly ash and quartz powder.
5. Conclusions
The paper analyzes the cracking loads, the yield loads and so on of reactive powder concrete beams with different mixing methods and different contents of fly ash and quartz powder under the initial cracking and the yield moment. The following conclusions are obtained:

(1) Under the initial cracking moment, the cracking load of group A40 is higher than that of group S0, but the cracking loads of other groups are reduced. The differences of the mid-span deflections of RPC beams are small, and the variation of the maximum compressive stress is the same as that of the cracking load.

(2) Under the yield moment, the yield loads of group A are higher than that of group S0, yet the yield loads of other groups are reduced. The variation of the mid-span deflections is similar with that of the yield load, and the variation of the maximum compressive stress is the same as that of the yield load.

(3) The maximum compressive stresses occur in the compression zone of the middle and upper part of the RPC beams under the initial cracking and the yield moment.

(4) In this paper, the contribution of concrete in tension zone to the cross-section flexural capacity is considered, and the formulas for calculating flexural capacity of reactive powder concrete beams with different mixing methods and different contents of fly ash and quartz powder are derived.

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