The fractal characteristics of C80 high performance concrete pore structure subject to high temperatures

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Abstract. The pore structure of C80 high-performance concrete (HPC) without and with 0.2% polypropylene fiber (PPHPC) was tested by mercury intrusion porosimetry, combining with fractal theory, the high temperature, PP fiber, pore parameters and fractal dimension was discussed. Results showed that porosity, the most probable pore size, the volume intermediate pore size and the threshold pore size all increase with the rising of temperature, the deterioration of the internal pore structure becomes serious. The pore growth rate of HPC is higher than PPHPC, and the porosity of HPC is about the same as PPHPC at 600℃. With temperature gradually increased, the fractal dimension of HPC increases first and then decreases, and the PPHPC shows a decreasing trend as a whole. The incorporation of PP fibers improves the internal connectivity of materials, reduces the deterioration of micro-structure after high temperature.

1. Introduction
The research on concrete’s high temperature performance dates back to 1902. So far, it is definite that when any concrete of certain proportion is exposed to high temperature, every mechanics index will be in the state of decaying[1-5]. When the temperature is 800℃, there will be no strength in the concrete. Compared with the ordinary concrete, HPC’s strength loss rate is higher[1][3][6][7], and it is more easily to explode[4-5,8-13]. Therefore, the phenomenon of HPC’s explosive spalling under high temperature has been one of the research hotspots at home and abroad.

There hasn’t a consensus on the mechanism of the explosive spalling under high temperature. Nowadays, there are three kinds of spalling mechanism: vapor pressure induced crack mechanism, thermal stress induced crack mechanism, and thermal induced crack mechanism. Many scholars think that vapour pressure induced crack mechanism is the main reason for the HPC’s explosive spalling. That is because of the low internal porosity, the evaporation and escape of the internal vapor will be limited for HPC’s compact structure and the incoherent capillary pores under the high temperature of a fire. And then the similar saturated zone will appear at a certain thickness of HPC. Due to the saturated plug effect, the accumulating vapor pressure, and the internal structure with incoherent and compact pores are considered the main reason for the explosive spalling[1,4,12-14].

At present, the research on HPC’s high-temperature performance ranges from previous macroscopic mechanical property’s deterioration law to microscopic aspects, combined with the advanced testing method such as scanning electron microscope, x-ray diffraction, CT testing, which explains the macroscopic property substantially. About the reason for HPC’s spalling , there is no doubt that it is more effectively to reveal the essence of the macroscopic spalling through the analysis from the microscopic aspects. Nowadays, many scholars hold the view that the root cause of HPC’s
spalling is the compact pore structure. Therefore if the concrete is mixed with the right quantity and size of polypropylene fiber, the pressure in the internal pores of concrete will be effectively released, which will improve HCP’s high-temperature performance[15-21]. Besides, the pore space’s pore-size distribution and connectivity limit HPC’s internal vapor’s permeation, accumulation, diffusion and migration[21-24]. Therefore, a study on the internal pore space’s distribution features of the HPC with polypropylene fiber (PPHPC) is significant.

Fractal dimension is an important parameter to characterize fractal features; pore structure in porous materials has remarkable fractal characteristics. It can be used to evaluate the spatial distribution characteristics of pore surface roughness and pore volume of porous materials. Pore distribution in concrete is irregular and disordered, so the self-similarity of concrete at different sizes and levels can be accurately evaluated by fractal theory[25].

After the high-temperature test of C80 HPC and PPHPC is conducted, mercury intrusion method is adopted to study the sample’s pore structure after high-temperature test, and the variation of pore structure was analyzed. Fractal theory is used to analyze the influence of temperature on volume fractal dimension of high performance concrete.

2. Test program

2.1. Test materials and mix proportion
Concrete specimens were prepared with ordinary Portland cement (P.O. 52.5, China), Fine aggregate (local natural sand, fineness modulus 2.85) ,coarse aggregate (limestone, 5-20 mm continuous grain size), mineral powder(level of S95, China), fly ash ,super plasticizer and polypropylene fiber. Two different types of concrete mixes were prepared, as shown in Table 1. Polypropylene fiber was fascicular monofilament, of which melting point was about 165℃, vaporization temperature was about 340℃, specific gravity was 0.91g/cm3, length is 8mm, and diameter was 25μm.

| Concrete types | Cement | Mineral powder | Fly ash | Water | Super plasticizer | Coarse aggregate | Fine aggregate | PP fiber |
|----------------|--------|----------------|---------|-------|-----------------|-----------------|---------------|--------|
| HPC            | 414    | 128            | 38      | 125   | 7.54            | 1020            | 670           | 0      |
| PPHPC          | 414    | 128            | 38      | 125   | 7.54            | 1020            | 670           | 1.8    |

2.2. Test material preparation
Cube specimens with dimensions of 15 cm×15 cm×15 cm were cast for each mixture according to China national standard GB/T 50081-2002 Standard for Test Methods of Mechanical Properties of Ordinary Concrete. After 24 h of curing, all the specimens were carefully unmolded and then were cured under the conditions of 20 ± 2℃ and 95% humidity for 28 days. The compressive strength of NHPC cube and PPHPC cube is 89.3 MPa and 88.4 MPa respectively, which meet the test requirements. The cubes were incised and drilled by static force, and the cylinders with 6mm in diameter and 10mm in thickness were achieved, which were heated, mercury intruded.

2.3. Test method

2.3.1. Heat treatment
The above test pieces intruded by mercury were heated by the chamber electric resistance furnace SRJX produced by Zhejiang Civil Engineering Instrument Co., LTD. The rated voltage of the electric resistance furnace was 220V, the rated power was 15kW, and the average heating rate was 6℃/min. The maximum temperature was 1200℃, and the temperature in the furnace was controlled by the ancillary temperature controller with display functions.

The target heating temperatures of the test pieces intruded mercury respectively were: room temperature (20℃), 200℃, 300℃, 400℃, 500℃, 600℃. Because the test pieces were not big, they
should be put into the ceramic cup first and then heated in the electric resistance furnace. After the test pieces are put into the furnace, the heating temperature was set. After the furnace temperature reached the target temperature, the temperature would be constant for 10min, and the test pieces would be taken out. When the test pieces were cooled down to room temperature, they would be put into a bottle for reservation. In order to ensure the reliability of the test results, there respectively were 3 concrete test pieces under every temperature.

2.3.2. Mercury intrusion test
The mercury injection Apparatus Pore Master GT60 in the test was produced by America Quanta chrome Instrument Company. The aperture test ranged from 3.6nm to1mm, which was suitable for the aperture analysis of every porous material. Mercury intrusion test’s low pressure ranged from 1.5kPa to 350kPa, and the high pressure ranged from 140kPa to 420MPa. The mercury intrusion test was conducted according to the operating instructions of the test instrument and China national standard GB/T21650.1-2008 Pore Size Distribution and Porosity of Solid Materials by Mercury Porosimetry and Gas Adsorption. Continuous scanning was conducted in the test, and the mercury contact angle was 140°, and the mercury surface tension was 480 erg/cm².

3. Results and analysis

3.1. The analysis of the initial pore pressure
The dV/dP and P double logarithmic curves of HPC and PPHPC under different temperatures were shown in Fig. 1.

![Fig. 1 The dV/dP and P double logarithmic curves under different temperatures (a: HPC, b:PPHPC)](image)

As the Fig.1 shown, there were different characteristics of HPC and PPHPC. The double logarithmic curves were divided into several sections under different temperatures. The lower the temperature was, the more obvious the subsection was. When the temperature was lower than 400°C,
the curve was divided into 2 or 3 sections, and the segment points were mainly on $\lg P = 5.5 \text{Pa}$. When the temperature was higher than 400°C, the curve was prone to being constant, and the linear characteristics appeared. When the temperature was lower than 300°C, the curve of PPHPC was divided into 2 or 3 sections, and the segment points were mainly on $\lg P = 5.5 \text{Pa}$. When the temperature was higher than 300°C, the curve was prone to being constant, and the linear characteristics appeared.

According to Fig. 1, it could be analyzed that when the temperature was relatively low, the segment points were mainly on $\lg P = 5.5 \text{Pa}$, which meant when $\lg P < 5.5 \text{Pa}$, the mercury intrusion test was on the initial period, and the impressed pressure was obviously small. But mercury inflow was relatively large, and the mercury was mainly into the void between the sample and the experimental pipe, the pores on the surface of the sample and the internal pores which were not belong to the test pieces[26]. In order to decrease the test errors, the data collected when the temperature of HPC was lower than 400°C, the temperature of PPHPC was lower than 300°C, and $\lg P < 5.5 \text{Pa}$ would be uniformly deleted. Besides, $\lg P = 5.5 \text{Pa}$ was regarded as the initial air pressure, and the pore volume was minus the initial volume in the test.

3.2. The results of pore-diameter distribution

The results of pore diameter distribution of HPC and PPHPC under different temperatures were shown in Fig. 2. As was shown in Fig. a, the pore diameters at the normal temperature were less than 1μm, which mainly ranged from 20nm to 200nm. At the intervals of 0.01μm–0.1μm and 0.1μm–1μm, there respectively was one peak point, 49nm and 617nm. When the temperature was 200°C, the pore diameters were mainly less than 1μm, but the amount of pores increased obviously. The left of the curve was prone to extending to the interval of 1μm–10μm. Compared with the curve at the normal temperature, on the right of the curve at 200°C which was less than 20 nm, the distribution of the pore diameters increased obviously. At the intervals of 0.01μm–0.1μm and 0.1μm–1μm, there respectively was one peak point, 49nm and 633nm. When the temperature was 300°C, the distribution of pore diameters became obviously widespread. There was an obvious increase at the interval of 1μm–10μm, and there was a peak point 1.665μm. In addition, the distribution of pore diameter which was less than 1μm is in accordance with the curve when the temperature is 200°C. Compared with the curve at 300°C, there was no relatively big change of the pore diameter distribution when the temperature is 400°C. When the temperature was 500°C, there was a distribution of pore diameter at the interval of 0.001μm–1000μm, which meant there was obvious concrete cracking. At the intervals of 100μm–1000μm, 10μm–100μm and 0.01μm–0.1μm, there were obvious peak, and the peak points were respectively 456μm, 14μm and 47nm. When the temperature was 600°C, the distribution of pore diameter at the interval of 0.001μm–1000μm was more obvious. Compared with the curve of 500°C, the number of pore diameters at every interval increased obviously, especially at the interval of 0.1μm–100μm, at which the peak pints increased dramatically.

As is shown in Fig. b, at the normal temperature, the pore diameters of PPHPC were less than 1μm, which were mainly at the interval of the 7.5μm–200μm. The peak points were respectively 17 nm, 43nm and 607nm at the intervals of 0.01μm–0.1μm and 0.1μm–1μm. When the temperature was 200°C, the curve form and the peak point were in accordance with whose of the normal temperature. When the temperature was 300°C, compared with the previous temperature, the distribution of pore increases obviously at the interval of 1μm–10μm, and there was one peak point, 3.55μm. When the temperature was 400°C, compared with the previous curve, obviously there were more peak points at very interval, the curve obviously extend to 100μm, and the number was large. The peak point was 28.14μm at this interval, which means the seriousness of PPHPC’s internal cracking became significant. When the temperature was 500°C, there was the distribution of pore diameter at the interval of 0.001μm–1000μm, which meant the concrete cracks obviously. At the peak, the maximum pore diameter was 501.5μm. The number of pores at the interval of 10μm–100μm was smaller than at other intervals. The curve forms of 600°C were similar to that of 500°C, but the number of pore diameters obviously increased at the interval of 10μm–100μm.
Fig. 2 The distribution of pore diameter under different temperatures (a:HPC,b:PPHPC)

When the pore diameter was less than 1μm, the pore was called as micropore. When the pore diameter was between 1μm and 100μm, the pore is called as mesopore. When the pore diameter was between 100μm and 1mm, the pore was called as macropore. When the pore diameters were less than 1μm, the pores could be divided into more harmful pore (200nm~1000nm), harmful pore (100nm~200nm), less harmful (20~100nm), and harmless pore (<20nm) [27]. The data collected after mercury intrusion were calculated and analyzed, and then the porosities of HPC and PPHPC at every pore-diameter distribution scope after exposure to high temperature are obtained. Table 2 and Table 3 were respectively the porosities of HPC and PPHPC at different scopes after exposure to high temperature.

| Temp/℃ | <20nm | 20–50nm | 50–200nm | 200–1000nm | 1~10μm | 10~100μm | 100~1000μm |
|--------|-------|---------|----------|------------|--------|----------|------------|
| 20     | 1.2   | 48.6    | 34.9     | 11.5       | 3.7    | 0        | 0          |
| 200    | 14.2  | 31.6    | 28.7     | 21.1       | 4.4    | 0        | 0          |
| 300    | 7.6   | 26.6    | 21.8     | 17.5       | 26.5   | 0        | 0          |
| 400    | 2.1   | 36.9    | 25.6     | 14.5       | 16.9   | 4.0      | 0          |
| 500    | 5.9   | 16.5    | 14.3     | 8.4        | 8.2    | 8.4      | 37.9       |
| 600    | 3.9   | 16.3    | 13.5     | 6.3        | 6.6    | 17.4     | 35.9       |
| 700    | 6.4   | 12.5    | 16.3     | 9.8        | 7.8    | 13.7     | 33.5       |

Table 2. The porosity of HPC at different scopes after exposure to high temperature (%)
Table 3. The porosity of PPHPC at different scopes after exposure to high temperature (\%)

| Temp/℃ | <20nm | 1μm | 20~50nm | 50~200nm | 200~1000nm | 1~10μm | 10~100μm | 100~1000μm |
|--------|-------|------|---------|----------|------------|--------|---------|------------|
| 20     | 15.2  | 37.9 | 26.1    | 15.4     | 5.4        | 0      | 0       |            |
| 200    | 11.7  | 37.5 | 29.8    | 15.1     | 5.9        | 0      | 0       |            |
| 300    | 7.8   | 24.1 | 28.8    | 14.0     | 25.3       | 0      | 0       |            |
| 400    | 5.5   | 15.0 | 19.3    | 11.0     | 29.6       | 19.0   | 0.6     |            |
| 500    | 3.2   | 13.8 | 17.1    | 14.0     | 11.9       | 8.8    | 31.1    |            |
| 600    | 4.7   | 11.1 | 10.1    | 10.2     | 8.3        | 36.7   | 19.7    |            |
| 700    | 5.7   | 12.3 | 17.8    | 9.8      | 9.1        | 14.6   | 30.7    |            |

It could be seen from Table 2 and 3 that with the increase of temperature, the material’s internal pore-diameter distribution increased gradually. From room temperature to 200 ℃, HPC and PPHPC were mainly less than 1μm, which were mainly micropores, and the porosities of more harmful pores and harmless pores of HPC increased by about 10% compared with whose of normal temperature, while the porosities of harmful pores and harmless pores respectively decreased by about 10%. There was no obvious change in the porosities of PPHPC, indicating that the additional pore volume was not provided after melting of polypropylene fibers. And the molten objects still occupied the original space. Furthermore, the addition and melting of fibers could refine and uniformly distribute the pore structure. There was significant change in the porosities of HPC and PPHPC with pore diameters between 1μm and 10μm, which increased significantly to over 25% at 300 ℃. There was no significant change in porosity of HPC at 400 ℃, but 19% of PPHPC’s pores were mesopores (10μm~100μm). At 500 ℃ and higher temperature, the HPC and PPHPC’s pores began to be distributed in each pore-diameter range, which were mainly dominated by meso-macropores. In general, the harmful pores accounted for more than 60% at 500 ℃, which was the initial temperature at which the pores were seriously deteriorated.

The biggest difference between HPC and PPHPC was that the contents of polypropylene fiber were different, but from room temperature to 300 ℃, although the pore volume increased, the overall pore-diameter distribution showed good consistency, and there was no obvious difference because of the mixing of polypropylene fiber. When the temperature was 400 ℃, the obvious difference appeared in PPHPC pore-diameter distribution.

3.3. Pore structure parameters

Table 3 gave the results of the pore structure characteristic parameters of HPC and PPHPC at various temperatures. In this paper, the porosity refers to the ratio of the volume of mercury pressed into the sample to the volume of mercury pressed into it. The most probable pore diameter referred to the pore volume with the largest volume change when the pore size changed. The volume intermediate pore diameter was the 50% of the intruded mercury volume, the corresponding equivalent pore diameter. The threshold pore diameter referred to the corresponding maximum pore diameter when the mercury was intruded and the volume increased significantly.
Table 4. Characteristic parameters of internal pore structure of NHPC and PPHPC measured by mercury intrusion method

| Parameters                | HPC     | Temperature/℃ | PPHPC   | Temperature/℃ |
|---------------------------|---------|---------------|---------|---------------|
| Porosity /%               |         | 20            | 200     | 300           | 400     | 500     | 600     |
|                           |         | 3.710         | 5.440   | 7.590         | 12.530  | 23.510  | 51.780  |
|                           |         | 4.670         | 5.030   | 10.250        | 14.960  | 23.510  | 32.300  |
| most probable pore diameter/μm |         | HPC           |         | PPHPC         |         |
|                           |         | 0.049         | 0.633   | 1.700         | 14.000  | 834.400 | 502.000 |
|                           |         | 0.043         | 0.621   | 3.600         | 28.100  | 501.500 | 541.100 |
| volume intermediate pore diameter/μm |         | HPC           |         | PPHPC         |         |
|                           |         | 0.050         | 0.070   | 0.084         | 0.620   | 3.510   | 4.620   |
|                           |         | 0.048         | 0.051   | 0.079         | 0.800   | 1.530   | 3.210   |
| threshold pore diameter/μm |         | HPC           |         | PPHPC         |         |
|                           |         | 0.049         | 1.460   | 2.510         | 2.700   | 3.510   | 26.240  |
|                           |         | 0.054         | 2.010   | 3.550         | 4.780   | 4.120   | 24.450  |

The results in Table 4 showed that the parameters of the pore volume, the most probable pore diameter, the volume intermediate pore diameter and the threshold pore diameter of HPC and PPHPC increased significantly with the temperature increasing. Compared with room temperature, the average increased rates of HPC’s pore volume at 200 °C, 300 °C, 400 °C, 500 °C and 600 °C were respectively about 46.9%, 104.9%, 238.3%, 534.6%, 1297.5%, while those of PPHPC are about 7.8%, 119.6%, 220.6%, 403.9%, and 592.2%. It could be seen from the table that with the increase of temperature, each parameter showed an increasing trend, and the variation range was the largest when the temperature is 500°C.

It was worth mentioning that after 500 °C, the mercury volume of HPC was close to and gradually overtakes PPHPC, indicating that the mixing of polypropylene fiber improved the internal connectivity of the materials and alleviated the deterioration of concrete material after elevated temperature.

3.4. Discussion

3.4.1. Discussion on pore structure parameters change with temperature

At normal temperature, there are many kinds of pores in the hydrated cement slurry, mainly: ① the pores among the particles in the C-S-H interlayer, of which the size range is 1nm~4nm; ② capillary pores, of which the size range is 10nm~1000nm. In the fully hydrated slurry with low water-cement ratio, the capillary pores are concentrated in the range of 10nm~50nm, and the water present in the pores above 5 nm is called as capillary water; ③ the C-S-H particle aggregate, of which the size range is 700nm~8μm; ④ Ca(OH)₂ and low-sulphur sulphoaluminate hexagonal crystals in cement paste, of which the size range is 700nm~10μm; ⑤ introduced bubbles, of which the size range is 500μm~1mm; ⑥ introduced pores, of which the size is generally larger than 1mm[5].

As mentioned before, as the temperature increases, the pore structure parameters of the concrete material will change. The main reason for the change of pores is that when the temperature is lower than 200 °C, the moisture in the pores of the material is in the state of evaporation, so the size change always varies around 10 nm to 1000 nm. When the temperature reaches 200 °C or higher, the test pieces are in the physical dehydration process, that is, the evaporation of free water. When the temperature reaches 300 °C, the cement slurry loses the water between the CSH layers, and the hydrated sulphoaluminate begins to decompose[5,21,28]. At 400 °C, a large amount of water begins to evaporate, and calcium hydroxide begins to decompose into calcium oxide, and the chemical reaction is Ca(OH)₂→CaO+H₂O. At 500 °C, the calcium hydroxide is completely decomposed. When the temperature is higher than 600 °C, limestone, the main component of the coarse and fine aggregates begins to decompose, and the chemical reaction is CaCO₃→CaO+CO₂[29-32].
3.4.2. Discussion on mechanism of high-temperature action of polypropylene fiber

Regarding the role of fibers in preventing spalling, it was believed that the melting of the fiber can provide additional pore volume, so that the moisture inside the material was more likely to be lost[1][13][14][15][16][17]. However, the results indicate different points that polypropylene fiber play different roles in inhibiting of concrete’s spalling under high temperature.

Under normal temperature, Polypropylene fiber is an organic material, and its bonding effect with cement-based slurry is relatively poor. The pore volume of PPHPC is higher than NHPC. According to Figure 2, PPHPC has three peaks below 1μm, and the pore-diameter distribution is relatively uniform. This is because the polypropylene fiber is organic, and distributed in three dimensions in the concrete materials, which can refine and uniformly distribute the pore diameters. Especially, the number of the pore diameters less than 20nm is more than that of NHPC. This can illustrate that the blending of polypropylene fibers can refine and uniformly distribute the pore size.

At 200 °C, the capillary pores’ water evaporates and escapes, leaving pores and causing peak differentiation of NHPC. A peak point appears between 100nm and 1000nm, and from 10nm to 20nm peaks’ sharpening is obvious. However, the pore-diameter distribution and curve form of PPHPC are almost in accordance with those at room temperature, this means the melting of polypropylene fiber does not increase the extra excess pore volume, and it does not increase excess porosity due to evaporation of water. This is because that the fiber melts at about 165 °C, the viscous objects remain in the original pores after melting, indicating the pores are not released, and at the normal temperature, the refining and distributing pore diameters uniformly effects of polypropylene fiber lead that the water in the capillary pores can evaporate and escape through the original pores. There is no need to produce additional pores to evaporate water.

At about 350 °C, the melted fiber vaporizes and the original occupied space is completely released. Therefore, at 400 °C, PPHPC has a pore-diameter distribution of 10μm–100μm before NHPC, and the most probable pore diameter at 400 ° C is 28.14 μm. The reason is that polypropylene fiber of the diameter of 25 μm releases space after vaporization.

When the temperature rises to 500 °C, under the same conditions, the mercury volume of HPC is close to and gradually overtakes that of PPHPC, indicating that the addition of polypropylene fiber has a significant effect on the internal pore distribution of the concrete materials, which can reduce the further deterioration of the materials after high temperature. The reason is that as the temperature rises, the cement hydration products are further dehydrated and decomposed, and the internal pores gradually increase. To some extent, the increased pores are connected with the melted channels of the fiber to form continuous pores. Therefore, the internal connectivity is significantly improved, so that the vapor pressure inside the materials is more easily diffused and consumed from the inside of the materials, and the pore pressure can be alleviated, and correspondingly, the damage of the materials can be alleviated.

4. Fractal

Fractal dimension is a function of porosity and pore size distribution[33]. The fractal dimension calculated by different mathematical models is different. In this paper, fractal dimension model is used to simulate mercury intrusion test[34]. The concrete is a porous structure, and the research on concrete pore structure is mostly based on Menger cavernous model. The basic process of Menger cavernous model is as follows: there is a cube with side length of R, each side is divided into 3 sections, from the 33 small cubes, 6 small cubes in the middle of the face and 7 small cubes in the centre of the body are dug out. At this time, the fractal dimension is \[ D = \frac{\log 20}{\log 3} \]. In this mode, there is a cube with side length of R, each side is divided into m sections, from the m^3 small cubes; n small cubes are dug out, the remaining m^3-n cubes iterate over k times, the minimum side length of cube element \( r_k \) is received.

\[
r_k = \frac{R}{m^k}
\]

\[
k = \frac{\log(R/r_k)}{\log m}
\]

Suppose D represents fractal dimension, and it shows as follows:
The number of remaining cubes \( N_k \) is showed as follows:

\[
N_k = (m^3 - n)^k
\]

Substituting Eq. (1) and (3) into Eq. (4) yield

\[
N_k = (m^3 - n)^k = (r^k - R)^{-\beta(m^3 - n)^{\gamma n}} = (r^k - R)^{-D}
\]

The porosity \( P \) is defined as follows:

\[
P = \frac{R^3 - (r_k / R)^D \cdot r_k^{-1}}{R^3} = 1 - (r_k / R)^{-D}
\]

So, the fractal dimension \( D \) is showed as follows:

\[
D = 3 - \frac{\lg(1 - P)}{\lg(r_k / R)}
\]

According to the results obtained by mercury intrusion method, the slope can be obtained, and then the volume dimension of the pore can be directly calculated. The pore structure of concrete after high temperature has multifractal characteristics. The pore structure is divided into < 50 nm and > 50 nm. The fractal results are shown in Fig. 3.

![Fig. 3 Fractal dimension of concrete pore at different temperatures](image)

Fig. 3 shows that: 1) For the same type of concrete, the change trend of fractal dimension with the increase of temperature is roughly the same. 2) The fractal dimension of HPC is larger than that of PPHPC, which indicates that the damage degree of HPC is greater than that of PPHPC, and PP fiber can slow down the deterioration of internal porosity of concrete. 3) At room temperature, the fractal dimension of HPC is lower than that of PPHPC. According to Table 2, the pore size of HPC is 83.5% between 20 and 200 nm, and the pore concentration is high. The pore size of PPHPC is uniform in the range of 1 micron. This shows that the fractal dimension depends on the pore distribution range when the porosity is constant. The narrower the range is, the smaller the fractal dimension is. Therefore, the fractal dimension of PPHPC is larger in the range of 1 micron. 4) The fractal dimension of HPC increases before 400°C, then decreases. The fractal dimension of PPHPC decreases as a whole. According to Table 3, the pore size distribution of HPC is more uniform in the range of 1 micron at 200°C. The original larger pore size begins to shift to the left (<20 nm) and right (<200 nm~1000 nm), and the pore size begins to homogenize, while the pore size distribution of PPHPC does not change much at room temperature. Therefore, the fractal dimension of HPC increases greatly, while that of PPHPC changes little. 5) The fractal dimension of both kinds of concrete decreases after 400 °C, which may be caused by the thermal decomposition of calcium hydroxide crystals at 500 °C, the damage of aggregates and the serious deterioration of materials. The original micro-pore is interconnected and fused, and deteriorated into micro-macro-pore (accounting for more than 50%). The porosity increases obviously, so the fractal dimension. The fractal dimension \( D \) decreases with the increase of porosity when the pore distribution range is fixed.
5. Conclusions

(1). With the increase of temperature, the porosity, the most probable pore diameter, the volume intermediate pore diameter and the threshold pore structure parameters of HPC and PPHPC are obviously increased, and the high temperature causes the cracking of concrete’s internal pore structure.

(2). At normal temperature, HPC and PPHPC are mainly micropores. With the increase of temperature up to 500 °C, the pores begin to be dominated by macropores, and the proportion of harmful pores is more than 60%. 500 °C is the starting temperature at which the pore structure begins to deteriorate seriously.

(3). When the C80 HPC is mixed with Polypropylene fiber, polypropylene fiber has different inhibiting effects on the spalling under each temperature. At room temperature, the fiber refines and uniformly distributes the pore structure. At 200 °C, the fiber melts and still occupies the original space after molten. The pore volume does not increase, and the water evaporation does not cause the increase of pores. Compared with the normal temperature, The pore-diameter distribution and the porosity are high consistent. At 400 °C, the fiber is completely vaporized, and the original occupied space is completely released. Compared with NHPC, PPHPC first peaks at a fiber diameter of 25 μm. After 500 °C, the released pores and the deterioration of the materials increase the connectivity among pores, and lower the deterioration rate of the materials’ internal damage.

(4). Temperature and pore size distribution have different effects on fractal dimension. Before 300°C, The pore size distribution of PPHPC is larger and more uniform than that of HPC, and its fractal dimension is higher than that of HPC. After 300°C, the deterioration of concrete material accelerates, the porosity increases, and the fractal dimension decreases as a whole. 500°C is the initial temperature for serious deterioration of pore structure, and the fractal dimension decreases significantly. The fractal characteristics of HPC are improved obviously by adding polypropylene fibers.

(5).The incorporation of PP fibers improves the internal connectivity of materials, reduces the deterioration of micro-structure after high temperature.

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