



Article

The Study of the Three-Parameter Normal Distribution Characteristics of the Pore Structure in C80 High-Performance Self-Compacting Concrete (HPSCC)

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Abstract: To investigate the distribution characteristics of the micropore structure in high-performance self-compacting concrete (C80), high-resolution X-ray computed tomography, AVIZO software (version 2024.1), and scanning electron microscopy were employed to observe and analyze the internal pore structure of C80 self-compacting concrete specimens. The main conclusions are as follows: There is a large number of pore structures within the carbonate rock-based high-performance self-compacting concrete. At a testing precision range of 10 μm , the micropores exhibit a circular feature with good overall circularity. Observations through SEM, scanning electron microscopy, reveal that there are micro-cracks or interconnected crack structures within the high-performance concrete, with widths ranging from 0.5 to 2 μm , and the sample contains tiny voids of 3 to 10 μm . A statistical analysis of the micropores within the carbonate rock-based self-compacting concrete indicates that the pore diameter follows a three-parameter normal distribution. Due to the limitations of experimental observation and precision, the experimental statistical results show a positively skewed (high peak and left-skewed) phenomenon. This paper proposes a “correction of skewed peak” method for the analysis and discussion of the calculation of the “third parameter C” in the statistical results. The results show that the method proposed in this paper can quickly, objectively, and optimally determine the third parameter, compensating for the missing data not accounted for below 10 μm and the limitations of the finite number of experimental samples, providing a reference for examining the distribution of pores within concrete.

Keywords: C80 high-performance self-compacting concrete (HPSCC); pore structure; three-parameter normal distribution; CT imaging analysis



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1. Introduction

High-performance self-compacting concrete (HPSCC) is a novel composite material made from cement as the base material, high-strength materials as coarse and fine aggregates, and mixed with admixtures such as high fluidity, micro-expansion, and anti-segregation characteristics, which provides good crack resistance. HPSCC, due to its excellent fluidity and high compressive strength, is widely used in the structures of super high-rise buildings; densely reinforced and complex-shaped structures, bridges, tunnels, and underground engineering structures; nuclear power plant construction; marine port and wharf engineering; protective fortifications and military works; and industrial facility construction. It can effectively improve the seismic performance, bending and tensile strength, and durability of structures, reducing construction difficulty and costs.

HPSCC incorporates air into the mixture during the stirring process, forming bubbles. After hardening, the concrete structure contains a large number of structurally discontinuous and irregularly shaped micropores. The size and distribution of these micropores significantly affect the mechanical behavior upon failure, the permeability, and the durability of the concrete. Currently, experimental methods for studying the internal void structure of concrete include scanning electron microscopy, X-ray CT [1], mercury intrusion porosimetry, the straight-line method and area ratio method [2], and nuclear magnetic resonance imaging analysis techniques.

The quality of concrete's mechanical and durability properties is not only related to the internal pore structure of the concrete but also to the number, size, distribution, and air void spacing of the pore system's characteristic parameters [3]. Researchers, by testing the pores within the concrete, have attempted to establish relationships between parameters such as pore distribution and porosity with indicators such as compressive strength, frost resistance, and durability [4–6].

Zhao Shiyang [7] and others, through experimental techniques such as electron microscopy scanning and mercury intrusion porosimetry, found that an appropriate amount of air-entraining agents, when combined with fly ash and silica fume, can reduce bubble spacing and improve the pore structure. Chen Yanwen [8,9] and others discovered that as the salt freeze time increases, the internal pore structure of concrete deteriorates, and increasing the air content can enhance the concrete's frost resistance. Yang Shuai and others [6] used low-field nuclear magnetic resonance imaging analysis technology and found that the porosity of concrete gradually increases with the increase in sand ratio and initial air content. Sun Lei and others [10] found that there is a negative correlation between porosity, the average chord length of air voids, and compressive strength and a positive correlation between the bubble spacing coefficient and compressive strength. The impact of the content of pores of different diameters on strength varies, with a higher content of small pores leading to higher compressive strength. Ridengaoqier E [11] and others proposed a physical model of permeable concrete composed of pores, aggregates, and cement paste, studying the relationship between the elastic modulus and porosity of permeable concrete. Ye Linjie and others [12,13] found that as the porosity decreases, the compressive strength of foam concrete shows an exponential growth trend.

Different regions' sand and gravel, different manufacturers' mineral admixtures, and different additives have a significant impact on the pores and their distribution within a concrete structure [14]. Research has found that the average pore diameter and spacing within concrete increase with the increase in increase of the water–cement ratio, while the compressive strength of concrete shows an opposite trend [15]. Fly ash [16] can improve the internal pore structure of concrete and, thus, has a significant impact on the compressive strength of concrete. Zeng Zhi [17] and others found that there is a good correlation between the comprehensive factor of the pore structure of steel slag–slag foam concrete and its compressive strength. G. Lifshitz Sherzer [18] proposed the concept of a “fictitious” water–cement ratio (w/c) to study the characteristics of the increase in material porosity and the changes in the microstructure of concrete. The amount of water used is an important indicator affecting the porosity content of concrete; excessive free water [19,20] will produce capillary pores within the concrete, which is equivalent to increasing the water–binder ratio and will also increase the number of pores within the concrete, significantly improving the compressive strength.

Yang Zhe [21] analyzed the pore structure characteristics, mechanical properties, and durability of concrete under different atmospheric pressure environments. Xu Fang [22], using the physical foaming method, observed the micro-morphology of the internal pore structure of polymer concrete under different pre-foamed foam mix ratios. Li Fangxian [23] established dense packing models and non-dense packing models, and derived formulas for calculating the main parameters of the pore structure, including porosity, air void internal surface area, and air void wall thickness, based on different theoretical models. Ridengaoqier E [24] detected the porosity of permeable concrete through ultrasonic testing

and proposed an approximate quadratic function relationship between ultrasonic velocity and concrete porosity.

In summary, both domestic and international research has been conducted on the pore structure and distribution of concrete materials [25–27], but there has been no relevant report on the characteristics of the internal pore structure distribution of high-performance concrete, especially for HPSCC prepared with carbonate rock-based manufactured sand and crushed stone as aggregates in the southwest region of China. Carbonate rocks, with calcite and dolomite as the main metamorphic minerals, are widely distributed in the karst regions of the southwest, such as Yunnan, Guizhou, Guangxi, Hunan, Sichuan, Chongqing, Guangdong, and Hubei, covering eight provinces, cities, and regions. These carbonate rocks have complex structural components, developed biological relics, and characteristics such as easy solubility and weathering [28], but they are indeed a good alternative raw material for manufactured sand and stone.

This article takes the carbonate rock mine in the Bijie area of Guizhou Province as the parent rock and produces manufactured sand and crushed stone through processes such as mechanical crushing, shaping, screening, and powder control. These are used to replace natural sand and stone in the preparation of C80 HPSCC. By employing industrial CT scanning, SEM scanning, and other techniques, a predictive model for the internal pore distribution within HPSCC is established. The research findings will provide a reference to further enrich and perfect the damage theory and durability studies of HPSCC.

2. Sample Preparation

2.1. Experimental Materials

The materials required for preparing the HPSCC experiment include cement, carbonate rock-based manufactured sand, carbonate rock-based gravel, slag powder, silica fume, microspheres, expansive agent, water reducer, etc.

The cement is P.O 42.5 ordinary Portland cement, produced by “Luzhou Said Cement Co., Ltd. (Luzhou, China)”, with a standard consistency of 26.8%, an initial setting time of 125 min, a final setting time of 223 min, an average value of mortar fluidity of 210 mm, representative values of flexural strength at 7 days of 6.1 MPa, and a compressive strength of 33.8 MPa. The flexural strength of this cement at 28 days is 7.6 Mpa, and the compressive strength is 50.7 Mpa. The particle size distribution of cement was analyzed by a laser particle size analyzer as shown in Figure 1.

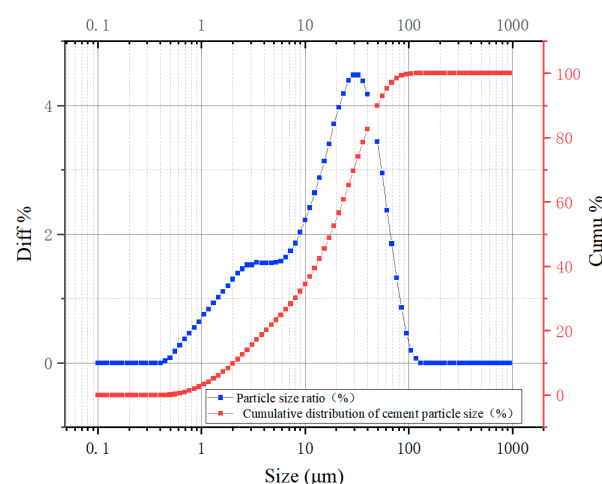


Figure 1. Cement particle size distribution and particle size cumulative distribution diagram.

To improve the strength of concrete and reduce the amount of cementitious materials, we selected two sizes of crushed stone as coarse aggregate. The first type is “melon gravel” with a diameter ranging from 5 mm to 10 mm, and the second type of crushed stone has a diameter between 10 mm and 16 mm.

The machine-made sand used in the experiment was prepared by Guizhou Panshi Building Materials Company. The grading sieve residue and cumulative sieve residue of the manufactured sand were measured, with the results presented in Figure 2.

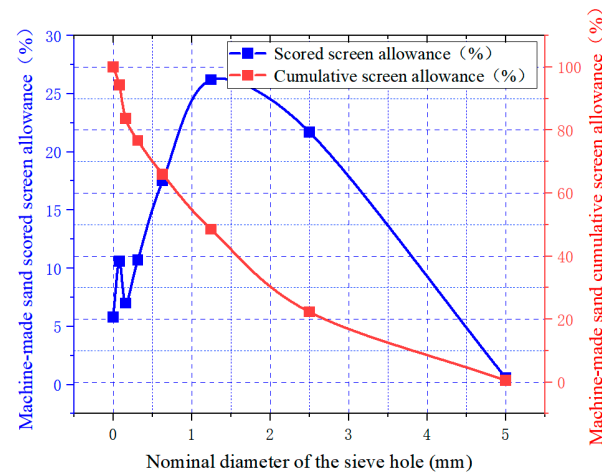


Figure 2. Machine-made sand scored screen allowance and cumulative screen allowance.

The slag powder and expansion agent used in the experiment were provided by Guizhou “Guixin Building Materials Co., Ltd. (Chongqing, China)”. The silica fume, microspheres, and expansive agent used in the experiment were provided by China Railway 11th Bureau Group Co., Ltd. (Shiyan, China)., according to GB/T176-2017 <<Method for chemical analysis of cement>>, GB/T8074-2008 <<Method for determination of specific surface area of cement, Bosch method>>, and JC/T721-2006 <<Method for determination of gradation of cement particles, laser method>>. The samples were randomly selected and submitted to Guizhou Building Materials Quality Inspection and Testing Institute for testing. The fineness (specific surface area) of slag powder was 462 m²/kg, and the particle size distribution of slag powder was analyzed by a laser particle size analyzer as shown in Figure 3. The fineness (specific surface area) of microspheres was 1520 m²/kg, and the particle size distributions of S95 slag powder, silica fume, microspheres, and expansion agent were analyzed by a laser particle size analyzer as shown from Figures 3–6. The mineral composition and the content of experimental materials are shown in Table 1.

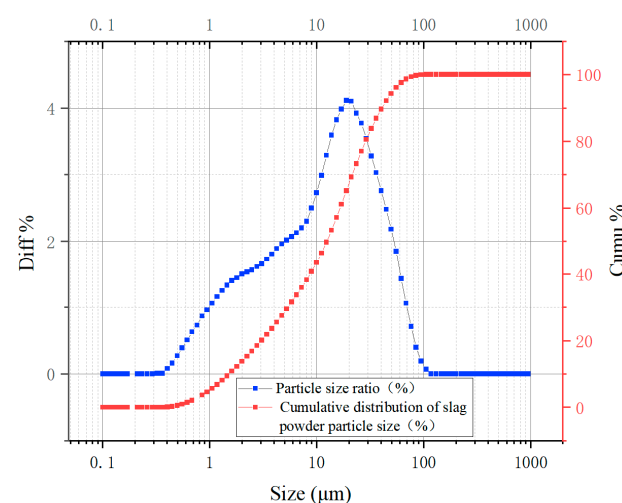


Figure 3. S95 Slag powder particle size distribution and particle size cumulative distribution diagram.

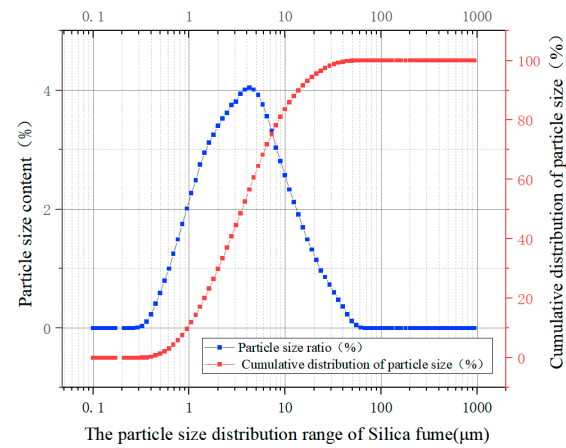


Figure 4. Silica fume particle size distribution and particle size cumulative distribution diagram.

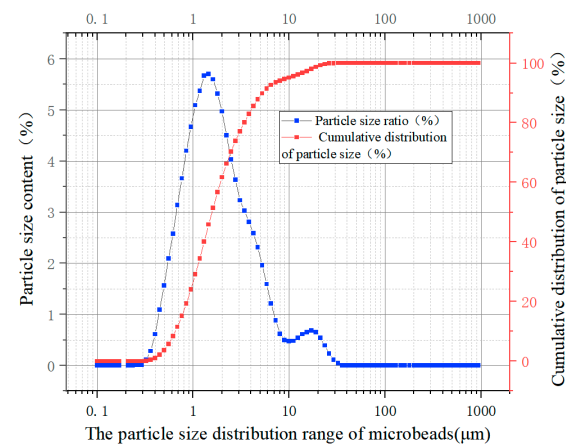


Figure 5. Microsphere particle size distribution and particle size cumulative distribution diagram.

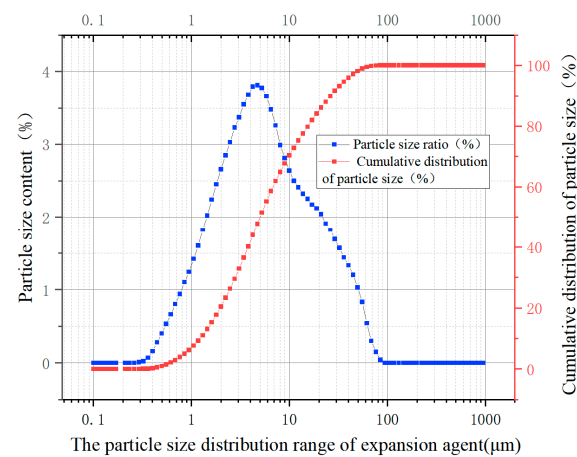


Figure 6. Expansion agent particle size distribution and cumulative particle size distribution diagram.

Table 1. Mineral composition and content of experimental materials.

Test Items	SO ₃	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	CL [−]	K ₂ O	Na ₂ O	P ₂ O ₅	Specific Surface Area
cement	2.5%	18.2%	4.3%	6.2%	62.2%	1.5%	NO	1.01%	0.31%	0.2%	352 m ² /kg
S95 slag powder	2.7%	24.2%	3.2%	16.7%	37.8%	7.5%	NO	1.2%	NO	0.2%	462 m ² /kg
silica fume	0.7%	92.1%	0.2%	0.8%	0.2%	0.5%	No	0.3%	No	0.04%	
microspheres	0.4%	64.4%	5.4%	10.2%	10.0%	1.1%	No	2.6%	0.7	0.7%	1520 m ² /kg

According to the requirements of high-performance concrete, in combination with the properties of raw materials and the adaptability of cement, the polycarboxylate-based admixtures configured by team members were used. Following the regulations of GB 8076 <<Concrete Admixtures>> and GB/T 8077 <<Test Methods for the Homogeneity of Concrete Admixtures>>, random sampling was conducted and tested by the Guizhou Provincial Building Materials Quality Inspection and Testing Institute, with the results shown in Table 2.

Table 2. Ingredient and content of admixture.

Test Items	Chloride Ion Content	Alkali Content	Solid Content	Density	PH	Na ₂ SO ₄
Test results	No	0.35%	24.9%	1.04%	5.6%	0.1%

2.2. Mix Proportion Design of HPSCC

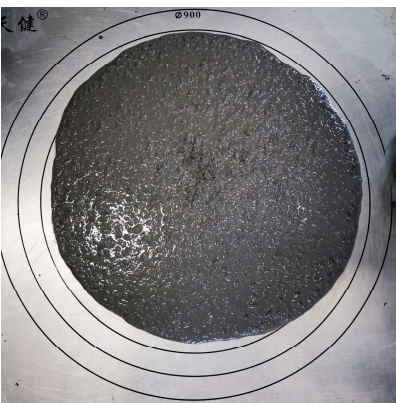
The design strength grade of HPSCC is C80, the designed density is 2500 kg/m³, the sand ratio is 0.47, and the water–binder ratio (W/C) is 0.20. The mix design is shown in Table 3.

Table 3. C80 HPSCC mix design (kg/m³).

Sand Rate	W/C	Water	Machine-Made Sand	Total Amount of Cementitious Material (620 kg/m ³)					Gravel with a Diameter of 5–10 mm	Gravel with a Diameter of 10–20 mm	Polycarboxylic Admixture
				Cement	Microspheres	Slag Powder	Silica Fume	Expansive Agent Expansion Agent			
0.47	0.2	130	620	380	62	76	70	32	367	551	2.8% of cementitious material

2.3. Experimental Sample

The specimen dimensions were 100 mm × 100 mm × 100 mm and the work was conducted at the Laboratory of Panshi Building Materials Laboratory in Bijie City, Guizhou Province. According to the test method for the properties of an ordinary concrete mixture (GB/T 50080-2002), the physical properties of the concrete mixture, such as extensibility, clearance rate (J-ring Test, V-type funnel test), air content, etc., were as shown in Figure 7.



(a)



(b)



(c)

Figure 7. Cont.

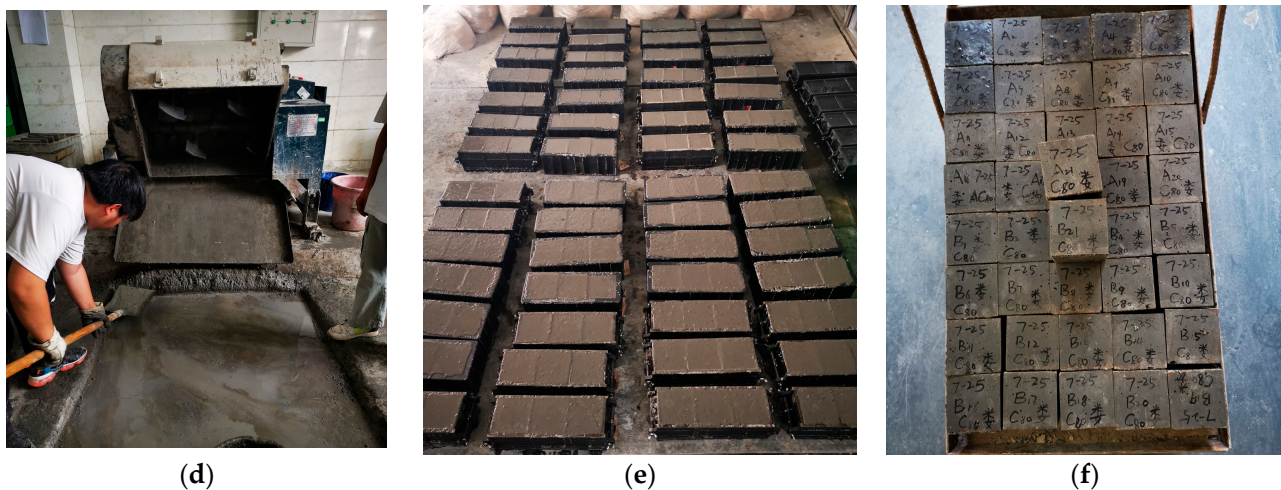


Figure 7. HPSCC experimental samples' preparation process. (a) Expansion plate test: used to measure the fluidity of concrete paste. (b) J-ring test: used to test the ability of concrete slurry to move through a narrow space. (c) V-type funnel test: used to test the stickiness and anti-segregation of concrete slurry. (d) Mixing the concrete. (e) Sample casting. (f) Completed specimens.

2.4. Sample Testing Methods

Cube concrete specimens with standard curing for 28 days were cut into cubic structures of $10 \times 10 \times 10 \text{ mm}^3$. Wuxi Airdo Detection Technology Co., Ltd. (Wuxi, China). Conducted high-resolution X-ray computed tomography (also known as industrial CT) on the samples. This testing observation technology obtains the internal pore distribution map of the solid structure without destroying the concrete structure and can provide high-resolution stereoscopic imaging of the pore distribution of the observed samples.

To observe the internal micro-morphological characteristics of concrete, the pore structure and morphology of the concrete structure were analyzed using SEM scanning technology.

3. Analysis of Test Results

3.1. Compressive Strength Test

According to the national standard (GB/T 50081-2019) “Standard for Test Methods of Physical and Mechanical Properties of Concrete”, specimens cured for 28 days under standard conditions were tested for the compressive strength of the self-compacting concrete using an automatic constant stress loading testing machine, with a loading rate of 0.5 Mpa/s. Five specimens were cast with the same mix design. Specimens with a range of test results greater than 15% were removed, and the average value of the remaining specimens was taken, as listed in Table 4.

Table 4. Compressive strength test results of HPSCC samples.

Sample Number	Failure Load of Specimen (kN)	Conversion Factor of Dimension	Sample Validity	Ultimate Strength (Mpa)	Compressive Strength (Mpa)
A-1	910	0.95	Yes	86.45	$f_c = 0.95 \times N/A$ $= 89.59 \text{ MPa}$
A-2	982		Yes	93.29	
A-3	959		Yes	91.11	
A-4	780		NO	73.15	
A-5	112		Yes	106.40	

3.2. CT Imaging Analysis of HPSCC Samples

In order to comprehensively describe the morphology and distribution characteristics of the micropore structure within hardened concrete, the present study entailed the

preparation of cubic centimeter-sized test blocks from HPSCC samples. Subsequently, these specimens underwent three-dimensional scanning utilizing X-ray computed tomography technology. The experimental setup featured a radiation tube voltage of 150 kV, a current intensity of 500 μA , and a voxel resolution of 10 μm , ensuring high-resolution imaging. The acquired three-dimensional images of the samples were then reconstructed employing the industry-standard software VG Studio MAX 2.0 (depicted in Figure 8), which facilitated the direct extraction of key parameters such as pore count, volume, surface area, and diameter. The comprehensive pore-related information detected is summarized in Table 5.

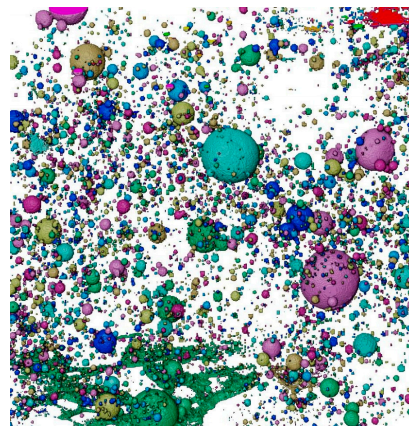


Figure 8. Three-dimensional image of the reconstructed sample using VG Studio MAX.

Table 5. Computed tomography scan results.

	Three-Dimensional Volume (μm^3)	Area (μm^2)	Diameter (μm)
Average	1.14766×10^6	3832.48	66.44
Minimum	1329.15	363.169	13.6414
Maximum	3.951574×10^7	2.8215×10^5	911.08

As shown in Figure 8, a large number of pores are randomly distributed within the hardened HPSCC, with pore diameters ranging from 10 μm to 911.08 μm . From the three-dimensional images of the reconstructed samples, these micropores are distributed in a circular pattern. The ratio of the surface area of an equivalent volume sphere to the actual surface area of the pores is defined as the roundness of the pores, which can be used to characterize the regularity of the micropore morphology. The specific expression is as follows:

$$Q = \sqrt{\frac{36\pi V_p^2}{s^3}} \quad (1)$$

In Equation (1), V_p represents the actual volume of the mesoscopic voids, and s represents the actual surface area of the mesoscopic voids.

The distribution of circularity of the HPSCC samples observed in this article is shown in Figure 9. As can be seen from Figure 9, 81.62% of the pore circularity values are between 0.8 and 1.4, indicating that most of the micropores are close to a circular structure. Additionally, 10.02% of the pore circularity values are greater than 2.2, which means these pores are distributed in an oblong shape.

Slicing the three-dimensional images allows for the observation of the internal structural pore morphology of the sample. The VG Studio MAX 3D data processing software outputs two-dimensional CT slices of the sample in three directions: X-axis (front view), Y-axis (side view), and Z-axis (top view). We observed the slices of a particular pore from its inception to disappearance along the Z-axis (side view), as shown in Figure 10.

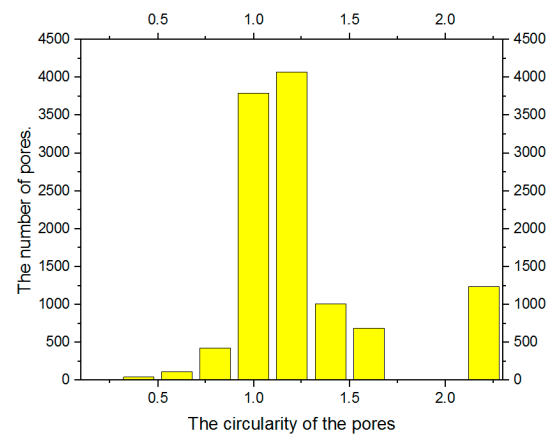


Figure 9. A circularity distribution chart of the pores.

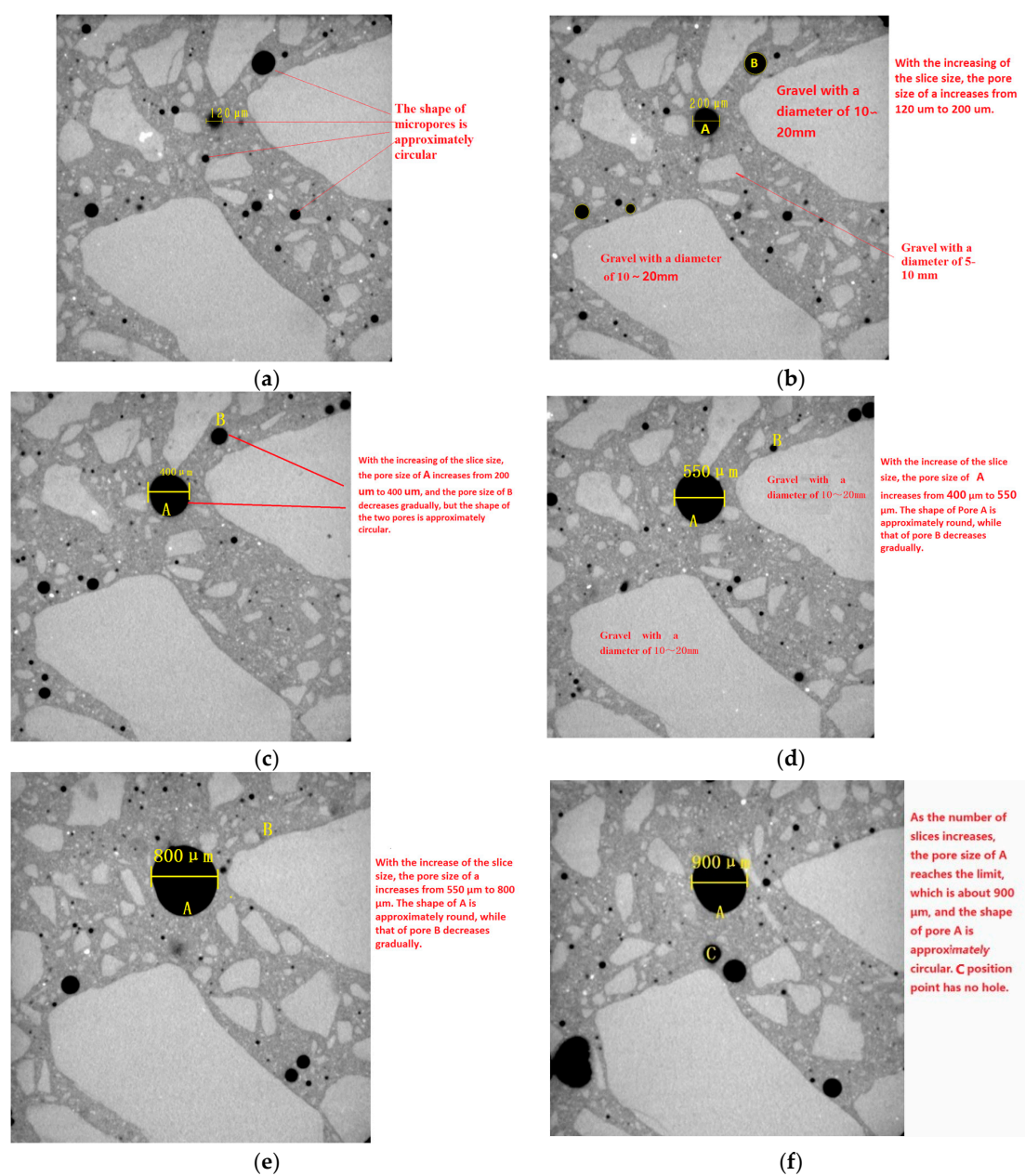


Figure 10. The micropores(a–f) were observed along the Z-axis (side view).

From the perspective of sections (a) to (f) in Figure 10, as the slicing depth increases, the fluctuation in the micropore content in the lateral direction is significant. Most of the micropores are approximately circular and are randomly distributed in the HPSCC structure, with no aggregation or regular spacing. The sizes of these micropores vary greatly, with larger pore diameters approaching 1 mm and smaller ones ranging from 10 μm to 50 μm . This is due to the fact that during the mixing of concrete, the rough surfaces of coarse and fine aggregates carry a certain amount of air into the paste, which, after the concrete hardens, forms a structure with air pores of varying sizes.

3.3. Micro-Scale Internal Pore Characteristics of HPSCC

To further understand the internal pore structure characteristics of C80 HPSCC, we selected concrete specimens with a 28-day strength for slicing and polishing and analyzed their micro-morphology using a scanning electron microscope (SEM) as shown in Figure 11.

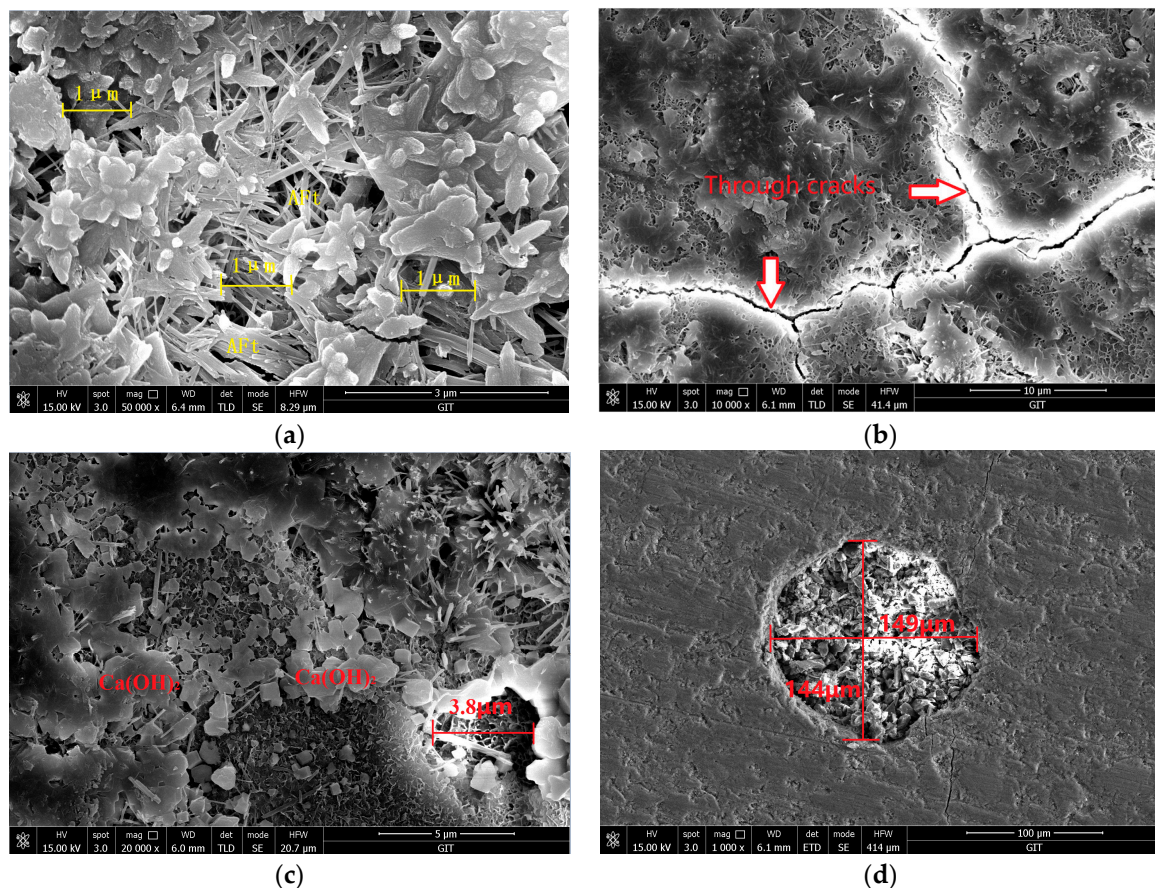


Figure 11. HPSCC SEM observation results. (a) Magnification of point A by 5×10^4 times. (b) Magnification of point B by 1×10^4 times. (c) Magnification of point C by 2×10^4 times. (d) Magnification of point D by 1×10^4 times.

As shown in Figure 11a, when point A in the sample is magnified to 5×10^4 times, the “needle-like” ettringite (AFt) structure can be observed to be connected with a structure resembling a “lily flower”. The overall structure is relatively dense, but there are still a large number of pores about 1 μm in size. In Figure 11a, the connection between the AFt structure and the lily flower structure in the sample may have a significant impact on the mechanical properties of the material. This connection may help to form a more robust microstructure, thereby increasing the overall strength and durability of the material. The AFt (ettringite) structure, with its needle-like form, contributes to the early strength of the cement stone, and their interlocking can form a mesh-like structure, which is very favorable for increasing the early strength of the mortar. However, it should be noted that although

this structure may improve the early strength of the material, if too much AFt is formed, it may lead to a decrease in later strength. This is because the transformation of AFt to AFm (single-sulfate hydrate of calcium sulfoaluminate) may cause volume expansion, creating internal stress that can lead to structural failure.

As shown in Figure 11b, when point B in the sample is magnified to 1×10^4 times, significant cracks can be observed going through the structure, with the width of these cracks ranging between approximately 0.5 and 1 μm . The presence of these cracks can reduce the mechanical properties of HPSCC, especially the pores of about 1 μm , which could serve as the starting point for crack propagation, affecting the durability and strength of the material. Therefore, although the connection between AFt and lily flower structures may improve the mechanical properties of the material to some extent, the impact of cracks must still be considered, and it is necessary to seek optimization of the overall microstructure to achieve the best mechanical performance.

As shown in Figure 11c, when point C in the sample is magnified to 2×10^4 times, “hexagonal flake-like” calcium hydroxide ($\text{Ca}(\text{OH})_2$) crystalline flake structures can be observed adhering to the surface of the structure. Some “flake-like” structures are connected together by needle-like “ettringite” structures, and the flake-like structures are randomly combined with each other to form micropore structures with a diameter of about 3.8 μm .

As shown in Figure 11d, when point D in the sample is magnified to 1×10^3 times, a significant hole can be seen to exist. The hole is circular with a horizontal diameter of about 149 μm and a vertical diameter of about 144 μm , and its shape is approximately circular. Circular volumetric holes have a significant impact on the mechanical properties of concrete. The presence of holes can reduce the overall strength and durability of the concrete because they provide a starting point for cracks and fissures, which may lead to structural failure. The existence of holes reduces the effective cross-sectional area of the concrete, leading to stress concentration, which may cause damage under lower loads. In addition, holes can also affect the durability of the concrete as they provide pathways for the penetration of water and harmful chemicals, potentially leading to steel reinforcement corrosion or other durability issues.

3.4. The Three-Parameter Log-Normal Distribution Characteristics of Micropores

To quantitatively analyze the porosity of HPSCC, the three-dimensional X-ray computed tomography scanning data were organized and analyzed to obtain a frequency histogram of equivalent pore size distribution, as shown in Figure 12. The equivalent diameter refers to the diameter of a circle with the same area as the pore, reflecting the size of the microvoids and the characteristics of the micropores within the concrete.

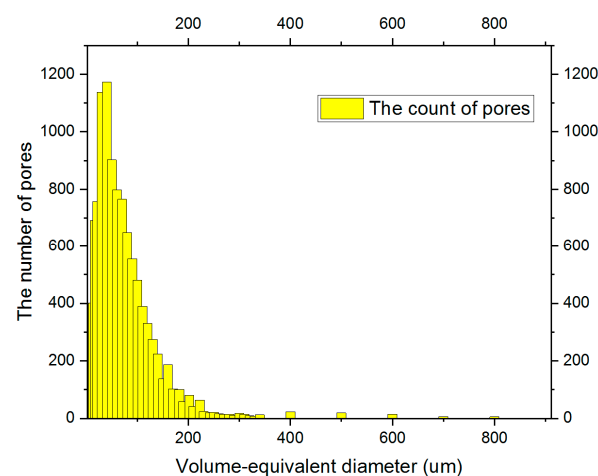


Figure 12. Frequency distribution of pore size in C80 HPSCC.

From Figure 12, it can be seen that the number of large pores with a diameter greater than 400 μm within the HPSCC structure is relatively low, with a distribution frequency of 69, accounting for 0.61% of the total pore frequency. The number of pores with a diameter between 13 μm and 100 μm is 8310, which accounts for 72.95% of the total pore frequency. The number of pores with a diameter between 100 μm and 200 μm is 1885, accounting for 16.54% of the total pore frequency. Statistical principles can be used to analyze and fit the curve as shown in Figure 13. As can be seen from Figure 13, the equivalent diameter distribution of the sample is skewed.

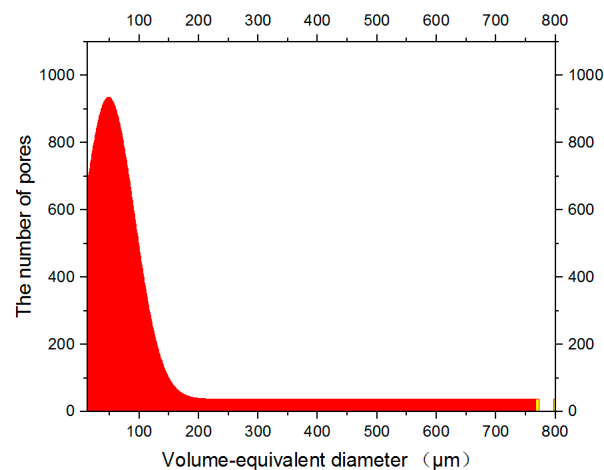


Figure 13. Fitted curve of pore size frequency distribution for C80 HPSCC.

Dvorak's research results indicate that the diameter of micropores inside the material follows a log-normal distribution. Let X be a random variable with observed data x (diameter of micropores). If $\ln(x - C)$ (C is constant, $x > C$) follows a normal distribution $N(\mu, \sigma^2)$, it suggests that x follows a three-parameter (μ, σ^2, C) log-normal distribution. The probability density $f(x)$ expression F for this is

$$f(x) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi}(x-C)} \exp\left\{-\frac{[\ln(x-C)-\mu]^2}{2\sigma^2}\right\}, & x > C \\ 0, & x \leq C \end{cases} \quad (2)$$

If $\ln(C - x)$ follows a normal $N(\mu, \sigma^2)$ distribution, where $C > x$, then x follows a three-parameter inverse log-normal distribution with parameters (μ, σ^2, C) , and its probability density can be expressed as

$$f(x) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi}(C-x)} \exp\left\{-\frac{[\ln(C-x)-\mu]^2}{2\sigma^2}\right\}, & x < C \\ 0, & x \geq C \end{cases} \quad (3)$$

In Equation (3), x is the diameter of the micropores, obtained through high-resolution X-ray computed tomography experiments, as shown in Figure 12. σ is the standard deviation of the logarithmic variable. μ is the mean.

From Equations (2) and (3), it can be seen that after observing the distribution frequency of pore sizes obtained from high-resolution X-ray computed tomography experiments, fitting a three-parameter log-normal or inverse log-normal distribution, the key is to reasonably estimate the value of the third parameter C based on the observed sample x values, and then estimate μ and σ^2 based on the data $\ln(C - x)$ or $\ln(x - C)$, testing whether they follow a normal distribution.

As can be seen from Figure 12 and Table 5, in this X-ray computed tomography experiment, the pore diameter x is positively skewed, with a minimum value of 13.64 μm , a maximum value of 911.08 μm , and an average value of 66.44 μm . It is assumed that the most

frequent occurrence of micropore diameter is x_{most} . When determining the three-parameter normal distribution, if the choice of C is inappropriate, the frequency density of $\ln(C - x)$ or $\ln(x - C)$ may be biased. To eliminate the bias in the probability density, the following method is used to determine the third parameter C .

When the probability density is normally distributed with the peak centered, since the pore diameter x_{most} occurs most frequently, the following equation holds:

$$\ln(x_{\text{most}} - C) = \frac{1}{2}[\ln(x_{\text{max}} - C) + \ln(x_{\text{min}} - C)] \quad (4)$$

By transforming Equation (4), the following form can be derived:

$$\ln(x_{\text{most}} - C) = \ln[(x_{\text{max}} - C)(x_{\text{min}} - C)]^{\frac{1}{2}}$$

$$\text{Then, } (x_{\text{most}} - C) = [(x_{\text{max}} - C)(x_{\text{min}} - C)]^{\frac{1}{2}}.$$

$$(x_{\text{most}} - C)^2 = (x_{\text{max}} - C)(x_{\text{min}} - C)$$

$$C = \frac{x_{\text{most}}^2 - x_{\text{min}}x_{\text{max}}}{2x_{\text{most}} - x_{\text{min}} - x_{\text{max}}} \quad (5)$$

In Equation (5), when $2x_{\text{most}} - x_{\text{min}} - x_{\text{max}} < 0$, $C < x_{\text{min}}$, it indicates that the probability density curve is skewed to the left, which is positive skewness. Then, $2x_{\text{most}} - x_{\text{min}} - x_{\text{max}} > 0$, $C > x_{\text{max}}$, and

$$\ln(C - x_{\text{most}}) = \frac{1}{2}[\ln(C - x_{\text{max}}) + \ln(C - x_{\text{min}})],$$

Based on the previous analysis, it is known that the value of C determined by Equation (3) can center the peak of $\ln(C - x)$ or $\ln(x - C)$ within the normal distribution curve. According to Equation (5), to confirm the third parameter C , one must first determine the values of x_{most} , x_{min} , and x_{max} .

The selection method for x_{most} is as follows. Choose the rectangle with the highest frequency interval $[x_i, x_{i+1}]$ and the two adjacent columns, as shown in Figure 14. Let the intersection of AC and BD be point E ; then, the abscissa of point E is x_{most} . The calculation formula for x_{most} is given by Equation (6):

$$x_{\text{most}} = x_i + \frac{AB \times BC}{AB + CD} = x_i + \frac{(f_i - f_{i-1})(x_{i+1} - x_i)}{2f_i - f_{i-1} - f_{i+1}} \quad (6)$$

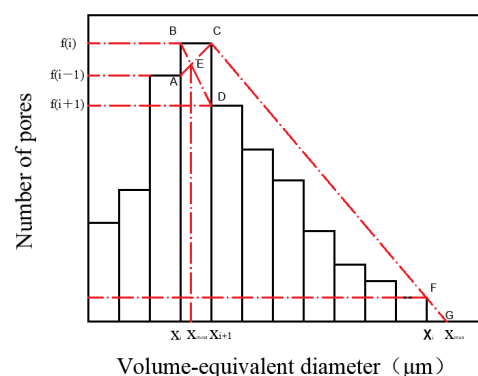


Figure 14. Schematic diagram of the determination method for x_{most} and x_{max} .

In Equation (5), f_i represents the maximum frequency of micropore diameter occurrence. f_{i-1} and f_{i+1} are the frequencies of occurrence for the left and right groups of pore diameters, respectively.

Since the sample for the three-dimensional X-ray computed tomography experiment is extracted from a portion of the specimen (the volume of the test sample is 1 cm³), the actual volume of the HPSCC structure is significantly larger than that of the scanned sample. Therefore, the value of $x_{\max}$ might be larger than the experimental data, or $x_{\min}$ might be smaller than the measured data. Consequently, the selection of $x_{\max}$ should generally be larger than the largest value in the measured data. How much larger it should be can be determined with the help of a bar chart, as shown in Figure 14. The intersection point of the CF line with the coordinate axis is taken as $x_{\max}$, and its expression is as follows:

$$x_{\max} = x_{m+1} + \frac{f_m(x_{m+1} - x_{i+1})}{f_i - f_m} \quad (7)$$

In Equation (7), x_{m+1} represents the upper limit of the rightmost group. f_m is the frequency of the largest group of micropores in the CT scan.

Using Equations (3) and (4), a statistical analysis was conducted on the diameters of the 11,390 micropores detected in the three-dimensional X-ray computed tomography experiment. The results are shown in Table 6. The fitting results of the corrected three-parameter log-normal distribution are shown in Figure 15.

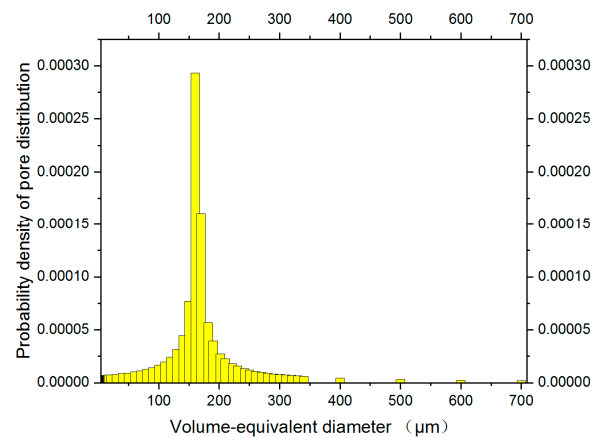


Figure 15. Corrected three-parameter log-normal distribution of micropores.

Table 6. Computer results of the three-parameter log-normal distribution parameters for the porosity of C80 HPSCC.

x_{most} (μm)	$x_{\max}$ (μm)	μ (μm)	σ^2	C
31.173	802.61	40	33,369.87	163.53

According to the statistical results, the internal pore distribution of the C80 HPSCC structure is more consistent with the three-parameter log-normal distribution, which can be represented by Equation (8).

$$f(x) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi}(163.53-x)} \exp\left\{-\frac{[\ln(163.53-x)-40]^2}{2\sigma^2}\right\}, & x < C \\ 0, & x \geq C \end{cases} \quad (8)$$

4. Conclusions

This paper uses carbonate rock as the parent rock, and crushed sand and stone as coarse aggregate, to prepare C80 high-strength self-compacting concrete. By combining high-resolution X-ray computed tomography experiments with SEM (scanning electron microscopy) observations, an experimental study was conducted on the internal pore structure and pore distribution characteristics of HPSCC. The following conclusions were drawn:

- (1) Observations using high-resolution X-ray computed tomography revealed that there is a large number of pore structures within the carbonate HPSCC. Within the testing precision range of 10 μm , these structures exhibit a circular characteristic and have a relatively good overall circularity.
- (2) Through SEM (scanning electron microscopy) observations, it is known that there are micro-cracks or through-cracks within the high-performance concrete. The width of these cracks is between 0.5 and 2 μm . Additionally, tiny voids ranging from 3 to 10 μm were observed inside the samples. Under the action of external forces, cracks may first form along these micro-cracks, severely affecting the structural load-bearing capacity and durability.
- (3) Statistical analysis of the pores and cavities within the carbonate rock-based C80 self-compacting concrete revealed that the cavity diameters follow a three-parameter normal distribution. However, due to the limitations of experimental precision, the experimental results show a positively skewed (high peak to the left) phenomenon. This paper presents a method for estimating the third parameter, C, which can quickly, objectively, and optimally determine parameter C. This method compensates for the missing data that were not accounted for below 10 μm and the limitations of the finite test samples, providing a reference for examining the distribution of cavities within the concrete and for the study of concrete mechanical properties.
- (4) This paper analyzes the pore structure morphology observed through CT scanning experiments and the mathematical model of the three parameters of HPSCC pore structure. This can help us quantitatively understand the pore structure and distribution state of HPSCC, providing theoretical support for studying the anti-pore melting, anti-chemical erosion, thermal resistance, and anti-seepage performance of HPSCC. In addition, analyzing the distribution state of the pore structure helps us to deeply understand the relationship between the microstructure and macroscopic performance of concrete, assess the performance changes in concrete in specific environments, and provide a basis for the selection and maintenance of concrete.

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Data Availability Statement: The data that support the findings of this study are available upon request.

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