Fractal Characteristics of the Pore Structure of Coral Powder–Cement Slurry under Different Fractal Models

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Abstract: In this study, coral powder with different contents and levels of fineness were incorporated into cement; then, the pore structure of a coral powder–cement slurry was measured using the MIP test at days 3 and 28, respectively. Neimark’s model, Ji’s model, and Pfeifer and Avnir’s model were also used to analyze the fractal characteristics of the coral powder–cement slurry. The results show that the coral powder–cement slurry has multifractal characteristics when using Neimark’s model, and the entire pore size range of the cement slurry can be divided into three parts: Region I (1–200 µm), Region II (70 nm–4 µm), and Region III (5–500 nm). The pore surface fractal dimension of both Regions I and III is less than 3, while that of Region II is greater than 3. This indicates that Regions I and III have obvious fractal characteristics, which Region II does not. Meanwhile, the pore surface fractal dimension of Region I is positively correlated with hydration age, while the pore surface fractal dimension of Region III is less affected by hydration age and coral powder contents. Ji’s model reveals that coral powder–cement slurry also has multifractal characteristics, but the entire pore size range of the cement slurry can be divided into two parts: Region I (5,482 nm–500 m) and Region II (120 nm–370 µm). The pore volume fractal dimension of Region I is greater than 2 and less than 2.5, while that of Region II is greater than 2.9 and less than 3. Therefore, both Regions I and II have fractal characteristics. In addition, the coral powder admixture, fineness, and age have large effects on the pore volume fractal dimension and pore size range of Region II. Pfeifer and Avnir’s model reveals that the entire pore size range of cement slurry can also be divided into two regions: Region I (5,482–600 nm), Region II (120 nm–10 µm), and Region III (5–365 µm), and that the pore surface fractal dimension of both Regions I and III is less than 3, while that of Region II is greater than 3. This indicates that Regions I and III have fractal characteristics, while Region II does not have fractal characteristics.

Keywords: coral powder; MIP; Neimark’s model; Ji’s model; Pfeifer and Avnir’s model; fractal dimension

1. Introduction

Classical Euclidean geometry can only describe some geometries with regularity, and it is difficult to describe and characterize complex nonlinear things such as complicated coastlines, mountain scenery, and rock structures [1]. Meanwhile, pore structure parameters such as porosity [2,3], pore size distribution [2,3], and pore surface area [4] can only reflect the overall characteristics of pore structure and not the spatial distribution or tortuous degree of pore structure [5,6]. Therefore, fractal theory provides theoretical support and a basis for describing fragmented, irregular, and fractional objects. Fractal geometry is a new nonlinear science with the two characteristics of local and global self-similarity and non-integer dimensions, providing a method for describing irregular, complex, and
self-similar geometries [7]. The fractal dimension is the most important parameter in fractal geometry and can accurately describe the geometric characteristics of a material. Based on the characteristics of fractal geometry and the more accurate description of the complexity and irregularity of that geometry and due to the rapid development of disciplines and interdisciplinary disciplines, many disciplines combine fractal theory with their own methods of research, thus providing a convenient means for related research, such as materials science, fracture mechanics, biology, physics, and chemistry. Additionally, other disciplines borrow fractal theory; thus, the integration and research of fractal theory with related disciplines is also a hot research topic today.

The pore structure of cement-based materials is characterized by discontinuity, disorder, complex irregularities, and self-similarity; therefore, it is difficult to characterize and describe the complexity of these structures using traditional Euclidean geometry. As a result, the error involved in establishing the relationship between the pore structure of cement-based materials and their macroscopic properties (strength, durability, permeability resistance, frost resistance, etc.) is large. As Winslow’s study showed that the inner surface of cement-based materials was basically fractal [8], researchers at home and abroad have applied fractal theory to cement-based materials and tried to establish the relationship between fractal dimensions and the macroscopic properties of cement-based materials [9–11]. With the diversification of testing methods, more and more advanced testing techniques for investigating the pore structure of cement-based materials, such as optical microscopy [12,13], electron microscopy [12,13], scanning acoustic microscopy [12,13], X-ray diffraction [14,15], resistivity [16], nitrogen adsorption/desorption [17], nuclear magnetic resonance [18], and MIP [19,20], have become available. Consequently, more and more fractal models have been proposed to describe the pore structure of cement-based materials, such as the Menger sponge model [21], Pfeifer and Avnir’s model [22], Friesen’s model [23], Usteri’s model [24], Ji’s model [25], Neimark’s model [26], and Zhang’s model [21]. However, some of these models are based on different assumptions and have different definitions of fractal dimensions; thus, the fractal dimensions obtained by different models are less comparable. The Menger sponge model is generally applicable to low- and medium-strength cement-based materials, but not to high-strength cement-based materials. Neimark’s model was proposed based on the law of energy conservation during mercury intrusion and was able to explain the energy balance between the extension of a non-wetting surface of an inner surface required for mercury intrusion and external work [26]. Without considering the heat loss, the work done by the external force on the mercury was equal to the work done by the mercury surface tension on the inner surface of the pores. In this model, the pore surface fractal dimension is obtained by establishing the relationship between the inner surface of the pore and the pressure. Ji’s model is a space-filling model based on hydration reaction combined with the MIP test method and is able to establish the relationship between fractal dimensions and pore volume, where the calculated fractal dimension is the pore volume fractal dimension [25]. However, a large number of studies have found that the pore structure of cement-based materials has multifractal characteristics—i.e., the fractal dimensions are different for different pore size ranges. Studies by Winslow [8], Ji [25], Lang [27], and Livingston [28] have shown that the pore structure of cement paste has multifractal characteristics. Zhang proposed Zhang’s model based on MIP data and found that the pore surface fractal dimension of cement-based materials is scale-dependent; these fractal characteristics indicated that the pore structure of cement-based materials is multifractal [5]. Pfeifer and Avnir [22] found that the inner pore surfaces of cement-based materials exhibited fractal characteristics and the pore surface fractal dimension was obtained by MIP data, which can characterize the roughness of the internal pore surfaces of cement-based materials. In this model, when the fractal dimension is equal to 2, the pore surface is smooth, while when the pore surface fractal dimension is close to 3, the pore surface is irregular and rough. When Atzeni et al. [10] applied the Pfeifer model [22] to study the fractal characteristics of cement slurry, they found that cement slurry had obvious multifractal characteristics and pointed out that the
Fractal dimension of the transition zone was greater than 3 and thus did not have fractal characteristics. Gao et al. [29] believed that multifractal systems can better characterize the fractal characteristics of cement slurry with local singularities and size dependence. When Zeng et al. used Zhang’s model to study the pore structure of cement-based materials, the results confirmed that the pore surface fractal dimension of cement-based materials was scale-dependent and that the whole pore size range could be divided into three regions: the macro-fractal region, the transition region, and the micro-fractal region. The macro-fractal region mainly reflected the accumulation pattern of hydration products, the transition region was mainly related to the random space between C-S-H and different sizes of CH and AFT hydration products, and the micro-fractal region mainly reflected the microstructure of C-S-H hydration products [5]. In addition, Zeng et al. used Neimark’s model and Zhang’s model to study the pore surface fractal dimension of fly ash–cement slurry, and the results showed that fly ash–cement paste had obvious multifractal characteristics. However, Zhang’s model was more accurate in characterizing the pore surface fractal dimension of the pore structure. Meanwhile, the fractal dimension of the large pore region tended to increase with the increase in the water–cement ratio and age and gradually decrease with the increase in fly ash admixture, which was mainly affected by its physical filling effect. In addition, they found that the fractal dimension of the small-pore region was less affected by the water–cement ratio, age, and fly ash admixture; the transition region did not have fractal characteristics; and the range of its fractal dimension was more affected by the fly ash content [30].

However, due to the diversity of methods used for testing pore structures, problems relating to comparison arise. For example, the use of different methods for testing pore structures, the different understanding of fractal dimensions in existing fractal models, and the different assumptions on which related models are based make the comparability between related studies poor. At the same time, based on the same test method, different researchers also obtain different fractal dimensions, and may even get contradictory conclusions. For example, the research by Yu et al. [31] found a good negative correlation between compressive strength and pore fractal dimension when studying the fractal characteristics of cement paste containing perlite using the Menger sponge model, and similar conclusions were obtained by other researchers [25]. However, when Li et al. [32] used the Menger sponge model to study the pore fractal characteristics of fly ash–cement slurry, they found that the strength of fly ash–cement slurry increased with the increase in the fractal dimension. The results of Wei et al. [33] showed that the compressive strength of concrete is positively correlated with its fractal dimension. This was in contrast to the findings of Ji et al. [25] and Yu et al. [31]. In summary, the same model was used to calculate the fractal dimension of cement-based materials, but opposite conclusions were reached, and there was not a comparison of the fractal dimensions obtained from different models. Therefore, it is effective to use fractal theory to study the pore structure of cement-based materials, characterize the spatial distribution and tortuous degree of pore structure, and establish the relationship between the fractal dimension and macroscopic properties. However, this theory is still in the development stage, so a large number of data are needed to verify the accuracy of the existing conclusions so as to establish the microstructure and macro performance.

As the physical and mechanical properties of coral aggregates are quite different from those of terrigenous sand and gravel, researchers have carried out a great deal of research on the physical and mechanical properties of coral aggregates, their foundation bearing capacity, and coral concrete [34–37]. However, relevant studies have shown that there is a large amount of calcareous silt in artificial islands, which has an important impact on the formation of underground freshwater on artificial islands [38]. In addition, these coral aggregates are rich in calcareous silty soil and will reduce the use of coral aggregate concrete to some extent. At the same time, there have been relatively few studies on the effects of coral powder on the macroscopic and microscopic properties of cement-based materials and their pore structure. Fractal theory has been used to investigate the fractal characteristics of the pore structure of cement-based materials. Therefore, in this paper, the
pore structure distribution of cement paste containing coral powder with different levels of fineness and added amounts at days 3 and 28 was tested by MIP. Then, Neimark’s model, Ji’s model, and Pfeifer and Avnir’s model were used to analyze the fractal characteristics of these cement pastes, which provide data support and scientific basis for the study of fractal characteristics and multifractal characteristics of pore structure of coral powder–cement paste, so as to promote the application of fractal theory in cement-based materials. At the same time, the research results of this paper not only promote the application of fractal theory in the study of pore structure of coral powder–cement slurry, but also provide an effective method for establishing the relationship between the macroscopic properties (such as mechanical properties, durability, and permeability) of cement-based materials and fractal dimension. On the other hand, the influence of coral powder on cement hydration, working performance, mechanical properties and microstructure should be the focus of researchers in the future.

2. Materials and Methods

2.1. Raw Materials

The cement used in this paper was P·O 42.5, whose $D_0$ was 12.86 μm, and coral powder with different levels of fineness was obtained from coral sand after grinding, which were denoted as fine coral powder ($D_0 = 2.57 \mu m$) and coarse coral powder ($D_0 = 9.36 \mu m$). The chemical compositions of cement and coral powder are shown in Table 1. The main mineral components of coral powder are aragonite and low-magnesium calcite, as shown in Figure 1. The microscopic morphology of cement, fine coral powder, and coarse coral powder are shown in Figure 2. In the figure, it can be seen that the surface of cement is smoother and the surface of coral powder is rougher and more porous. The particle size distribution of cement, fine coral powder, and coarse coral powder are as presented in Figure 3.

Table 1. Chemical composition of cement and coral powder (%).

| Sample         | SiO$_2$ | CaO | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO | Na$_2$O | SO$_3$ | K$_2$O | P$_2$O$_5$ | TiO$_2$ | LOI |
|----------------|--------|-----|-------------|------------|-----|---------|--------|-------|-----------|--------|-----|
| Cement         | 23.6   | 64.2| 5.6         | 2.9        | 1.7 | 0.3     | 0.5    | -     | -         | -      | 1.37|
| Coral Powder   | 2.5    | 53.3| 0.2         | 0.8        | 0.1 | 0.2     | 0.1    | 0.1   | 0.04      | 39.8   |     |

- Aragonite CaCO$_3$
- Calcite,magnesian(Ca,Mg)CO$_3$

Figure 1. XRD pattern of coral powder.
Figure 2. SEM diagram of cement and coral powder. (a) Cement. (b) Fine coral powder. (c) Coarse coral powder.

Figure 3. Particle size distributions of the materials used.

2.2. Mixing Ratio Design

The water–cement ratio in this paper is 0.5, and the mix proportion is shown in Table 2. OPC0 is the cement paste without admixture; FCP10 and FCP30 denote the cement paste.
with 10% and 30% fine coral powder, respectively; and CCP10 and CCP30 denote the cement paste with 10% and 30% coarse coral powder, respectively.

Table 2. The proportion of cement slurry.

| Sample NO. | W/C | Mass Fraction/% |   |   |
|------------|-----|-----------------|---|---|
|            |     | Cement | Fine Coral Powder | Coarse Coral Powder |
| OPC0       | 0.5 | 100    | 0               | 0               |
| FCP10      |     | 90     | 10              | 0               |
| FCP30      | 0.5 | 70     | 30              | 0               |
| CCP10      |     | 90     | 0               | 10              |
| CCP30      |     | 70     | 0               | 30              |

2.3. Test Methods

2.3.1. Mercury Intrusion Porosimetry Test (MIP)

The pore structure distribution of different types of cement pastes at days 3 and 28 was tested using a McPretic AutoPore Iv 9510 mercury piezometer, USA. The maximum mercury pressure of the piezometer was 414 MPa and the pore size of the piezometer ranged from 5 nm to 340 µm. The cement paste of the corresponding age was cut into the side length of 5 mm cubic blocks, placed into anhydrous ethanol to stop hydration, and put into a 40 °C oven to dry to constant weight.

2.3.2. Neimark’s Model

Neimark’s model was proposed based on the law of energy conservation during mercury intrusion, which explained the energy balance between the extension of the non-wetting surface of the inner surface required for mercury intrusion and the external work [26]. Without considering the heat loss, the work done by the external force on the mercury is equal to the work done by the mercury surface tension on the inner surface of the pore; thus, the specific surface area of the pore is as in Equation (1).

$$S = - \frac{1}{\gamma \cos \theta} \int_0^{V_p} p \, dV,$$

where $S$ denotes the pore specific surface area, $\gamma$ represents the surface tension of mercury (0.458 N/m), $\theta$ is the contact angle between the pore surface and mercury (130°), $V$ denotes the volume of intruded mercury, and $p$ represents the mercury pressure (MPa). The study of Pfeifer and Avnir showed that the inner pore surface of cement-based materials has obvious fractal characteristics [22], and the fractal dimension can be obtained through Equation (2):

$$\frac{dV}{dr} \propto r^{2-D},$$

where $r$ denotes the pore diameter and $D$ represents the fractal dimension, which can characterize the roughness of the pores on the inner surface of cementitious materials, and its value is generally between 2 and 3. When $D$ is less than 2, this means that the pores are very smooth and do not have fractal characteristics; when $D$ is close to 3, this means that the inner surface of the pores is rougher and uneven. In the MIP test, the volume of mercury intrusion is closely related to the mercury pressure; therefore, the following relationship (shown by Equation (3)) exists between the mercury pressure and the pore diameter when the tension of the surface inside the pore is in equilibrium with the mercury pressure applied during the mercury intrusion.

$$p = \frac{-2 \gamma \cos \theta}{r}.$$
We substitute Equations (2) and (3) into Equation (1) and take logarithms of both sides of the equals sign so as to obtain $D$, as shown in Equation (4).

$$\log(S) \propto (D - 2) \log(p). \quad (4)$$

### 2.3.3. Ji’s Model

Ji et al. [25] proposed Ji’s model to obtain the fractal dimension of cement paste based on the fact that the hydration products continuously fill the pores of cement paste with hydration and verified that the $D$ of the cement paste is between 2 and 3. At the same time, the water–cement ratio, hydration degree, and pozzolanic material all affect the fractal dimension of cement slurry. Suppose that there is a cube with side length $l$ and that each of its sides is divided equally into $m$ equal parts, so that a cube with side length $l$ forms $m^3$ cubes with side length $l/m$. Then, it is considered that $n$ ($n < m^3$) cubes have been filled with hydration products, meaning there are $m^3-n$ cubes left that are not filled with hydration products—i.e., there are $m^3-n$ cubes of pores. Then, continuing through $i$ iterations, the number of pores increases to $(m^3-n)^i$ and the minimum pore size of the cube is $l/m^i$. Thus, the space-filling model simulates the situation where the hydration products keep filling the pores and the pores keep refining.

According to fractal theory, when the unit square generates $N$ small blank squares and the side length of the small square is $l/r$ of the unit square, the fractal dimension $D$ of the blank square is as in Equation (5). By analogy, the expression for the fractal dimension $D$ of Ji’s model can be obtained according to Equation (6). The cumulative pore volume $V$ obtained from the MIP test is obtained by sequentially accumulating the pore volumes in the order of large pore sizes to small pore sizes, but Ji redefined the cumulative pore volume $V^*$—i.e., the cumulative pore volume $V^*$ is obtained by sequentially accumulating the pore volumes in the order of small pore sizes to large pore sizes. Assuming that the pore is a cylinder with radius $\rho$ and height $h(\rho)$, when the pore diameter changes from $\rho$ to $\rho + d\rho$, the number of pores is $dM$; the expression for this is shown in Equation (7). The number of air molecules of radius $r_1$ that a pore can accept is $n$ and its expression is shown in (8); thus, the total number of air molecules that a pore $dM$ can accept is as shown in Equation (9).

According to fractal theory, if the pore fractal dimension is $D$, the total number of air molecules in the whole pore is $N_a$, whose expression is shown in Equation (10). Therefore, only pores with radius $\rho \geq r_1$ can accept air molecules of radius $r_1$, and the total number of air molecules $N_a$ can thus be obtained by integrating Equation (9) from $[r_1, \rho_{\text{max}}]$, as shown in Equation (11). Equation (9) is equal to Equation (11)—that is, Equation (12) is obtained—and then, the fractal dimension can be found by taking the logarithm of both sides of the equation, as shown in Equation (13).

$$D = \frac{\log N}{\log r}, \quad (5)$$

$$D = \frac{\log(m^3 - n)}{\log m} = 3 + \frac{\log \left( 1 - \frac{n}{m^3} \right)}{\log m} < 3, \quad (6)$$

$$dM = \frac{dV^*_r}{dp} \frac{dp}{[\pi \rho^2 h(\rho)]}, \quad (7)$$

$$\frac{2\rho h(\rho)}{r_1^2}, \quad (8)$$

$$dM \times n = \frac{dV^*_r}{dp} \frac{dp}{[\pi \rho^2 h(\rho)]} \times \frac{2\rho h(\rho)}{r_1^2} = \frac{dV^*_r}{dp} \times \frac{2dp}{\pi \rho r_1^2}, \quad (9)$$

$$N_a = c r_1^{-D} \quad (10)$$
where \( N_a \) is the total number of air molecules, \( c \) is a constant, \( r_1 \) is the radius of air molecules, and \( D \) is the fractal dimension.

\[
N_a = \int_{r_1}^{\rho_{\text{max}}} dM \times n = \int_{r_1}^{\rho_{\text{max}}} \frac{dV^*}{d\rho} \times \frac{2d\rho}{\pi \rho r_1^2}, \tag{11}
\]

\[
V^* = \int_0^V dV^* = \int_0^\rho \frac{c \pi}{2} (2 - D) \rho^{2-D} d\rho = \frac{c \pi (D - 2) \rho^{3-D}}{3 - D} = t \rho^{3-D}, \tag{12}
\]

\[
\log V^* = \log t + (3 - D) \log \rho. \tag{13}
\]

2.3.4. Pfeifer and Avnir’s Model

Assuming that the pore is a cylinder with radius \( \rho \) and height \( h(\rho) \), when the pore diameter changes from \( \rho \) to \( \rho + d\rho \), the number of pores is \( dM_1 \), whose expression is shown in Equation (14). Pfeifer and Avnir studied the number of monolayer spherical molecules with radius \( r \) formed on the pore surface, showing that each pore with radius \( \rho \geq r \) can contain \( 2\pi \rho h(\rho)/(\pi r^2) \) molecules. Therefore, the total number of molecules can be calculated from Equation (15) [22]. In fractal pores, the number of molecules required to build a monolayer \( (n) \) is limited by Equation (16). To ensure this, the relation of Equation (17) should be satisfied; then, the fractal dimension \( D \) can be calculated by taking the logarithm of both sides of Equation (17), as shown in Equation (18).

\[
dM_1 = \frac{dV}{d\rho} \left| \frac{d\rho}{\pi \rho^2 h(\rho)} \right|, \tag{14}
\]

\[
n \propto \int_\rho^\infty - \frac{dV}{d\rho} \left( \frac{2h(\rho)}{\rho^2} \right)^{-1} \left[ \frac{h(\rho)}{r^2} \right] d\rho, \tag{15}
\]

\[
n \propto \rho^{-D}, \tag{16}
\]

\[
- \frac{dV}{d\rho} \propto r^{2-D}, \tag{17}
\]

\[
\log \left( - \frac{dV}{d\rho} \right) \propto (2 - D) \log \rho. \tag{18}
\]

3. Results and Discussion

3.1. Analysis of Fractal Characteristics of Different Types of Cement Pastes Using Neimark’s Model

According to the formula of Neimark’s model, the fractal dimensions of different pore sizes of OPC0, FCP10, FCP30, CCP10, and CCP30 at days 3 and 28 are shown in Figures 4–8, respectively. The pore surface fractal dimensions of Region I, Region II, and Region III of OPC0 at 3 days are 2.7751, 4.4236, and 2.8410, respectively, and their corresponding pore size scopes are 179.130–5.175 \( \mu \)m, 3.759–226.806 nm, and 202.691 nm–5.482 nm, respectively. The pore surface fractal dimensions at 28 days for Region I, Region II, and Region III are 2.8615, 4.8661, and 2.7774, respectively, and the corresponding cement paste pore size ranges are 144.079–1.314 \( \mu \)m, 938.197–77.142 nm, and 69.059–5.482 nm, respectively. The pore surface fractal dimensions of Region I, Region II, and Region III of FCP10 at 3 days are 2.6855, 4.0447, and 2.6891, respectively, which correspond to the pore size zones of 179.835–4.527 \( \mu \)m, 3.758–151.072 nm, and 120.845–5.482 nm, respectively. The pore surface fractal dimensions at 28 days for Region I, Region II, and Region III are 2.8935, 4.5335, and 2.6891, respectively, and the corresponding pore size intervals are 120.222–1.315 \( \mu \)m, 1.046–77.145 nm, and 69.062–5.482 nm, respectively. The pore surface fractal dimensions of Region I, Region II, and Region III of CCP10 at 3 days are 2.7751, 4.4236, and 2.8410, respectively, and the corresponding pore size intervals are 120.222–1.315 \( \mu \)m, 1.046–77.145 nm, and 69.062–5.482 nm, respectively. The pore surface fractal dimensions of Region I, Region II, and Region III of CCP30 at 3 days are 2.8036, 4.7519, and 2.7787, respectively, and the corresponding pore size intervals are 120.231–1.043 \( \mu \)m, 938.010–77.151 nm, and 69.062–5.482 nm, respectively.
nm. The pore surface fractal dimensions of Region I, Region II, and Region III of CCP10 at 3 days are 2.8954, 4.4563, and 2.8351, respectively, and their corresponding pore size intervals are 144.019–4.828 μm, 1.309–202.798 nm, and 182.236–5.482 nm. The pore surface fractal dimensions of Region I, Region II, and Region III at 28 days are 2.9263, 4.5130, and 2.7905, respectively, and the corresponding pore size ranges are 120.231–1.313 μm, 938.113–77.149 nm, and 69.059–5.482 nm, respectively. The pore surface fractal dimensions of Region I, Region II, and Region III of CCP30 at 3 days are 2.9160, 6.3323, and 2.8378, respectively. Additionally, the corresponding pore size scopes are 119.973–2.472 μm, 2.058–551.657 nm, and 485.159–5.482 nm, respectively. At 28 days, the pore surface fractal dimensions of Region I, Region II, and Region III are 2.9026, 4.8445, and 2.8227, respectively. Additionally, the corresponding pore size ranges are 120.143–1.044 μm, 936.878–77.154 nm, and 69.056–5.482 nm, respectively.

**Figure 4.** Multifractal characteristics of OPC0 at different ages under Neimark’s model. (a) 3 days, (b) 28 days.

**Figure 5.** Multifractal characteristics of FCP10 at different ages under Neimark’s model. (a) 3 days, (b) 28 days.
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Figure 6. Multifractal characteristics of FCP30 at different ages under Neimark's model. (a) 3 days, (b) 28 days.

Figure 7. Multifractal characteristics of CCP10 at different ages under Neimark’s model. (a) 3 days, (b) 28 days.

Figure 8. Multifractal characteristics of CCP30 at different ages under Neimark’s model. (a) 3 days, (b) 28 days.

Table 3 represents a multifractal analysis of coral powder–cement slurry by Neimark’s model. According to the fractal theory, the value of the pore surface fractal dimension ranges from 2 to 3. When the pore surface fractal dimension value in a certain aperture region is >3 or <2, the region is considered not to have fractal characteristics. From the table,
it can be seen that OPC0, FCP10, FCP30, CCP10, and CCP30 have obvious multifractal characteristics in the whole pore range. Their fractal dimensions in Region I and Region III are less than 3, but their pore surface fractal dimensions in Region II are greater than 3, which indicates that OPC0, FCP10, FCP30, CCP10, and CCP30 have obvious fractal characteristics in Region I and Region III, but not in Region II. Meanwhile, the pore size range of Region II gradually moved toward the direction of smaller pore sizes with the increase in age—for example, the pore size range of Region II is 3.759–226.806 nm at 3 days for OPC0 and 938.197–77.412 nm at 28 days for Region II. The pore size range of Region II for FCP10 at 3 days is 3.758–150.965 nm, while that of Region II at 28 days is 1.046–77.145 nm. The pore surface fractal dimension of Region I basically develops in an increasing trend with increasing age, while the pore surface fractal dimension of Region III basically decreases with increasing age, which may be due to the proceeding hydration and the filling of capillary pores with hydration products, thus blocking the connection of capillary pores and reducing the connectivity of the capillary pores. At the same time, it can be seen from the figure that the pore diameter of Region I is basically above 1000 nm, placing it in the category of large pores. Therefore, the filling of large pores by hydration products is extremely limited, which leads to the hydration products not filling large pores and blocking the connectivity of large pores well, but increasing the complexity and roughness of the surface of large pores to a certain extent, thus increasing the fractal dimension of the pore surface.

### Table 3. Coral powder–cement slurry multifractal analysis by Neimark’s model.

| Sample NO. | Age | Region I | Region II | Region III |
|------------|-----|----------|-----------|------------|
| OPC0       | 3 days | 2.7751   | 4.4236    | 2.8410     |
| FCP10      |       | 2.6855   | 4.0447    | 2.6891     |
| FCP30      |       | 2.9970   | 4.6613    | 2.7639     |
| CCP10      |       | 2.8954   | 4.4563    | 2.8351     |
| CCP30      |       | 2.9160   | 6.3323    | 2.8378     |
| OPC0       | 28 days | 2.8615   | 4.8661    | 2.7774     |
| FCP10      |       | 2.8935   | 4.5335    | 2.7202     |
| FCP30      |       | 2.8036   | 4.7519    | 2.7787     |
| CCP10      |       | 2.9263   | 4.5130    | 2.7905     |
| CCP30      |       | 2.9026   | 4.8445    | 2.8227     |

Relevant studies have shown that the pore structure of cement paste has multifractal characteristics, and the multifractal characteristics can more accurately characterize the fractal nature of the pore structure of cement paste [39]. From Figures 4–8, it can be seen that the coral powder–cement slurry has obvious jump points in Region II, which is also found in the cement slurry, and it is believed that the above phenomenon may be caused by the “ink bottle”-shaped pores and the fracture/defects on the intrusion pressure scale [32]. Meanwhile, Zeng et al. used Neimark’s model and Zhang’s model to study the fractal nature of the pore structure of high-volume fly ash–cement slurry. The results showed that the fractal dimension calculated by Neimark’s model was basically larger than that of Zhang’s model, which may be because Neimark’s model is based on the assumption of cylindrical tube pores. However, this assumption is only valid when pores of different sizes are well connected. However, when Chen et al. used Neimark’s model to study the fractal nature of the pore structure of cement paste, they found that the pore surface fractal dimension was basically greater than 3 [40]. The reason for this is that they performed a fractal analysis of the sizes of all the pores in the cement slurry and did not perform a fractal analysis of different pore size ranges; thus, they obtained different results from those in this paper. Guo et al. [39] showed that the fractal dimension obtained using the whole pore size range did not accurately reflect the fractal characteristics of cement-based materials, and that the correlation between the fractal dimension and permeability is poor. Thus, the permeability coefficient cannot be accurately calculated using the fractal dimension.
Therefore, when using fractal theory to calculate permeability, the use of the pore range without fractal characteristics should be avoided as far as possible. At the same time, fractal analysis should be carried out for the pore size range related to permeability. In conclusion, when using fractal theory to study the relationship between fractal dimension and related properties, it is necessary to pay attention to the multifractal characteristics of cement-based materials so as to obtain more accurate results.

3.2. Analysis of Fractal Characteristics of Different Types of Cement Pastes Using Ji’s Model

The pore volume fractal dimensions according to Ji’s model are shown in Figures 9–13. The pore volume fractal dimensions of Region I and Region II of OPC0 at 3 days are 2.3290 and 2.9948, respectively, and their corresponding pore size ranges are 5.482–484.752 nm and 484.752 nm–365.094 μm, respectively. The pore volume fractal dimensions of Region I and Region II at 28 days are 2.2107 and 2.9942, respectively, and their corresponding pore size intervals are 5.482–120.852 nm and 120.852 nm–365.094 μm, respectively. The pore volume fractal dimensions of Region I and Region II of FCP10 at 3 days are 2.0137 and 2.9929, respectively, and their corresponding pore size intervals are 5.482–150.965 nm and 150.965 nm–365.095 μm, respectively. The pore volume fractal dimensions of Region I and Region II at 28 days are 2.0954 and 2.9922, respectively, and their corresponding pore size intervals are 5.482–120.854 nm and 120.854 nm–365.054 μm, respectively. The pore volume fractal dimensions of FCP30 at 3 days for Region I and Region II are 2.0731 and 2.9917, respectively, and their corresponding pore size intervals are 5.482–484.431 nm and 484.431 nm–365.095 μm, respectively. The pore volume fractal dimensions of Region I and Region II of FCP10 at 3 days are 2.0487 and 2.9951, respectively, and their corresponding pore size intervals are 5.482–120.852 nm and 120.852 nm–365.094 μm, respectively. The pore volume fractal dimensions of Region I and Region II at 28 days are 2.2569 and 2.9921, respectively, and their corresponding pore size intervals are 5.482–120.854 nm and 120.854 nm–365.054 μm, respectively. The pore volume fractal dimensions of CCP30 at 3 days for Region I and Region II are 2.2107 and 2.9929, respectively, and their corresponding pore size intervals are 5.482–484.431 nm and 484.431 nm–365.095 μm, respectively. The pore volume fractal dimensions of Region I and Region II of CCP10 at 3 days are 2.0137 and 2.9929, respectively, and their corresponding pore size ranges are 5.482–120.852 nm and 120.852 nm–365.094 μm, respectively. The pore volume fractal dimensions at 28 days for Region I and Region II are 2.1942 and 2.9922, respectively, and their corresponding pore size intervals are 5.482–133.352 nm and 133.352 nm–363.870 μm, respectively.

Figure 9. Multifractal characteristics of OCP0 at different ages under Ji’s model. (a) 3 days, (b) 28 days.
Figure 10. Multifractal characteristics of CCP10 at different ages under Ji’s model. (a) 3 days, (b) 28 days.

Figure 11. Multifractal characteristics of FCP10 at different ages under Ji’s model. (a) 3 days, (b) 28 days.

Figure 12. Multifractal characteristics of CCP10 at different ages under Ji’s model. (a) 3 days, (b) 28 days.
Figure 13. Multifractal characteristics of CCP30 at different ages under Ji’s model. (a) 3 days, (b) 28 days.

Table 4 shows a multifractal analysis of coral powder–cement slurry carried out using Ji’s model, from which it can be seen that the entire pore size of OPC0, FCP10, FCP30, CCP10, and CCP30 is divided into two ranges, with the pore volume fractal dimension of these two ranges being less than 3, which indicates that Region I and Region II both have significant fractal characteristics. Additionally, the pore volume fractal dimension of Region I is less than 2.5, while the pore volume fractal dimension of Region II is greater than 2.9 and less than 3. Therefore, the pore volume fractal dimension of Region I is less than that of Region II—i.e., the pore volume fractal dimension of small pores is less than that of large pores—which is consistent with the results of related studies [25]. In addition, the pore size ranges of Region I and Region II gradually move toward the direction of smaller pore sizes with increasing age. For example, the pore size range of OPC0 at 3 days is 5.482–484.752 nm for Region I and 484.752 nm–365.053 μm for Region II; the pore size range of Region I at 28 days is 5.482–120.852 nm and the pore size range of Region II is 120.852 nm–365.053 μm. Coral powder has a greater effect on the pore size range of Region I in the early stage of cement paste and a smaller effect on the pore size range of Region I at the later stage. Meanwhile, fine coral powder is beneficial for reducing the pore size range of Region I, but the coarse coral powder will increase the pore size range of Region I. For example, the pore size range of Region I of OPC0 at 3 days is 5.482–484.752 nm, the pore size range of Region I at 28 days is 5.482–120.852 nm, the pore size range of Region I of FCP10 at 3 days is 5.482–150.965 nm, the pore size range of Region I at 28 days is 5.482–120.854 nm, the pore size range of Region I of CCP10 at 3 days is 5.482–1.047 μm, and the pore size range of Region I at 28 days is 5.482–151.107 nm. In addition, the pore volume fractal dimensions of Region I and Region II basically decrease with increasing age, and coral powder has a greater effect on the pore volume fractal dimension of early cement paste. Meanwhile, coral powder decreases the pore volume fractal dimension of cement paste in Region I and Region II. However, the pore volume fractal dimension of fine coral powder–cement slurry is smaller than that of coarse coral powder–cement slurry.
Table 4. Multifractal analysis of coral powder–cement slurry by Ji’s model.

| Sample NO. | Age   | Region I | Region II |
|------------|-------|----------|-----------|
| OPC0       | 3 days| 2.3290   | 2.9948    |
| FCP10      |       | 2.0137   | 2.9929    |
| FCP30      |       | 2.0731   | 2.9917    |
| CCP10      |       | 2.4741   | 2.9927    |
| CCP30      |       | 2.2929   | 2.9939    |

In summary, coral powder–cement slurry has multifractal characteristics and the pore volume fractal dimension of the large pore range is larger than that of the small pore range. The reason for this is that as cement hydration proceeds, more and more hydration products are generated and fill the pores of the cement slurry. At the same time, the hydration products gradually fill in or “refine” the large pores, thus forming small pores. Therefore, the $n$ in Equation (6) becomes larger and larger, meaning that the pore volume fractal dimension of the small pore range becomes smaller than that of the large pore range, which is consistent with Ji’s results [25]. However, when Chen et al. [40] studied the pore volume fractal dimension of cement-based materials using Ji’s model, they concluded that the pore volume fractal dimension of cement paste was between 2.97 and 2.99, which is quite different from the results of this paper. This is mainly because Chen used Ji’s model for the fractal analysis of the entire pore size range of the cement paste and did not distinguish between the different pore sizes before performing fractal analysis. Therefore, when the pore structure of cement paste has multiple fractal characteristics, its pore size should be determined before fractal analysis is carried out.

3.3. Analysis of Fractal Characteristics of Different Types of Cement Pastes Using Pfeifer and Avnir’s Model

The pore surface fractal dimensions according to Pfeifer and Avnir’s model are shown in Figures 14–18. The pore surface fractal dimensions of Region I, Region II, and Region III of OPC0 at 3 days are 2.7030, 3.8545, and 2.4861, respectively, and their corresponding pore size intervals are 5.482–484.752 nm, 484.752 nm–10.057 µm, and 10.057–365.094 µm. The pore surface fractal dimensions of Region I, Region II, and Region III at 28 days are 2.6460, 3.8253, and 2.5861, respectively, and the corresponding pore size intervals are 5.482–120.852 nm, 120.852–9.056 µm, and 9.056–365.053 µm, respectively. The pore surface fractal dimensions of FCP10 at 3 days for Region I, Region II, and Region III are 2.3889, 4.6138, and 2.9342, respectively, and their corresponding pore size intervals are 5.482–120.819 nm, 150.965 nm–2.868 µm, and 5.175–179.130 µm, respectively. The pore surface fractal dimensions at 28 days for Region I, Region II, and Region III are 2.7447, 3.8635, and 2.5536, respectively, and their corresponding pore size intervals are 5.482–62.571 nm, 130.725 nm–4.828 µm, and 5.172–365.054 µm, respectively. The pore surface fractal dimensions of CCP10 at 3 days for Region I, Region II, and Region III are 2.7690, 4.6290, and 2.6429, respectively, and their corresponding pore size intervals are 5.482–485.157 nm, 551.142 nm–9.056 µm, and 10.056–364.142 µm, respectively. The pore surface fractal dimensions at 28 days for Region I, Region II, and Region III are 2.9591, 3.9104, and 2.5153, respectively, and their corresponding pore size
intervals are 5.482–62.555 nm, 120.863 nm–9.056 μm, and 10.056–364.142 μm, respectively. The pore surface fractal dimensions of Region I, Region II, and Region III of CCP30 at 3 days are 2.8751, 4.5752, and 2.7028, respectively, and their corresponding pore size intervals are 17.102–551.657 nm, 1.048–9.052 μm, and 10.057–364.142 μm, respectively. The pore surface fractal dimensions at 28 days for Region I, Region II, and Region III are 2.9250, 4.0302, and 2.6436, respectively; their corresponding pore size intervals are 2.9250, 4.0302, and 2.6436, respectively; and the corresponding pore size intervals are 5.482–69.056 nm, 151.109 nm–9.051 μm, and 10.054–363.870 μm, respectively.

**Figure 14.** Multifractal characteristics of OPC0 at different ages under Pfeifer and Avnir’s model. (a) 3 days, (b) 28 days.

**Figure 15.** Multifractal characteristics of FCP10 at different ages under Pfeifer and Avnir’s model. (a) 3 days, (b) 28 days.
Table 5 represents the multifractal analysis of coral powder–cement slurry carried out using Pfeifer and Avnir’s model. According to the results of Pfeifer and Avnir’s model, there are obvious multifractal characteristics of OPC0, FCP10, FCP30, CCP10, and CCP30.
in the whole aperture range—i.e., Region I, Region II, and Region III. Additionally, the pore surface fractal dimensions of Region I and Region III are less than 3, but the pore surface fractal dimensions of Region II are greater than 3, which indicates that they have obvious fractal characteristics in Region I and Region III, but not in Region II. The pore size ranges of Region I, Region II, and Region III gradually move toward smaller pore sizes with increasing age. Fine coral powder causes the pore size range of Region II to gradually move toward the direction of small pores, while increasing the range of Region II, but the range of Region II is closely related to the amount of fine coral powder in the mixture. For example, the ranges of Region II of FCP10 at 3 days and 28 days are 150.965 nm–5.175 µm and 130.725 nm–275.500 µm, respectively, while the ranges of Region II for FCP30 at 3 days and 28 days are 551.142 nm–10.057 µm and 151.097 nm–9.056 µm, respectively. However, coarse coral powder causes the range of Region II to gradually move toward the direction of large pore sizes, and the greater the amount of coarse coral powder mixed in is, the more obviously the range of the cement slurry in Region II moves to the left. For example, the pore size ranges of Region II for CCP10 at 3 days and 28 days are 552.074 nm–9.053 µm and 120.863 nm–9.056 µm, respectively, but the pore size ranges of Region II for CCP30 at 3 days and 28 days are 1.048–9.052 µm and 151.109 nm–9.051 µm, respectively. The pore surface fractal dimensions of Region I basically increase with age, while those of Region III basically decrease with age. The pore surface fractal dimensions of Region I and Region III are less affected by the specific surface area and the amount of coral powder.

| Sample NO. | Age     | Region I | Region II | Region III |
|------------|---------|----------|-----------|------------|
| OPC0       | 3 days  | 2.7030   | 3.8545    | 2.4861     |
| FCP10      |         | 2.3889   | 4.6138    | 2.9342     |
| FCP30      |         | 2.7294   | 4.0258    | 2.7854     |
| CCP10      |         | 2.7690   | 4.6290    | 2.6429     |
| CCP30      |         | 2.8751   | 4.5752    | 2.7028     |
| OPC0       | 28 days | 2.6460   | 3.8253    | 2.5861     |
| FCP10      |         | 2.7447   | 4.3689    | 2.7037     |
| FCP30      |         | 2.7444   | 3.8635    | 2.5536     |
| CCP10      |         | 2.9591   | 3.9104    | 2.5153     |
| CCP30      |         | 2.9250   | 4.0302    | 2.6436     |

When Chen et al. used Pfeifer and Avnir’s model to study the fractal characteristics of the pore structures of paste, mortar, and concrete at different water–cement ratios, they found that the fractal dimension calculated using Pfeifer and Avnir’s model was greater than 3 [40]. This indicates that the pore structures of paste, mortar, and concrete do not have fractal characteristics, which is contrary to the findings of related studies [8,10,22,25–29]. However, Pfeifer and Avnir [22] found that the inner pore surface of cementitious materials had fractal characteristics. Meanwhile, when Atzeni et al. [10] used Pfeifer and Avnir’s model [22] to study the fractal characteristics of the pore structure of cement paste, they found that there were obvious multifractal characteristics, and pointed out that the fractal dimension at the pore diameter mutation was greater than 3, meaning that the pore structure at this location did not have fractal characteristics, which is consistent with the results of this paper. Therefore, when comparing Chen’s results [40] with those of the above-mentioned researchers and this paper, it was found that both obtained inconsistent conclusions when using the same experimental method and theoretical model. The reason for this is that Chen used the entire pore size range to calculate the fractal dimension of the pore structure of cementitious materials and did not divide the entire pore size range before calculating the fractal dimension. Meanwhile, after analyzing Figure 2 [40], it can clearly be seen that there are obvious jump points in the figure; thus, the entire pore range should be divided before calculating its fractal dimension. In summary, when using fractal theory to study whether the pore structure of cementitious materials has fractal characteristics and
to establish the relationship between the fractal dimension and the related properties of cementitious materials, it is necessary to first judge whether the pore structure has obvious multifractal characteristics and then use the relevant fractal models to calculate the fractal dimensions for different pore ranges.

4. Conclusions

In this paper, coral powder with different contents and levels of fineness was mixed into cement paste; then, the MIP test was used to obtain the pore structure data of different types of cement paste. Based on the pore structure data, Neimark’s model, Ji’s model, and Pfeifer and Avnir’s model were used to obtain the fractal dimensions of different types of cement paste in different pore size ranges. Accordingly, the effect of coral powder on the pore structure of cement paste from the fractal point of view can be elaborated. The main conclusions are as follows:

(1) When Neimark’s model, Ji’s model, and Pfeifer and Avnir’s model were used to analyze the fractal nature of the coral powder–cement pastes, it was found that the coral powder–cement pastes all had multifractal characteristics. The pore surface fractal dimensions of Region II calculated by Neimark’s model and Pfeifer and Avnir’s model were greater than 3; therefore, the pore structure in the range of Region II did not have fractal characteristics. Ji’s model divided the entire aperture into two regions (Region I and Region II), both of which had a pore volume fractal dimension of less than 3, and the pore volume fractal dimension of Region I was smaller than that of Region II.

(2) The pore size range of Region II in cement paste basically moved gradually in the direction of small pore sizes with the increase in age, but after mixing with coral powder, the pore size range of Region II was more influenced by the amount and fineness of coral powder, which may have been related to its filling effect. The difference between the pore surface fractal dimension values obtained from Neimark’s model and Pfeifer and Avnir’s model was not significant, and Neimark’s model was better than Pfeifer and Avnir’s model in general. However, the difference between the pore surface fractal dimension and the pore volume fractal dimension obtained by Ji’s model was larger.

(3) The pore surface fractal dimension of large pores calculated by Neimark’s model was positively correlated with age, while the pore surface fractal dimension value of small pores decreased with increasing age and the pore surface fractal dimension of the transition region had little relationship with age, coral powder fineness, or dosage. The pore volume fractal dimension of large and small pores calculated by Ji’s model decreased with increasing age, and the pore volume fractal dimension of large and small pores was correlated with coral powder fineness. The pore surface fractal dimension of large pores was negatively correlated with age, while the pore surface fractal dimension of small pores increased with age. The specific surface area and dosage of coral powder had less effect on the pore surface fractal dimension of Region I and Region III, as calculated by Pfeifer and Avnir’s model.

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**References**

1. Wang, D.J.; Cao, L. *Chaos, Fractals and Their Applications*; University of Science and Technology of China Press: Hefei, China, 1995; pp. 93–103. (In Chinese)

2. Hou, D.; Li, D.; Hua, P.; Jiang, J.; Zhang, G. Statistical modelling of compressive strength controlled by porosity and pore size distribution for cementitious materials. *Cem. Concr. Compos.* 2019, 96, 11–20. [CrossRef]

3. Li, D.; Li, Z.; Lv, C.; Zhang, G.; Yin, Y. A predictive model of the effective tensile and compressive strengths of concrete considering porosity and pore size. *Constr. Build. Mater.* 2018, 170, 520–526. [CrossRef]

4. Panesar, D.K.; Francis, J. Influence of limestone and slag on the pore structure of cement paste based on mercury intrusion porosimetry and water vapour sorption measurements. *Constr. Build. Mater.* 2014, 52, 52–58. [CrossRef]

5. Zeng, Q.; Luo, M.; Pang, X.; Li, L.; Li, K. Surface fractal dimension: An indicator to characterize the microstructure of cement-based porous materials. *Appl. Surf. Sci.* 2013, 282, 302–307. [CrossRef]

6. Zhang, L.; Zhou, J. Fractal Characteristics of porous structure of hardened cement paste prepared by pressurized compact molding. *Constr. Build. Mater.* 2020, 259, 119856. [CrossRef]

7. Tang, S.; Huang, J.; Duan, L.; Yu, P.; Chen, E. A review on fractal footprint of cement-based materials. *Powder Technol.* 2020, 370, 237–250. [CrossRef]

8. Winslow, D.N. The fractal nature of the surface of cement paste. *Cem. Concr. Res.* 1985, 15, 817–824. [CrossRef]

9. Jin, S.; Zhang, J.; Han, S. Fractal analysis of relation between strength and pore structure of hardened mortar. *Constr. Build. Mater.* 2017, 135, 1–7. [CrossRef]

10. Atzeni, C.; Pia, G.; Sanna, U. A geometrical fractal model for the porosity and permeability of hydraulic cement pastes. *Constr. Build. Mater.* 2010, 24, 1843–1847. [CrossRef]

11. An, Q.; Chen, X.; Wang, H.; Yang, H.; Yang, Y. Segmentation of concrete cracks by using fractal dimension and UHK-net. *Fractal Fract.* 2022, 6, 95. [CrossRef]

12. Guzmán-Castañeda, J.I.; García-Bórquez, A.; Arizalbo-Salas, R.D. Fractal dimension determined through optical and scanning electron microscopy on FeCrAl alloy after polishing, erosion, and oxidizing processes. *Phys. Status Solidi B* 2012, 249, 1224–1228. [CrossRef]

13. Stanczak, G. Fractal Analysis of the Pore Space in Sandstones as Derived from Mercury Porosimetry and Image Analysis. In Proceedings of the International Multidisciplinary Microscopy Congress, Antalya, Turkey, 10–13 October 2014. [CrossRef]

14. Bernardes, E.E.; Carrasco, E.V.M.; Vasconcelos, W.; de Magalhães, A.G. X-ray microtomography (μ-CT) to analyze the pore structure of a Portland cement composite based on the selection of different regions of interest. *Constr. Build. Mater.* 2015, 95, 703–709. [CrossRef]

15. Yang, X.; Zhang, R.; Ma, S.; Yang, X.; Wang, F. Fractal dimension of concrete meso-structure based on X-ray computed tomography. *Powder Technol.* 2019, 350, 91–99. [CrossRef]

16. Tang, S.; Cai, X.; He, Z.; Shao, H.; Li, Z.; Chen, E. Hydration process of fly ash blended cement pastes by impedance measurement. *Constr. Build. Mater.* 2016, 113, 939–950. [CrossRef]

17. Wang, F.; Li, S. Determination of the surface fractal dimension for porous media by capillary condensation. *Ind. Eng. Chem. Res.* 1997, 36, 1598–1602. [CrossRef]

18. Ji, Y.; Sun, Z.; Jiang, X.; Liu, Y.; Shui, L.; Chen, C. Fractal characterization on pore structure and analysis of fluidity and bleeding of fresh cement paste based on 1H low-field NMR. *Constr. Build. Mater.* 2017, 140, 445–453. [CrossRef]

19. Wang, L.; Song, X.; Yang, H.; Wang, L.; Tang, S.; Wu, B.; Mao, W. Pore structural and fractal analysis of the effects of MgO reactivity and dosage on permeability and F–T resistance of concrete. *Fractal Fract.* 2022, 6, 113. [CrossRef]

20. Ma, H. Mercury intrusion porosimetry in concrete technology: Tips in measurement, pore structure parameter acquisition and application. *J. Porous Mater.* 2014, 21, 207–215. [CrossRef]

21. Zhang, B.Q.; Liu, W.; Liu, X.F. Scale-dependent nature of the surface fractal dimension for bi- and multi-disperse porous solids by mercury porosimetry. *Appl. Surf. Sci.* 2006, 253, 1349–1355. [CrossRef]

22. Pfeifer, P.; Avnir, D. Chemistry in noninteger dimensions between two and three. I: Fractal theory of heterogeneous surfaces. *J. Chem. Phys.* 1983, 79, 3558–3565. [CrossRef]

23. Friesen, W.L.; Mikula, R.J. Fractal dimensions of coal particles. *J. Colloid Interface Sci.* 1997, 120, 263–271. [CrossRef]

24. Usteri, M.; Bonny, J.D.; Leuenberger, H. Fractal dimension of porous solid dosage forms. *Pharm. Acta Helvetiae.* 1990, 65, 55–61.

25. Ji, X.; Chan, S.; Feng, N. Fractal model for simulating the space-filling process of cement hydrates nd fractal dimension sions of pore structure of cement-based materials. *Cem. Concr. Res.* 1997, 27, 1691–1699. [CrossRef]

26. Neimark, A. A new approach to the determination of the surface fractal dimension of porous solids. *Phys. A* 1992, 191, 258–262. [CrossRef]

27. Lange, D.; Jennings, H.M.; Shah, S.P. Image analysis techniques for characterization of pore structure of cement-based materials. *Cem. Concr. Res.* 1994, 24, 841–885. [CrossRef]
28. Livingston, R.A. Fractal nucleation and growth model for the hydration of tricalcium silicate. *Cem. Concr. Res.* **2000**, *30*, 1853–1860. [CrossRef]

29. Gao, Y.; Jiang, J.; De Schutter, G.; Ye, G.; Sun, W. Fractal and multifractal analysis on pore structure in cement paste. *Constr. Build. Mater.* **2014**, *69*, 253–261. [CrossRef]

30. Zeng, Q.; Li, K.; Fen-Chong, T.; Dangla, P. Surface fractal analysis of pore structure of high-volume fly-ash cement pastes. *Appl. Surf. Sci.* **2010**, *257*, 762–768. [CrossRef]

31. Yu, L.H.; Ou, H.; Duan, Q.P. Fractal dimension of perlite doped cement stone pores and its relationship with pore structure and strength. *J. Mater. Sci. Eng.* **2007**, *25*, 201–205. (In Chinese) [CrossRef]

32. Li, Y.; Chen, Y.; He, X.; Wei, J.; Zhang, W.; Zhang, H.; Guo, S. Fractal dimension of pore volume of fly ash-cement slurry and its relationship with pore structure and strength. *J. Chin. Ceram. Soc.* **2003**, *31*, 774–779. (In Chinese) [CrossRef]

33. Wei, J.X.; Yu, Q.J.; Zeng, X.X.; Bai, R.Y. Study of fractal dimension of pore structure in concrete. *J. South China Univ. Technol.* **2007**, *35*, 121–124. (In Chinese) [CrossRef]

34. Wang, X.-Z.; Wang, X.; Jin, Z.-C.; Meng, Q.-S.; Zhu, C.-Q.; Wang, R. Shear characteristics of calcareous gravelly soil. *Bull. Eng. Geol. Environ.* **2017**, *76*, 561–573. [CrossRef]

35. Wang, X.; Weng, Y.; Wei, H.; Meng, Q.; Hu, M. Particle obstruction and crushing of dredged calcareous soil in the Nansha Islands, South China Sea. *Eng. Geol.* **2019**, *261*, 105274. [CrossRef]

36. Zhang, L.; Niu, D.; Wen, B.; Fu, Q.; Peng, G.; Su, L.; Blackwood, D.J. Initial-corrosion condition behavior of the Cr and Al alloy steel bars in coral concrete for marine construction. *Cem. Concr. Compos.* **2021**, *120*, 104051. [CrossRef]

37. Da, B.; Chen, Y.; Yu, H.; Ma, H.; Chen, D.; Wu, Z.; Liu, J.; Li, Y. Preparation technology, mechanical properties and durability of coral aggregate seawater concrete in the island-reef environment. *J. Clean. Prod.* **2022**, *339*, 130572. [CrossRef]

38. Wang, X.; Wang, X.; Hu, M.; Zhu, C.; Meng, Q.; Wang, R. Study of permeability of calcareous silty layer of foundation at an artificial reclamation island. *Rock Soil Mech.* **2017**, *38*, 3127–3135. (In Chinese) [CrossRef]

39. Guo, M.L.; Xiao, J.; Zuo, S.H. Multifractal Analysis on Pore Structure of Cement-Based Materials Blended with Ground. Limestone and Its Relationship with Permeability. *J. Chin. Ceram. Soc.* **2019**, *47*, 617–624. (In Chinese) [CrossRef]

40. Chen, X.; Zhou, J.; Ding, N. Fractal characterization of pore system evolution in cementitious materials. *KSCE J. Civ. Eng.* **2015**, *19*, 719–724. [CrossRef]