Analysis of Effects of Winter Construction Treatments on Fiber Concrete Samples Using an Improved Box Dimension Method

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Abstract. The influence of winter construction on the microstructure of hybrid fiber concrete was studied. Ordinary concrete, basalt-polypropylene (BP) fiber reinforced concrete, and steel-polypropylene (SP) fiber reinforced concrete were investigated under three different working conditions: construction during winter without any protective measures, with some construction modification, and with standard curing and protection. The characteristic parameters of the resulting concrete microstructure were obtained using the Denmark Rapidair457 test system. Because the traditional box dimension method is unable to accurately analyze the uniformity of the pore size distribution, an improved box dimension method was used to accurately determine the scale-free interval, allowing comparative analysis of the fractal characteristics of the same concrete material under different working conditions. The results show highest air content for samples constructed during winter without any protective measures, followed by samples constructed during winter but with modified construction measures, and then lowest for samples constructed using standard maintenance practices. The specific surface of pores and the fractal dimension was highest for samples constructed using standard maintenance practices, followed by samples constructed during winter with modified construction measures, and then lowest for samples constructed during winter without any protective measures. The fractal dimension increased as the air content decreased, and increased as the specific surface increased. The pore structure test results were consistent with the analysis of the fractal dimension.

1. Introduction
Most studies of problems with the winter construction of concrete projects have mainly focused on construction technology and quality control, with few studies examining the influence of winter construction conditions on concrete microstructure. The macroscopic properties of concrete are closely related to its microscopic pore structure. Winslow et al. (1985) first introduced fractal theory to describe the pore size distribution of cement slurry. The Menger sponge model is the most widely used fractal method based on mercury intrusion (Zhang et al. 2016). There are many scale-free intervals in the measured pore area of concrete. Additionally, the calculation accuracy of the traditional box dimension method is limited by the size of the box, resulting in large differences in fractal images but giving the same calculation results (Pia et al. 2014 & Atzeni et al. 2016). To improve the accuracy of fractal calculation, the fractional box counting method (Gun et al. 2017) and the improved differential box counting method (Yu et al. 2014) have been developed. Using five calculation models, the fractal dimension of cement paste, mortar and concrete is calculated (Chen et al. 2015). The fractal dimension of cement particle size distribution has a correlation with cement specific surface area and median particle size, which can be used as a comprehensive parameter reflecting the characteristics of cement...
particles (Guo et al. 2018). The variation of pore distribution and the rate of pore volume variation in concrete can reflect the frost resistance of concrete well, and can be used as an important index to evaluate the frost resistance of concrete structure (Wei et al. 2018).

The complex structure of hybrid fiber concrete is seriously damaged by early frost damage. In this study, three kinds of concretes were tested: ordinary concrete (C), basalt-polypropylene fiber concrete (BP), and steel-polypropylene fiber concrete (SP). These materials were prepared without winter construction measures, with winter construction measures, and with standard maintenance. The Denmark Rapidair457 test system was applied to obtain the microscopic pore structure characteristic parameters of the concrete. Because the traditional box dimension method cannot accurately analyze the uniformity of the pore size distribution, the improved box dimension method was adopted. The fractal characteristics of the same concrete material under different working conditions were compared and analyzed.

2. Test Overview

2.1. Raw Materials

Cement: Dalian Xiaoyetian Cement Co., Ltd. Huari Brand 42.5# Ordinary Portland Cement; fine aggregate: high quality river sand, medium sand with a fineness modulus of 2.5; coarse aggregate: gravel, particle size 5-10mm; water reducing agent: Kao naphthalene water reducing agent, maximum water reduction rate of 30%; polypropylene fiber: Hong Kong Henglue Grace company Dura fiber; basalt fiber: Sichuan Aerospace Extension Xin Basalt Industrial Co., Ltd., length 30mm; steel fiber: Bekart's 3D-end curved steel fiber; paraffin: high-efficiency slicing wax. The concrete mix ratios are shown in Table 1. C is ordinary concrete, BP is polypropylene-basalt fiber concrete, and SP is polypropylene-steel fiber concrete. According to the Construction Engineering Winter Construction Regulations (JGJ 104-2011), three working conditions were set to mimic the natural conditions of winter construction. Working condition 1 is without winter construction measures. Samples were prepared with cold water mixing and outdoor bare curing, and the test pieces were designated C-1, BP-1, and SP-1. Working condition 2 indicates winter construction measures. Samples were prepared with 60 °C water mixing and outdoor cover cotton-wool maintenance. The test pieces were designated for the three kinds of concretes(C-2, BP-2, SP-2). Working condition 3 represents standard maintenance, and the test pieces are C-3, BP-3, and SP-3.

| Specimen Numbering | water | Cement | sand | gravel | Water reducing agent | Dura fiber | Basalt fiber | Steel fiber | Lead gas Agent |
|--------------------|-------|--------|------|--------|-----------------------|------------|-------------|-------------|---------------|
| C                  | 172   | 400    | 639  | 1186   | 3.2                   | 0          | 0           | 0           | 0.08          |
| BP                 | 172   | 400    | 639  | 1186   | 3.2                   | 0.9        | 2.5         | 0           | 0.08          |
| SP                 | 172   | 400    | 639  | 1186   | 3.2                   | 0.9        | 0           | 30          | 0.08          |

(a) C-1 (b) C-2 (c) C-3
2.2. Microscopic Test Methods

Microstructure parameters were obtained using the Denmark Rapidair457 hardened concrete microstructure test system. As shown in Figures 1, the chord length frequency and air content fraction percentage, where the abscissa indicates the chord length of the pore, the left ordinate is the frequency of the pore for a certain interval, and the right ordinate indicates the ratio of the pore to the area of the test block for a certain interval.

2.2.1 Air Content. The air content of concrete was measured for samples prepared under different conditions, and the results are presented in Figure 2. The following conditions were tested:

(1) Impact of working conditions. The air content of concrete was in the following order, from highest to lowest: working condition 1, working condition 2, and working condition 3. The air content values of C, BP, and SP that did not have winter application treatment were 1.6 times, 2.7 times, and 3.5 times that of the standard, respectively, and the samples with winter application were 1.1 times, 1.2 times, and 1.3 times the value of the standard. (2) Influence of materials. When fiber was added to the concrete substrate, compared with C, the air content of the concrete samples prepared under working conditions 1, 2, and 3 increased, and was in the order from highest to lowest of BP, SP, and C. The mechanism analysis of the air content test is similar to that of the air permeability test, and a large air diffusion coefficient corresponds to high air content. The addition of fibers increases the weak interface, and the introduction of open pores increases the gas content of the concrete, providing a more convenient channel for gas diffusion.

2.2.2 Bubble Spacing Factor. The concrete bubble spacing factor was next determined for the different concrete samples. The results are presented in Figure 3. The velocity coefficient obtained by Rapidair457 was calculated according as in equation (1).

$$\bar{L} = \frac{3[1.4(1 + \frac{P}{A})^{1/2} - 1]}{4N \frac{T_e}{T}}$$

(1)
Where: \( \bar{\lambda} \) - bubble spacing coefficient (mm); \( P \) - concrete cement paste; \( A \) - concrete gas content (%); \( N \) - bubble appearance frequency for a certain interval (%); \( T_a \) - bubble chord length (mm).

The following conditions were tested:
1. Impact of working conditions. For C, BP, SP, the relationship between the coefficients of concrete bubble spacing was, from highest to lowest, in the order of working condition 1, working condition 2, and working condition 3. For the same kind of concrete, as the curing conditions improved, the air content of the concrete decreased, which typically increases the bubble spacing coefficient. However, as can be seen from Figure 1, the frequency of relatively large bubbles with a chord length of 0.02 mm to 0.06 mm was remarkably lowered, and the frequency of relatively small bubbles with a chord length of less than 0.02 mm was significantly increased. Bubbles obtained by the formula (1) were reduced. The gas content of the concrete, the length of the bubble chord, and the numbers of large bubbles were reduced under taking winter application, so the winter application was used to enhance the frost resistance of the concrete.
2. Influence of materials. Under working conditions 2 and 3, the gas content of C was the smallest and the corresponding bubble spacing coefficient was the largest. The gas content of BP was the largest, and the corresponding bubble spacing coefficient was greater than that of C. The gas volume of SP was between C and BP, and the diameter of small bubbles ranging from 0.01 mm to 0.02 mm was significantly larger than that of C and BP, that is, SP has more small bubbles, making its bubble pitch coefficient the smallest. Under working condition 1, it can be clearly seen that the frequency of bubble chord length shifted to large holes, that is, the frequency of relatively small bubbles with chord length less than 0.03 mm decreased, and the chord length was 0.06. The frequency of relatively large bubbles of 0.06 mm~0.18 mm increased significantly. For C, the influence of the frequency of small bubbles on the bubble spacing coefficient is dominant, so that the bubble spacing coefficient of C was slightly lower than that of BP and SP.

![Figure 2. Air content.](image1)

![Figure 3. Bubble spacing coefficient.](image2)

2.3. Improved Box Dimension Method
The distribution of concrete microstructure has strong self-similarity and irregularity within a certain range. Covering samples with different sizes of boxes, the number of boxes covering the fractal body is \( N \), so then there is

\[
N = r^{-D}
\]  

(2)

Where: \( D \) is the fractal dimension obtained by the box dimension method. In order to improve the objectivity and accuracy of the self-similar interval, the box dimension method is improved. The identification method of the second derivative of the double logarithmic curve is adopted. The first derivative of the \( i \)-th point (\( \ln N(r_i) \)) is

\[
\ln N(r_i) = \frac{d[\ln N(r_i)]}{d(\ln r_i)} = \frac{\ln N(r_{i+1}) - \ln N(r_{i-1})}{\ln r_{i+1} - \ln r_{i-1}}, (i = 2, 3, \ldots, K - 1)
\]

(3)
Where: $\ln'N(r_i)$ is the local slope of the i-th point; K is the number of points on the double logarithmic curve. In the self-similar region, the local slope of the point on the double logarithmic curve is close to a certain fixed value. If the local slope is again derived, the second derivative of the double logarithmic curve can be obtained. The second derivative of a point within the self-similar interval should fluctuate slightly around 0. The second derivative of the i-th point ($\ln r_i$, $\ln N(r_i)$) is

$$\ln'N(r_i)=\frac{d[\ln N(r_i)]}{d(ln r_i)}=\frac{\ln N'(r_i)-\ln N(r_{i-1})}{\ln r_{i+1}-\ln r_{i-1}}, (i=3,4,\ldots,K-2)$$

(4)

Therefore, the search for the self-similar interval is to find a continuous region of the $\ln r - \ln'N(r)$ curve whose value is near zero. The goal is to find a longer continuous area so that the self-similar area contains more points. The specific search plan is as follows: $\ln r - \ln'N(r)$ select N (3 ≤ N ≤ K - 5) continuous points, assuming the starting point is the j-th (3 ≤ j ≤ K - N - 1) point, and the coordinates corresponding to these N points are ($\ln r_i$, $\ln N(r_i))$ (i=j, j+1, ..., j+N-1). Assume that the area of the N points around the x-axis is S. Then, under the condition that the number of points N is the same, the smaller the S is, the smaller the fluctuation amplitude of the point is listed near 0, and the search for the self-similar interval is converted to find the largest N and the smallest S, which can be calculated as in equation (5).

$$S = \sum_{i=j}^{j+N-1} \ln'N(r_i) \times \Delta \ln r_i \times (3 \leq N \leq K - 5, 3 \leq j \leq K - N - 1)$$

(5)

The improved box dimension method is used to calculate the microstructural characteristic parameters, and the lgr-lgN curve (Figure 4), the relationship between the gas content and the fractal dimension (Figure 5), and the relationship between the specific surface area and the fractal dimension are obtained (Figure 6).

As shown in Figures 5, the fractal dimension of C, BP, and SP increased as the air content decreased. For the different working conditions, fractal dimension was in the order, from highest to lowest, of working condition 3, working condition 2, and working condition 1. Gas content was in the order, from highest to lowest, of working condition 1, working condition 2, and working condition 3. As can be seen from Figure 6, the fractal dimensions of C, BP, and SP increased with the increase of the specific surface area of pores. The relationship between fractal dimension and specific surface area was in the order, from highest to lowest of working condition 3, working condition 2, and working condition 1.

**Figure 4. Improving the box dimension curve**

For working condition 3, the hydration was the most complete, and the hydration products can repair the pore structure to refine the pores. The innermost part of the concrete was the densest, with the least defects and the lowest gas content. The small pores account for the highest proportion, the
specific surface area and the fractal dimension were the largest. The fractal dimension is the largest for samples prepared with working condition 1. The concrete hydration reaction slowed due to early freezing damage, and concrete frost heaving causes the hydration products to gradually change from a densely packed state to a loose state, coarsening the internal structure of the concrete. The pore size of the concrete does not change, and this material has the largest proportion of large pores, the largest gas content, the lowest proportion of small pores, the smallest specific surface area, and the smallest fractal dimension. Samples prepared with Condition 2 had air content, fractal dimension, and specific surface area values between those of working condition 1 and working condition 3. This indicates that winter application measures improve the completion of cement hydration and improve the concrete pore structure. As indicated by the results of the pore structure test in Figure 1, with improved curing conditions, the frequency of relatively large pores of pore length from 0.02 mm to 0.06 mm was significantly reduced and the frequency of relatively small pores with a chord length of less than 0.02 mm increased significantly. Therefore, the pore structure test results are consistent with the fractal dimension changes.

![Figure 5. Air content and fractal dimension](image1)

![Figure 6. Specific surface and fractal dimension](image2)

3. Conclusions
(1) For plain concrete (C), polypropylene-basalt fiber concrete (BP) and polypropylene-steel fiber concrete (SP), the air content and concrete bubble spacing coefficient were highest for samples prepared without winter construction measures, followed by samples prepared with winter construction measures, and samples prepared with standard maintenance. The specific surface area and the fractal dimension were opposite. The fractal dimension increased as the air content decreased, and increased as the specific pore area increased.

(2) Winter construction conditions affected the concrete pore structure. The better the curing conditions are, the greater the extent of hydration. Hydration products can repair the pore structure to refine the pores. Therefore, the more dense the interior becomes, the fewer the number of defects. The lower the gas content, the higher the proportion of small pores, resulting in a larger surface area and a larger fractal dimension. The pore structure test results are consistent with the conclusions of the fractal dimension tests. Adopting winter construction measures will improve complete hydration of cement and improve the pore structure of concrete.

(3) The improved box dimension method improves the objectivity and accuracy of identifying the self-similar interval. Since concrete as a porous medium, there are multiple fractals in its pore interval, and the improved fractal dimension first determines the self-similar interval. Excluding the influence of multi-fractal, the obtained fractal dimension has a certain improvement in accuracy.

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5. References

[1] Winslow D N 1985 Fractal character in cement and concrete *Cement Concrete Res* **15**(10) pp 817-24

[2] Zhang Y S Gao F and Gao Y 2016 Fractal structure and model of granite pore size distribution under high temperature influence *Chinese Journal of Rock Mechanics and Engineering* **35**(12) pp 2426-38

[3] Pia G and Sanna U 2014 Intermingled fractal untits model and electrical equivalence fractal approach for prediction of thermal conductivity of porous materials *Applied Therm.Eng* **65**(1-2) pp 330-36

[4] Atzeni C and Pia G 2016 Fractal modelling of medium-high porosity sic ceramics *Eur. Ceram. Soc J* **28**(14) pp 2809-14

[5] Gun B S Hye R S and Gang G J 2017 Enhancement of the Box-Counting Algorithm for fractal dimension estimation *Pattern Recognition Letters* **98**(1) pp 53-8

[6] Yu L Ling Y C and He M W 2014 An improved differential box-counting method to estimate fractal dimensions of gray-level images *J vis Commun Image R* **25**(5) pp 1102-11

[7] Chen X Zhou J and Ding N 2015 Fractal characterization of pore system evolution in cementitious materials *Ksce J Civ Eng* **19**(3) pp 719-24

[8] Guo W, Qin H G and Ji X X 2018 Fractal study on properties of universal Portland cement *Concrete & cement products*. (4) pp 22-25.

[9] Wei Y M, Chai J R and Qin Y 2018 Effects of pore distribution and its antifreeze performance on recycled concrete under freeze-thaw cycles. *Bulletin of the Chinese Ceramic Society* **37**(3) pp 825-830.