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A quantitative study on the surface crack pattern of concrete with high content of steel fiber

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Abstract

The mechanical properties and digital image analysis of slurry-infiltrated fiber reinforced concrete (SIFCON) were investigated experimentally. Fractal dimension is used as a parameter to characterize the crack pattern on the surface of SIFCON. It is found that there exists fractal phenomenon for different fiber contents of SIFCON, fractal dimension can be a parameter to characterize crack pattern on the surface of SIFCON quantitatively, and there exists a good correlation between mechanical properties and fractal dimension.

Keywords: Fiber reinforced concrete; Digital image analysis; Characterization

1. Introduction

It is a well known fact that the primary function of the fibers in a fiber reinforced concrete (FRC) material is to act as crack arresters and crack closers, to ensure that distributed and not localized cracking takes place during loading, and to stabilize the distributed cracking. Thus, compared with plain concrete, FRC has higher compressive strength, bending strength, and tensile strength, especially flexural toughness. For conventional construction technique, the fiber volume of normal FRC is generally limited to about 2% so that the reinforced effect of steel fiber is not as high as what some need in civil engineering. However, in the past 20 years, a new construction technique was developed to increase the addition volume content of steel fiber, leading to the development of slurry-infiltrated fiber reinforced concrete (SIFCON), whose fiber volume ranges from 4% to 20%. Because of its higher fiber content, SIFCON has superior properties for both strength and ductility than ordinary steel FRC. The mechanical properties of SIFCON have been investigated widely and it is found that the strength of SIFCON can reach as high as several times than that of matrix and the increase of flexural toughness is even more enormous [1–3]. Furthermore, it has also been concluded that the high content of steel fiber makes the fracture mode from single crack propagation to irregular multicrack mode under bending load [4].

Because the crack pattern is considered as an external phenomenon to study the reinforced mechanism of SIFCON, it is very important to characterize the cracking pattern in SIFCON materials quantitatively. Stang et al. [5] and Mobasher et al. [6] have presented an algorithm for completely automatic quantification of microcrack patterns in polypropylene fiber reinforced cement-based materials. Based on the crack propagations, Balaguru and Shah [7] and Chiaia et al. [8] have studied the toughening mechanism of different type of fiber and aggregate on concrete, respectively. Li [9] and Karihaloo and Wang [10] considered fiber/matrix interaction, including the debonding, frictional sliding, and inclined angle effects associated with random orientations, and established toughening micro-mechanics model of FRC with multicrack pattern. However, to the SIFCON, there exist little or no geometric parameters to characterize the crack pattern quantitatively. Thus, it is necessary to define a parameter to characterize the crack pattern in order to better understand the reinforced mechanism of SIRCON. In the past 20 years, fractal geometry has been found to be an effective way to

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Table 1
Controlled mix proportion of mortar (kg/m^3)

Water–binder ratio	Binder–sand ratio	Cement	Sand	Water	Fly ash	UEA
0.26	1	817.7	1062	276.1	159.3	84.92

characterize the irregular crack pattern quantitatively [11]. Therefore, in this paper, the digital image analysis is used to investigate the multicrack map and fractal dimension is introduced as a parameter to characterize the crack pattern of SIFCON with different fiber volume contents quantitatively. The experimental results in this study confirm that the phenomenon of crack pattern on the surface of SIFCON in heterogeneous media processes a well-defined fractal character. There exists a good correlation between fractal dimension of crack pattern on the surface of SIFCON and fiber volume content. Furthermore, the experimental results show that the mechanical properties of SIFCON correlate with fractal dimension well.

2. Experimental procedure

2.1. Raw materials

The ordinary Portland cement corresponding to ASTM Type I cement was used in all mixture proportions. River sand with a fineness modulus of 2.59 was used as the fine aggregate. Fly ash of Type I was provided by a power plant of Shanghai. The expansive agent UEA is added to reduce the shrinkage of mortar due to the high content of cement. The length of steel fiber is 31 mm, the aspect ratio of steel fiber is 60 and it has a hooked end. The controlled mix proportion of mortar is listed in Table 1. The volume content of steel fiber was 4%, 6%, 8%, and 10% for the same controlled mix proportion. Superplasticizer is used to improve the workability of mortar.

Table 2
Mechanical properties of SIFCON

Code	V_f (%)	f_c (MPa)	f_{ft} (MPa)	I (Nm)
HPC	0	86.6	9.15	0.823
SFRCV4	4	94.5	25.3	122.9
SFRCV6	6	105.8	43.6	259.8
SFRCV8	8	121.2	66.4	312.0
SFRCV10	10	127.8	78.7	329.9

2.2. Preparation and mechanical properties measurement of SIFCON

SIFCON is cast using a preplacing technique in which fibers were placed in the mold and infiltrated with cement-based slurry. For each mix proportion, three cubes of 100 × 100 × 100 mm and three beams of 100 × 100 × 500 mm were cast for the measurement of compressive strength, bending strength as well as toughness index. The specimens were demolded 1 day after casting and were cured in the room with a temperature of 20 ± 2 °C and a relative humility of 90% for 27 days. The compressive strength was tested in conventional testing machine. Four-point bending test for the complete load–deflection curve was performed by means of an Instron 8501 testing machine.

2.3. Technique of digital image analysis

For each beam after the four-point bending test, the lateral plane of the specimen is grabbed by a CCD camera with high resolution. The gray contrast between the crack and other parts of the surface is not sharp enough to extract the profile of crack directly. Therefore, it is necessary to take several steps to obtain the profile of crack of fracture surfaces by means of the image analysis program. The procedure of digital image analysis is shown in Fig. 1 as an example. Fig. 1(b) illustrates the achieved image after the use of double thresholding, feature-based logic, binary

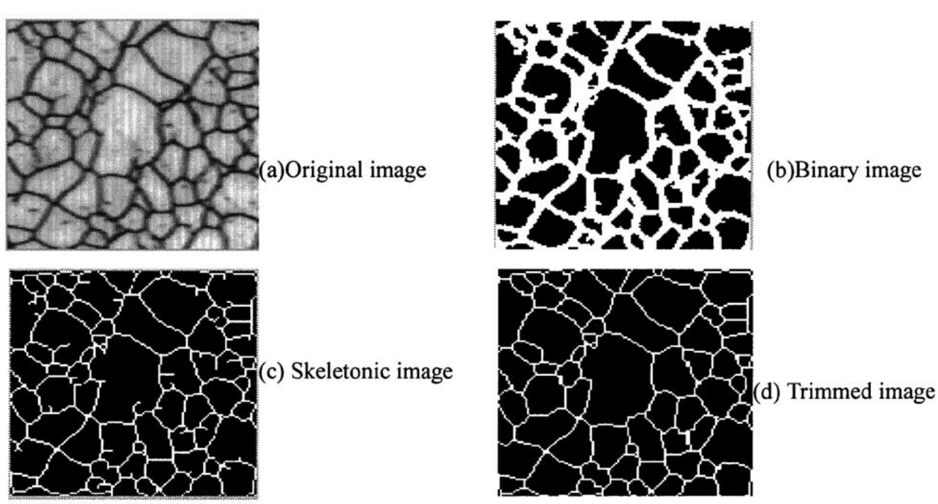

Fig. 1. Procedure of digital image analysis.

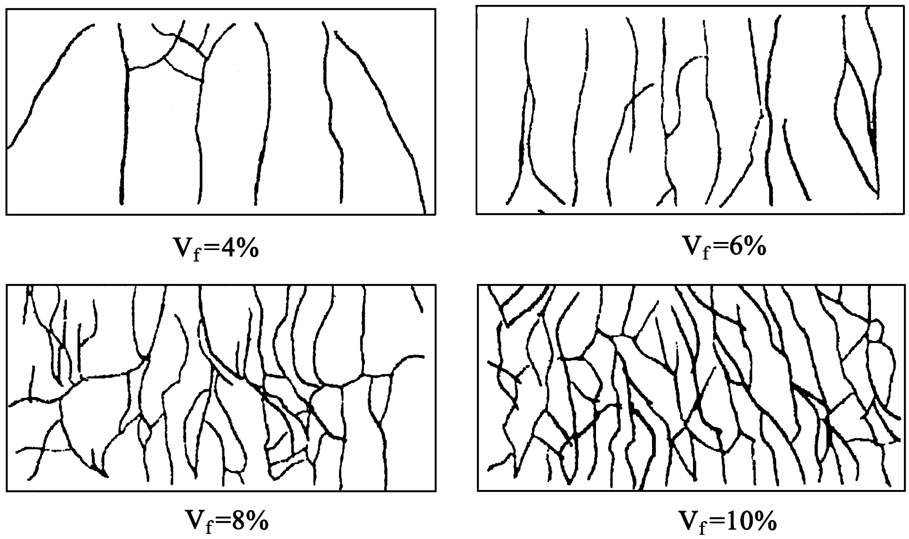

Fig. 2. Crack pattern of different fiber contents.

morphology, and connected components labeling to locate crack boundaries. As shown in Fig. 1(c) and (d), the bwmorph function is used to skeletonize the result of minor region removal and the bwmorph function is used again to prune the spur pixels from the skeletonized image.

3. Experimental results and discussions

3.1. Mechanical properties and crack pattern of SIFCON

The compressive strength, bending strength, and toughness index of mortar are 86.6, 9.15, and 0.823 N.m, respectively. Table 2 presents the compressive strength f_c, bending strength f_{st}, and index I (achieved according to the recommendation of JCI due to the convenient calculation) for SIFCON of different fiber volume percent. From Table 2, it can be seen that the increase of compressive strength ranges from 9.1% to 47.1% as the fiber content increases from 4% to 10%. The average increase of bending strength varies from 2.71 times for 4% fiber content to 8.6 times for 10% fiber content. The increase of toughness index varies from 149.3 times for 4% fiber content to 400.8 times for 10% fiber content. In general, it is shown that SIFCON has more advantageous properties than conventional FRC.

Fig. 2 shows the map of lateral crack pattern for the beams with the fiber content range from 4% to 10% after the complete load–deflection test. From Fig. 2, it is found that compared to propagation of one main crack for conventional FRC, crack propagation of SIFCON presents irregular multi-crack phenomenon and the density of crack increases with the increase of fiber content conspicuously. For 4% fiber content, there exist straight cracks in the middle part of the beams and steep cracks in the end part of the beams. It can be contributed that tensile stress plays an important role in the middle part while shear stress performs a significant role in the end part. For 10% fiber content, the crack propagation is arrested greatly so that the cracks ramify and connect to each other. Thus, the map shows that crack pattern becomes more irregular and dense with the increase of fiber content.

3.2. Characterization of crack pattern

As shown in Fig. 2, the cracking map is more irregular with the increase of fiber content. The irregular cracking maps are necessary to characterize quantitatively in order to determine relationship between cracking maps and mechanical properties for better understanding of the reinforced mechanism of SIFCON. Because fractal geometry is a useful way to characterize irregular topography during the past 20 years, fractal dimension is thus introduced as a

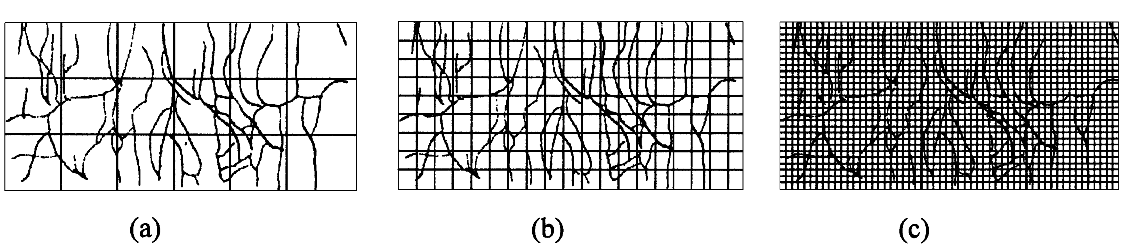

Fig. 3. The crack pattern covered with different grid sizes.

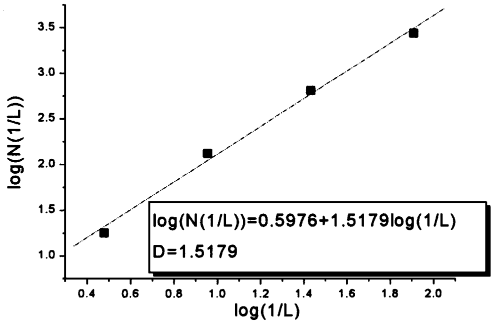

Fig. 4. Log$N(L)$ vs. Log$(1/L)$.

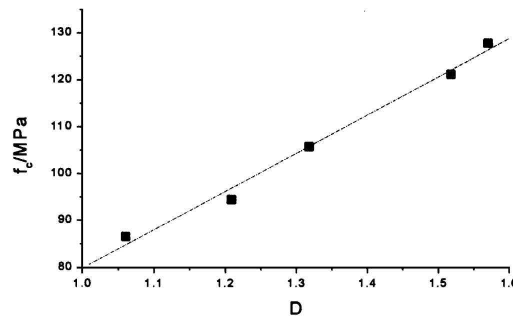

Fig. 6. f_c vs. D.

geometric parameter to characterize the irregularity of cracking maps in this study.

Fractal dimension has various definitions in condition to the different research interests. In terms of the characterization of cracking maps in this study, the box-counting method is applied to determine the fractal dimension of SIFCON on the lateral side. The square grid is used to cover the total area of the lateral surface of the beam and the grids containing cracks are counted and accumulated. The fractal dimension could be evaluated from the rate growth of number N of grids, necessary to cover the entire surface, as the size L of elementary grids (whose area is $A = L \times L$) decreased. The lateral surface was assumed to be an invasive self-affine fractal in a statistical sense. The following equation holds (Eq. (1)):

$$D = \lim_{L \to 0} \frac{\log N(L)}{\log(1/L)} \tag{1}$$

where initial size of grid L_0 is 1 and that of grid L decreased three times, i.e., $L_n/L_{n+1} = 3$; $N(L)$ is the number of grids containing cracks when the size of grid is L and acquired fractal dimension reflects both tortuous degree and crack density. For example, according to the box-counting method, the cracking map of SFRCV8 is covered with different sizes of the grids and the corresponding number of grids containing cracks is counted by program. As shown in Fig. 3, $N(L)$ is 18 when L is equal to 1/3, $N(L)$ is 133 when L is equal to 1/9 and $N(L)$ is 651 when L is equal to 1/27 and so on.

The logarithmic $N(L)$ is plotted against logarithmic $1/L$ in Fig. 4. From this figure, it can be seen that there exists a linear correlation between $\log[N(L)]$ and $\log(1/L)$, which indicates that a fractal phenomenon exists. The acquired fractal dimension D is 1.5179. For different fiber contents, fractal dimension is obtained using the method above. Fig. 5 gives the relationship between fractal dimension and fiber volume content. It is shown that fractal dimension increases with the increase of fiber volume content. The crack pattern becomes more irregular as the fiber volume content increases.

3.3. Mechanical properties correlating with fractal dimension of crack pattern

The correlation between mechanical properties, including compressive strength, bending strength, and toughness index is given in Figs. 6–8. As expected, the mechanical properties of concrete increase with the increase of fractal dimension in this study. The toughening effect of SIFCON can be reflected obviously through the fractal dimension of the cracking maps, especially for bending strength and toughness index.

The increment of fractal dimension $(D-1)$ can be linearly related to f_c, f_{ft} and I:

$$\begin{cases} f_c = 79.9 + 81.4(D-1), & r = .995 \\ f_{ft} = 0.250 + 134(D-1), & r = .996 \\ I = -7.2 + 634(D-1), & r = .962 \end{cases} \tag{2}$$

where r is the linear correlation coefficient. As shown from Eq. (2), the increase of bending strength and toughness index is influenced more greatly than that of compressive strength

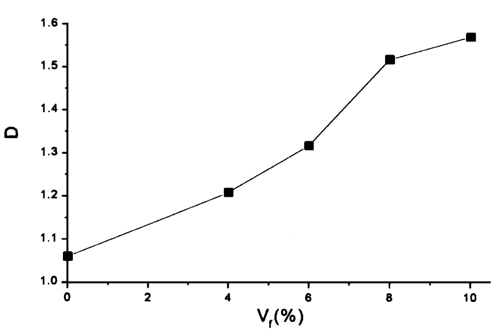

Fig. 5. D vs. V_f.

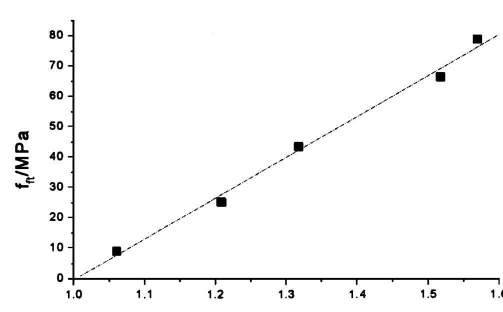

Fig. 7. f_{ft} vs. D.

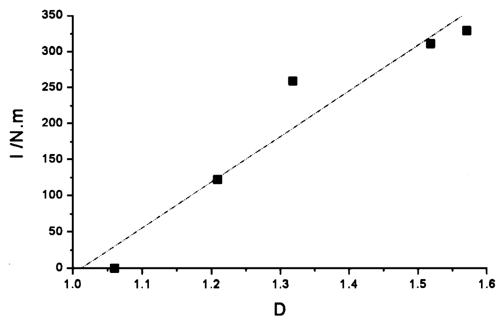

Fig. 8. *I* vs. *D*.

by the increment of fractal dimension. This can be due to the bending strength, toughness index, and fractal dimension achieved by means of the four-point bending test. Therefore, the brittle concrete performs a more ductile mechanical behavior as the increase of fractal dimension on the surface crack by incorporating steel fiber of high volume content.

4. Conclusions

The crack pattern of SIFCON is studied quantitatively by fractal dimension in the study. The following conclusions can be drawn.

(1) SIFCON has more advantageous properties than conventional FRC. The crack propagation of SIFCON presents irregular multicrack phenomenon and the density of crack increases with the increase of fiber content.

(2) The phenomenon of crack pattern on the surface of SIFCON in heterogeneous media processes a well-defined fractal character. Fractal dimension can be a geometric parameter to characterize the crack pattern on the surface of SIFCON and fractal dimension increases with the increase of fiber volume content.

(3) The compressive strength, bending strength, and toughness index increase with the increase of fractal dimension simultaneously and the increment of fractal dimension can be linearly related to these mechanical properties.

Acknowledgments

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