Cement & Concrete Composites 25 (2003) 153–157

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Influence of concrete composition on the characterization of fracture surface

An Yan *, Ke-Ru Wu, Dong Zhang, Wu Yao

State Key Laboratory of Concrete Materials Research, Tongji University, Siping Road 1239, Shanghai 200092, People's Republic of China

Received 1 June 2001; accepted 10 November 2001

Abstract

An experimental method based on laser triangulation was used to measure the 3-D profile of fracture surface of concrete. The projective-covering method was established to determine the fractal characteristics of fracture surface. Based on the experiment, the influence of composition of concrete on the fractal dimension, including water–binder ratio, maximum aggregate size and aggregate type, was investigated. The variation of fractal dimension with the material composition was also analysed to make further understanding of fracture mechanism of concrete.

Keywords: Fracture surface; Fractal dimension; Composition of concrete

1. Introduction

Due to roughness and irregularity of crack inside the concrete materials, more energy is required to form new fracture surface. Mindess [1,2] has ever pointed out that this extra energy should be taken into consideration to make the fracture model more reasonable. However, due to the complexity of fracture surface, to date, the fracture surface is still idealized as 2-D plane in the fracture mechanics research of concrete materials. The fracture surface, as important post-mortem evidence, helps to reveal the micro-mechanism of fracture and plays an essential part in the evaluation of fracture mechanics properties of cementitious materials.

Many researchers have paid attention to the importance of fracture surface [3–6]. The researches on the fracture surface are made in an attempt to establish the relationship between characterization of fracture surface and mechanical behaviour. The characterization of fracture surface is determined mainly by composition of concrete materials and loading conditions so that the relationship between composition of concrete and characterization of fracture surface is important to study the mechanical behaviour of concrete. However, there are few systematic reports on the influence of concrete composition on the fracture surface. In our previous paper [7], the laser triangulation method was used to measure the fracture surface to improve our understanding of the failure mechanism of concrete and to measure fracture parameters more precisely. In this paper, based on the information of fracture surface achieved, the project-covering method is employed to determine the fractal dimension of fracture surface. The relationship between fractal dimension and materials composition is investigated to provide evidence for further understanding of fracture process of concrete materials.

2. Experimental procedures

2.1. Raw materials and mix proportion

Different material compositions of concrete, including water–binder ratio, maximum aggregate size and aggregate type, were considered in this study in order to investigate the relationship between fractal dimension and composition of concrete. The controlled mix proportion was shown in Table 1, named by HPC–X–Y–Z, where X is the water–binder ratio, Y is the maximum

* Corresponding author. Tel.: +86-21-659-8-2412; fax: +86-21-6598-3465.

E-mail address: yanank@hotmail.com (A. Yan).

0958-9465/03/$ - see front matter
PII: S0958-9465(02)00004-5

Table 1
Controlled mix proportion (HPC–X–Y–Z)

Series	Cement (kg/m^3)	Slag (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	X	Y (mm)	Z	Fractal dimension
I	267	115	1110	740	0.44	20	CG	2.126
	420	180	986	657	0.30	20	CG	2.091
	472	202	948	632	0.26	20	CG	2.082
II-1	267	115	1110	740	0.44	5	CG	2.051
	267	115	1110	740	0.44	10	CG	2.087
	267	115	1110	740	0.44	16	CG	2.121
	267	115	1110	740	0.44	20	CG	2.126
II-2	472	202	948	632	0.26	5	CG	2.048
	472	202	948	632	0.26	10	CG	2.074
	472	202	948	632	0.26	16	CG	2.078
	472	202	948	632	0.26	20	CG	2.082
III	267	115	1110	740	0.44	16	CG	2.121
	267	115	1110	740	0.44	16	RG	2.083
	267	115	1110	740	0.44	16	LG	2.072

aggregate size and Z represents the aggregate type. The cement used was ASTM type I portland cement with a 28-day compressive strength of 63.5 MPa. The ultrafine slag powder was provided by Jinshan cement factory of Shanghai, and had a Blaine fineness of 600 m^2/kg. The fine aggregate used had a 2.85 fineness modulus. Four different maximum aggregate sizes of coarse aggregate were used: 5, 10, 16, and 20 mm. For the series with water–binder ratio 0.44 and maximum aggregate size 16 mm, three different types of coarse aggregates were used: crushed gravel (CG), round gravel (RG) and light-weighted gravel (LG). The size of notched beam was $515 \times 100 \times 100$ mm^3. The specimens were demoulded one day after casting and cured in the curing room at 20 ± 2 °C and r.h. of 90% for further 27 days. The ratio of span to depth was 4 and the notched depth was 50 mm. The fracture surface was achieved by Instron 8501 testing machine.

2.2. Determination of fractal dimension

The theory of fractal geometry can be used to deal with irregular 3-D profile of fracture surface of concrete materials [7]. Among the different algorithms for the fractal dimension evaluation, the box-counting method is used to calculate fractal dimension directly. Due to the difficulty in measuring the fracture surface directly in the previous research, indirect methods such as slit-island method and vertical profile method are employed [3,5]. These methods would destroy the fracture surfaces, which makes checking the results impossible and destroys the meso-structure of fracture surfaces, hence impairing the measurement accuracy. Based on the method in previous paper [8], thus the digitized fracture surfaces can be analysed directly by using projective-covering method, which is similar to box-counting method. The fractal dimension is evaluated from the rate of divergence of apparent area A as the size of elements r decreases. The equation of projective-covering method can be expressed as

$$D = 2 - \lim_{r \to 0} \frac{\log A(r)}{\log r}, \tag{1}$$

where D is the fractal dimension and A is the total area of the fracture surface with the grid size r. In Fig. 1(a), it is shown that more and more details are counted as the resolution increases. The algorithm computes the area by triangulating the surface area between adjacent grids, as shown in Fig. 1(b). All surface area elements A_1 and A_2 over the entire image are summed to estimate actual surface area; all surface area elements A_n over entire image are summed to give total surface area. The counted area covers the whole area of fracture surface projected on the ligament part for a notched three-point-bending specimen.

As shown in Fig. 1(c), the fractal dimension can be evaluated from the rate of growth of the entire surface area as the grid size r decreases. Good linear correlation is observed between the logarithm apparent surface area and logarithm grid size. According to the fractal theory, it is shown that meso-structure of fracture surface of concrete is a type of fractal structure and the fractal dimension can be used to characterize the fracture surface of concrete from Fig. 1(c). In final, the fractal dimension used to characterize the fracture surface is the average value of three specimens. The results of fractal dimension in the study are shown in Table 1. It can be preliminarily shown that, compared with the previous results determined by vertical profile method [5] and slit-island method [3], the values of fractal dimension obtained in the paper are approximately between those of the vertical profile method and slit-island method.

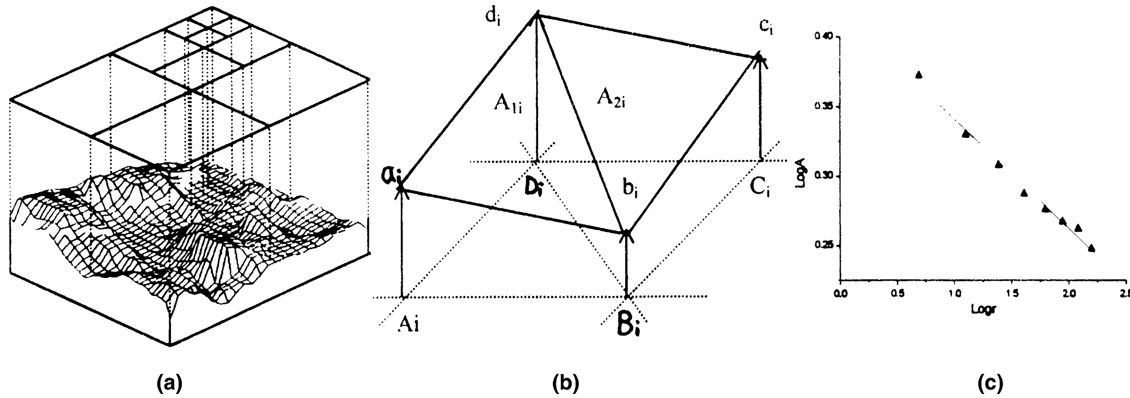

Fig. 1. The projective-covering method.

3. Experimental results

3.1. Effect of water–binder ratio on fractal dimension

In Fig. 2, for the concrete series with the maximum aggregate size 20 mm and CG, the fractal dimension is plotted against the water–binder ratio. From Fig. 2, it is found that fractal dimension increases as water–binder ratio increases with the range from 2.082 to 2.126. It means that fracture surface of concrete with higher water–binder ratio is more irregular than that of concrete with lower water–binder ratio. This trend can be attributed to the fact that the higher water–binder ratio, the more flaws and cracks inside the concrete. The fractal dimension possibly reflects the disordered crack growth characteristics of internal structure of concrete materials as concrete is subjected to external loads.

3.2. Effect of maximum aggregate size on fractal dimension

Fig. 3 shows the fractal dimension of fracture surface with different maximum aggregate sizes of concrete. From the figure, it can be concluded that, for the same

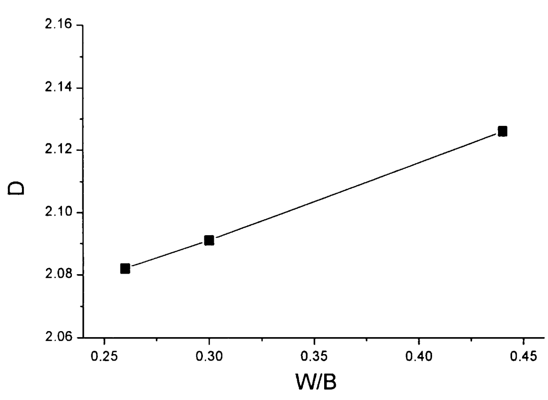

Fig. 2. Fractal dimension vs. water–binder ratio.

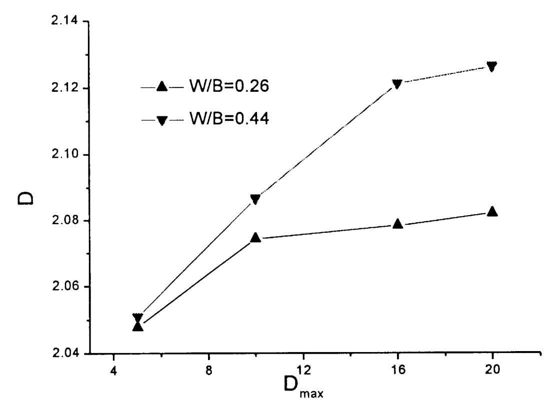

Fig. 3. Fractal dimension vs. maximum aggregate size.

water–binder ratio, fractal dimension increases for increasing maximum aggregate size. It can also be seen from the figure that the increase of HPC-44 series is greater than that of HPC-26 for the fractal dimension. The increase of fractal dimension indicates that the meso-structure of concrete becomes more irregular as the aggregate size increases. With the increase of aggregate size, the perimeter and thickness of interfacial layer between hardened cement paste and aggregate increase so that the larger flaw can be formed easily and the bond strength decreases. As shown in Fig. 4, the deteriorated bond strength between hardened cement paste and aggregate leads to the transition of fracture mode from the passing-around coarse aggregate to the trans-granular type. In Fig. 4, mode (a) represents that a crack passes through the aggregate directly, while mode (b) shows that a crack runs around the aggregate.

3.3. Effect of aggregate type on fractal dimension

As shown in Fig. 5, for the series with water–binder ratio 0.44 and maximum aggregate size 16 mm, CG aggregate concrete has the highest value of fractal dimension, while that of light-weighted aggregate is the

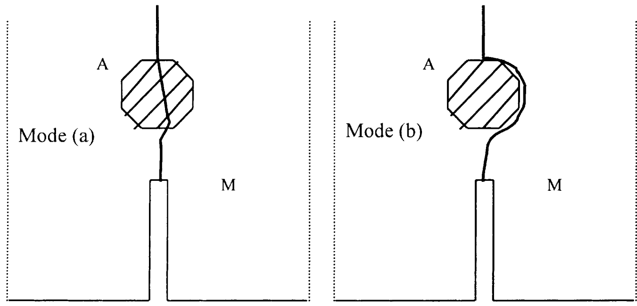

Fig. 4. Two possible fracture paths.

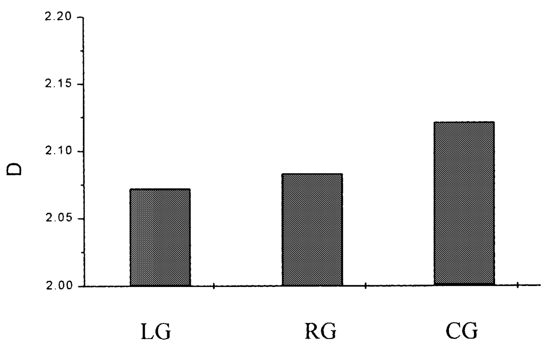

Fig. 5. Fractal dimension vs. aggregate type.

lowest. Due to different strengths and textures of aggregate, the kinking effect of crack growth will perform differently. Fig. 6 gives a simplified generator representing the kinking effect of crack growth. According to the fractal theory, the fractal dimension in Fig. 6 can be expressed as

$$N = 3,\ \frac{1}{r} = (5 + 4\cos\theta)^{1/2},$$
$$D = \log 3/\log(5 + 4\cos\theta)^{1/2}. \tag{2}$$

As shown in Eq. (2), fractal dimension increases with the increase of kinking angle so that there exists more remarkable effect associated with fractal behaviour of crack growth. For high strength concrete, the interfacial bonding strength between aggregate and hardened cement pastes is strong enough so that most of the aggregate are split by cracks. But high quality aggregate has high internal strength to resist this fracture mode so that the fracture surface becomes more irregular and tortuous. The more irregular the fracture surface, the higher the fractal dimension of fracture surface. It is possible that the quality of aggregate can be evaluated using the value of fractal dimension of fracture surface.

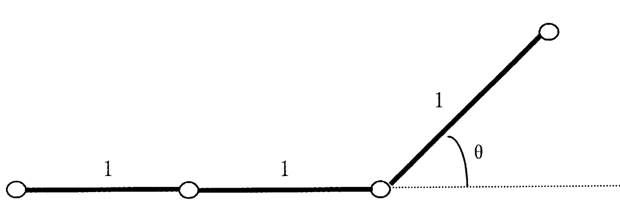

Fig. 6. Generator of kinking crack.

As to the study of fracture surface, the most important significance is to improve the mechanical properties of concrete. The paper only deals with the characterization of fracture surface related to the materials composition. The relationship between the characterization of fracture surface and tough or energy dissipated during the fracture needs to be further studied.

4. Conclusions

Several conclusions can be drawn as follows:

1. The laser triangulation method is used to measure the 3-D profile of fracture surface of concrete so that the projective-covering method can be employed to calculate the fractal dimension directly.
2. The experimental results suggest that the fracture surface of concrete has remarkable fractal characteristic.
3. Material composition of concrete, including water–binder ratio, aggregate size and aggregate type, influences the fractal dimension apparently. With the increase of water–binder ratio, the fractal dimension increases. For the same water–binder ratio, the fractal dimension increases as the increase of aggregate size and the increase of higher water–binder ratio series is greater than that of lower water–binder ratio. The fractal dimension of CG concrete is the highest, while that of LG concrete is the lowest.
4. The variation of fractal dimension with the materials composition is also analysed to help us make further understanding of the fracture mechanism of concrete in this study.

Acknowledgements

The authors gratefully acknowledge the support provided by the Ministry of Education of People's Republic of China.

References

[1] Mindess S, Lawrence JR, Kesler CE. The cracking and fracture of mortar. Mater Struct 1982;15:107–13.
[2] Mindess S, Lawrence JR, Kesler CE. A device for direct observation of cracking of cement paste or mortar under compressive loading within a scanning electron microscope. Cem Concr Res 1982;12:569–76.

[3] Issa MA, Hammad AM. Assessment and evaluation of fractal dimension of concrete fracture surface digitized images. Cem Concr Res 1994;24:325–34.
[4] Saouma VC, Barton CC. Fractals, fractures and size effects in concrete. J Eng Mech ASCE 1994;120(4):835–54.
[5] Saouma VE, Barton CC, Gamaleldin NA. Fractal characterization of fracture surface in concrete. Eng Fract Mech 1990;35:47–53.
[6] Issa MA. Correlation between crack tortuosity and fracture toughness in cementitous materials. Int J Fract 1993;60:75–105.
[7] Carpinteri A, Chiaia B, Invernizzi S. Three-dimensional fractal analysis of concrete fracture at the meso-level. Theor Anal Fract Mech 1999;31:163–72.
[8] Wu KR, Yan A, Liu JY, Zhang D, Yao W. Reconstruction and analysis of 3-D profile of fracture surface of concrete. Cem Concr Res 2000;30(6):981–7.