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EVALUATION OF ROUGHNESS OF JOINT CONCRETE SURFACES AND BOND PROPERTIES

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Abstract
The roughness of the joint concrete surfaces after roughening treatment was quantified by using spectrum analysis and fractal analysis. Power-spectrum and fractal dimension were adopted as roughness indices, and the relationship between these indices and bond properties was examined. Consequently, it was clarified that constitutions of the wavelength in a roughness waveform could be relatively grasped with power-spectrum diagrams. It was possible to quantitatively evaluate the surface roughness with fractal dimension. It was confirmed that as the fractal dimension increased, the flexural strength in concrete joint increased as well as the fracture energy, which was obtained by calculating the area under the tension softening diagrams.
Key words: Roughness, spectrum, fractal dimension, fracture energy, flexural strength

1 Introduction

The mechanical behavior of concrete structures with construction joints is

Table 1. Mix proportions and properties of concrete

Type	W/C (%)	Unit weight (kg/m³)					Strength (MPa)			Elastic mod. (GPa)	Age (days)
		W	C	S	G	Ad.	Com.	Ten.	Flex.		
Old conc.	50.4	171	339	782	1023	1.018	59.2	4.53	6.27	34.6	123
New conc.	50.6	170	336	773	1010	1.005	47.3	3.85	5.75	29.3	31

W : Water, C : Cement (High early strength portland cement), S : Sand,
G : Coarse aggregate (Crushed stone), Ad : Admixture (AE water reducing agent)

strongly affected by the performance of the joint part. In practice, the surface of a joint is treated to be rough in order to obtain good bond properties. It has been well known that this roughness of joint affects the performance of jointed members. However, the way of quantitative evaluation for roughness has not been sufficiently established. The relationship between the roughness and the performance of jointed members has not been well clarified.

The tension softening diagram, which is one of the fracture mechanics parameters, represents the relationship between the transfer tensile stress and the crack opening in a fracture process zone. The diagram also shows the resisting performance against cracking. Kurihara et al. (1996) have already indicated that the bond properties of jointed specimens in different conditions of surface treatments can be characterized with the shape of tension softening diagrams and that it is effective to use the tension softening diagrams for evaluation of bond properties.

In this study, the roughness affecting the bond properties of the joint was quantified by spectrum analysis (index : power-spectrum) and fractal analysis (index : fractal dimension), and then the relationship between the roughness and the bond properties of jointed specimens was examined.

2 Outline of experiments

2.1 Specimens

The beam specimens with a vertical joint at the center were made of ordinary concrete. The size of the jointed specimens was 10×20×120 (width×depth×length) cm. The mix proportions of old and new concrete are shown in Table 1 together with the results of strength tests.

A notch was set at the joint of each specimen. The notch size was one-third of the specimen depth.

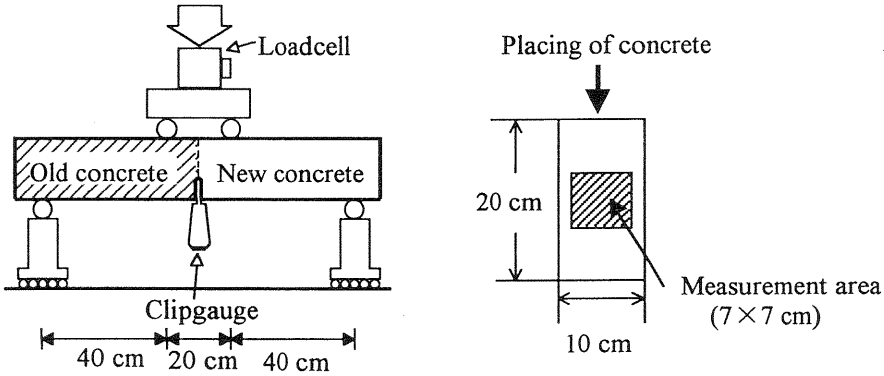


Fig. 1. Four-point bend test and measurement area

Table 2. Surface treatment methods

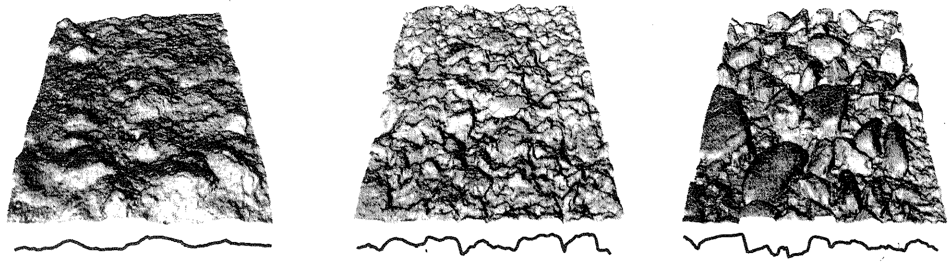
Series	Surface treatment method	Distance between peak and bottom (mm)
A1	Shot-blast method Projection density : 150kg/m^2	6.7
A2	Shot-blast method Projection density : 300kg/m^2	11.6
B1	Water-jet method Jet pressure : 2000kgf/cm^2 Distance : 10 cm	6.7
B2	Water-jet method Jet pressure : 2000kgf/cm^2 Distance:5cm	8.9
C1	Wash-out method Specified depth : 4mm	8.1
C2	Wash-out method Specified depth : 6mm	10.7

Four-point bend tests (shear span : 40 cm, moment span : 20 cm) were carried out as illustrated in Fig. 1. The load and CMOD (crack mouth opening displacement) were measured by using a loadcell (capacity : 1 kN) and a clipgauge (sensitivity : 1/400 mm), respectively.

As shown in Table 2, the joint surfaces were treated to be rough in two levels with three different methods (shot-blast, water-jet and wash-out) before casting new concrete.

2.2 Measurements of surface roughness

The joint surfaces were filled up with liquid silicon-rubber. After the



(a) Shot-blast method (b) Water-jet method (c) Wash-out method

Fig. 2. Examples of surfaces and section lines

silicon-rubber hardened, the reproduction of the joint surface was made of gypsum using the silicon rubber as a form. The coordinates of the reproduced surface were measured at intervals of 0.4 mm using a 3D shape measurement apparatus (contact type). The area for the measurement was 7×7 cm as shown in Fig. 1. Examples of 3D shape measurement results are shown in Fig. 2, where the difference of surface roughness can be seen.

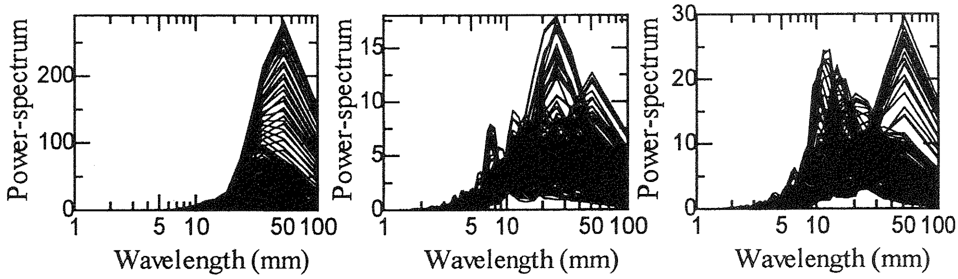
2.3 Determination of tension softening diagrams

The tension softening diagrams of concrete were determined through the poly-linear approximation method (Kitsutaka (1995)) combined with the finite element analysis with fictitious crack model at the center of specimens (Uchida et al. (1995)). In this method, the coordinates of each knee point of softening diagrams are determined step by step with the development of the fictitious crack in the analysis, so that the analytical load-displacement curve agrees with the experimental one. Young's modulus obtained in compressive strength tests was adopted in the analysis.

3 Quantification of surface roughness

3.1 Surface area

A triangular network of mesh data was made to digitize a realistic rough surface. The summation of areas of the triangular elements was taken as the surface area, and is shown in Table 3. The differences of the surface treatment methods were indicated as the differences of the surface area. The surface area obtained in Series C2 (treated by wash-out method) was the largest, and the area in Series A1 (treated by shot-blast method, projection density : 150kg/m^2) was the smallest. In the case of the shot-blast method (Series A1 and A2), the increment of the surface area with a



(a) Shot-blast method (b) Water-jet method (c) Wash-out method

Fig. 3. Power-spectrum

change in the degree of treatment (projection density was changed from 150 kg/m^2 to 300 kg/m^2) was 5%, and the increments of the surface area were about 10 % in other methods.

3.2 Power-spectrum

The power-spectrum of surface roughness was calculated from the 3D shape measurement results, which were assumed to be chronological data. Figure 3 shows the power-spectra obtained by the measurement results of 176 lines per specimen. In the case of the shot-blast method, the power-spectrum contained a single peak in the range of long wavelength, and there was no content in the range of short wavelength (smaller than 5 mm). On the other hand, in the case of other treatment methods, the power-spectrum contained many small peaks in the range of long wavelength in addition to many small peaks in the range of short wavelength due to a wide distribution of the wavelength content.

3.3 Fractal dimension

A fractal developed by Mandelbrot (1982) is a geometrical set with self-similarity and non-integer dimension (fractal dimension). The fractal dimension has been applied as an index to quantitatively evaluate complicated shapes. The roughness of the surface at the concrete joint was evaluated by the fractal dimension in this study.

In general, as the shape becomes more complicated, the fractal dimension increases. There are some methods how to calculate the fractal dimension. The box counting methods (Takayasu 1986) were adopted to obtain the fractal dimension in this study. Two-D fractal dimensions were obtained from the process to cover a line data (Fig. 2) in a surface section with a square. Three-D fractal dimensions were obtained from the process to cover a surface with a cube.

Table 3. Test results

Series	Surface area (cm^2)	Fractal dimension		Flexural strength(MPa)	Fracture energy(N/mm)
		2D	3D		
A1	53.5	1.036	2.070	1.68	0.0135
A2	56.3	1.038	2.079	1.96	0.0202
B1	61.3	1.061	2.108	1.88	0.0207
B2	68.1	1.076	2.135	2.03	0.0247
C1	70.6	1.073	2.130	1.63	0.0184
C2	78.0	1.088	2.166	2.31	0.0286

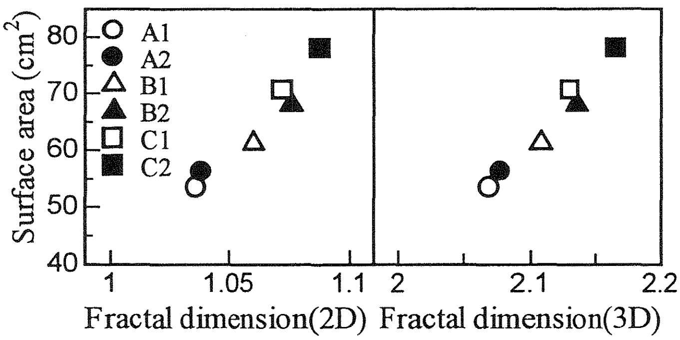


Fig. 4. Surface area and fractal dimensions

The calculated fractal dimensions are shown in Table 3. A fractal dimension is thought to be affected by the degree of plane or spatial extensions of an object. When the object completely covers all plane or space, the fractal dimension is 2 or 3, respectively. Since the plane and spatial extensions in this study were small as shown in Fig. 2, the values of the calculated fractal dimension were close to 1 or 2. The fractal dimension of Series C2 was the biggest in both 2D and 3D analysis, and that of Series A1 was the smallest. As shown in Fig. 4, there was a good correlation between the calculated fractal dimension and the surface area. In the case of the shot-blast method, in spite of the increase of the projection density (from 150 kg/m^2 to 300 kg/m^2), the increase of the fractal dimension from Series A1 to A2 was smaller compared with other treatment methods.

4 Surface roughness and flexural strength

Examples of the load-CMOD curves obtained from experiments are shown

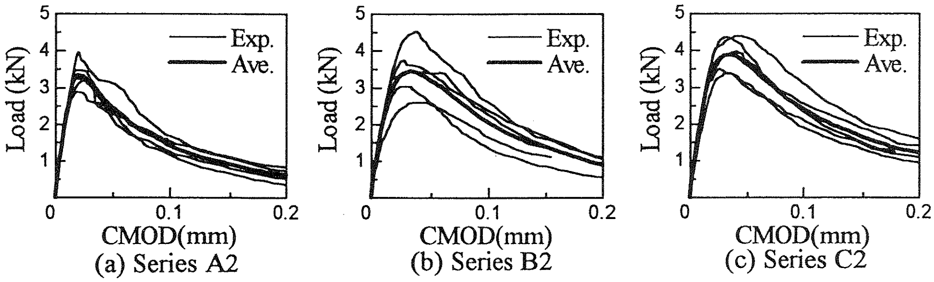


Fig. 5. Load-displacement curves

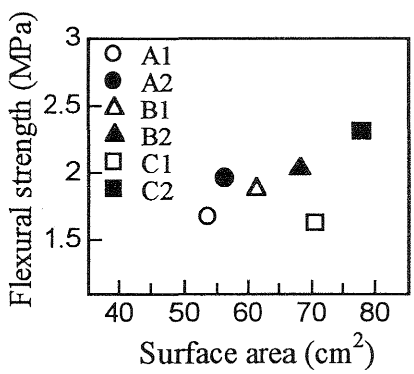


Fig. 6. Flexural strength and surface area

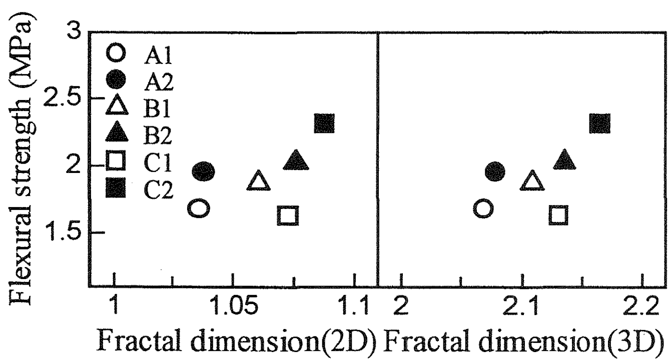


Fig. 7. Flexural strength and fractal dimensions

in Fig. 5. The mean values of the flexural strength are shown in Table 3. These flexural strengths were modified in consideration of the influence of the dead load of a specimen and loading apparatus. The flexural strength of Series C2 was the largest, and that of Series C1 was the smallest.

Figure 6 shows the relationships between the surface area and the flexural strength. As the surface area increased, the flexural strength

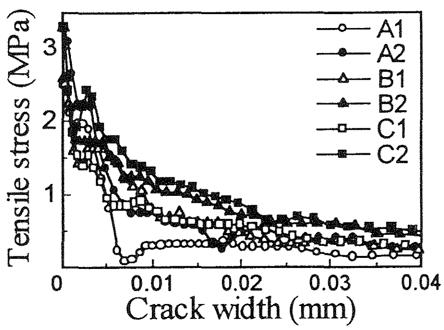


Fig. 8. Tension softening diagrams

became large.

The relationship between the fractal dimensions (2D and 3D) of surface and the flexural strength are shown in Fig. 7. A correlation between the fractal dimension and the flexural strength existed as well as that between the surface area and the flexural strength. As the fractal dimension of surface increased, the flexural strength became large. For the water-jet method, the increase of the flexural strength with an increase of the fractal dimensions was smaller than that for the other methods.

5 Surface roughness and fracture mechanics parameters

Figure 8 shows the tension softening diagrams that are determined from load-CMOD curves in experiments. The tensile stress in the tension softening diagram of Series C2 was higher than that of other series. The tensile stress of Series A1 had already decreased to 0.3 MPa at a crack width of 0.01 mm. Since the shape of the tension softening diagrams varied among series as shown in Fig. 8, it was thought that the bond properties in a concrete joint having different treatment conditions could be evaluated by the characteristics in the shape of the tension softening diagrams. As seen from Fig. 8, the resisting performance against cracking was the highest in Series C2 and the lowest in Series A1.

It has been well known that the maximum flexural strength of a beam specimen corresponds to the tensile stress level in the range of a small crack width in the tension softening diagram, and that the softening behavior after a peak load corresponds to the tensile stress level in the range of a large crack width in that diagram. The fracture energy calculated as the area under the tension softening diagrams in the range of a

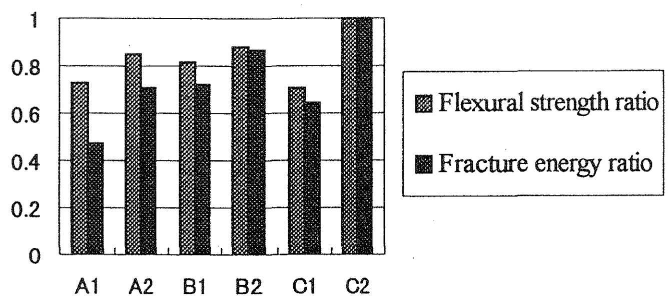


Fig. 9. Flexural strength ratios and fracture energy ratios

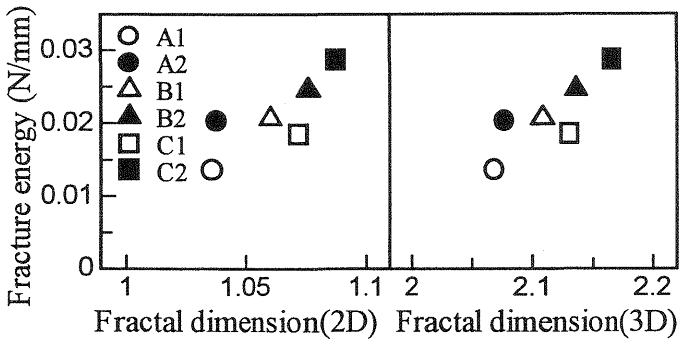


Fig. 10. Fracture energy and fractal dimensions

crack width of 0 to 0.02 mm is shown in Table 5, together with the flexural strength. Figure 9 shows the fracture energy and the flexural strength of each series in the form of the ratios to those of Series C2. The difference in the fracture energy ratio among series was larger than that in the flexural strength ratio. Consequently, the fracture energy was considered to be more sensitive than the flexural strength as the index to evaluate the bond properties. This fact agreed with the results reported by the authors (Rokugo et al. (1998)). Figure 10 shows the relationship between the fractal dimension of the surface and the fracture energy. The fracture energy showed the tendency to increase with an increase in the fractal dimension.

6 Conclusions

The surface roughness affecting bond properties in a concrete joint was quantified. The relationships among the roughness of surface, the flexural strength, the tension softening diagram and the fracture energy were investigated. The following conclusions were obtained :

(1) In the evaluation of the surface roughness, constitutions of the wavelength in the roughness waveform could be grasped with the power-spectrum.

(2) The surface roughness was quantified with the fractal dimension. The increase of the fractal dimension due to higher degree of the shot-blast treatment was smaller than that of other methods.

(3) As the fractal dimension of the surface increased, the flexural strength became larger. The higher the degree of the surface treatment, the larger the fractal dimension, flexural strength and fracture energy.

(4) The fracture energy was confirmed to be more sensitive than the flexural strength as an index to evaluate the bond properties of the concrete joint.

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