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Evaluation of Fracture Behavior of Concrete Joints under Shear Force

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ABSTRACT: Simple methods for evaluating the effect of the degree of surface treatment at construction joints on their shear bond properties were investigated. Uniaxial compression tests were conducted, in which axial compressive forces are applied to rectangular specimens having slant construction joints with different joint angles and degrees of surface treatment to cause normal and shear stresses at the joints. When the joint angle is 60°, it was possible to evaluate the effect of the degree of surface treatment on the shear bond properties by determining and comparing the peak loads and consumed energy expressed by the areas under the load-displacement curves. AE source location and AE parameter analyses were also conducted to investigate the fracture process of these jointed specimens.

1 INTRODUCTION

Bond properties at construction joints under various kinds of external force should be evaluated appropriately. When testing the tensile bond properties of construction joints, direct tensile tests and bending tests are adopted in most cases, providing bond strength calculated from the peak load, as well as fracture mechanics parameters dealing with the behavior of concrete after cracking (Kaneko et al. 1997, Kamada et al. 1998, Kurihara et al. 1999).

As for the evaluation of shear bond properties of construction joints, there have been reports on the relationship between the shear bond strength and the roughness of joint surfaces (Goto et al. 1976, Makitani et al 1995), which is quantified by mean depth. Direct shearing tests of concrete lead to wide scatter of strength values and fracture behavior. Also, fabrication and loading manner for the specimens having construction joints are complicated, making it difficult to bring them to failure solely by shear stress. The slant shear bond test method is applied to evaluation of bond between repair materials and concrete, e.g., as specified in Part 4 of BS 6319, ASTM C 882-87. When applying this method to construction joints of concrete, strength is used for evaluating the shear bond properties between the concretes.

In order to develop a simple test method for evaluating the effect of the degree of joint surface treatment on the shear bond properties, this study adopted the uniaxial compression test method, in which axial compressive forces are applied to rectangular specimens having slant joints with different joint angles and degrees of joint surface treatment, thereby generating normal and shear stresses at the interface. In addition, acoustic emission (AE) was measured during loading to investigate the difference of fracture process depends on the degree of joint surface and surface treatment.

2 OUTLINE OF EXPERIMENT

2.1 *Specimens*

As given in Table 1, the old and new concretes had the same mix proportions. The cement was high-early-strength portland cement with a density of 3.12 g/cm^3. The fine and coarse aggregates were river sand with a density of 2.59 g/cm^3 and crushed stone with a density of 2.61 g/cm^3 and maximum size of 15 mm, respectively. Rectangular specimens 100 $\times$ 100 $\times$ 400 mm in size were fabricated with slant construction joints in the centers. Jointless specimens were also made for comparison. Three specimens each were prepared for 13 combinations of joint angles and degrees of joint surface treatment, as shown in Table 2.

Four types of joint surface were adopted: non-treated surface (N); wash-out surface using a retarder sheet (with a wash-out depth of 2 and 4 mm, respectively); and wire-brushed surface (W).

In order to quantitatively evaluate the roughness of the treated concrete surface, an surface profile for each surface was taken by silicone rubber and reproduced using gypsum. The central 70$\times$70 mm area

Table 1. Mix proportions and properties of concrete

Type	W/C (%)	Unit content					Strength		
		Water (kg/m^3)	Cement (kg/m^3)	Fine agg. (kg/m^3)	Coarse agg. * (kg/m^3)	Admixture** (kg/m^3)	Compressive (MPa)	Tensile (MPa)	Flexural (MPa)
Old concrete	55	171	312	793	1002	0.927	48.8	3.7	4.1
New concrete	55	171	312	793	1002	0.927	46.8	4.3	5.3

* Maximum size: 15mm
**AE water reducing agent

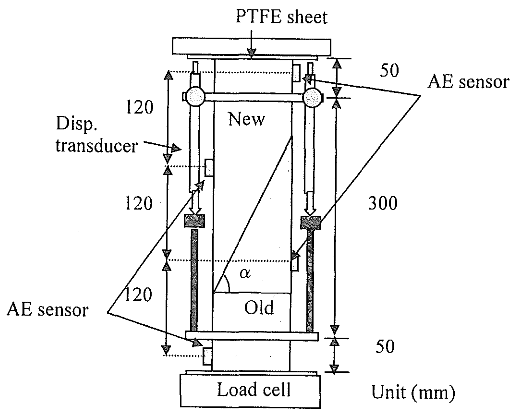

Figure 1. Test setup and location of AE sensors

Table 2. Surface area ratio and peak load

Joint angle α	Series	Surface type	Surface area ratio	Peak load (kN)
Jointless	O	-	-	454.7
45°	4N	Non-treated	1.00	248.9
	4W	Wire-brushed	1.13	368.8
	42	Wash-out (2mm)	1.32	464.5
	44	Wash-out (4mm)	1.42	441.0
52.5°	5N	Non-treated	1.00	217.6
	5W	Wire-brushed	1.13	362.6
	52	Wash-out (2mm)	1.32	463.5
	54	Wash-out (4mm)	1.42	473.3
60°	6N	Non-treated	1.00	164.6
	6W	Wire-brushed	1.13	354.7
	62	Wash-out (2mm)	1.32	464.5
	64	Wash-out (4mm)	1.42	442.0

of the reproduced surface was scanned at 0.4 mm intervals using a contact-type 3-D shape measurement apparatus. The measured points were then connected into triangles, the total area of which was calculated as the total surface area of the joint surface. Surface area ratio, A/A_0, where A is the measured total surface area and A_0 is the projected area, was determined to examine the effect of surface roughness. The surface area ratio of a non-treated surface (N) was assumed to be 1.0. Calculated surface area ratio is shown in Table 2. The surface area ratio was largest in 4-mm deep wash-out surfaces using retarder sheets, followed by 2-mm deep wash-out surfaces using retarder sheets, and wire-brushed surfaces in this order.

2.2 *Loading manner*

Compressive forces were applied to all rectangular specimens using Amsler type testing machine (capacity: 2 MN) so that normal and shear stresses would act on the construction joints. Since the joint angle univocally determines the ratio of normal stress to shear stress acting on the joint, 45°, 52.5°, and 60° were adopted as the joint angle (α), as shown in Figure 1, to examine the effect of stress combination.

As shown in Figure 1, two displacement transducers (sensitivity: 1/1000 mm) were attached to the both sides of each specimen, while the load was measured using a load cell (capacity: 1 MN), and the load-displacement was recorded with a data logger.

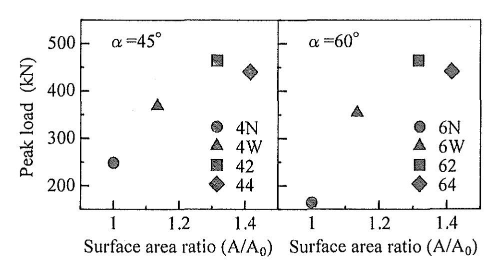

Figure 2. Peak load and surface area ratio

2.3 *AE measurement*

The AE method is a technique for detecting elastic waves induced by the occurrence and propagation of cracks in concrete and is effective in evaluating the fracture process. In this study, AE was measured in specimens with joint angles (α) of 45° and 60° using an AE measuring system (MISTRAS produced by

PAC). Four AE sensors (150-kHz resonance type) were arranged across the joints as shown in Figure 1. The acoustic emission detected by the sensors was amplified by 80 dB: 40 dB with a preamplifier and 40 dB by a main amplifier, with the threshold value set at 45 dB. A PTFE sheet with a thickness of 0.1 mm was inserted between the loading apparatus and the specimen to prevent the detection of noise.

3 RESULTS OF UNIAXIAL COPRESSION TESTS AND DISCUSSIONS

3.1 *Peak load and surface roughness*

The peak loads obtained from the uniaxial compression tests (averages of three specimens) and their relationship with the surface area ratios are shown in Table 2 and Figure 2, respectively. The peak load increased as the surface area ratio increased. In the case of wash-out surfaces using retarder sheets or wire-brushed surfaces, the effect of joint angle on the peak load was marginal, and so was the effect of the depth of wash-out. The peak load of non-treated surface, however, decreased as the joint angle increased.

Accordingly, the roughness of joint surfaces was found to have a large effect on the shear bond properties of construction joints.

3.2 *Load-displacement curves*

Figure 3 shows the load-displacement relationships obtained from the experiments. As the joint angle increased and the degree of joint surface treatment decreased, a brittle fracture could be observed. The scatter of Series 54 after the peak load may be attributed to flaking of the portions where the displacement transducer touched it. The differences in the curve shapes in the softening zone clearly represented the differences of the joint angle and surface treatment.

The effect of the degree of joint surface treatment became larger as the joint angle increased. When the degree of treatment was lower (non-treated, wire-brushed and 2mm wash-out surface), snap-back occurred after the peak load. It seems that the fracture due to concentrated stress was localized on the joint with a low degree of roughness. In specimens with a joint angle of 60°, the peak load decreased as the roughness decreased, with a stronger tendency towards snap-back.

As a result of evaluating the relationship between the degree of surface treatment and the shear bond properties using load-displacement curves, it was found that low degrees of joint surface treatment lead to low peak loads and snap-back in load-displacement relations. This tendency was particu-

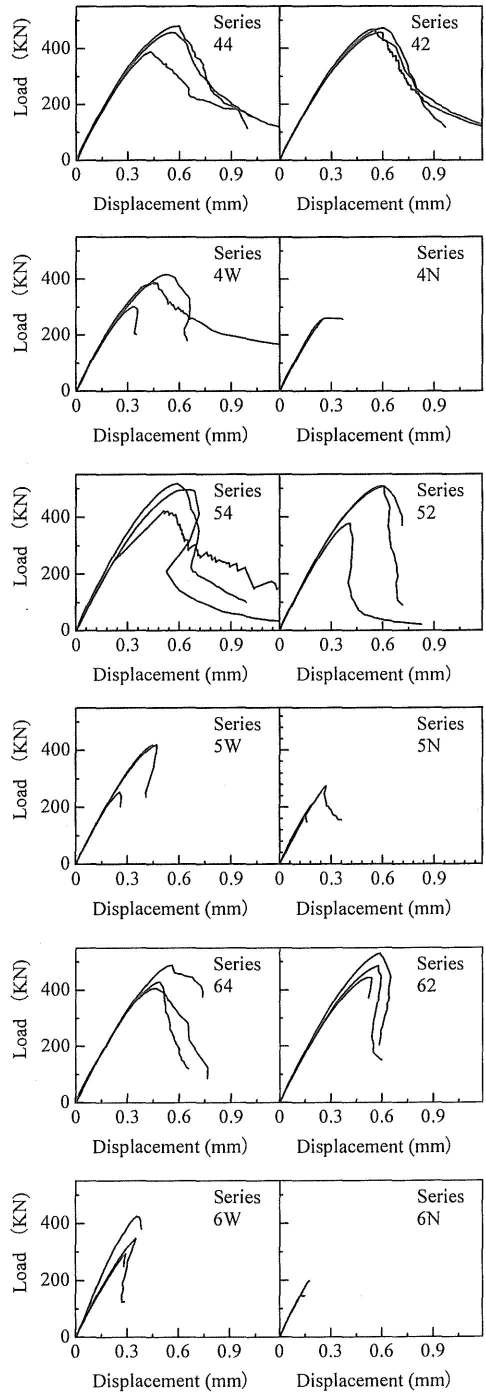

Figure 3. Load-displacement curves

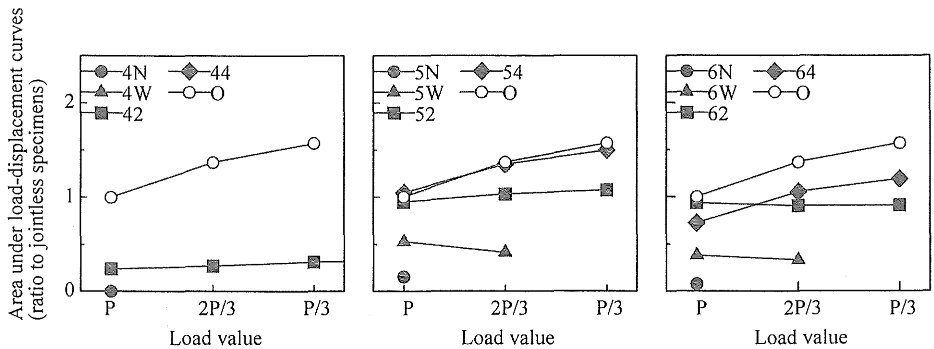

Figure 4. Area under load-displacement curves

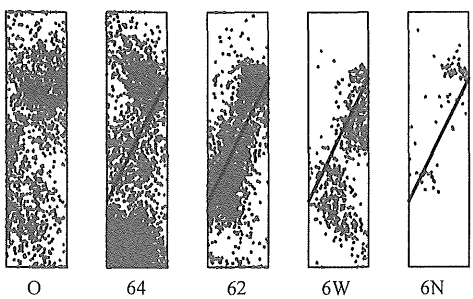

Figure 5. AE source location

larly evident in the load-displacement curves of specimens with a joint angle of 60°.

3.3 *Area under the load-displacement curve (consumed energy)*

The areas under the load-displacement curves, which represents consumed energy, were divided into three zones: up to the peak load (P) and up to 2/3 (2P/3) and 1/3 (P/3) of the peak load in the declining phase. Figure 4 shows the ratios of these values to the value up to peak load for jointless specimens. Measurement up to 1/3 of the peak load in the declining phase was impossible for wire-brushed and non-treated surface joints. The values up to P and 2P/3 are therefore shown for these specimens.

When the old concrete was treated by wash-out using retarder sheets or by wire-brushing, the area under the load-displacement curve up to post peak loading steps decreased as the joint angle increased. When the degree of joint surface treatment was lower, the area under the load-displacement curve decreased as the angle decreased. Also, in the case of specimens with a joint angle of 60°, the degree of roughness evidently affected the area under the load-displacement curve.

The degree of joint surface treatment has a large effect on the shear bond properties of specimens. When the joint angle is 60°, the effect of the degree of surface treatment on the shear bond properties can be evaluated by the peak load and the area under the load-displacement curve that indicates consumed energy.

4 RESULTS OF AE MEASUREMENT AND DISCUSSIONS

4.1 *Evaluation by AE source location*

Figure 5 shows the AE sources locations detected during loading. The concentration of AE sources on joints with a low degree of surface treatment suggests the stress concentration at joints and crack propagation along the joint surface. Whereas numerous discrete cracks parallel to the loading axis were found in Series O and 64, a single crack developing along the joint to failure was found after the tests in Series 62, 6W, and 6N. This cracking behavior nearly agrees with the results of AE source location. The lower the degree of joint surface treatment (non-treated, wire-brushed and 2mm wash-out surface), the smaller the number of AE events located. A lower degree of surface treatment causes weak bond at the joint, leading to a few AE counts strong enough to be detected. When the degree of surface treatment is higher, the surface roughness resists the crack propagation, causing the cracks to disperse. This leads to wide areas of AE sources located.

4.2 *Investigation by AE parameter*

The fracture process of specimens having joints with different degrees of surface treatment was investigated using an AE parameter. The maximum amplitude, which correlates with the scale of microfracture, was adopted in this study.

Detected AE sources were analyzed to determine the frequency distribution as shown in Figure 6. The

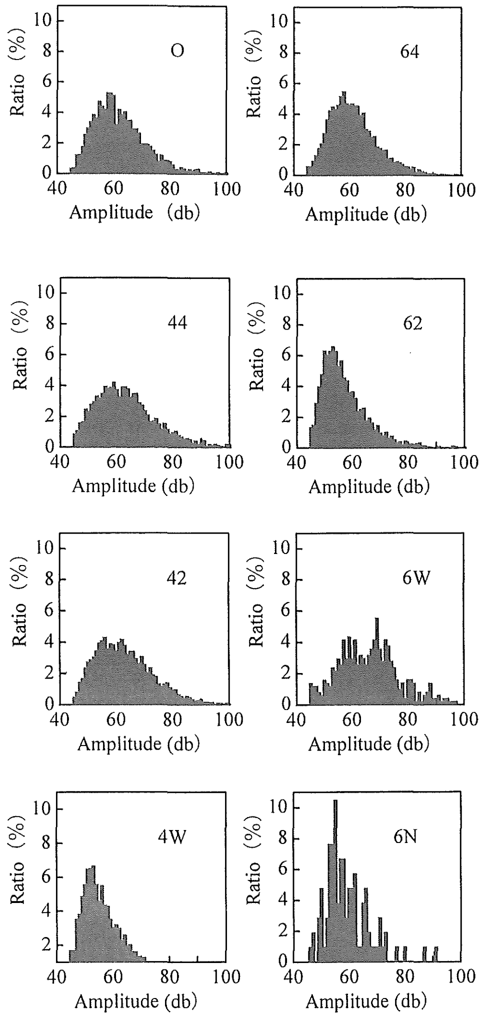

Figure 6. Amplitude distribution

shapes of the histograms for Series 44, 42, and 64 are similar to that of Series O, the jointless type, which is failed in compression. This suggests that the fracture process of Series 44, 42, and 64 is similar to that of failure in compression of monolithic specimens. In contrast, the peak frequency of Series 62 shifts to lower amplitude scales, with the proportion of large amplitude AE counts for over 80 dB being low. Referring to a past study (Kamada et al. 1998), this indicates that Series 62 exhibits a stronger tendency towards shear slip than Series 64. Also, the fact that a high degree of joint surface treatment leads to a high shear resistance agrees with past study results. This tendency was more evident with larger joint angle.

5 CONCLUSIONS

The effects of the degree of joint surface treatment at construction joints on its shear bond properties were investigated. The results are summarized as follows:

- The relationships between the surface roughness and bond properties of construction joints were evaluated based on the peak load. As a result, the peak load increased as the surface roughness increased. However, in the case of wash-out surfaces using retarder sheets, the difference in the depth of wash-out caused no marked difference in the peak load, exhibiting no appreciable effect.
- The difference in the bond properties of joints due to the difference in the degree of surface treatment was indicated more clearly by the shape of the load-displacement curve and the area under the curve. These are therefore found to be more sensitive indices to bond properties.
- A lower degree of joint surface treatment led to a brittle fracture behavior, which is represented by the area under the load-displacement curve. This was more evident when the joint angle was 60°.
- Fracture process of the specimens with differently treated joints was assessable by AE source location. AE parameter was an effective index to interpret the fracture process of concrete with construction joint.

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