ORAL REFERENCE: 851

EVALUATION OF BOND PROPERTIES OF CRACK INJECTION REPAIR FOR CONCRETE STRUCTURES

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ABSTRACT

Bond quality is an important factor that affects the performance of repaired members. For crack injection repair, bond strength tests based on Japanese Industrial Standard (JIS) were carried out under conditions that were different from those normally encountered in the field (i.e. the tests involved smaller specimens, smoother surfaces and finer grained materials). Testing methods to evaluate the bond property of repair materials involve a plain concrete as the bulk one. Most repair materials were, however, used in reinforced concrete members. The behavior of repair materials in the members should be also evaluated appropriately. This paper presents the influence of injected surface roughness on the bond properties, in which the bond properties of crack injection materials were evaluated using fracture mechanics parameters. This paper also describes the results of bending tests for reinforced concrete beams repaired by crack injection techniques. The effects of the injected and un-injected parts on the mechanical behavior of repaired reinforced concrete were investigated.

KEY WORDS

Crack Injection Repair, Bond Property, Surface Roughness, Standard Tests, Flexural Bond Strength

INTRODUCTION

Good bonding between repair materials and bulk concrete is one of the basic performances required for repaired members. For crack injection repairs, good bonding may increase the stiffness of the repaired members and prevent the penetration of substance (e.g. chloride ions and water). In Japan, the bond property of crack injection materials has been evaluated with the flexural bond strength based on Japanese Industrial Standard (JIS) testing method, where smaller specimens with smooth surfaces for injection are used. This testing method helps to interpret the relative performance of repair materials. However, the evaluated values (indices) obtained from the standard tests depend on the testing methods, such as specimen geometry, loading manner and so on. There is few relation between the evaluated values and the performance of repair materials in existing concrete structures. Regarding the testing method for bond properties in repairs, the location of fracture might be more important (i.e. the fracture of bulk concrete or repair materials, or the delamination of repair materials should be observed).

The conventional indices to evaluate the bond property are the tensile bond strength, the flexural bond strength, the shear bond strength and so on. However, it is important to evaluate the bonding after the maximum load in order to estimate the failure process of repaired members. The fracture mechanics parameters, such as tension softening diagrams or fracture energy, were applied to the evaluation of the bond property on construction joint [1,2] and on repair material [3,4].

In the first part of this paper, the effects of the injected surface roughness on the bond property were investigated through the bending tests. The testing method using fractured surfaces of concrete as injection surfaces was proposed. In addition, the fracture mechanics parameters such as tension softening diagram and fracture energy were adopted as the indices. In the second part of this paper, the cracking behavior of reinforced concrete beams repaired by crack injection technique was described. The relationship between bond property of repair materials and mechanical behavior of repaired beams were discussed, in which the behavior of un-injected and injected cracks were investigated.

BOND PROPERTY OF CRACK INJECTION MATERIALS AND INJECTED SURFACE ROUGHNESS

Outline of Experiments

The test procedures are shown in Fig. 1. The size of the specimens was 100×100×400mm. The mix proportions of the concrete are tabulated in Table 1. The water to cement ratio was 50%. The compressive strength at the age of 47days was 52MPa. Four specimens were made for each series. The bulk concrete was cast and cured in water for 35days, and the wet curing (20℃) was carried out for 5days. A notch of 1/3 of the specimen depth was made by a concrete cutter. As shown in Fig. 2, the four point bending tests with the span of 300mm were carried out and the

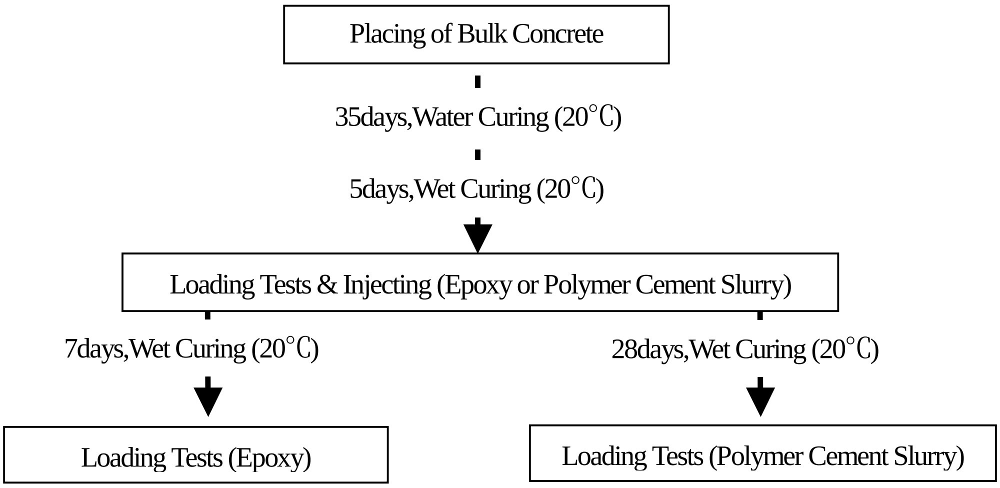


Figure 1: Test Procedures

TABLE 1
MIX PROPORTIONS OF BULK CONCRETE

W/C (%)	Slump (cm)	Air (%)	Units (kg/m^3)				
			Water	Cement	Fine Agg.	Coarse Agg.	Ad.*
50	13	4.1	165	330	765	1000	0.99

*Admixture (AE Water Reducing Agent)

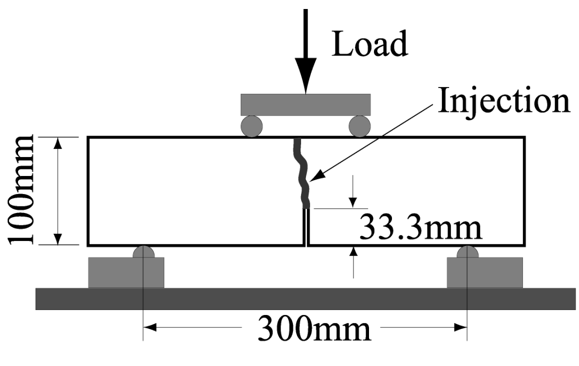


Figure 2: Test Setup

applied load and crack mouth opening displacement (CMOD) curves were measured. The fractured surfaces after bending tests and the smooth surfaces after removing the casting form were adopted for the injection surfaces. A clearance of 1.0mm thickness for injecting was made by using a spacer and the sides and bottom of the crack were sealed to prevent leakage. The epoxy or polymer cement slurry was injected into the clearance between the specimen halves. The material properties of the injections are tabulated in Table 2. For comparison, control un-cracked specimens were also made. The loading tests of the repaired specimens were carried out at 7 days (total: 47days) after injecting for the epoxy injected specimens, and 28days (total:
68days) for the polymer cement slurry injected specimens. The loading tests of the control specimens were also carried out at the age of 47days that was equal to the age of the epoxy injected specimens.

TABLE 2
MATERIAL PROPERTIES OF CRACK INJECTION MATERIALS (EXTRACTED FROM CATALOGS)

Properties	Epoxy	Polymer Cement Slurry
Shrinkage (%)	0.0	0.2
Young's Modulus (GPa)	2.9	9.7
Flexural Bond Strength (MPa) (JIS A 6024)	6.9	4.1
Viscosity (mPa・s) (JIS K 6833)	600	—
Consistency J14 (sec) (JSCE-F531)	—	2.4

The poly-linear approximation analysis method [5] combined with a fictitious crack model was used for the determination of the tension softening diagrams. In the repaired specimens, only one macro crack propagated and mainly consumed the energy that was indicated by the area of load-displacement relations. It was assumed that these back analysis concepts with the fictitious crack model could be applied to the determination of tension softening diagrams in the crack injection repair.

TABLE 3
TEST RESULTS

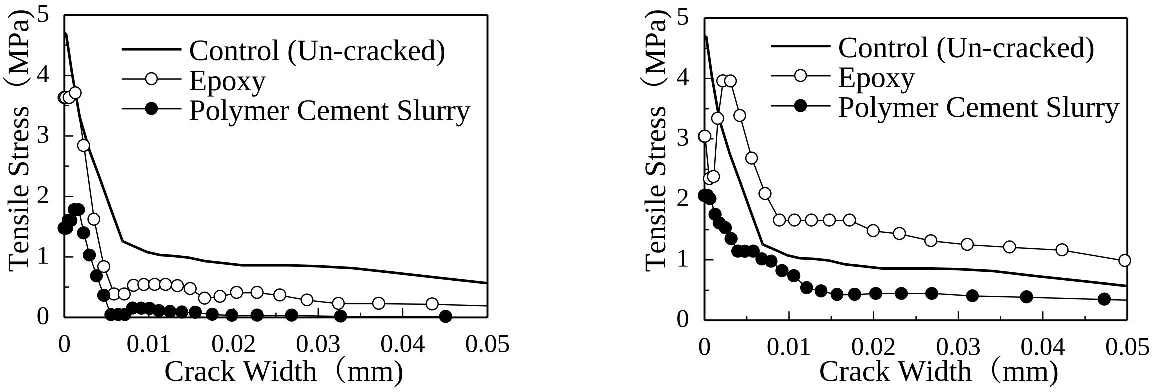
Injection Materials	Injected Surfaces	Number of Specimens	Flexural Bond Strength (MPa)	Fracture Energy* (N/m)	Location of Fracture
Epoxy	Smooth Surface	4	3.25	15.1	Interface & Injection
	Fractured Surface	4	4.41	27.6	Bulk
Polymer Cement Slurry	Smooth Surface	4	2.01	6.50	Interface & Injection
	Fractured Surface	4	2.43	12.8	Injection
Control	(Uncracked)	4	3.89	22.8	—

*Fracture Energy up to Crack Width of 0.01mm

Effect of Injected Surface Roughness on Bond Property in Plain Concrete Beams

The flexural bond strength of the each repaired specimens is shown in Table 3, along with those of the control un-cracked specimens. In all injected specimens with the smooth surfaces, the fracture occurred along the interface and within injection. The flexural bond strength of the these specimens was smaller than that of the control un-cracked specimens.

The tension softening diagrams of the injected specimens are compared with those of the control un-cracked specimens in Fig. 3. The difference in bond properties can be visually distinguished by the shape of the tension softening diagrams. In the case of the fractured surfaces, the tensile stress at each crack width was larger than that of the smooth surfaces. Especially, the tensile stress of the repaired specimens with epoxy injection was larger than that of the control un-cracked specimens. As shown in Table 3, the fracture energy of the specimens with injection on the fractured surfaces was twice as large as those with injection on the smooth surfaces. The fracture energy was a more sensitive index than the flexural bond strength. In this study, the flexural bond strength and fracture energy of the repaired specimens with epoxy injection became larger than those of the control un-cracked ones. Because the crack path of repaired specimen, in which the injections have good bond properties, was longer than that of un-cracked specimen, the consumed energy was increased [4]. In addition, as the Young's modulus of the epoxy was smaller than that of concrete, the ductility of repaired members with epoxy became larger [3]. For repaired specimens with the epoxy injection on the fractured surfaces, a crack propagated in the bulk concrete. For repaired specimens with the polymer cement slurry injection on the fractured surfaces, a crack, however, propagated the injection material. These crack patterns, which depends on the difference of the injection materials, could be also observed in the repaired reinforced concrete, which will be described in the next part of this paper.



(a) Repaired with Smooth Surfaces　　(b) Repaired with Fractured Surface

Figure 3: Determined Tension Softening Diagrams

INJECTED REPAIR MATERIALS IN REINFORCED CONCRETE BEAMS

Outline of Experiments

The mix proportions of the concrete, which are used ones in the previous part, are shown in Table 1. The compressive strength at the age of 19 days was about 50MPa. The size of the specimens was 100×300×1800mm, as shown in Fig. 4. The reinforcement ratio, in which yield point of the re-bar was over 295N/mm^2, was 0.5%. After removing the casting forms, the wet curing (20°C) were carried out for 2 weeks. In order to obtain the dried specimens for the sealing, the specimens were exposed in the laboratory for 5 days.

The four point bending tests were carried out to induce cracks (first cracks) in original specimens. The applied load and relative displacement in the moment span were measured. The loading was continued up to the curvature of 1.5×10^{-4}(1/mm), and un-loaded to be the applied load of zero. The epoxy and polymer cement slurry, which are also used ones in the previous part, were used as the injection materials. Each material was injected into the first cracks that have dried injected surfaces in original specimens by means of the low-pressure injection method. The first cracks were, however, classified into two main groups; (a) injected cracks each having the crack width of 0.2-0.8mm were repaired by the crack injection techniques, (b) un-injected cracks each having the crack width under 0.04mm were not repaired. In

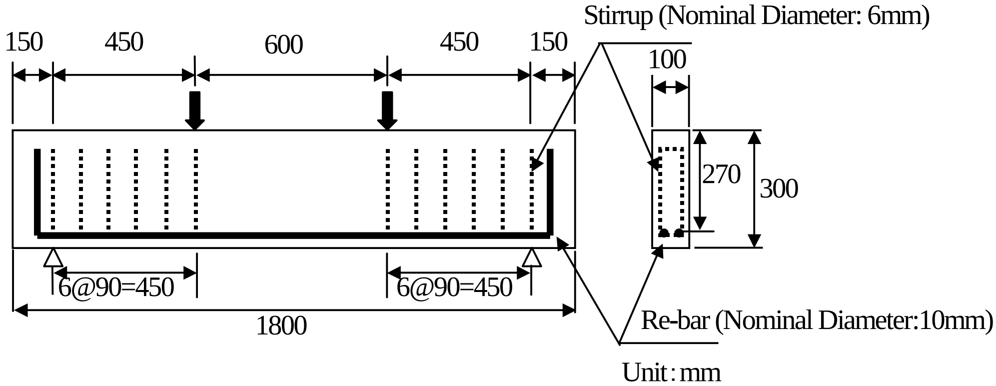
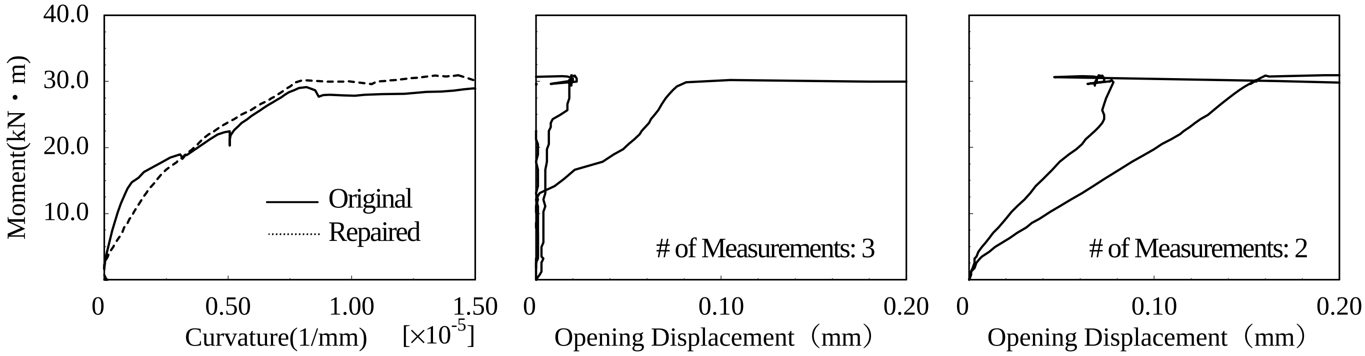
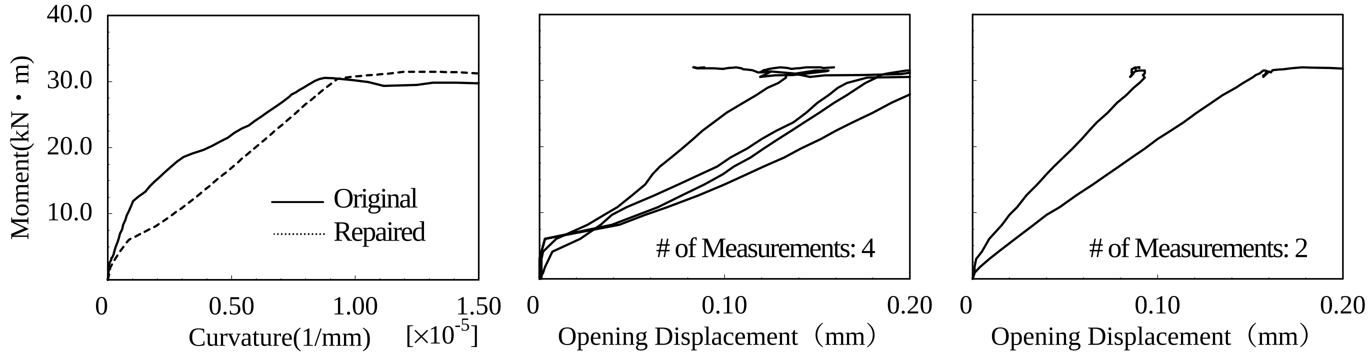


Figure 4: Test Setup



(a) Moment-Curvature (b) Opening Disp. of Injected cracks (c) Opening Disp. of Un-injected cracks

Figure 5: Mechanical Properties of Repaired Reinforced Concrete Beams with Epoxy Injection



(a) Moment-Curvature (b) Opening Disp. of Injected cracks (c) Opening Disp. of Un-injected cracks

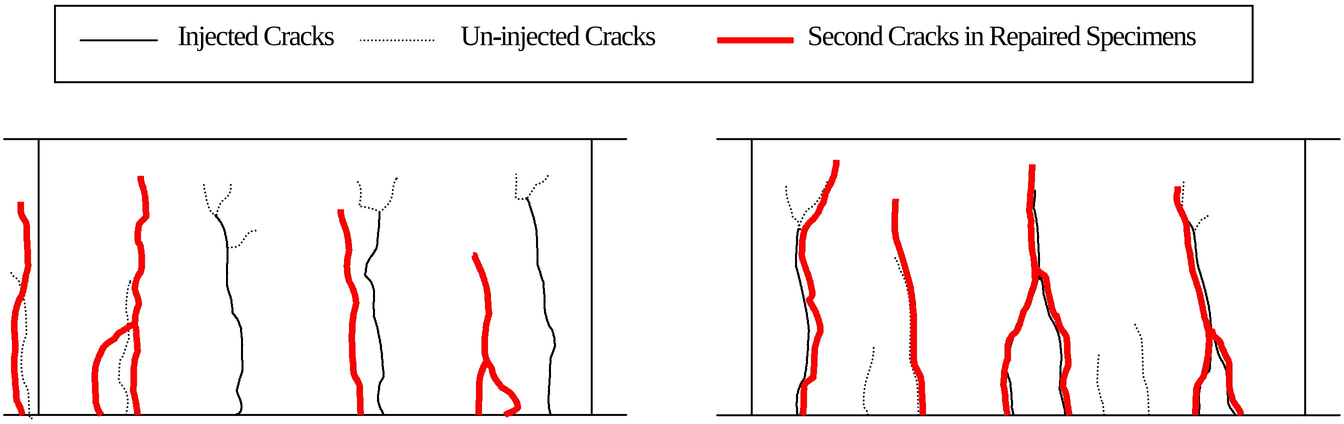
Figure 6: Mechanical Properties of Repaired Reinforced Concrete Beams with Polymer Cement Slurry Injection

these beam specimens, the crack having the crack width of 0.2-0.04mm could not be observed. After the injection repair, the bending tests used for the original specimens were also carried out, and the opening displacement of injected and un-injected cracks was measured through the crack opening displacement transducers.

Cracking Behavior of Repaired Reinforced Concrete Beams

The relationships between moment and curvature in each specimen are shown in Fig 5(a) and 6(a). The initial stiffness of repaired specimens using each injection material was lower than that of original specimens. The crack opening displacement of each crack in repaired specimens is shown in Fig. 5(b),(c) and 6(b),(c). For the un-injected cracks, the opening displacement became larger with increasing of the applied load. Especially, the opening displacement of the un-injected cracks was larger than that of injected cracks in lower loading level. The un-injected cracks imparted the lower stiffness to the repaired specimens. Figure 7 shows the crack patterns after the loading tests for the repaired specimens. As shown in Fig. 6(b), because the opening displacement rapidly increased at the moment of 6-7kN・m, the cracking would be occurred at the injected cracks with the polymer cement slurry injection. The new cracks (second cracks) in repaired specimens could be observed at the injected cracks. The cracking in the polymer cement slurry injection imparted the lower stiffness to the repaired specimens, as shown in Fig 6(a), because the each inflectional point in moment-curvature and moment-crack opening displacement relations was similar to each other. The opening displacement of injected cracks with the epoxy injection, however, suddenly increased at the moment of 14kN・m, which was higher than that of injected cracks with the polymer cement slurry injection. In addition, some of the injected cracks with the epoxy injections were not opened, as shown in Fig. 5(b). The second cracks in repaired specimens with the epoxy injection could be observed at the bulk concrete near the injected parts, as shown in Fig. 7.

These results show that the difference of bond properties of each crack injection material could be observed in not only load-displacement relations but also load-crack opening displacement ones. Especially, the un-injected cracks having larger crack width in each loading level would affect not only the mechanical behavior of repaired members but also the durability due to permeability of substance. The un-injected cracks in concrete structures should be detected, or injecting and coating techniques should be used jointly for a durable repair.



(a) Epoxy Injection (b) Polymer Cement Slurry Injection

Figure 7: Examples of Crack Patterns in Moment Span of Repaired Reinforced Concrete Beams

CONCLUSIONS

In the first part of this paper, the bond property in crack injection repair was investigated by using the plain concrete beams, and the following conclusions were obtained;

1 In order to evaluate the bond property in crack injection repair, the testing method with the fractured surfaces of concrete was proposed. The bond property of the injected specimens with fractured surfaces was better than that with smooth surfaces. Regarding this testing method with the fractured surfaces, the failure mode is one of the effective indices to evaluate bond properties of repair materials (i.e. good bonding and poor one gave the fracture of bulk concrete and the delamination of repair materials, respectively) .

2 The fracture mechanics parameters were applied to the evaluation of bond property in crack injection repair. Especially, the fracture energy of the repaired specimens with the fractured surfaces was twice as large as that with the smooth surfaces.

In the second part of this paper, the mechanical properties of the repaired reinforced concrete beams, which have injected and un-injected cracks, were discussed, and following conclusions were obtained;

3 The un-injected cracks impart the lower stiffness to the repaired reinforced concrete beams. Locally, the opening displacement of the un-injected cracks was larger than that of the injected cracks in lower loading level. This result shows that the un-injected cracks in concrete structures should be detected, and coating techniques might be effective in a durable repair.

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