Flexural Capacity of RC Beams Damaged by Combined Deterioration due to ASR and Corrosion

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ABSTRACT

It is important to clarify the residual performance of the loading capacity of RC members damaged by ASR and corrosion. In addition, the deterioration of bond strength between concrete and reinforcing steel bar due to ASR and corrosion is concerned. In this study, RC beams, which are damaged by combined deterioration, are tested to evaluate the flexural capacity. The bond strength between concrete and reinforcing steel bar due to ASR and corrosion is evaluated by loading tests for the bond specimens. From these results, in the case of bond specimens with confined reinforcement, the bond strength between concrete and reinforcing steel bar due to ASR and corrosion are larger than sound specimens. The bond strength between concrete and reinforcing steel bar are increased by chemical prestress.

Keywords. ASR, Corrosion, loading capacity, RC beams, Deterioration of bond strength

INTRODUCTION

The combined deterioration due to ASR and Corrosion are confirmed in some bridges (Technical Committee on Evaluation of Combined Deterioration on Concrete Structures and Its Maintenance Planning, 1998). The safety of structures is considered not to be seriously compromised. However, the safety of structures becomes questionable when the cross section areas of reinforcements are decreased due to corrosion (Yamamoto, 2008). In addition, the bond strength between concrete and reinforcing steel bar due to ASR and corrosion are decreased (Mikata, 2012). When many steel bars are fractured, strengthening is often required because of the problem of possible over-loading caused by the reduced performance of the member or structure due to decreased concrete strength, concrete Young's modulus and the bond strength between concrete and reinforcing steel bar. In such a situation, it is important to clarify the residual performance of the loading capacity of RC members damaged by ASR and corrosion. In addition, the deterioration of bond strength between concrete and reinforcing steel bar due to ASR and corrosion is concerned.

In this study, RC beams, which are damaged by combined deterioration, are tested to evaluate the flexural capacity. The bond strength between concrete and reinforcing steel bar due to ASR and corrosion is evaluated by loading tests for the bond specimens.

MEASUREMENT AND TEST METHOD FOR BEAM SPECIMENS

Test variables. As shown in Figure 1, test specimens are RC simple beams with a rectangular cross section of 100×200mm and total length of 1800mm.

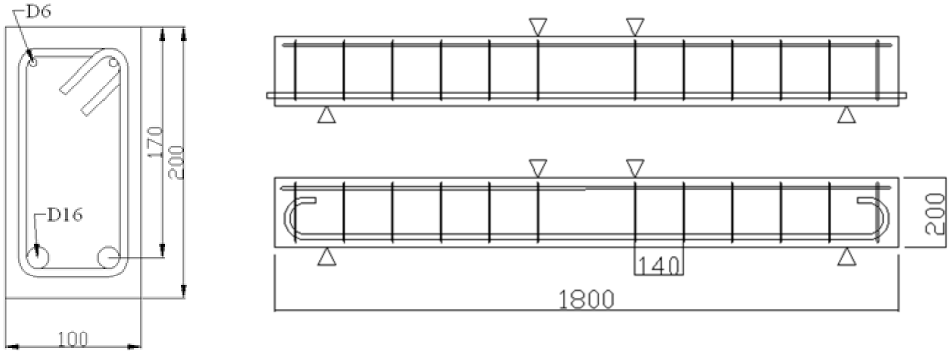


Figure 1. Dimension of the specimens (mm)

The test variables are as follows:

Deterioration type: ASR (A-series specimens), corrosion(C-series specimens), combined deterioration due to ASR and corrosion (AC-series specimens) and sound (N-series specimens).

Anchorage of main reinforcement: In order to evaluate the effect of bond strength between reinforcement and concrete, two types of specimens with or without 180 degree hook at both ends of the main reinforcement were fabricated. In the specimens without hooks, the both ends of main reinforcement were revealed in order to measure slip displacement during loading test.

The main reinforcements used are 2-D16 (SD295A). Shear reinforcements used are D6 (SD345). The spacing of shear reinforcement was 140mm (shear reinforcement ratio ρ_w=0.46%). All the specimens were cured for 4weeks under normal moist-curing at 20℃.

In the A-series specimens, after 4 weeks of curing, they were placed in a constant temperature-humidity chamber to progress ASR under high temperature (40℃) and high humidity (90%) for 730days.

In the C-series specimens, they are placed at outdoors of laboratory and sprayed with 3% saline water from 28days to 365days for every week days after curing.

In the AC-series specimens, they are placed at outdoors of laboratory and sprayed with 3% saline water from 28days to 365days for every week days. They were placed in temperate humidity chamber to progress ASR under high temperature (40℃) and high humidity (90%) from 365days to 730days.

Detail of test specimens are shown in Table 1. Mix proportion of concrete is shown in Table 2. In the A-series and AC-series specimens, the equivalent alkali content was 13.1kg/m^3 using NaCl. The main reactive components identified in texture of andesite crushed stone were a volcanic glass, cristobalite and tridymite. Properties of concrete are shown in Table 3.

Table 1. Details of test specimens

Series	Specimens	Concrete type	The hook of main reinforcement	*1 Curing term (year)
N	N-F	Sound	Existence	－
	N		Nothing	－
C	C-F-1	Corrosion	Existence	1
	C-1		Nothing	1
A	A-F-2	ASR	Existence	2
	A-2		Nothing	2
AC	AC-F-2	ASR+ Corrosion	Existence	2
	AC-2		Nothing	2

*1 Curing term of N-F and N is 4weeks

Table 2. Mix proportion of concrete

*1 Series	G_{max}	Slump	W/C	Air	s/a	Unit weight (kg/m^3)							
						W	C	*2 S		*3 G		NaCl	*4 A
	(mm)	(cm)	(%)	(%)	(%)			S_n	S_r	G_n	G_r		(cc)
N	25	8	63	4.0	45.8	183	290	791	0	988	0	0	725
C	25	8	63	4.0	45.8	183	290	791	0	988	0	13.1	725
A, AC	25	8	63	4.0	45.8	183	290	396	411	494	492	13.1	725

*1 N: Sound specimens, C: Corrosion specimens, A: ASR specimens and AC: Combined deteriorated specimens

*2 S_n: normal fine aggregate, S_r: reactive fine aggregate

*3 G_n: normal coarse aggregate, G_r: reactive coarse aggregate

*4 A: air entraining and water reducing admixture

Table 3. Properties of concrete

Series	N	C		A		AC	
Age of concrete (day)	28	28	443	28	761	28	761
Compressive strength f'_c (N/mm^2)	25.0	21.5	28.2	31.2	23.6	28.1	38.9
Elastic modulus E_c (kN/mm^2)	21.9	25.6	32.1	28.3	15.4	28.0	13.4

Measurements of ASR expansion. Contact gauge tip was attached in both sides of tests piece specimens and beam specimens to measure ASR expansion. On one hand, ASR expansion of tests piece specimens are evaluated free expansion without reinforcement. On the other hand, the ASR expansion strains of beam specimens are measured in surface concrete on the position of longitudinal reinforcement (the length of extreme compression fiber of the section 30mm and 170mm).

Measurements of corrosion. The ratio of corrosion weight loss was calculated from the sound (original) weight of the reinforcement and the corrosion weight loss in the overall length. The sound (original) weight of the reinforcement was derived from measuring the reinforcement alone before casting the RC beam. The corrosion weight loss was measured by removing the rust of corroded longitudinal reinforcement, which was taken out of RC beam after the loading test, using a 10% di-ammonium hydrogen citrate solution at 60˚C.

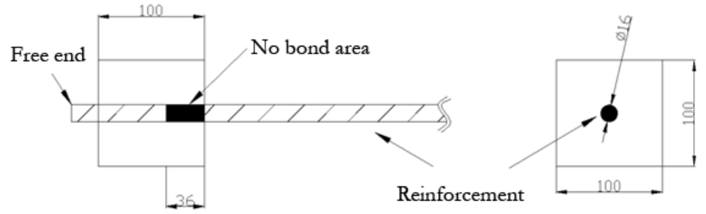
Loading test. All specimens were tested under symmetrical two-point loads with a flexural span of 300mm, and a shear span of 600mm. The shear span-effective depth ratio of these beams are a/d=3.53. In the case of all specimens, calculation of ultimate flexural capacity is smaller than that of ultimate shear capacity.

MEASUREMENT AND TEST METHOD FOR BOND SPECIMENS

Test variables. 2 type bond specimens are tested to evaluate bond strength between concrete and reinforcement.

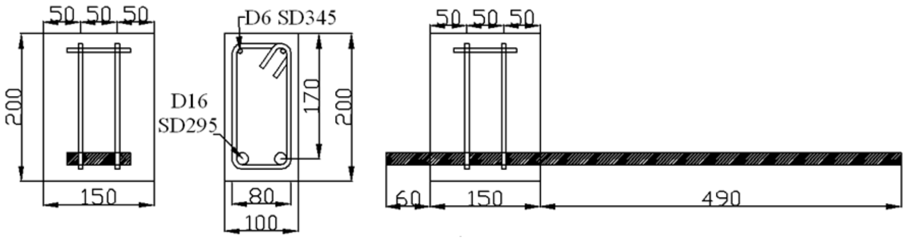
Specimens: Type-1 bond specimens are specified by JSCE code (JSCE-G503, JSCE Standard Specification for Concrete Structures, 2010). Type-2 bond specimens are simulated beam cross section to evaluate effect of hoop reinforcement. Their cross section is equivalent to beam cross section of 100×200mm and total length of 150mm with hoop reinforcement and longitudinal reinforcement. Type-2 specimens are shown in Figure 2.

Deterioration type: ASR (A-series specimens), corrosion(C-series specimens), combined deterioration due to ASR and corrosion (AC-series specimens) and sound (N-series specimens).



One side view **Cross section**

(a) Type-1 bond specimens



One side view **Cross section** **Another side view**

(b) Type-2 bond specimens

Figure 2. Dimension of the specimens (mm)

In the case of type-2, 3 specimens are made in each deterioration type. A total of 12 specimens are made. Mix proportion of concrete and kind of reinforcement for bond specimens was equivalent to beam specimens. They are cured and preserved in the same condition as beam specimens.

RESULTS AND DISCUSSION FOR BEAM SPECIMENS

ASR expansion. Figure 3 shows the axial strain of ASR expansion for A-series and AC-series beam specimens. On one hand, ASR expansion strains of A-F-2, A-2 are about 1400(μ), 1200(μ) at 735days. On the other hand, those of AC-F-2, AC-2 are about 1100(μ), 700(μ). ASR expansion of A-series is larger than that of AC-series because ASR progressive curing term of A-series is longer than that of AC-series. In the case of type-1, 5 specimens are made in each deterioration type. A total of 20 specimens are made.

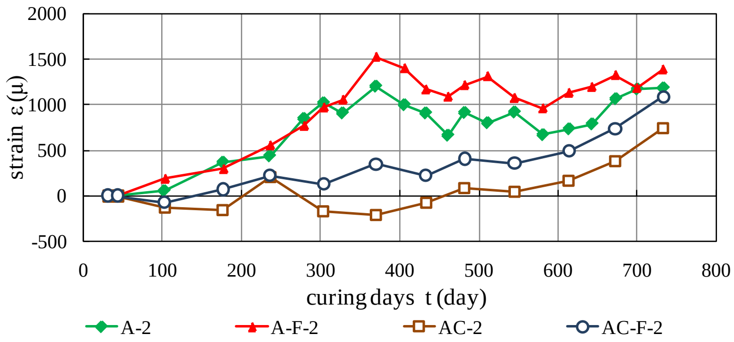


Figure 3. Axial strain of ASR expansion

Condition of crack. Figure 4 shows condition of crack before loading tests. In the case of A-F-2, ASR cracks are occurred in whole area of specimens. Almost cracks are 0.2mm width. In the case of C-F-1, corrosion crack was occurred in the surface concrete on the position of longitudinal reinforcement due to corrosion of reinforcement. Crack is 1mm under width. In the case of AC-F-2, Both ASR crack and corrosion crack are occurred. Crack is 1mm over width in the surface concrete on the position of longitudinal reinforcement. Other cracks are 1mm under width. Maximum crack width of AC-F-2 is larger than that of A-F-2 in spite of small ASR expansion compared with A-F-2. Therefore, in the case of combined deterioration, crack width becomes large on the position of longitudinal reinforcement, because corrosion of reinforcement is progressed due to penetration of chloride ion through ASR crack.

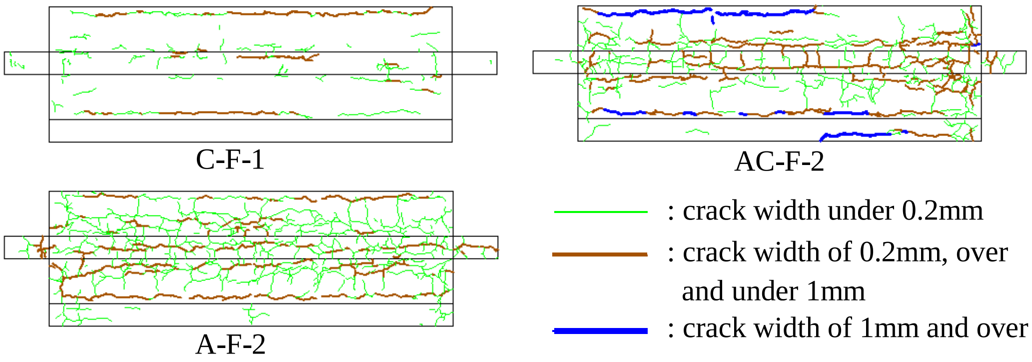


Figure 4. Condition of crack before loading tests

Measurements of corrosion. The ratio of corrosion weight loss, yield strength and Young's modulus of corroded reinforcing bars are listed in Table 4.

Table 4. Mechanical properties of corroded reinforcing bars

Specimens	reinforcing bars	The ratio of corrosion weight loss (%)	*1 Yield strength (N/mm^2)	*1 Elastic modulus (kN/mm^2)
C-1	No.1	1.55	354.8	197.1
	No.2	2.43	326.9	196.2
C-F-1	No.1	4.70	386.9	195.8
	No.2	5.43	357.8	202.5
A-2	No.1	3.67	329.1	200.6
	No.2	2.76	365.2	199.0
A-F-2	No.1	5.53	332.9	202.8
	No.2	5.37	359.7	203.3
AC-2	No.1	3.60	318.8	201.9
	No.2	5.44	331.8	201.7
AC-F-2	No.1	6.86	318.8	201.1
	No.2	8.45	330.6	203.5

*1 Corroded longitudinal reinforcement was taken out of RC beam after the loading test. Yield strength and elastic modulus is calculated by experimental values using nominal cross sectional area.

On one hand, the ratios of corrosion weight loss of AC-F-2 are 6.86 and 8.45. On the other hand, those of C-F-1 are 4.70 and 5.43. Those of A-F-2 are 5.53 and 5.37. The ratio of corrosion weight loss of AC-F-2 is larger than that of C-F-1 and A-F-2.

Failure mode. Figure 5 shows the final failure mode. Results of loading tests are listed in Table 5. All the specimens showed flexural tension failure. On one hand, in the case of N-F, shear crack is occurred from loading point to support point in shear span. Finally, this beam is failed due to the compressive failure in flexural span. On the other hand, in the case of C-F-1, shear crack is occurred nearby loading point. The spacing of flexural crack is larger than that of N-F due to decreasing the bond strength between main reinforcement and concrete. In the case of A-F-2 and AC-F-2, shear crack is not occurred due to chemical prestress of ASR. Especially, in the case of AC-F-2, flexural cracks are occurred only in flexural span and the distribution of flexural crack is decreased, because of decreasing the bond strength between main reinforcement and concrete.

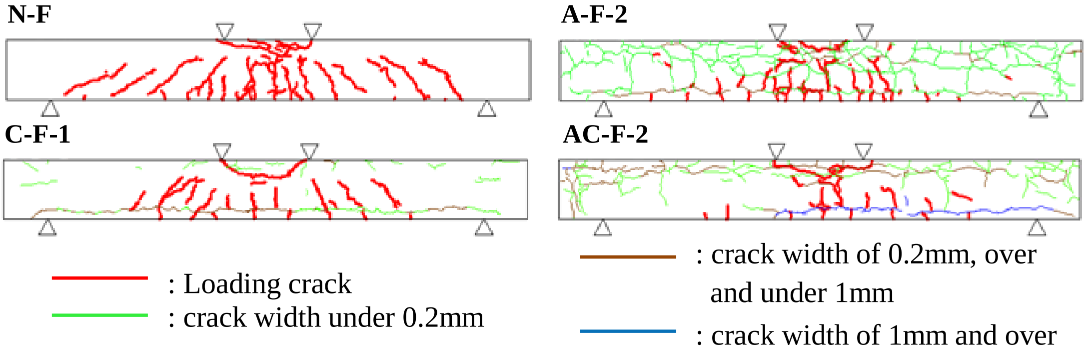


Figure 5. Final failure mode

Table 5. Details of test specimens and results of loading tests

Series	Specimens	Concrete type	The hook of main reinforcement	[*1] Curing term (year)	Ultimate flexural capacity (cal.) P_{ub} (kN)	[*2] Ultimate shear capacity (cal.) P_{us} (kN)	Ultimate load capacity (mea.) P_u (kN)	[*3] Failure mode
N	N-F	Sound	Existence	—	62.7	86.7	75.2	FT
	N		Nothing	—	62.7	86.7	76.9	FT
C	C-F-1	Corrosion	Existence	1	67.1	87.9	73.3	FT
	C-1		Nothing	1	62.5	87.9	67.8	FT
A	A-F-2	ASR	Existence	2	60.9	86.2	74.7	FT
	A-2		Nothing	2	61.0	86.2	75.2	FT
AC	AC-F-2	ASR+ Corrosion	Existence	2	63.3	91.4	67.4	FT
	AC-2		Nothing	2	63.5	91.4	65.2	FT

*1 Curing term of N-F and N is 4weeks

*2 Calculated ultimate shear capacity (P_{us}=2(V_c +V_s)) (JSCE Standard Specification, 2007)

*3 FT: flexural tension failure

Load and deflection. Figure 6 shows the relationship between load and deflection in N-F, C-F-1, A-F-2 and AC-F-2. N-F has ductility behaviour in post-peak state. On one hand, Ultimate load of C-F-1, A-F-2 and N-F are same behaviour in load and deflection. On the other hand, initial stiffness of C-F-1, A-F-2 and AC-F-2 are larger than that of N-F, because concrete strength of C-F-1 are increased by one year preservation and stiffness of A-F-2 and AC-F-2 are increased by chemical prestress. However, ductility of C-F-1, A-F-2 and AC-F-2 are smaller than that of N-F in post-peak state, because the cross section areas of reinforcements are decreased due to corrosion in these specimens. Especially, ultimate load and ductility for post-peak state of AC-F-2 are smaller than other specimens, because the ratio of corrosion weight loss of AC-F-2 is larger than that of A-F-2 and C-F-2.

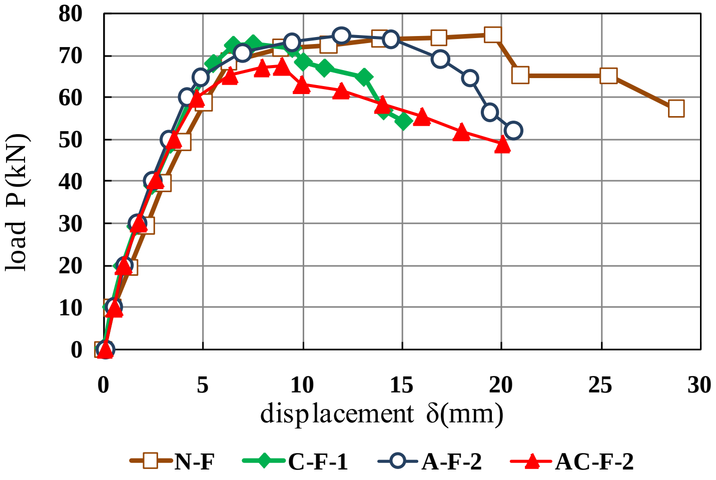
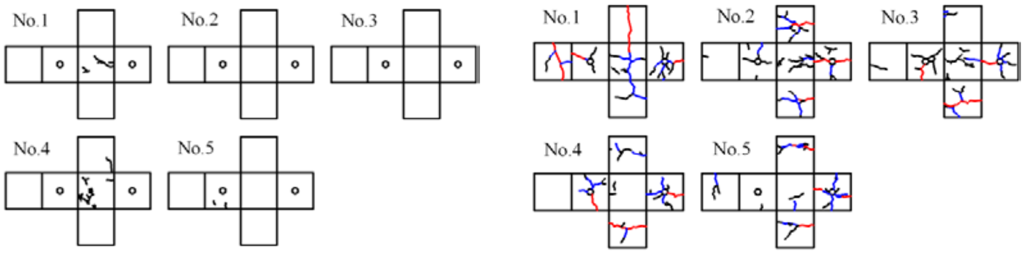


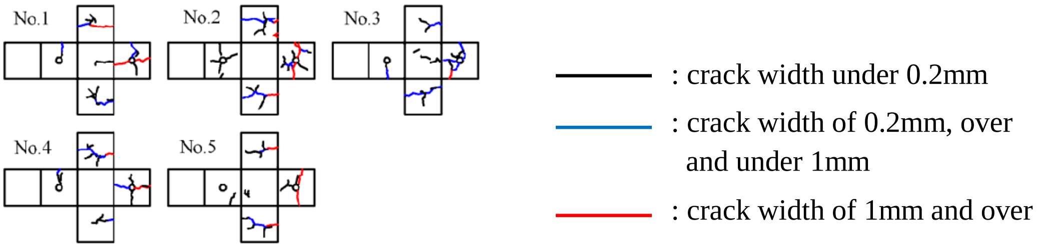
Figure 6. The relationship between load and deflection

RESULTS AND DISCUSSION FOR BOND SPECIMENS

Condition of crack. Figure 7 and Figure 8 show the condition of crack before loading tests in type-1 and type-2 specimens. In the case of C-series specimens, corrosion crack was occurred in the surface concrete on the position of longitudinal reinforcement due to corrosion of reinforcement. On one hand, In the case of type-1 specimens, crack is 1mm over width in A-series and AC-series specimens. ASR expansion is not confined without hoop reinforcement. Therefore, ASR cracks widths are increased in type-1 specimens.

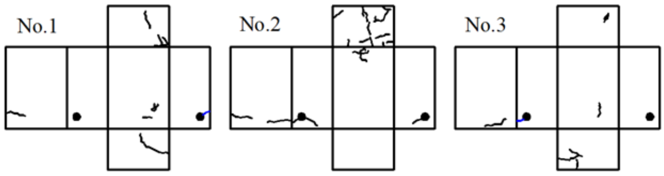


(a) C-series specimens (b) A-series specimens

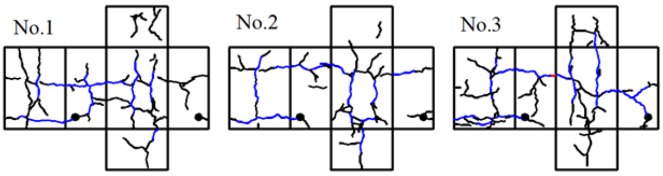


(c) AC-series specimens

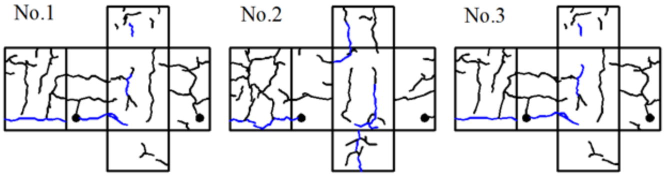
Figure 7. Condition of crack before loading tests (Type-1 specimens)



(a) C-series specimens



(b) A-series specimens



— : crack width under 0.2mm

— : crack width of 0.2mm, over and under 1mm

— : crack width of 1mm and over

(c) AC-series specimens

Figure 8. Condition of crack before loading tests (Type-2 specimens)

On the other hand, in the case of type-2 specimens, crack width of A-series specimens was 0.2mm over in whole area of specimens due to ASR. Crack width of AC-series specimens was 0.2mm over in the surface concrete on the position of longitudinal reinforcement, because corrosion of reinforcement is progressed due to penetration of chloride ion through ASR crack.

Bond strength. Bond strength between concrete and reinforcement are listed in Table 6. On one hand, In the case of type-1 specimens, bond strength of N-series specimens is the largest of all series specimens. Bond strength of A-series specimens is smaller than that of N-series specimens due to ASR crack. Bond strength of AC-series specimens is the smallest of all series specimens, because crack width of AC-series specimens is large and bond strength is decreased due to ASR crack and corrosion of reinforcement. On the other hand, In the case of type-2 specimens, bond strength of A-series specimens is the largest of all series specimens. ASR expansion is confined by hoop reinforcement in type-2 specimens. Therefore, bond strength is increased by chemical prestress of ASR expansion. A result of type-2 specimens is different from of type-1. From these effects, it is assumed that bond strength of ASR affected beam specimens is increased by chemical prestress compared with sound specimens. The bond strength of ASR affected beam specimens can not be evaluated appropriately by type-1 specimens (JSCE-G503). The bond specimen which is defined by JSCE-G503 caused free expansion due to ASR without hoop reinforcement. It is necessary to take the chemical prestress caused by the ASR expansion into account in evaluating bond strength of ASR affected beam specimens.

Table 6. Bond strength between concrete and reinforcement

Specimens	Type-1		Type-2	
	Maximum load (N)	Bond strength (N/mm^2)	Maximum load (N)	Bond strength (N/mm^2)
N	40.7	12.74	41.0	5.46
C-1	38.0	11.77	49.2	6.56
A-2	28.2	8.87	63.5	8.47
AC-2	18.5	5.81	52.0	6.93

CONCLUSION

The main conclusions obtained from this study are as follows:

(1) According to results for beam specimens, in the case of C-F-1, shear crack is occurred nearby loading point. The spacing of flexural crack is larger than that of N-F due to decreasing the bond strength between main reinforcement and concrete. In the case of A-F-2 and AC-F-2, shear crack is not occurred due to chemical prestress of ASR. Especially, in the case of AC-F-2, flexural cracks are occurred only in flexural span and the distribution of flexural crack is decreased, because of decreasing the bond strength between main reinforcement and concrete.

(2) According to results for bond specimens, ASR expansion is confined by hoop reinforcement in type-2 specimens. Therefore, bond strength is increased by chemical prestress of ASR expansion.

(3) The bond strength of ASR affected beam specimens can not be evaluated appropriately by the bond specimen without hoop reinforcement. It is necessary to take the chemical prestress caused by the ASR expansion into account in evaluating bond strength of ASR affected beam specimens.

ACKNOWLEDGEMENTS

The author expresses sincere gratitude to Professor Dr. Oguzhan Bayrak and Mr. Dean J. Deschenes in F.S.E.L. of The University of Texas at Austin for their advices to this study.

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