Failure Behavior of Reinforced Concrete Beams Deteriorated by Alkali-Silica Reactions

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ABSTRACT: Laboratory tests were made to assess the effects of deterioration due to ASR on the failure behavior of RC beams. Ordinary and steel fiber added RC beams were tested. For short term static loading, the negative effects of cracks caused by ASR was not significant.

1. INTRODUCTION

An assessment of the safety of concrete structures deteriorated as a result of alkali-silica reactions (ASR) was needed. Laboratory tests were carried out to assess the effects of deterioration due to ASR on the strength and deformation property and toughness of reinforced concrete beams. They were examined under static loading conditions. The results on beams deteriorated due to ASR were compared to those of undeteriorated reference beams. Ordinary reinforced and steel fiber added reinforced concrete beams were tested. Degradation of mechanical properties and crack formation due to ASR were also examined.

2. EXPERIMENTAL PROCEDURES

Ordinary portland cement was used. The alkali content of the cement was 0.67% (Na_2O equivalent). Alkali reactive crushed coarse aggregate (bronzite andesite: max. size 20mm) and nonreactive river sand were used. To accelerate the reaction, NaOH solution was added to concrete at the time of mixing to adjust the alkali content to 2.3 % (Na_2O equivalent). Three kinds of concrete were chosen; these are indicated as N, A and SA series, hereafter. A and SA series were deteriorated concrete due to ASR, while N series is without deterioration. One percent by volume of indented steel fibers of 0.5x30 mm were added in the SA series. N and A series had different curing methods and their crack conditions were completely different, though they had the same concrete mix. Deformed re-bar of 13 and 10 mm nominal diameter (σsy=36.0 and 37.1 kgf/mm^2, respectively) was used. In all the mixes, unit water content and unit cement content were 177 and 354 kg/m^3, respectively. The absolute fine aggregate ratio was 0.44.

For each series, reinforced concrete beams were made with different compression reinforcement ratios but the tensile reinforcement ratio was kept constant. Eighteen beams were made. The description of these specimens and test conditions are listed in Table 1. Cross section and length of the RC beams were 10x18 cm and 170 cm. Cylindrical specimens of 10x20 cm and beam

Table 1 Test Conditions

No.	reinforcement ratio (%) p	reinforcement ratio (%) p'	fiber content (vol.%)	stirrup spacing (cm)	testing ages (days)	note
N-1	1.66	0	0	10.0 (ø4)	27	reactive crushed
N-2	1.66	0.93	0	8.5 (ø4)	27	coarse aggregate
N-3	1.66	1.66	0	12.5 (ø6)	27	(without cracking)
A-1	1.66	0	0	10.0 (ø4)	160,430	reactive crushed
A-2	1.66	0.93	0	8.5 (ø4)	160,430	coarse aggregate
A-3	1.66	1.66	0	12.5 (ø6)	160,430	
SA-1	1.66	0	1.0	10.0 (ø4)	160,430	reactive crushed
SA-2	1.66	0.93	1.0	8.5 (ø4)	160,430	coarse aggregate
SA-3	1.66	1.66	1.0	12.5 (ø6)	160,430	with steel fibers

specimens of 10x10x40 cm were also made. All specimens were removed from molds on the day after casting and then cured in a moist condition at 20°C for 13 days. After the curing, specimens for N series were stored at room temperature for 27 days. The specimens of SA and A series were transfered to the accelerated condition of 40°C and R.H. 100 % until 7 days before testing. During this period crack formation and expansion due to ASR were observed. Changes of dynamic Young's modulus were also measured with 10x10x40 cm specimens.

Loading tests of RC beam specimens were made as shown in Fig.1. The testing age of deteriorated beams (series A and SA) was 160 and 430 days, when many cracks had formed due to ASR. The load and average deflection at the loading points were recorded on an X-Y recorder. The load-displacement (gage length: 18 cm) curves of cylindrical specimens (ø10x20 cm) for compressive strength tests were also recorded.

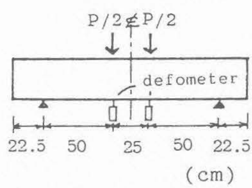

Fig.1 Loading manner

3. RESULTS AND DISCUSSIONS

(1) Cracking and Expansion Properties

The patterns of cracks on RC beams due to ASR just before loading tests at 160 days are shown in Fig. 2(a) to 2(f). Only a quarter length of each specimen is shown in the figure. The maximum crack widths were 0.2 to 0.25

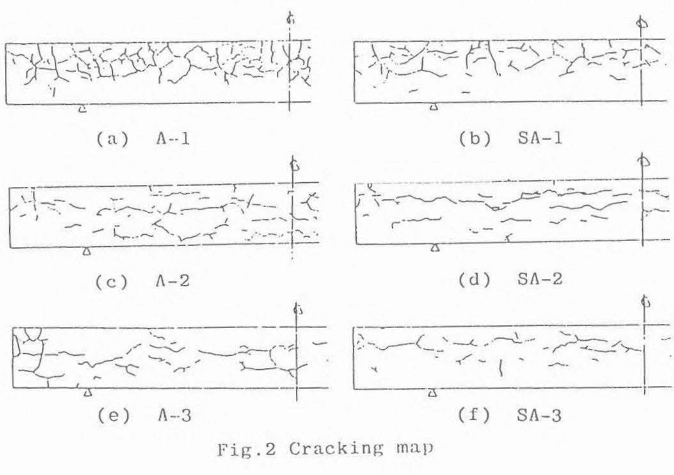

Fig.2 Cracking map

mm. The following results were obtained from Fig. 2. In the case of single reinforced beam A-1 and SA-1, many crazing cracks were formed in random directions on the upper side where no axial reinforcing bars were provided. In the case of double reinforced beams fewer cracks were formed overall but cracks occurred in the direction of re-bar.

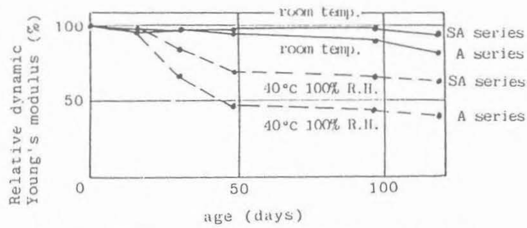

Fig.3 Relative dynamic Young's modulus

Comparison between A and SA series shows that the amount of cracking in the SA series was less than the amount in A series. This indicates that the steel fibers restrained expansion due to ASR. Almost all the cracks were formed before 160 days and the increase in the number of cracks from 160 days to 430 days was not significant.

Time - dependent changes of relative dynamic Young's modulus are shown in Fig. 3. It is evident that cracks due to ASR were formed after 14 days, when the specimens had been exposed to high temperature and high humidity conditions. It is also evident that almost no cracks were formed while the specimens were stored at room temperature. Decay of the modulus due to ASR was smaller for SA series than for A series.

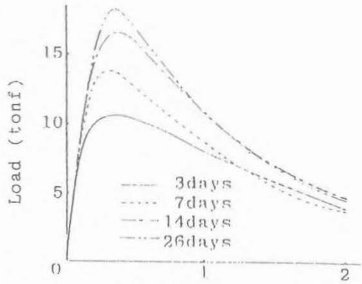

Fig.4 Load displacement Curve (N series)

(2) Mechanical Properties of Cylindrical Specimens

Figs. 4 through 6 show the compressive load-displacement curves of cylindrical specimens for each series at different testing ages. Compressive strength and compressive toughness (expressed by the area below the load-displacement curves up to 2 mm displacement) at various ages of N series are shown in Table 2 and those of SA and A series in Table 3. Compressive strength and toughness increased with the increase of age

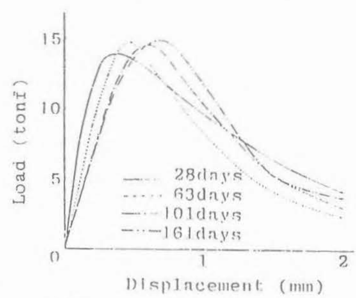

Fig.5 Load displacement curve (A series)

Table 2 Strength and Toughness (N series)

Series	ages (days)	3	7	14	26
N	σ_c (kgf/cm²)	138	178	209	234
	Tc (kgf·cm)	1450	1620	1900	2020

σ_c:compressive strength, Tc:compressive toughness

Table 3 Strength and Toughness (A and SA series)

Series	ages (days)	28	63	101	161	430
A	σ_c (kgf/cm²)	189	197	192	197	255
	Tc (kgf·cm)	1800	1600	1640	1780	2290
SA	σ_c (kgf/cm²)	181	230	223	247	297
	Tc (kgf·cm)	2140	2760	2420	2780	3500

σ_c:compressive strength, Tc:compressive toughness

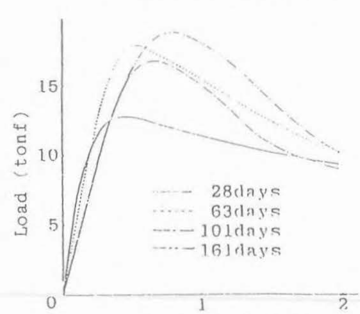

Fig.6 Load displacement curve (SA series)

for N series, where no cracks formed due to ASR. Because of the progressive cracking in the specimens of A series, the static modulus of elasticity decreased and displacement at the maximum load point increased as the testing ages increased. The compressive strength and the compressive toughness did not change with an increase in the testing ages to 160 days, as shown in Table 3. For the SA series, the maximum load and the compressive toughness increased somewhat with testing age, though initial gradient was slightly decreased. It is considered this is caused by the triaxial stress states within the concrete, which was produced by the steel fibers confining expansion due to ASR. After 160 days compressive strength and toughness increased considerably in both A and SA series. During this period, expansion due to ASR seems to cease and curing seems to come into effect.

(3) Failure Behavior of RC Beams

The loading test results of RC beams are shown in Table 4. Load-deflection curves of the RC beams are shown in Figs. 7 through 9. Toughness in Table 4 means the area under the load-deflection curve up to 6 cm. The flexural cracking and shear cracking loads of SA and A series were larger than those of N series. This was caused by the prestressing force created in the concrete. As the reinforcing bars restricted the expansion of concrete due to ASR, compressive stresses were produced in concrete, while tensile stresses were produced in reinforcing bars. The SA series has a tendency to have a larger cracking load than the A series. As shown in Figs. 7 and 8, the load-deflection curves of N-1 and A-1 are almost the same as are those of N-2 and A-2. Cracks caused by ASR had little effect on the failure behavior of these RC beams. Beams of N-3 series lost load carrying capacity adruptly due to shear failure at the region of large deflection. On the other hand, shear failure did not occur in A-3 beam. It is evident that the failure type changes from shear to flexure if the prestressing stress due to ASR exists in concrete. Toughness of beams for A series is almost the same as or even greater than that of corresponding beams for N series. Steel fibers improve all the mechanical properties of RC beams. The failure process of deteriorated beam specimens showed little change for testing done between 160 and 430 days.

Table 4 Loading test results of RC beams

No.	load (tonf)					toughness $\times 10^3$ (kgf·cm)	testing age (days)
	flex. crack	shear crack	yield	crush	max.		
N-1-1	1.0	-	5.2	5.2	5.2	16.3	27
N-1-2	0.9	-	5.3	5.3	5.3	19.7	
N-2-1	1.2	2.5	5.4	5.4	5.4	26.4	
N-2-2	1.1	3.8	5.3	5.5	5.7	29.3	
N-3-1*	1.2	3.8	5.3	5.4	5.9	28.0	
N-3-2*	1.0	-	5.4	5.4	6.4	32.7	
A-1-1	2.7	3.4	4.6	4.7	4.9	15.7	160
A-2-1	3.1	-	5.3	5.3	5.6	26.8	
A-3-1	1.4	5.3	5.5	5.7	6.6	36.4	
A-1-2	2.8	5.5	4.6	5.1	5.1	24.6	430
A-2-2	2.9	-	5.4	5.7	6.0	33.9	
A-3-2	1.2	-	5.8	6.9	7.3	37.6	
SA-1-1	2.4	5.2	5.2	5.5	5.6	29.3	160
SA-2-1	2.8	5.8	5.6	5.8	6.6	36.4	
SA-3-1	3.2	6.8	5.7	5.8	7.0	39.3	
SA-1-2	3.4	-	5.4	5.8	5.9	33.7	430
SA-2-2	3.6	-	5.7	6.0	6.6	39.0	
SA-3-2	4.0	7.1	5.8	6.0	7.4	40.2	

* : failed in shear

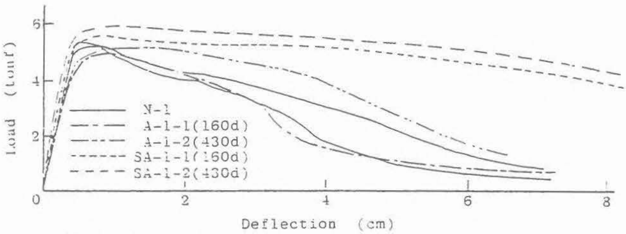

Fig.7 Load deflection curves (N-1,A-1,SA-1)

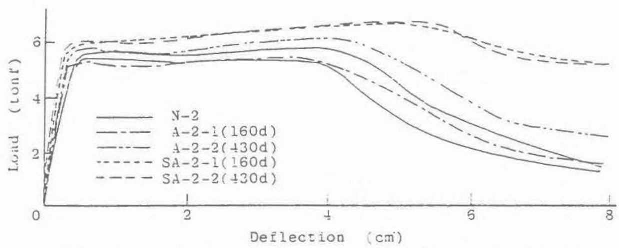

Fig.8 Load deflection curves (N-2,A-2,SA-2)

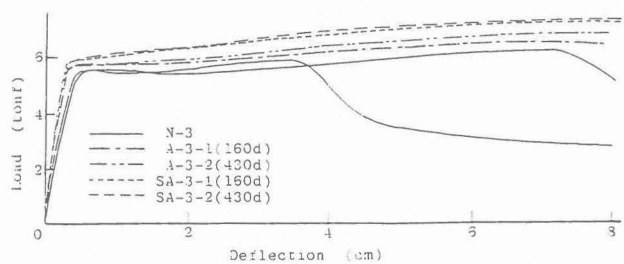

Fig.9 Load deflection curves (N-3,A-3,SA-3)

4. CONCLUSIONS

Principal conclusions derived are as follows:

(1) Expansion and cracking caused by ASR started after specimens were exposed to hot and high humidity conditions. Modulus of elasticity decreased with the increase of age but compressive toughness and compressive strength remained unaltered.

(2) Expansion of concrete caused by ASR was restrained by reinforcement. Because of this restraining compressive stress was induced in concrete. Cracks decreased in number with the increase of reinforcement ratio. Direction of cracks coincided with the direction of reinforcement.

(3) For short term static loading, the negative effect of cracks caused by ASR on the failure behavior of RC beams was not significant.

(4) Steel fibers improved all the mechanical properties of concrete, even reinforced concrete beams deteriorated by ASR.