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STRUCTURAL BEHAVIORS OF REINFORCED CONCRETE BEAMS AFFECTED BY ALKALI-SILICA REACTION

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1. INTRODUCTION

Since the damages of concrete structures caused by alkali-silica reaction (ASR) were reported in Japan, some experimental investigations as for the load carrying capacities of damaged reinforced or prestressed beams [1,2], as well as site inspection of existing structures [3,4], have been conducted to evaluate the structural safety of concrete structures affected by ASR. However, further investigations as for the structural behaviors of the affected concrete members after the long time elapsed are necessary for the reliable evaluation of their structural safety.

In this study, long-term expansion characteristics and structural behaviors of reinforced concrete (RC) beams using reactive coarse aggregate (described as ASR beam), which had a potential alkali-silica reactivity, were investigated in comparison with those of RC beams using non-reactive coarse aggregate (described as normal beam).

2. OUTLINE OF TESTS

2.1 Fabrication of Beam Specimens

As shown in Fig.1, test specimens were singly reinforced concrete beams having a rectangular cross section of width×full depth = 20×20cm and length of 170cm. Table 1 shows the mix proportions of normal concrete (N) and ASR concrete (A) adopted for the test beams. ASR concrete was prepared using a mixture of reactive crushed gravel (Bronzite Andesite) and normal crushed gravel in the 0.5:0.5 by weight. For two kinds of concrete mixes, the normal river sand was used as fine aggregate. Design compressive strength was 400kgf/cm^2 and total equivalent Na$_2$O was adjusted to 8kg/m^3 by adding a

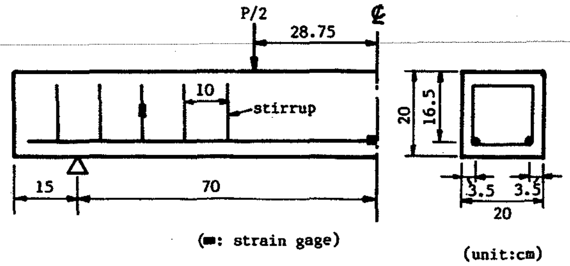


Fig.1 Details of Tested Beams

Table 1 Mix Proportions of Concrete

Mix	W/C (%)	s/a (%)	Unit Content (kg/m^3)					Admixture	Tatal *
			Water W	Cement C	Sand S	Gravel G		Vinsol (cc)	eq. Na_2O (kg/m^3)
						Normal	Reactive		
Normal(N)	50	44	176	352	783	1031	–	0.010×C	8
Reactive(A)	50	44	176	352	783	516	487	0.010×C	8

* Total alkali content: Na_2O included in cement plus additional Na_2O supplied by NaCl

proper amount of NaCl for two mixes. A total of 6 beams were prepared, in which three levels of tensile reinforcement ratio (p), that is, 0.77%, 1.20% and 1.74% were selected in both of ASR beams and normal beams. All the beams were provided with D6 stirrups ($fsy=32kgf/mm^2$) at web reinforcement ratio of $\rho s=0.30\%$.

2.2 Testing Method

2.2.1 Accelerated curing test   After cured for 14 days under 20°C–80%RH room, both of ASR and normal beams were placed under accelerated curing condition of 40℃ and 100%RH for 178 days. During the accelerated curing period, time-dependent strains in longitudinal steels, stirrups and upper fiber of concrete section were measured, and then expansive crack patterns of ASR beams were observed. Thereafter, these beams were placed in the laboratory room of average 20°C and 70%RH for further about two years in order to examine the residual amount of chemical prestress in ASR beam section.

2.2.2 Static loading test   Each beam was statically loaded under symmetrical two-points loading at shear span – effective depth ratio of a/d=2.5. After loaded to the design load corresponding to calculated steel stress of $1800kgf/cm^2$, the beams were fully unloaded and thereafter loaded up to failure. During the loading tests, mid-span deflection, curvature of mid-span section and strains of longitudinal steels and stirrups were measured.

3. RESULTS OF TESTS AND DISCUSSIONS

3.1 Expansion Characteristics

Table 2 shows the expansive strains of longitudinal steel, stirrup and upper fiber of concrete section at the end of accelerated curing. Table 2 also indicates the chemical prestress by ASR expansion estimated from the measured strain of longitudinal steel at the end of accelerated curing, together with the residual one derived by analyzing the load-longitudinal steel strain relationship obtained from the loading tests. Fig.2 shows strain vs. curing time relationships of longitudinal steel, stirrup and upper fiber

Table 2 Expansive Strain and Chemical Prestress

Specimen	*1 Mix	Re. Bar	*2 p (%)	Expansive Strain ($\times 10^{-6}$) *3			Chemical Prestress at Bottom Fiber (kgf/cm^2)	
				Longitudinal Steel	Stirrup	Upper Fiber of Concrete	at the end of curring	at loading tests *4
D13-N	N	2D13	0.77	338	–	238	–	–
D16-N		2D16	1.20	299		117		
D19-N		2D19	1.74	249		612		
D13-A	A	2D13	0.77	1384	1729	7864	41.6	16.4
D16-A		2D16	1.20	1075	1607	6536	48.9	21.2
D19-A		2D19	1.74	917	1477	6955	61.3	29.8

*1 see Table 1
*2 tensile reinforcement ratio
*3 at the end of accelerated curing period (178days)
*4 after about 2 years from the end of accelerated curing

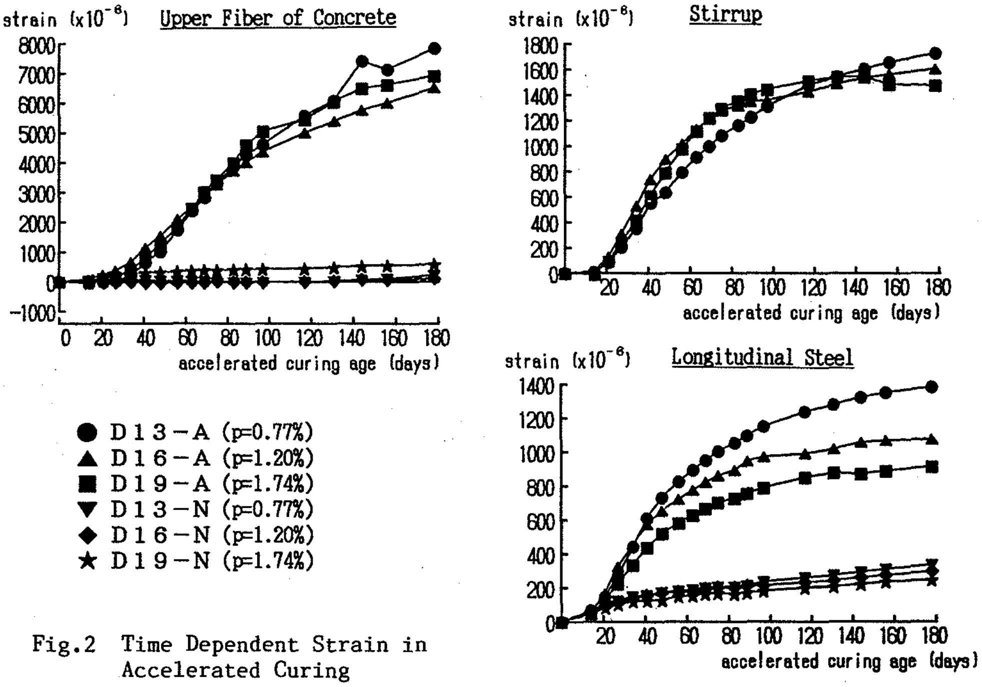


Fig.2 Time Dependent Strain in Accelerated Curing

of concrete section.

As can be seen in Table 2 and Fig.2, the tensile strain of $250\sim340\times10^{-6}$ occurred finally in longitudinal steel even in normal beams. This was due to the temperature difference and wet swelling, because the initial value of strain reading was taken under 20°C while the following measurement was done under accelerated curing condition of 40°C and 100%RH.

In ASR beams, a considerably high amount of expansive strain occurred in longitudinal steel, stirrup and upper fiber of concrete section. The expansive strain reached up to about 7000×10^{-6} at the upper fiber of concrete section without effective restraint due to longitudinal steel. On the other hand, the expansive strain in longitudinal steel and stirrup became larger with decreasing tensile reinforcement ratio. This suggests explicitly that the restraining action against ASR expansion by reinforcement has significant influence on an expansion ability of ASR concrete.

Longitudinal steel strain of ASR beam was larger by 1046×10^{-6}, 776×10^{-6} and 668×10^{-6} for p=0.77, 1.20 and 1.74% respectively than that of each corresponding normal beam at the end of accelerated curing. This implies that chemical prestress of approximately 42, 49 and 61 kgf/cm^2 for p=0.70, 1.20 and 1.74% respectively was introduced at the bottom fiber of ASR concrete section. And then, the loading tests indicated that approximately 40% of this initial chemical prestress still remained even under drying condition for about 2 years.

3.2 Structural Behaviors

3.2.1 Load carrying capacities Table 3 shows compressive strength, tensile strength and elastic modulus of normal and ASR concretes. In Table 4 are listed the measured flexural cracking load (Pcr), yield load (Py) and maximum ultimate load (Pu) together with calculated ones (Py', Pu'). Py' were estimated by elastic theory and Pu' were calculated by ultimate strength theory using the measured strengthes of concrete cylinder and longitudinal steel.

At the time of loading tests, compressive strength, tensile strength and elastic modulus of ASR concrete which were measured on the ϕ10×20cm cylinder specimens reduced to approximately 64%, 59% and 48% of that of normal concrete, respectively. This indicates that the strength and elastic modulus of ASR concrete deteriorates significantly when no restraint against expansion exists.

Flexural cracking strength of ASR beam was larger than that of normal concrete beam irrespective of longitudinal reinforcement ratio, although the tensile strength obtained from cylinder specimens of ASR concrete reduced to about 60% of that of normal concrete. This is due to that chemical prestress was introduced at the bottom fiber of concrete section in ASR beams as indicated in Table 2.

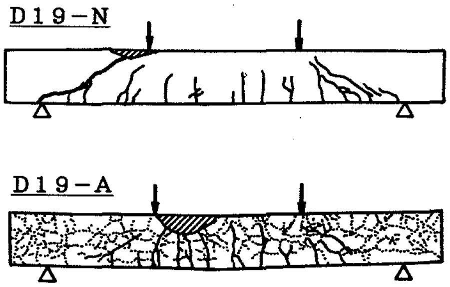
In all beams, both of measured yield strength (Py) and ultimate flexural strength (Pu) were larger than each calculated one (Py', Pu'). The reduction in measured yield strength and ultimate flexural strength of ASR beam was less than 10% in comparison with each corresponding normal beam, although a considerably high amount of tensile strain was induced potentially in the longitudinal steels by ASR expansion.

Fig.3 shows the schematical views of crack patterns and failure mode of test beams with ρs=1.74%. The normal concrete beam with ρs=1.74% failed

Table 3 Concrete Cylinder Strength

*1 Mix	Concrete Strenength *2							
	at 7 days		at 28 days			at Loading Tests *3		
	fc'	ft	fc'	ft	Ec	fc'	ft	Ec
N	335	31.3	440	33.0	3.32x10^5	602	39.4	3.43x10^5
A	352	31.0	423	33.2	3.08x10^5	384	23.3	1.65x10^5

*1 see Table 1
*2 fc': compressive strength (kgf/cm^2)
ft: tensile strength (kgf/cm^2)
Ec: elastic modulus (kgf/cm^2)
*3 after about 2 years from the end of accelerated curing



solid line: cracks by loading
dotted line: cracks by ASR expansion
▨ : crushing of concrete

Fig.3 Examples of Crack Patterns and Failure Mode

Table 4 Results of Loading Tests

Specimen	Design * Load Pd' (tonf)	Deflection at Design load δd (mm)	Measured Flexural Cracking Load Pcr(tonf)	Yield Load		Maximum Ultimate Load	
				Measured Py (tonf)	Calculated Py' (tonf)	Measured Pu (tonf)	Calculated Pu' (tonf)
D13−A	3.20	0.87	4.49	7.11	6.14	10.01	7.17
D16−A	4.90	0.94	5.48	10.37	9.82	13.32	10.96
D19−A	6.90	1.84	5.50	14.16	14.02	16.63	15.29
D13−N	3.20	0.30	2.85	7.75	6.84	10.53	7.29
D16−N	4.90	1.13	3.26	11.95	10.51	14.22	11.25
D19−N	6.90	2.57	3.74	16.50	14.89	16.50	15.90

* The load which causes tensile steel stress of 1800kgf/cm^2.

finally in shear while all other beams failed in flexure. This fact implies that chemical prestress induced by restraint of ASR expansion can improve effectively the shear resistance of concrete, in particular, when the premature shear failure may be caused in the heavily reinforced beam.

3.2.2 Deformation Properties The deflection at the design load (δd) and the load vs. mid-span deflection (P-δ) relationship of each beam are indicated in Table 4 and Fig.4. Fig.5 shows the moment vs. curvature (M-Φ) relationship together with each calculated one using stress-strain models of constitutive materials [5] and taking into account the effect of chemical prestress.

In case of lightly reinforced section with p=0.77%, δd-value of ASR beam is larger than that of corresponding normal beam. In other cases, however, δd-value of ASR beam was rather smaller than that of normal one although the predicted δd-value of ASR beam using the elastic modulus of cylinder specimens was to be approximately two times the corresponding normal beam deflection. From these facts, it was suggested that the restraint effect of ASR expansion existed in the inside concrete of the member and thus mitigated the deterioration of beam concrete.

As shown in Fig.4, the inelastic deformation ability of ASR beam scarcely reduced in case of p=0.77 and 1.20% in comparison with normal beam, although the yield strength and the ultimate flexural strength were somewhat smaller than those of normal one. In case of p=1.74%, on the other hand, normal beam showed less inelastic deformation ability than that of ASR beam because of brittle shear failure in the former.

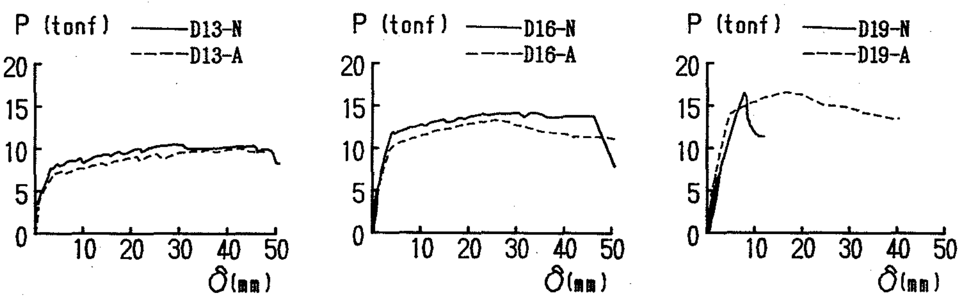


Fig.4 Load - Mid-span Deflection Relationship

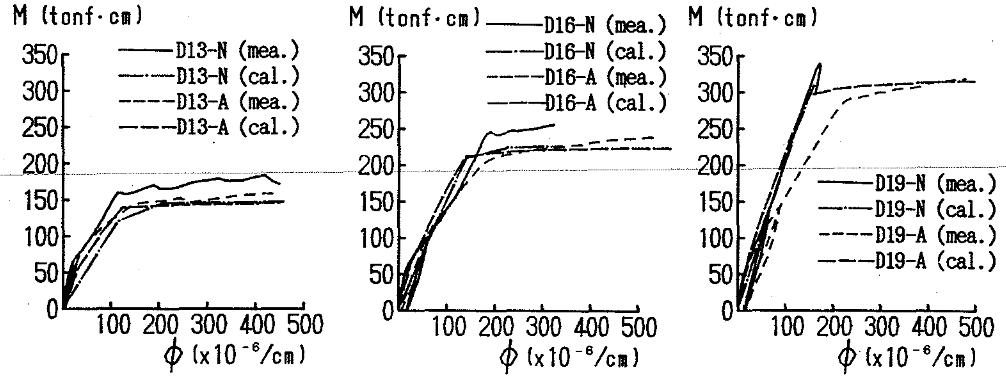


Fig.5 Moment - Curvature Relationship

The measured M-ϕ relationship of ASR beam was similar to that of normal concrete one except for the case of p=1.74%, in which the section rigidity of ASR beam was somewhat smaller than that of normal one. The calculated M-ϕ curve is found to agree relatively well with the measured one.

4. CONCLUSIONS

Expansion characteristics and structural behaviors of singly reinforced concrete beams using coarse aggregate with alkali-silica reactivity were investigated. Conclusions obtained from test results are summarized as follows.

(1) A considerably high amount of tensile strain occurred in the longitudinal steel by ASR expansion immediately after the accelerated curing for about 180 days. This induced the chemical prestress of 42, 49 and 61kgf/cm^2 for p=0.77, 1.20 and 1.74% respectively in the bottom fiber of the beam section. At least 40% of this initial chemical prestress still remained even under drying condition for about two years.

(2) The flexural cracking strength of ASR beam was larger than that of normal concrete beam because of the induced chemical prestress. The chemical prestress also acted effectively to improve the shear resistance of concrete. The reduction in the yield strength and the maximum ultimate strength of ASR beam was at most 10% compared with those of normal one, although a considerably amount of tensile steel strain and expansive cracks existed potentially in the ASR beams.

(3) The deflection at the design load of ASR beam was considerably smaller than the predicted one using the elastic modulus of cylinder specimens. The overall deformation behavior of ASR beam was similar to that of normal beam except for p=1.74% in which ASR beam failed in flexure with enough ductility while the normal one failed rather in shear.

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