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EXPERIMENTAL STUDY ON MECHANICAL BEHAVIOR OF REINFORCED CONCRETE MEMBERS AFFECTED BY ALKALI-AGGREGATE REACTION

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1. INTRODUCTION

A number of researches on the phenomena of alkali-aggregate reaction have been carried out in recent years. However, the researches on the mechanical behavior of reinforced concrete members affected by alkali-aggregate reaction are few. In order to diagnose the durability of reinforced concrete structures affected by alkali-aggregate reaction, it is necessary to research more on the mechanical behavior of the reinforced concrete members deteriorated by alkali-aggregate reaction.

The investigations described in this paper are the influence of alkali-aggregate reaction on the flexural yield strength and the ultimate shear strength of reinforced concrete members. The parameters in this experimental study are the tension reinforcement ratio and the degree of deterioration due to alkali-aggregate reaction.

2. EXPERIMENTAL INVESTIGATION

2.1 Test Specimens

The experimental study consists of three series of tests, AI, AII and AIII, where the tension reinforcement ratios are equal to 0.75 %, 1.17 % and 1.76 %, respectively. The shear reinforcing bars are identical in all specimens with the shear reinforcement ratio of 0.32 %. Thirty specimens are prepared in this study. The details and dimensions of the specimens are shown in Fig.1. The length of the specimens is 2.0m with the

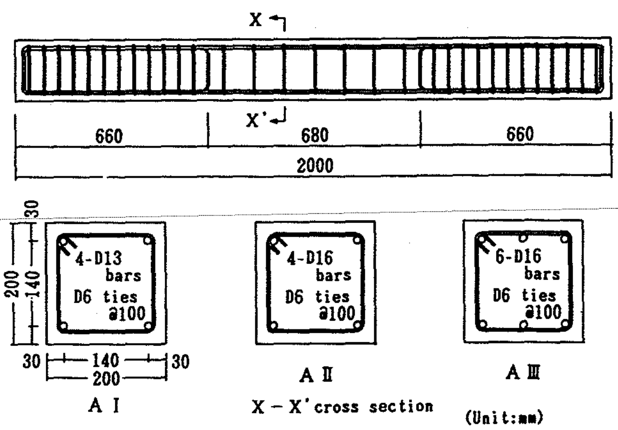

Fig.1 Details and dimensions of the specimens

test area of 0.68m in the midspan of the specimens. The section is 20cm × 20cm. The shear span length ratio (M/Qd) of the specimens is 2.0. Each series consists of ten specimens : three specimens unaffected by alkali-aggregate reaction, five affected and two repaired after affected. The repairing method is the injection of the epoxy resin into the cracks generated by alkali-aggregate reaction.

2.2 Test Procedure

The monotonous increasing loading was applied to the specimens at two points, using a longitudinal loading beam, to develop equal maximum positive and negative moments as shown in Fig.2. The relative deflection(δ) of the midspan of the specimens was measured using two dial gages. To calculate the flexural deflection, the deformations at both up and bottom surface of the specimens were measured using fourteen dial gages.

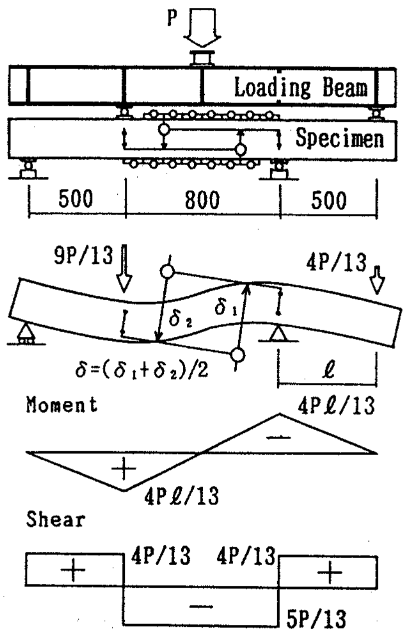

Fig.2 Test setup, and moment and shear diagrams due to loadings

Table 1 Mixture proportions of concrete

Type of concrete	Water-cement ratio	Air content, percent	Slump cm	Unit weight, kg/m³						
				Water	Cement	Sand	Crushed stone N	Crushed stone Q	Added alkali	Total alkali
Non-reactive	0.557	3.0	17.5	195	350	882	896	0	5.83	8.00
Reactive	0.557	2.8	17.5	195	350	882	448	438	5.83	8.00

N ; Sandstone   Added alkali ; $NaOH : NaCl : NaNO_2 = 1 : 1 : 1$ (Na_2O equivalent)
Q ; Andesite

Table 2 Mechanical properties of concrete

Concrete	Type of specimen	Age (days)	$_c\sigma_B$ (kgf/cm²)	$_cE$ (×10⁵kgf/cm²)
Unaffected concrete	Cylinder	28	339	2.89
		132	434	2.87
	Core	532	404	2.70
Affected concrete	Cylinder	28	346	2.84
		167	250	1.20
		513	267	1.52
	Core	532	378	1.92
Epoxy resin		19	891	0.28

$_c\sigma_B$: Compressive strength $_cE$: $_c\sigma_B/3$ Secant modulus

Table 3 Mechanical properties of reinforcing bars

Diam. of bar	$_s\sigma_y$ (kgf/cm²)	$_s\sigma_B$ (kgf/cm²)	$_sE$ (×10⁶kgf/cm²)
D16	3600	5100	1.8
D13	4030	5800	1.9
D 6	4000	5700	2.0

$_s\sigma_y$: Yield strength $_s\sigma_B$: Tensile strength
$_sE$: Young's modulus

2.3 Material Properties

Two kinds of mix of concrete shown in Table 1 were used. The ordinary portland cement (JIS R 5210) having an alkali content of 0.62 % was used. The total amount of alkali content in concrete was controlled to 8 kg/m³ by adding NaOH, NaCl and $NaNO_2$. Natural river sand and crushed stone of 15mm maximum size were used as aggregate. One of the two types of crushed stone was non-reactive aggregate which consisted of sandstone (N), and the other was reactive aggregate which consisted of andesite (Q).

The compressive strength and the secant modulus of concrete (on 100 × 200mm cylinders) and epoxy resin (on 15× 15× 43mm prisms) determined by the Japanese Standard test method are shown in Table 2. Cores in this table were drilled out from the core concrete of uncracked part of the specimens after tested. Affected concretes at 167 days and 513 days suffered a loss of strength of about 28 % and 23 %, respectively, compared to the compressive strength of affected concrete at 28 days in cylinder specimens, whereas the compressive strength of the cores resulted in excess of strength of about 9 % of the affected 28 days strength.

Tensile yield strength, tensile strength and Young's modulus of reinforcing bars (JIS G 3112) are shown in Table 3.

The expansions were measured on 10 × 10× 40cm prisms and on some specimens as shown in Fig.3. The measured expansions are shown in Fig.4. The each expansion ratio at three stages of progress of alkali-aggregate reaction is shown in Table 4. The specimens and prisms were cured under constant temperature (40 ℃) and high humidity. The expansion ratio seemed dependent on the confining force given by reinforcing bars. The quantity of reinforcing bars per 1cm² of concrete section in

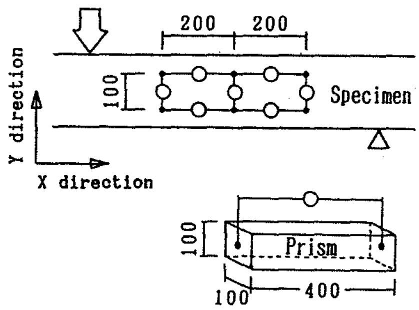

Fig.3 Measurement of expansions

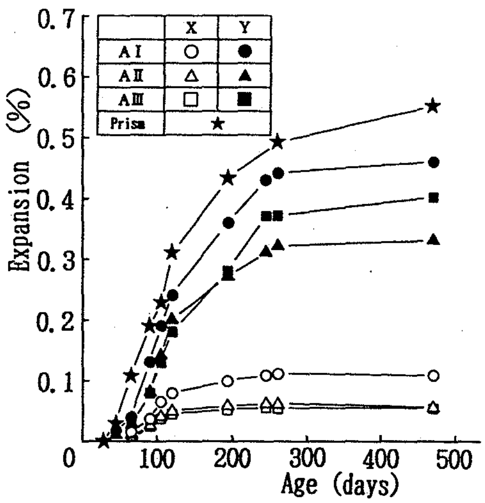

Fig.4 Expansion of specimens and prisms

Table 4 Expansion of affected specimens

Stage	Age (days)	Direction	A I (%)	A II (%)	A III (%)
1	192	X	0.10	0.06	0.05
		Y	0.36	0.28	0.27
2	262	X	0.11	0.06	0.06
		Y	0.44	0.32	0.37
3	470	X	0.11	0.06	0.06
		Y	0.46	0.33	0.40

the expanding direction was 0mm^2 in prisms, 0.32mm^2 in the Y direction of all the test specimens. In the X direction, it was 1.27mm^2 in Series AI, 1.99mm^2 in Series AII and 2.99mm^2 in Series AIII, and in this order, the expansion ratios decreased.

3. TEST RESULT

3.1 Behavior Under Load

The flexural cracks occurred first near the both ends of the test area. As the load increased, the cracks which had occurred at the previous loading grew in size and the flexural yield occurred. Finally, crushing of the concrete occurred at the support and at the load point. Shear cracks were observed on some specimens of Series AII and in all specimens of Series AIII. Typical crack patterns of affected specimens at 0.05 radian are shown in Fig.5 (a).

The failure mode of the specimens of Series AI and Series AII, except an unaffected specimen which failed by diagonal tension, was the flexural crush failure of concrete after flexural yield. In Series AIII, the failure mode of unaffected specimens was the diagonal shear tesion failure after flexural yield, while the failure mode of some of the affected specimens was the horizontal slip failure which occurred connecting the horizontal cracks generated by alkali-aggregate reaction. Two patterns of

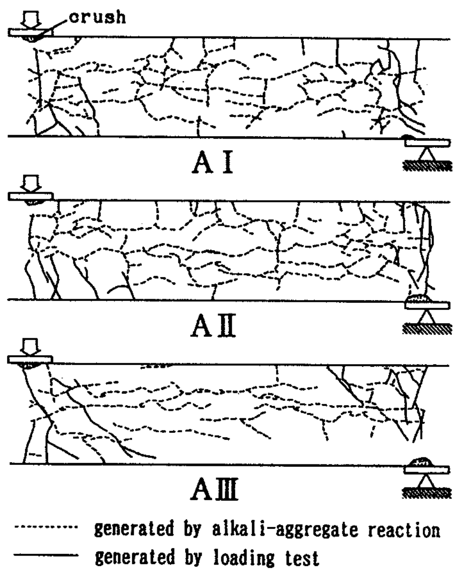

Fig.5 (a) Typical crack patterns (Deformation : 0.05rad.)

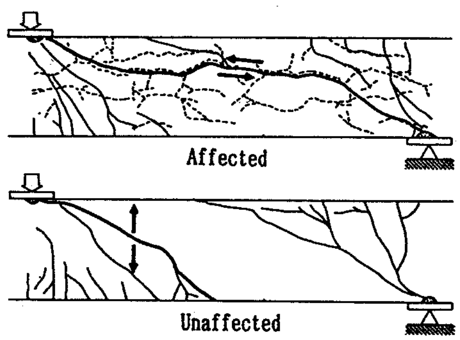

Fig.5 (b) Two patterns of failure mode in Series AIII

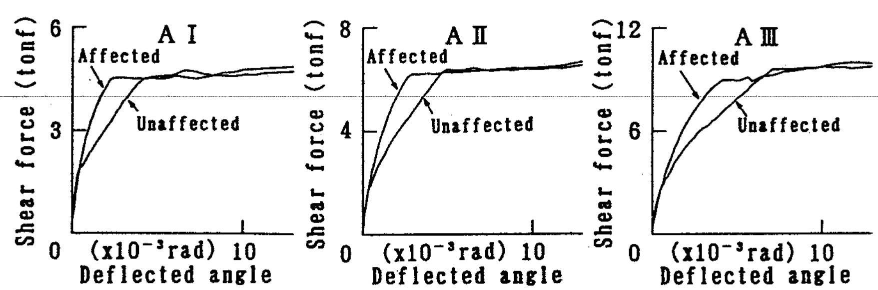

Fig.6 Typical examples of load-deflection relationship

failure mode of the specimens of Series AⅢ are shown in Fig.5 (b).

3.2 Flexural Yield Strength And Deflection

A comparison of load-deflection relationship of unaffected specimens and affected specimens (1st stage) is shown in Fig.6. At the early elastic stages, both of the unaffected and affected specimens had the same behavior. After that, the stiffness of affected specimens was higher than that of unaffected specimens to flexural yield.

The relation between yield strength and longitudinal expansion (X direction) is shown in Fig.7 , in which the marks of ○ , △ , □ indicate the results of this experiment and ● , ▲ , ■ show the results of calculation by e-function method. As longitudinal expansion increased, the yield strength of both experiment and calculation was slightly reduced.

The relation between the deflection at yield strength and longitudinal expansion is shown in Fig.8. As longitudinal expansion increased, the deflection at yield strength drastically decreased. The deflections at yield strength of affected specimens of Series AⅠ and AⅡ were about 50% of those of unaffected specimens, and of Series AⅢ , 60%.

3.3 Ultimate Shear Strength And Deformability

The ultimate shear strength and deformability of each specimen in Series AⅢ are shown in Fig.9. In spite of lower compressive strength of concrete of affected specimens than that of unaffected specimens, the ultimate shear strength of affected specimens was slightly higher than that of unaffected specimens. The deflection at ultimate shear strength of affected specimens was larger than

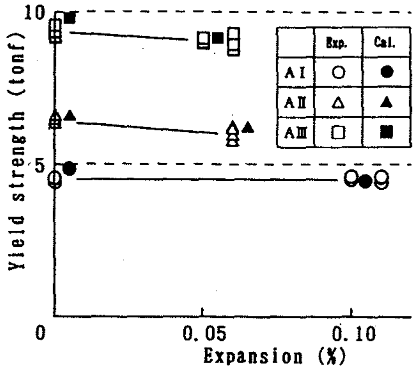

Fig.7 Variation of yield strength with expansion

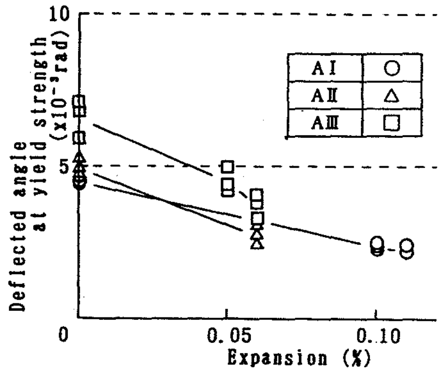

Fig.8 Variation of deflection at yield strength with expansion

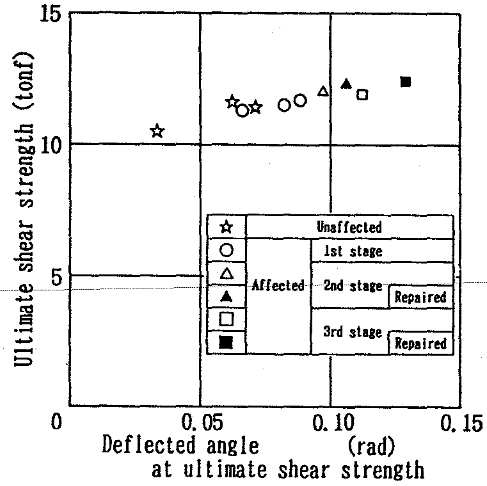

Fig.9 Ultimate shear strength and deformability in Series AⅢ

that of unaffected specimens.

The effect of repair on the ultimate shear strength and on the deformability slightly has been recognized.

3.4 Flexural Deflection

The ratios of flexural deflections to total deflections of each specimen when total deflections are 0.01 radian, are plotted in Fig.10. In Series AI and AII these ratios were above 80 %. On the other hand, in Series AIII these ratios of unaffected specimens were about 70 % and those of affected specimens were above 80 %. This tendency in Series AIII indicates that the shear deflection of affected specimens was lower than that of unaffected specimens. It seems that one of the reasons for it is that the deformability of affected specimens is better than that of unaffected specimens as shown in Fig.9 .

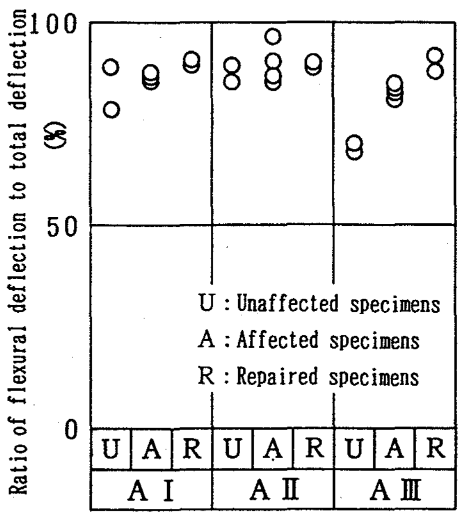

Fig.10 Ratios of flexural deflections to total deflections

4 . CONCLUSIONS

The following conclusions can be drawn out from this experimental study.

① The compressive strength of concrete cylinders affected by alkali-aggregate reaction was lower than that of unaffected concrete cylinders. However, the compressive strength of core specimens drilled out from the core concrete of the affected specimens was only sligtly lower than that of unaffected specimens.

② In Series AIII , the failure mode of unaffected specimens was the diagonal shear tension failure after flexural yield, however that for some of affected specimens was the horizontal slip failure along the horizontal cracks generated by alkali-aggregate reaction.

③ As longitudinal expansion increased, the yield strength was slightly reduced and the deflection at yield strength drastically decreased.

④ In Series AIII , the ultimate shear strength of affected specimens was sligtly higher than that of unaffected specimens in spite of lower compressive strength of concrete of affected specimens than that of unaffected specimens. The deformability of affected specimens failed in shear was better than that of unaffected specimens.