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STUDY ON THE INFLUENCE OF ALKALI-SILICA REACTION ON STRUCTUTRAL BEHAVIOR OF REINFORCED CONCRETE MEMBERS

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ABSTRACT

Expansion produced by alkali-silica reaction (ASR) has been observed in the turbine generator foundation of the unit 1, Ikata nuclear power station, Japan. The foundation is a reinforced concrete frame structure. This paper, as a part of the series of investigation and experiments, discusses tests on structural behavior of concrete members affected by ASR. The purpose of the study is to obtain experimental results on the effects of ASR on bending and shear behavior of reinforced concrete beams and shear walls, and compare with the calculated results by present evaluation methods for normal concrete structures

For the experiments on bending/shear behavior of beam, bending test models with a small amount of rebar and shear test models with larger amount were made of concrete in which ASR was induced by adding alkali or concrete without ASR. It was found from the results that bending strength of the bending test models and shear strength of the shear test models did not fall, nor was it lower than the calculated strength for concrete members without ASR.

In the shear wall test, the two test models were made of either concrete with ASR or one without it. Horizontal load was applied with actuators on the test model fixed on the test floor, while vertical load was applied with oil jacks. The results did not indicate that ASR lowered the stiffness or strength of the wall test models, showing the strength was able to be calculated with the same formula for reinforced concrete wall without ASR.

Keywords: Alkali-silica reaction, Bending strength, Shear strength, Stiffness

1. INTRODUCTION

Expansion produced by alkali-silica reaction (ASR) has been observed in the turbine generator foundation of the unit 1, Ikata nuclear power station, Japan. It is a PWR plant whose commencement of the commercial operation was in 1977. The foundation is a reinforced concrete frame structure supporting turbines and a generator. A series of investigation and experiments has been carried out on structural integrity of the turbine generator foundation, which has a length of 50 m, a width of 15 m, and a height of 18.7 m. This paper, as a part of the series of investigation and experiments, discusses tests on structural behavior of concrete members affected by ASR. The purpose of the study is to obtain experimental results on the effects of ASR on bending and shear behavior of reinforced concrete beams and shear walls, and compare with the calculated result by present evaluation methods for normal concrete structures.

2. BEAM MODEL TEST

2.1 TEST PLAN

Two types of test models were made. One was for investigation of shear behavior mainly, and the other was for bending behavior. Two shear test models, one made with ASR concrete and the other made with normal concrete, were tested. In the case of bending test models, prestress test model was made. The expansion by ASR is supposed to act as chemical prestress on reinforced concrete members. To compare the structural behavior by this action with the behavior by normal prestress, the prestress test model was made with normal concrete. The prestress was applied on main rebars before concrete casting in the test model. The list of the test model is shown in Table 1

Figure 1 shows the dimensions and the rebar arrangement of the beam test models. The rebar amount of bending specimen is commensulate with the reinforcement ratio of the foundation. The main rebar amount of the shear test models was approximately fourfold of one of the bending test model.

Table 2 shows concrete proportioning. Crushed sand and stone of andesite with reactivity were used as fine and coarse aggregate for both concrete with ASR and without ASR. Water-cement ratio was 60% equal to the ration in the actual turbine generator foundation. Alkali was added only in concrete with ASR, which was to generate expansion by ASR.

Table 3 shows the mechanical properties of rebars used for the test models.

The forms were removed after two weeks from concrete placing, and the test models were cured during six weeks after the placing, under "normal condition" meaning that they were covered with sheet to keep them wet. After the six weeks, the ASR test models were cured under "accelerated condition", at 40 degrees centigrade and at 100% relative humidity approximately in a specially designed curing room. The strains of the main rebars were measured during the curing period by wire strain gages(WSG) put on the rebars in each test model.

Figure 2 indicates test equipment. Two hydraulic jacks, whose reaction force was supported by crosshead, gave the load, monotonically increasing, on the test model so that it got bending moment by 4-point loading. The four points of the supports were all

Table 1 List of beam test model

test model		concrete	main rebar(one side)	prestressing on main rebar
bending	normal concrete	normal	4-D10	NO
	ASR concrete	ASR		NO
	prestressed concrete	normal		YES
shear	normal concrete	normal	6-D16	NO
	ASR concrete	ASR		NO

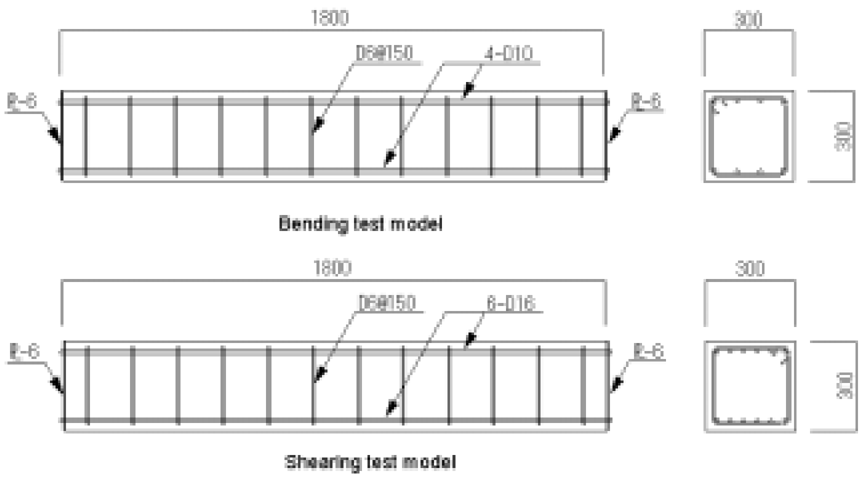

Fig.1 Beam test model

Table 2 Concrete proportioning

concrete type	unit weight of water (kg/m2)	volume (1/m^3)			surface dried weight(kg/m^3)			admixtutre		added alkali
			aggrigate			aggrigate				
		cement	fine	coarse	cement	fine	coarse	P70	SP-8S	NaOH
normal	176	93	319	372	293	845	990	C×0.26%		
ASR	176	93	319	372	293	845	990		C×2.2%	C×3%

pin-roller ones to reduce friction as much as possible.

Table 3 Mechanical properties of rebars

dia.	type	yield stress (N/mm^2)	ultimate strength (N/mm^2)	elongation (%)	elastic modulus ($\times 10^5$N/mm^2)
6mm(D6)	SD345	392	502	28.4	1.88
10mm(D10)	SD345	403	547	25.2	1.87
16mm(D16)	SD345	396	587	25.3	1.91

2.2 TEST RESULTS

The strains in member axial direction, measured with WSGs put on main rebars, after curing prior to loading test were as follows:

ASR bending test model : 1433 x10^{-6}

Prestress test model : 1547 x10^{-6}

ASR shear test model : 643 x10^{-6}

Numerous cracks were observed on the concrete surface of ASR concrete caused by ASR after curing.

Table 4 summarizes the loading test results.

Figure 3 illustrates vertical displacement measured at the center of each test models, comparing all the three bending test models,which were the normal concrete bending test model, the ASR concrete bending test model, and the prestress test model. The test models got almost the same maximum shear load with each other. The bending crack shear load of the ASR concrete test model was larger than that of the normal concrete test model. That was close to the shear load of the prestress test model. The stiffness of the ASR concrete test model was became bigger than the normal concrete test model with increase of load, which it was smaller in the initial stage. Figure 4 illustrates the vertical displacement measured at the center of each test model, comparing two shear test models, which were the normal concrete shear test model and the ASR concrete shear test model. Initial stiffness of the ASR concrete test model's and maximum shear load were nearly equal with those of the normal concrete test model. ASR concrete showed bigger bending and shear crack loads than the normal concrete test model.

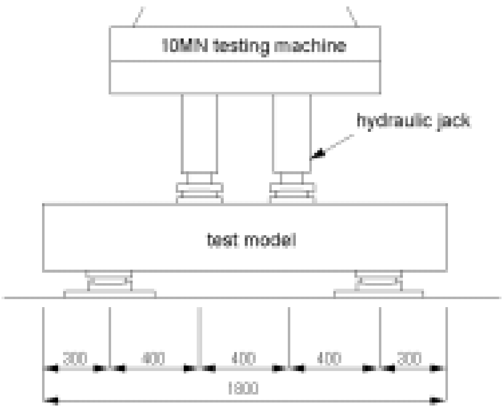

Fig.2 Loading equipment

Table 4 Test result of beam model test

		bending test model			shear test model	
		normal	ASR	PS	normal	ASR
initial stiffness	(kN/mm)	330	165	343	387	264
shearing force(kN)	first bending crack	36	50	55	75	90
	first shear crack	—	—	—	148	190
	main rebar yield	83.7	88.1	100.9	299.5	272.3
	ultimate	113.2	105.0	106.2	369.5	381.0

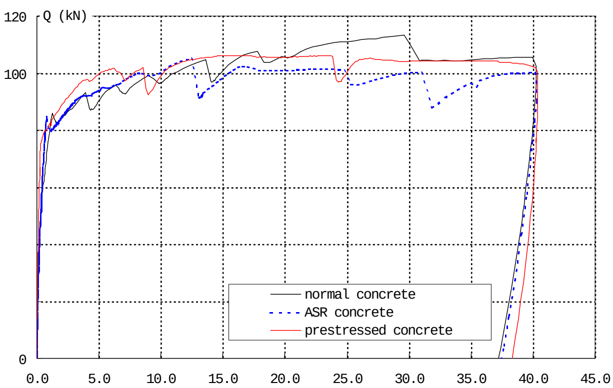

Fig.3 Relation between vertical load and displacement of bending test model

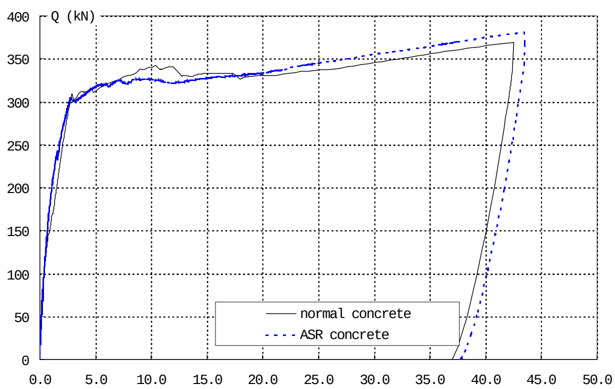

Fig.4 Relation between vertical load and displacement of shearing test model

Figure 5 shows the failure modes of each test model. All the test models got bending cracks, and bottom rebar (tension reinforcement) yielding. Shear cracks and the yield of shear reinforcement tookplace only in the shear test models.

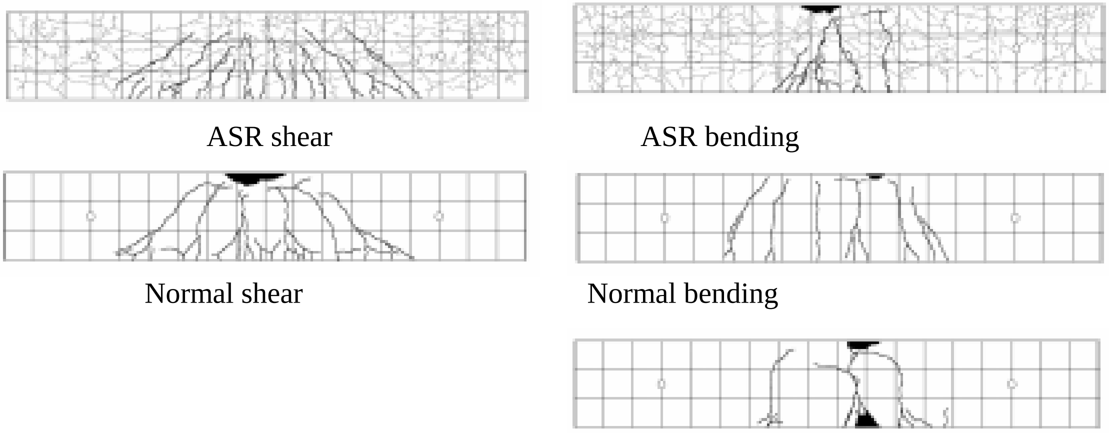

Figure 5 Fracture mode

Table 5 summarizes the maximum shear loads. The ultimate bending moment of the normal reinforced concrete beams is calculated with the following formula, and the ultimate shear strength is calculated with a formula shown in reference 1) for mean shear strength for concrete members without ASR.

$$M_u = 0.9 \cdot a_t \cdot \sigma_y$$

M_u : Ultimate bending moment

a_t : Tension reinforcement area

σ_y : Yield stress of main rebar

The ratios of the shear loads at the ultimate bending moment of the bending test models to the calculated values are around 1.5. The ratios of the maximum shear loads of the shear test models to the calculated mean values are around 1.5 or 1.9. The test results of the maximum shear loads sufficiently exceeds the calculated value, and the results of the test models with ASR were not lower than calculated values.

Table 5 Maximum shear load

	bending test model			shear test model	
	normal	ASR	PS	normal	ASR
observed A (kN)	113.2	105.0	106.2	369.5	381.0
calculated B (kN)	71.9	71.9	71.9	257.1	202.2
A/B	1.57	1.46	1.48	1.44	1.88

3. SHEAR WALL MODEL TEST

3.1 TEST PLAN

Figure 6 indicates the dimensions of the wall test models. Figure 7 shows the rebar arrangement of their wall part. Two test models were made and tested. I section wall part was made of ASR concrete in the one test model and the other parts were made of normal concrete.

Material used and the procedure followed to make test models were the same as the beam test models. I section wall part of each test model was made prior to the other parts. The wall part of the ASR concrete test model was made of the ASR concrete and cured under the accelerated condition to get expansion due to ASR. The loading slab and the base slab, which were respectively attached to the wall part of the test model, were placed with ordinary ready mixed concrete after the accelerated curing finished. The normal concrete test model was made with the same procedure with the exception that the wall part, which was made of normal concrete, was not cured under the accelerated condition but the normal one. Table 6 summarizes the material properties of the concrete. The strains of the vertical and the horizontal rebars were measured by WSGs put on the rebars during curing period in each test model.

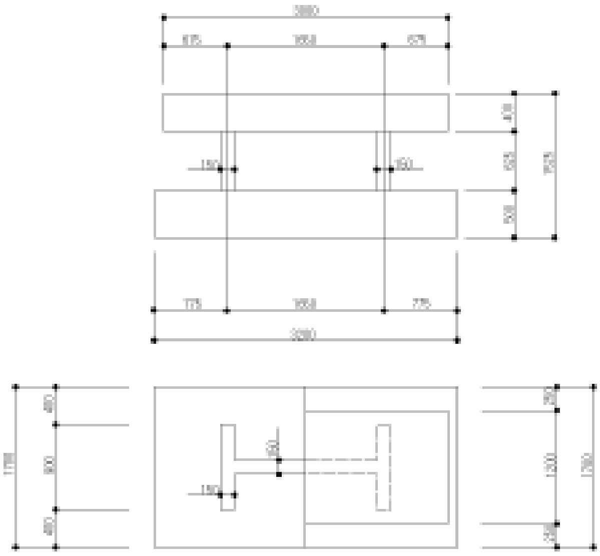

Fig.6 Wall test

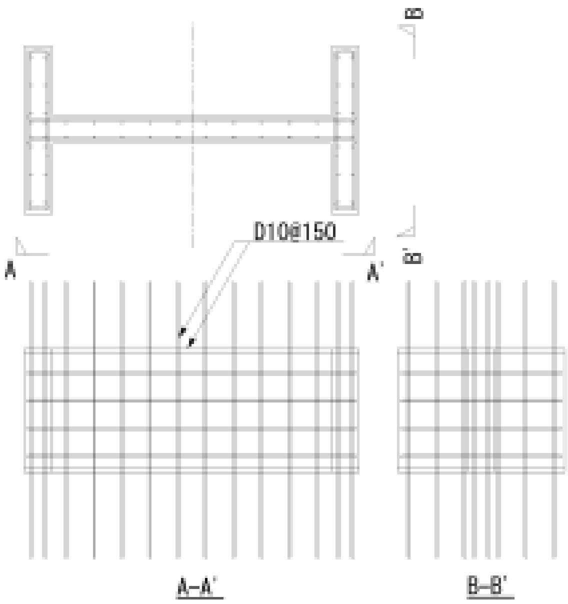

Fig.7 Rebar arrangement of wall part

Table 6 Mechanical properties of concrete

test model	compressive strength (N/mm^2)	elastic modulus ($\times 10^4 N/mm^2$)
normal concrete	38.2	2.88
ASR conrete	25.5	1.01

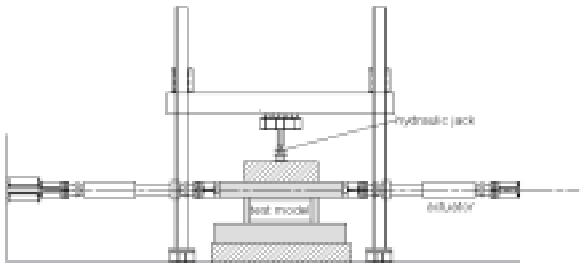

Fig.8 Loading equipment

Figure 8 illustrates the test equipment. A 500 kN hydraulic jack applied vertical load so that the axial stress in the wall part was to be 0.5 MPa, with the base slab of the test model fixed on test floor. The top slab, which was put on top of the test model, was horizontally loaded by four pieces oil actuators fixed on the abutment test wall. The top slab was simultaneously pushed and pulled from each side of the test model with the equal load with the each other.

Figure 9 illustrates the loading pattern of the horizontal load. Twelve cycles of the horizontal load in total were applied before the monotonic increased load in positive direction was applied.

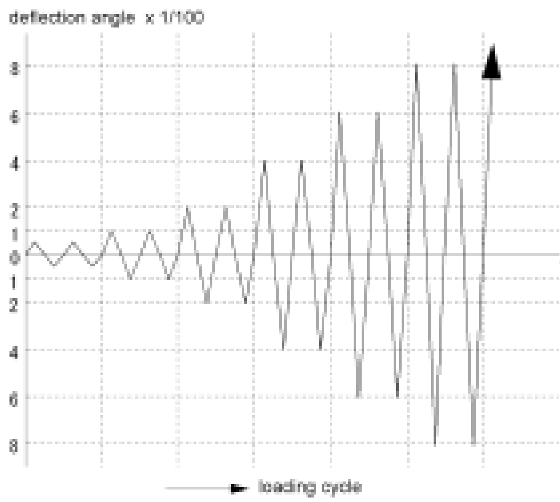

Fig.9 Loading cycle

3.2 TEST RESULT

Maximum horizontal and vertical strains after curing, measured by remaining WSGs, of reinforcement were from around 1,400 through 1,700 x10^{-6} in the ASR concrete. Numerous cracks were observed on the concrete surface of the ASR concrete.

Figure 10 illustrates the horizontal displacement at the bottom of the top slab on the wall part of each test model measured by a displacement meter. Figure 11 illustrates the envelope curve of the same relationship with Fig. 15 during the periods that the small where cyclic horizontal force was loaded.

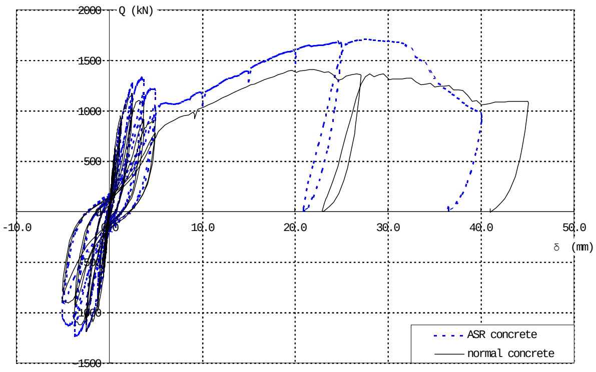

Fig.10 Relation between horizontal load and displacement of wall part

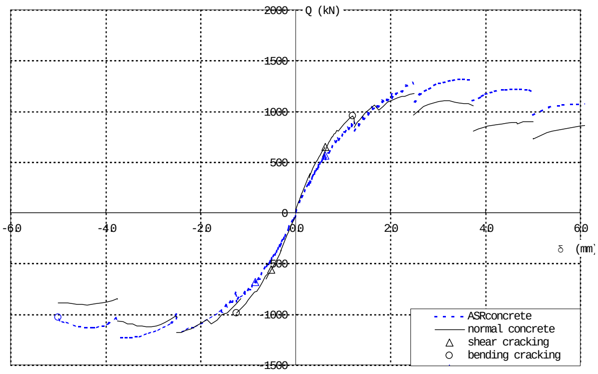

Fig.11 Relation between horizontal load and displacement of wall part

The ASR concrete test model showed slightly smaller initial stiffness than the normal concrete test model.

The peak shear load of either test model in each decreased during the cyclic loading cycles through the deformation angle of 8/1000, after which shear load gradually increased then decreased again for the horizontal deformation of 40 mm. The temporary decrease of the shear load was probably induced by slip between the wall part and the base slab of the test model. Each test part of the two test models for the study was made prior to the base slab and the loading slab, which was different from that ordinary wall test models whose base slab were made prior to their wall parts. The difference of the procedure probably made the fixation of the wall part to the base slab, lead to the slip between the parts, and temporarily made shear load lowered.

The maximum shear load of the ASR concrete test model, whose concrete compressive strength was lower, at large deformation after the cyclic loading finished was higher than that of the normal concrete test model. Also during the cyclic shear force loading, the ASR concrete test model showed higher shear force after the cyclic loading with deformation angle of 4/1000.

Photos 1and 2 shows the final failure modes of each test model. Both of the final failure modes were not significantly different from each other, whose shear crack was dominant cause of the fracture.

Photo 1 Fracture mode of normal concrete

Photo 2 Fracture mode of ASR concrete

Table 7 summarizes maximum shear loads. The calculation for the maximum shear load shown in the table was done with restoring force characteristics estimation method shown in the reference 2)

The ASR concrete test model, whose concrete compressive strength was lower, got higher maximum shear load than the normal concrete test model. The maximum shear load by the test of each test model exceeded the calculated estimation value. The test result of the ASR concrete test model was over 1.4 times the calculated result, and the test result of the normal concrete test model was just slightly higher than the calculated result.

Table 7 Ultimate shear strength

		normal	ASR
ultimate	observed A	1409.0	1707.0
Shears strength	calculated B	1388.0	1204.0
(kN)	A/B	1.02	1.42

4. CONCLUSION

The results of the tests on the beam, and the wall test models lead us to the following conclusions.

It was found from the results that the bending strength of the bending test models and the shear strength of the shear test models did not fall, nor was it lower than the calculated strength. The results also showed some chemical-prestress effect induced by ASR,which was observed as an increase of cracking load.

The results of the lateral loading test of the wall test model did not indicate that ASR lowered the stiffness or strength of the wall test models, showing the strength was able to be calculated with the same formula for reinforced concrete wall without ASR. It was also deduced that chemical-prestress effects by ASR might raise the strength of a shear wall.

It was concluded that the behavior of the beams and the walls affected by ASR was able to be evaluated by the present method for the normal concrete structures within the investigated expansion rate, of approximately 0.15%,investigated in our study.

REFERENCES

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