

EVALUATION OF THE DEGREE OF DETERIORATION IN AAR DAMAGED CONCRETES AND ANALYSIS OF THEIR PORE SOLUTIONS

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ABSTRACT

This study aims at investigating the influences of local environmental conditions on the degree of damage in existing ASR damaged concrete structures and proposing a method for predicting the progress of ASR damages in future on the basis of the data obtained in the investigations. The ASR damages in the structures were found to rapidly proceed after freezing-thawing cycles due to changes in the climate. It was also found from these investigations that the degree of deterioration in concrete depended on the local environmental conditions such as temperature, humidity, and the supply of water from the outside. We measured expansions of cores taken from the ASR-damaged concrete structures and analyzed the pore solutions extracted from these concrete cores. We found that the combination of the alkalinity of pore solutions extracted from damaged concrete structures and the expansion of concrete cores from the structures in the NBRI test was useful for predicting the progress of ASR damages in concrete structures.

Keywords : Alkali-Silica Reaction, environment, evaluation, deterioration, pore solution, prediction , NBRI test

INTRODUCTION

Many studies concerning ASR have been carried out. From these studies, we have understood the mechanisms of ASR, and factors influencing it. It is well known that ASR is a chemical reaction between the pore solution in concrete and reactive aggregates, and is accelerated by the alkalis supplied from cement, aggregates, and chemical admixtures. Temperature, humidity and their combinations also affect ASR damage in concretes. In addition, it has been pointed out that the degree of damage of a concrete structure due to ASR varied widely depending on environments. However, there were only a few studies concerning the progress of deterioration of reactive aggregate-containing concretes under different environments over a long period. Most studies concerning ASR have been carried out in laboratories. There were only a few studies dealing with concrete structure under natural environments.

In this study, we investigated concrete retaining walls for a rubber weir, which have been severely damaged by ASR, in order to reveal the effects of environmental conditions on the degree of damage. We also measured expansions of concrete cores (more than 100 pieces) from the retaining walls and analyzed pore solutions from various portions in the walls. From the relations between expansions and OH^- ion concentration in the pore solution, it is found that the prediction of the progress of deterioration of ASR damaged-concrete in the future can be made by the combination of the NBRI test and the analysis of pore solutions.

EVALUATION OF THE DEGREE OF DETERIORATION UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

Field Study of the ASR Damaged Structure and Evaluation of the Degree of Deterioration

The concrete retaining walls investigated in this study was constructed in 1982 (Fig. 1). Since this study was started in 1996, fourteen years passed. While the right bank wall was not so much exposed to solar radiation throughout a year because a steep cliff hangs over

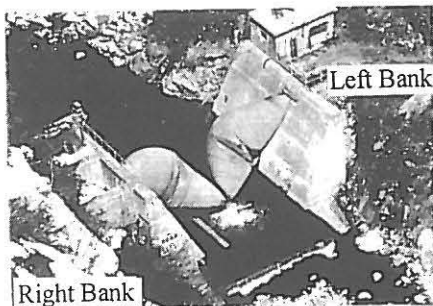


Fig. 1: Bird's eye view of the concrete

the bank, the left bank was strongly affected by the solar radiation. Observations of the level in the reservoir indicated that the rubber weir was lowered during the fresh period from early summer to autumn to keep the water level low, while it was elevated in winter to maintain the water at a higher level. This means that the lower sections of the upstream side always immersed in water during the

winter were not subjected to freezing- thawing cycles. On the other hand, it can be inferred that those sections of the downstream side always in an atmospheric exposure condition were severely subjected to freezing- thawing cycles during winter. As indicated in Fig. 2, the surfaces of a portion of the concrete retaining walls which were covered by the rubber weir (the light portion at the center in the photograph) were not directly exposed to the external environment.

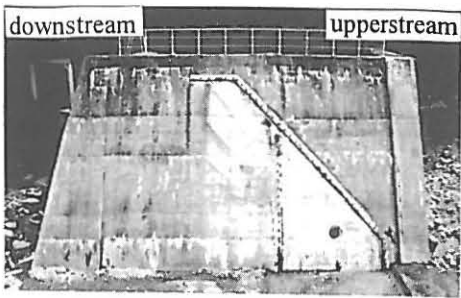


Fig. 2: Appearance of the surface of the structure on the right bank

Aging of the concrete retaining walls -- Fig.3 shows the situation of the surfaces of the retaining wall at the downstream side on the right bank. These photographs show that the progress of deterioration between 1989 and 1992 was considerable. In particular, from a comparison of the global appearance of the concrete body in 1986 with the one in 1989, the following indications was obtained. No trace of gel was observed on the surfaces of the concrete body in 1986, but a significant volume of gel extruded from many cracks the concrete body in 1989. It would be possible to explain the changes in the appearance of the concrete body as it follows. It appears that many cracks were generated by ASR in the concrete retaining walls from early stages after construction. As shown in Fig. 4, the number of freezing-thawing cycles drastically increased from 1988. The increase in the number of cycles after 1988 is found to correspond to the drastic aggravation of concrete. The infiltration of water through these cracks accelerated the absorption of water by gels which transform to sols. Accordingly, many factors were involved in the progress of ASR deterioration in the walls, including the progress of cracks caused by freezing-thawing cycles. It is presumed that the deterioration must be also promoted by the combined effect of these factors.

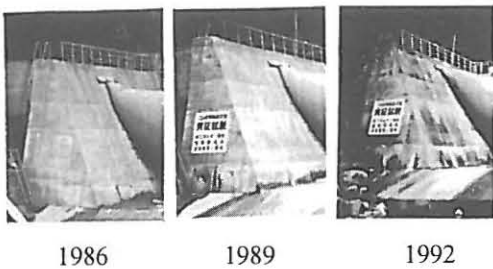


Fig. 3: Changes in the appearance of the structure during the period of 1986 to 1992

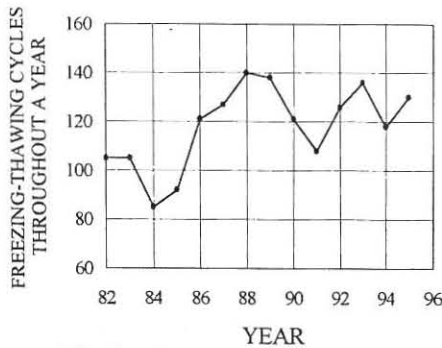


Fig. 4: Changes in freezing-thawing cycles in each year during the period of 1982 to 1996

Evaluation of the degree of deterioration -- Concrete portions exposed to high temperature and humidity atmosphere exhibited signs of deterioration caused primarily by ASR. The crack density in the portions was high, and the strength of cores from the portions was low. In contrast, concrete portions protected from insolation and water ingress showed a lower crack density, and provided higher strength. It is also conceived that cracks caused by freezing-thawing cycles were significantly involved with the progress of ASR deterioration. It was assumed that the deterioration was promoted by the combined effects of these factors.

PREDICTION OF THE PROGRESS OF DETERIORATION IN ASR – DAMAGED CONCRETE

Residual Expansion of Concrete Cores

Residual expansions for concrete cores of 96 mm in diameter obtained from the retaining walls were measured. These cores were stored in sealed containers maintained at 40°C, and 95% RH for 6 months (The Society of Materials Science 1985). We found that residual expansions for cores of the concrete walls were below about 0.02%. The average expansion of cores taken from the rubber weir anchored portion was 0.015%. Judging from the criteria in Japan (residual expansion: 0.01%), it was concluded that ASR expansion was almost completed through the retaining walls.

ASR Reactivity of Aggregate

Coarse and fine aggregate particles were taken from cores drilled from the ASR-affected concretes structure. After classifying these particles, several thin sections were made from them to identify the types of mineral existing in the aggregates. Table 1 indicates the types of rocks constituting the coarse aggregate. Observations of these thin sections with the

TABLE 1: Petrographic classification of aggregates
taken from concrete

classification	percentage of weight (%)	Chemical method (mmol/l)		Expansion (%)※	Remarks
		Sc	Rc		
Volcanic Rock	10.6	59.2	69.4	—	show rims
Rhyolite	9.4	61.9	73.8	—	
Hornfels	8.1	35.7	57.7	—	
Tuff	36.4	73.8	81.2	—	
Tuff breccia	12.6	52.7	66.7	—	
Dacite	11.3	66.7	72.7	—	
Granite, Diorite Porphyry	11.6	31.3	45.7	—	
Coarse Aggregate	—	45.9	80.2	0.035	retaining wall
Fine Aggregate	—	154.6	89.2	0.025	

※ The JIS mortar bar method (at 6 months)

polarization microscope, confirm reaction rims along the periphery of volcanic rock, rhyolite, and hornfels particles. The JIS chemical method indicated that all coarse aggregates were innocuous, while fine aggregates were deleterious. The JIS mortar bar method showed that expansions of all mortars were less than 0.03% at 6 months, allowing the conclusion

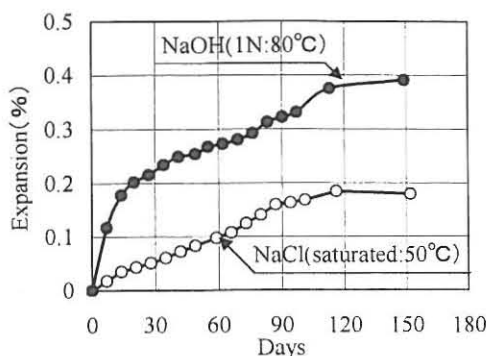


Fig. 5: Expansion curves of concrete cores

that both the fine and coarse aggregates in the ASR-damaged concretes were innocuous. However, when an accelerated test in a saturated NaCl solution (the Danish method ; Chatterji 1978), and in the 1N NaOH solution (the NBRI method ; Oberholster and Davies 1986) were conducted on concrete cores taken from the retaining walls, as shown in Fig. 5, the cores expanded drastically in both tests, thus confirming that the aggregates in concretes of the structures still contained reactive components even at 14 years after construction.

Analysis of Pore Solutions of Cement Pastes and Mortars

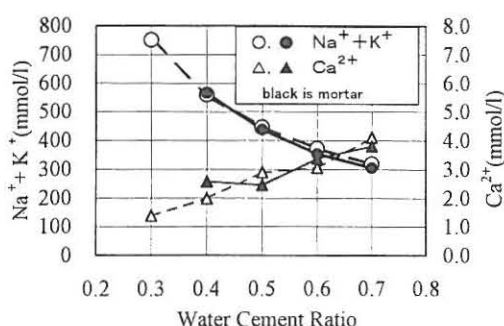


Fig. 6: ($\text{Na}^+ + \text{K}^+$) ion concentrations in the pore solution

The pore solutions in cement pastes and mortars with water/cement ratios of 0.3, 0.4, 0.5, 0.6, and 0.7 (cement: sand = 1: 2, 0.61% $\text{Na}_2\text{O}_{\text{eq.}}$) were analyzed. Cylindrical specimens ($\Phi 50 \times 100$ mm) were cured for 7 days in sealed containers at 20°C. These were then inserted into a high pressure apparatus to extract their pore solutions. The extracted pore solutions were immediately diluted by 100-200 parts of water and the Na^+ , K^+ , Ca^{2+} ion concentrations were measured by ICP method and OH^- by

titration against hydrochloric acid to the phenolphthalein end point. It was found from Fig. 6 and Table 2 that when the water/cement ratio was the same, the Na^+ , K^+ , Ca^{2+} and OH^- ion concentrations at 7 days were approximately the same as the values for cement pastes. As the water/cement ratio increased, the Na^+ , K^+ , and OH^- ion concentrations decreased, while Ca^{2+} ion increased. However, even in mortars with a water/cement ratio of 0.7, the OH^- ion concentration was around 300 mmol/l. According to Diamond (Diamond 1983), it was strong enough to cause ASR.

Analysis of Pore Solutions in Concrete Cores from ASR-Damaged Concretes

In order to predict the degree of deterioration of ASR-damaged concrete structures in the future, pore solutions extracted from concrete cores were analyzed. The concrete cores

TABLE 2: Ion concentration in cement pastes and mortars

Samples		OH ⁻	Ca ²⁺	Na ⁺	K ⁺	Σ ⁺	Σ ⁻
		(mmol/l)					
W/C =0.3	Cement	720.0	1.7	323.8	471.7	798.9	720.0
		708.0	1.2	335.1	451.2	788.8	708.0
		628.0	1.2	272.0	397.2	671.6	628.0
	Mortal	-	-	-	-	-	-
		-	-	-	-	-	-
		-	-	-	-	-	-
W/C =0.4	Cement	550.0	2.3	269.3	330.5	604.4	550.0
		500.0	1.8	236.1	301.7	541.4	500.0
		500.0	1.8	229.3	310.7	543.6	500.0
	Mortal	528.0	2.1	245.2	319.4	568.7	528.0
		464.0	4.5	282.2	303.9	595.1	464.0
		472.0	1.1	251.5	290.8	544.6	472.0
W/C =0.5	Cement	422.0	2.1	225.9	237.8	467.9	422.0
		410.0	3.3	213.1	230.1	449.8	410.0
		400.0	3.3	205.3	225.7	437.6	400.0
	Mortal	388.0	2.4	191.6	219.6	416.0	388.0
		424.0	2.3	228.5	239.9	473.0	424.0
		398.0	2.6	205.5	228.6	439.3	398.0
W/C =0.6	Cement	346.0	3.1	172.8	194.0	372.9	346.0
		352.0	3.1	168.5	194.4	369.0	352.0
		350.0	3.0	181.7	202.8	390.7	350.0
	Mortal	350.0	2.7	167.6	194.6	367.7	350.0
		336.0	3.8	155.4	186.2	349.3	336.0
		328.0	3.6	159.2	196.6	363.0	328.0
W/C =0.7	Cement	318.0	4.5	158.0	163.2	330.3	318.0
		308.0	4.1	158.2	159.7	326.2	308.0
		310.0	3.6	155.6	161.1	324.0	309.0
	Mortal	300.0	3.7	153.1	159.1	319.6	300.0
		292.0	4.3	142.5	153.1	304.1	292.0
		300.0	3.4	151.1	157.8	315.7	300.0

TABLE 3: Exposure Environments and W/C ratios of concrete

Structure	Front	Back	Sun-Shine	Age (years)	W/C
A	Open	Filled with soil	not good	14	0.59
B	Open	Open	not good	38-40	—
C	Open	Filled with soil	normal	38-40	—
D(valley)	Open	Filled with soil	very good	23	0.54
D(hill)	Open	Filled with soil	good	23	0.54

widely. The standard variations of ion concentrations at the surface and the interior, was 44.0 and 28.1 mmol/l respectively. The degree of variation in the alkali ion concentrations was greater at the surface. The greater variations in alkali concentration in the pore solution may be caused by a larger number of cracks on surface areas. The intrusion of CO₂ through many cracks near the surfaces caused carbonation of pore solutions, and the fixation of alkalis through drying process was particularly promoted in areas along cracks. It was inferred that this series of phenomena led to greater variations in the alkali ion concentrations in the surface concrete. Compared with the ion concentrations in cores

used to extract pore solution were taken from the rubber weir retaining walls (structure A), and other retaining walls (structure B) located nearby structure A, the concrete snowslide protection fences (structure C) and the retaining wall of the water tank (structure D). Table 3 shows the exposure environment of these structures and the water/cement ratio of the concrete used in the structures. As shown in Table 3, water/cement ratio of concretes in the structures was from 0.5 to 0.6. To prevent loss of alkalis from concrete cores, the concrete cores drilled at sites were immediately sealed in vinyl bags. Then, in the laboratory, from the central portions of original cores with a diameter of 96 mm, cores with a diameter of 46 mm in diameter and 100 mm in length were drilled. Immediately after drilling, we extracted 2 to 3 ml of pore solution from the smaller cores and analyzed it. The results of these analyses are shown in Tables 4 a-c.

They indicate that the positive and negative ions concentrations in pore solutions were well balanced. As seen in Fig. 7, plots for the (Na⁺+K⁺) ion concentration at various depths from surface varies

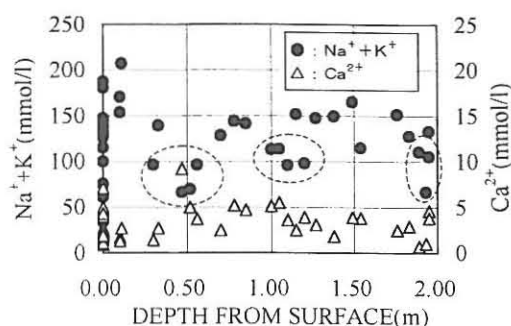


Fig. 7: Relations between alkali concentration and depth from surface

TABLE 4a: Result of Pore Solution Analysis of the Structure A (inner side)

core No.	location (m)	OH ⁻	Ca ²⁺	Na ⁺	K ⁺	Σ ⁺	Σ ⁻
		(mmol/l)					
Left Bank	⑥-1 0.52-0.66	70.0	5.0	45.1	24.5	79.6	70.0
	⑥-2 1.00-1.10	104.0	5.1	72.5	40.8	123.5	104.0
	⑥-3 1.10-1.19	80.0	3.6	63.8	32.0	102.9	80.0
	⑥-4 1.54-1.61	110.0	3.8	70.8	44.2	122.4	110.0
	⑥-5 1.95-2.08	120.0	4.6	83.7	49.2	142.0	120.0
	⑥-6 1.95-2.08	98.0	3.8	68.0	37.6	113.2	98.0
Average		97.0	4.3	67.3	38.0	—	—
Right Bank	①-1 0.00-0.10	122.0	2.1	74.9	51.8	131.1	122.0
	①-3 1.05-1.20	108.0	5.5	67.1	46.7	124.8	108.0
	①-4 1.38-1.48	140.0	1.8	86.7	62.9	153.1	140.0
	①-5 1.93-2.03	64.0	1.0	38.5	28.4	68.8	64.0
	②-1 0.30-0.36	92.0	1.4	51.6	44.5	98.8	92.0
	②-2 0.70-0.87	124.0	2.5	75.9	52.6	133.4	124.0
	②-3 1.20-1.30	98.0	3.9	58.7	39.5	105.9	98.0
	②-4 1.89-1.95	116.0	0.7	64.0	46.6	112.0	116.0
	③-1 0.47-0.58	72.0	9.2	39.6	26.5	84.4	72.0
	③-2 0.85-0.95	134.0	4.7	83.9	57.4	150.6	134.0
	④-1 0.56-0.65	84.0	3.7	64.0	32.0	103.4	84.0
	④-2 1.15-1.27	128.0	2.5	98.4	53.3	156.5	128.0
	④-3 1.76-1.87	142.0	2.5	88.7	63.0	156.6	142.0
	⑤-1 0.33-0.42	126.0	2.7	81.8	57.5	144.6	126.0
	⑤-2 0.78-0.89	136.0	5.2	90.4	53.4	154.2	136.0
	⑤-3 1.27-1.37	132.0	3.1	88.1	59.0	153.3	132.0
	⑤-4 1.49-1.59	160.0	3.9	98.2	66.8	172.9	160.0
	⑤-5 1.83-1.95	120.0	2.9	76.6	51.4	133.7	120.0
Average		116.6	3.3	73.7	49.6	—	—
Average		111.7	3.5	72.1	46.7	—	—

taken from other locations, alkali ion concentrations in cores taken from the locations indicated by dotted line circles in Fig. 7 were relatively low. Many cracks were found nearby the locations from which these cores were drilled. Since it was confirmed that these fractures did not occur during drilling of cores, possible causes for reduction in the ion concentrations in the locations may be the leakage of alkalis by the intrusion of rainwater through these cracks, the carbonation of

pore solutions as a result of the intrusion of carbon dioxide through the cracks, and the fixation of alkalis through the drying process of the areas adjacent to the cracks. As indicated with star marks (*) in Table 4b, the ion concentrations in the vicinity of the surface were lower than at depth. This fact endorses the proposition that alkali ions in the pore solutions near the surface of concrete were fixed when the areas were dried (Diamond 1996). The low alkali ion concentrations in concretes can be explained by the consumption of ions by ASR that have continued to progress over the long period of 14 years. It can be inferred, therefore, that the relatively low residual

expansions of cores were due to the low OH⁻ ion concentrations in the pore solution, because the presence of reactive components in concretes have been proved by considerable expansions of the cores in 1N NaOH solutions at 80°C (Fig. 5). The Na⁺, K⁺, Ca²⁺ and OH⁻ ion concentrations in the pore solutions extracted from cores taken from the structures B, C, D were approximately Na⁺ ≅ 38-45, K⁺ ≅ 15-22, Ca²⁺ ≅ 2, OH⁻ ≅ 51-63

TABLE 4b: Result of Pore Solution Analysis
of the Structure A (surface)

core No	location (m)	OH ⁻	Ca ²⁺	Na ⁺	K ⁺	Σ +	Σ -	Remarks
(mmol/l)								
Left Bank	R-1	0.00-0.10	120.0	4.0	77.2	50.4	135.5	120.0
	R-2	0.00-0.10	104.0	2.7	78.8	49.9	134.2	104.0
	R-3	0.00-0.10	166.0	2.0	115.1	72.3	191.4	166.0
	Average		130.0	2.9	90.4	57.5	—	—
	O-1	0.00-0.08	90.0	1.5	62.2	38.0	103.1	90.0
	O-2	0.00-0.06	158.0	0.9	106.2	74.6	182.7	158.0
	O-3	0.00-0.06	48.0	7.1	21.7	12.6	48.5	48.0
	Average		98.7	3.2	63.4	41.7	—	—
Right Bank	R-1	0.00-0.10	150.0	3.9	69.6	74.7	152.1	150.0
	R-2	0.00-0.10	134.0	5.0	78.6	59.3	147.9	134.0
	R-3	0.00-0.10	65.7	0.9	42.4	32.7	76.9	65.7
	R-4	0.00-0.10	72.0	2.5	42.0	33.7	80.7	72.0
	R-5	0.00-0.08	44.0	2.4	21.5	19.2	45.5	44.0
	R-6	0.00-0.08	82.0	2.3	55.5	72.2	132.3	82.0
	R-7	0.00-0.10	94.0	1.8	64.4	50.7	118.8	94.0
	Average		91.7	2.7	53.4	48.9	—	—
	O-1	0.00-0.10	128.0	2.4	84.7	54.6	144.2	128.0
	"	0.10-0.21	150.0	1.7	93.6	60.1	157.1	150.0
	O-2	0.00-0.11	132.0	4.0	79.3	52.1	139.4	132.0
	"	0.11-0.21	192.0	2.7	116.0	91.3	212.7	192.0
	O-3	0.00-0.10	118.0	4.3	81.7	51.0	141.2	118.0
	"	0.10-0.18	150.0	1.3	102.2	68.4	173.2	150.0
	O-4	0.00-0.09	60.0	1.1	33.7	27.5	63.4	60.0
	O-5	0.00-0.09	110.0	1.9	86.3	61.0	151.1	110.0
	Average		130.0	2.4	84.7	58.2	—	—
	Average		112.7	2.7	72.0	52.7	—	—

mmol/l on average, being comparatively lower than those in the pore solutions taken from the structure A. The differences in alkali ion concentration between different structures could be explained by the fact that the structures B, C and D were 38–40 years old, and ASR has progressed further along with the leakage of alkali from concrete by rainwater. Concerning the structure D, it was observed that the OH⁻ ion concentration in the pore solutions from the valley side (38 mmol/l) was smaller than that of the hill side (92 mmol/l), which was subjected to

more significant effects of solar radiation. The OH⁻ ion concentration in a saturated solution of calcium hydroxide at 20°C was 42 mmol/l. The OH⁻ ion concentrations in the pore solutions in the ASR-affected concretes exceeded this value. The above findings lead to the conclusion that little residual expansions generated in the concrete cores (at 40°C and more than 95% R.H.) with some residual reactive components were due to the reduction in OH⁻ ion concentrations caused by the progress of ASR. The threshold OH⁻ ion concentrations of 250 mmol/l for ASR has been proposed (Diamond 1983). The results in this study do not contradict such a proposition.

These experiments also suggest that it is possible to predict the progress of deterioration in ASR-damaged structures by combining the NBRI test to confirm the existence of the residual reactive components in aggregates and the analysis of pore solutions.

Proposal on the Criteria for Predicting the Progress of ASR Deterioration

Within the scope of informations and knowledges obtained from this study, we propose the criteria to predict the progress of deterioration in ASR-damaged structures given in Table 5. It is found from the results obtained in this study that the OH⁻ ion concentrations in the concrete cores taken from existing structures varied greatly.

TABLE 4c: Result of Pore Solution Analysis of the Structure B, C, D

core No. (structure)	location (m)	OH ⁻	Ca ²⁺	Na ⁺	K ⁺	Σ ⁺	Σ ⁻	Remarks
(mmol/l)								
B	①-1	0.00-0.10	62.5	1.2	50.4	15.4	68.3	62.5
	①-2	0.00-0.10	24.0	2.7	12.1	4.6	22.1	24.0
	①-3	0.00-0.11	80.0	1.7	60.8	24.9	89.1	80.0
	②-1	0.00-0.06	56.0	0.6	40.4	17.2	58.9	56.0
	②-2	0.00-0.07	58.0	1.0	41.4	19.1	62.5	58.0
	②-3	0.00-0.07	50.0	0.8	34.4	14.7	50.7	50.0
	②-4	0.00-0.06	66.0	0.8	43.3	16.8	61.6	66.0
	②-5	0.00-0.04	32.0	0.9	30.3	10.4	42.5	32.0
	③-1	0.00-0.08	30.0	0.5	21.3	7.5	29.8	30.0
	③-2	0.00-0.13	68.0	0.3	64.7	18.2	83.7	68.0
	④-1	0.00-0.10	62.0	1.7	49.5	19.5	72.2	62.0
	④-2	0.00-0.13	38.0	1.0	32.6	12.4	46.9	38.0
	⑤-1	0.00-0.09	46.0	5.9	22.2	10.5	44.5	46.0
	⑤-2	0.00-0.08	48.0	3.0	30.0	15.0	50.9	48.0
	Average		51.5	1.6	38.1	14.7	—	—
C	⑥-1	0.00-0.10	110.0	1.2	88.8	33.2	124.4	110.0
	⑥-2	0.00-0.10	50.0	3.2	35.3	16.7	58.3	50.0
	⑦-1	0.00-0.10	40.0	4.8	23.2	10.4	43.2	40.0
	⑦-2	0.00-0.04	40.0	2.0	32.1	16.9	53.0	40.0
	⑦-3	0.00-0.06	56.0	2.5	35.0	17.6	57.6	56.0
	⑧-1	0.00-0.08	70.0	1.8	55.8	25.6	85.0	70.0
	⑧-2	0.00-0.08	40.0	2.1	27.7	15.9	47.7	40.0
	⑨-1	0.00-0.10	50.0	2.3	41.9	16.4	62.9	50.0
	⑩-1	0.00-0.07	48.0	1.9	26.7	16.5	47.1	48.0
	⑩-2	0.00-0.10	80.0	0.3	55.1	38.7	94.5	80.0
	⑪-1	0.00-0.05	60.0	3.5	38.0	16.5	61.6	60.0
	⑪-2	0.00-0.08	16.0	0.7	8.4	2.9	12.6	16.0
	⑬-2	0.00-0.10	122.0	1.5	86.8	44.1	134.0	122.0
	⑬-3	0.00-0.10	100.0	0.9	68.0	38.1	107.8	100.0
	Average		63.0	2.1	44.5	22.1	—	—
D	H-1	0.15-0.27	42.0	3.8	22.2	8.8	38.7	42.0
	H-2	0.12-0.27	124.0	2.3	96.5	29.0	130.1	124.0
	H-3	0.12-0.27	110.0	2.2	81.5	20.0	106.0	110.0
	Average		92.0	2.8	66.7	19.3	—	—
	V-1	0.12-0.26	52.0	3.7	29.9	8.9	46.3	52.0
	V-2	0.13-0.27	30.0	4.1	16.7	5.3	30.1	30.0
	V-3	0.11-0.24	32.0	6.2	13.7	5.4	31.4	32.0
	Average		38.0	4.7	20.1	6.5	—	—

TABLE 5: Criteria to Determine the Possibility of the Progress of ASR in Future

		OH ⁻ ion Concentration	
		≥ 250 (mmol/l)	≤ 250 (mmol/l)
Expansion in NBRI test(14days)	≥ 0.1%	A	B
	≤ 0.1%	C	D

Note:

A: high possibility because of high OH⁻ ion concentration and expansionB: little possibility because of low OH⁻ ion concentration (※)

C: little possibility because of low expansion

D: little possibility because of low OH⁻ ion concentration and expansion※ In the evaluation of OH⁻ ion concentration, variations from portion to portion must be taken into consideration.

Therefore, for the evaluation of the OH⁻ ion concentrations, variations in OH⁻ ion concentrations must be taken into consideration. The determination of OH⁻ ion concentrations for a structure should be statistically treated.

CONCLUSION

The results obtained in this study are summarized as follows:

- (1) Many factors (temperature, humidity ,etc.), including the progress of cracks caused by freezing-thawing cycles, were involved in the progress of ASR deterioration in the walls of the concrete structure investigated.
- (2) The pore solutions in cement pastes and mortars with water/cement ratios of 0.3, 0.4, 0.5, 0.6, and 0.7 were analyzed. It was found that, when the water/cement ratio was the same, the Na^+ , K^+ , Ca^{2+} and OH^- ion concentrations were approximately the same as the values obtained from cement paste. As the water/cement ratio increased, the Na^+ , K^+ , and OH^- ion concentrations decreased while Ca^{2+} ion increased.
- (3) The low alkali ion concentrations in the concretes can be explained by the consumption of alkali ions by ASR that took place over a long period.
- (4) The degree of variation in the alkali ion concentrations was greater at the surfaces because of carbonation caused by intrusion of CO_2 through many cracks and the fixation of alkalis through drying process.
- (5) Within the scope of information and knowledge obtained from this study, we propose criteria to predict the progress of deterioration in ASR-damaged structures by combining the NBRI test to confirm the existence of residual reactive components in aggregates and the analysis of pore solutions.

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