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EVALUATION OF THE RESIDUAL EXPANSIVITY OF CORES DUE TO ALKALI-SILICA REACTION IN HOKURIKU DISTRICT, JAPAN

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Abstract

In Hokuriku district, river gravels and sands have been used as concrete aggregates for a long time, and have been found in seriously ASR-affected structures. Accordingly, the issue of the relevance of test methods for aggregate reactivity has become a matter of great concern in Japan. Establishment of methods for assessing and repairing ASR-damaged concrete structures are therefore, urgently required. The surface expansion behaviour, the petrographical evaluation of reactive aggregates and the residual expansivity in concrete cores drilled from 24 different road structures along Hokuriku Expressway, from 2008 to 2010, were compared with the results of a similar survey conducted about 10 years ago. Because external alkali supply from deicer salts is a typical feature in this region, accelerated ASR expansion tests were performed in accordance to Canadian and ASTM C1260 methods. Furthermore, the chemical composition of ASR-gels was investigated and ASR progress was assessed as level 2 and 3.

Keywords: Alkali-silica reaction, Residual expansivity of cores, EPMA (EDS), ASR gel, Andesite

1 INTRODUCTION

Increasing amounts of deicing salts have been used to ensure safety of road surfaces in Hokuriku district, in Japan. Sodium chloride, which accounts for the majority of deicers, has been causing damage to road concrete structures due to alkali-silica reaction (ASR) [1]. In this region, river gravel and river sand have been used as concrete aggregates for a long time, and these aggregates have been found in seriously ASR-affected structures [2]. ASR has occurred mostly in structures built from 1970 to 1985. Reactive river sand and gravel may not have been properly assessed by the normally practiced alkali-silica reactivity test methods (the chemical method and mortar bar method stipulated in JIS A 5308 “Ready-mixed Concrete”), since these aggregates contain a wide variety of rock types, as well as different types and contents of reactive minerals. Also, some structures that had been judged as having “no residual expansivity” by the JCI-DD2 method (moist-air-cured at 40°C) and were repaired accordingly, continued to expand, re-damaging the repairs in a few years [1]. On the other hand, for some of these reactive aggregates, if the mixing ratio significantly exceeds pessimum values, moisture-based JCI-DD2 method has been found to be ineffective in evaluating residual expansivity of concrete cores. In this regard, the issue of the relevance of test methods for aggregate reactivity has became a matter of great concern in Japan. Establishment of methods for assessing and repairing ASR-damaged concrete structures is therefore, urgently required [3,4].

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This paper discusses the petrographical evaluation of reactive aggregates in concrete cores drilled from 24 different road structures (abutments, piers, C-Box, RC slab, PC girder) in the Hokuriku Expressway from 2008 to 2010, and compares the results with a field survey (crack distribution) and thin section observations conducted about 10 years ago (1998-1999 research). Because external alkali supply is a typical characteristic in this region, accelerated ASR expansion test (Canadian method, ASTM C1260, saturated 1N NaOH solution at 80°C) were also conducted and the results compared with those of 10 years ago, including surface expansion currently observed in these strutures. Furthermore, the chemical composition of ASR-gel was investigated and ASR progress was assessed as 2 and 3.

2 SURVEY AND TEST METHODS

2.1 Surveyed structures

The survey included 24 structures in Hokuriku Expressway along the Hokuriku district. The aggregates are representative of the region in which the structures are built. River gravels vary widely by river basin and quarry location, ranging from volcanic rocks (andesite, rhyolite and welded tuff), to plutonic rocks (granite, diorite and gabbro) and sedimentary rocks (sandstone and shale) all mixed together. These structures entered service in the period between 1972 and 1983, and were generally built with high concentration alkali cements (about 1%) which were of common usage in Japan at the time [5].

2.2 Petrographic analysis of concrete cores

Core sampling

Two to three cores, Ø=55mm, L=400m, were drilled in the vicinity of ASR-related cracks in the surveyed structures. If no ASR cracks were observed, the cores were drilled near the corner of the structure. Immediately after drilling, the specimens were stored in sealed nylon bags to preserve the in-situ conditions [5].

Lithological composition of gravels

On the surface of concrete cores, all the visible particles exceeding 5mm diameter were lithologicaly classified. Image analysis software provided the tools to determine the overall mineralogical composition, by measuring the surface area of each mineral component.

Polarizing microscopy of thin concrete sections

Thin sections (t = 20μm) were prepared from concrete slides (25mm×35mm) obtained from the cores. The type of reactive rock, reaction rim, gel spot and gel conditions in the thin sections were observed by a polarizing microscope. According to Katayama proposals [6], ASR degradation grade was divided into four levels.

2.3 Alkali content of cement

Cement hydrates and unhydrated cement particles were also identified in polished thin sections by polarizing microscope. After carbon coating the samples, the alkali content of cement was determined by quantitative EPMA analysis for each of the alite (C_3S), belite (βC_2S), aluminate (C_3A), and ferrite (C_4AF) phases. The alkali content was calculated by assuming the mass proportions of C_3S, βC_2S, C_3A, and C_4 AF to be 0.6:0.2:0.1:0.1 after converting to an equivalent alkali content (Na_2O + 0.658 K_2O).

2.4 Expansion behavior of structures

The expansion of the structures was investigated by measuring crack lengths with a contact micron gauge, near the core sampling points. In addition, after chipping out the concrete cover in the structure *e*, strain gauges were installed to determine the reinforcement steel strain.

2.5 Residual expansion of concrete cores

Canadian method

The time-related changes in the expansion of drilled concrete cores (Ø=55mm, L=150mm, initial depth= 100mm) were measured in accordance with the accelerated mortar method (ASTM C1260-1994). The specimens were immersed in 1N NaOH solution at 80°C. Referring to the evaluation criteria applied for the Hokuriku Expressway, cores with an expansion ratio exceeding 0.1% at 21 days were judged as having deleterious expansivity [1].

2.6 Chemical composition of ASR gel

After completing the polarizing microscopy of polished thin sections, SEM observation and quantitative EPMA (EDS) analysis (at 15KV, 1nA, data acquisition time 100s, dead time 30%, ZAF correction) were conducted to determine the chemical composition of ASR gel. The compositions are plotted in [Ca/Si]-[Ca]/[Na+K] diagrams.

3 RESULTS AND DISCUSSION

3.1 Petrological characterization of the structures

Lithological composition of river gravels was determined from concrete cores drilled from the structures. Based on the visual observation, the ASR-related degree of deterioration of the structures was divided into four levels [1], as shown in Figure 1. Volcanic rocks (andesite, rhyolite and welded tuff) and sedimentary rocks (shale) were confirmed as the rock types associated with alkali-silica reactivity. The structures that used Jyouganji river and Kuzuryu river aggregates were severely affected by ASR degradation, as shown in Figure 1 and Figure 2. Fig. 3 shows the relationship between the type of reactive rock and ASR degree of deterioration. The reactive minerals contained in andesite were highly reactive cristobalite and volcanic glass.

3.2 ASR degree of deterioration in the field survey and observed by polarizing microscope

The comparison of ASR degree of deterioration in the field survey and that observed by polarizing microscope with 10 years old data are shown in Table 1. Figure 4 shows examples of images captured by polarizing microscope.

Figure 4 (1) referring to structure *e*, pier 1, had small ASR-related cracks 10 years ago, classified as deterioration level C, but in this survey, crack network increased significantly to the extent of deterioration level A, due to water leakage from the expansion joint. In Figure 4 (2), from structure *h*, not only crack surface but also crack width increased. The severity of ASR progress has led this structure to deterioration level A. Similarly, in Figure 4 (3) from structure *s*, cracks increased considerably in the past 10 years, up to deterioration level A. Thin section observations by polarizing microscope in these three structures revealed that, andesite from river sand and river gravel were extremely reactive. Dense ASR gel expanded into the cement paste and filled the air voids, which fits ASR deterioration level 4 in the petrographic scale.

As for Figure 4 (4) from structure *c*, ASR cracking didn't occur 10 years ago and the deterioration level in the field survey was judged as OK. In addition, thin section observation confirmed the presence of a reaction rim, dacite and rhyolitic welded tuff rocks in the river gravel, which led to ASR deterioration level 1 in the petrographic scale. The reactive minerals were found to be cryptocrystalline quartz and volcanic glass. However, in the present study, cracks due ASR, classified as level C, have been observed in the structure. In the thin section observations, ASR gel was detected in rhyolitic welded tuff (deterioration level 2 in petrographic scale), thus confirming a typical case of ASR progress.

On the other hand, in Figure 4 (5) from structure *k*, level C ASR cracks already occurred 10 years ago. A mix of various reactive rocks such as dacite, andesite and rhyolitic welded tuff were found in the river gravel and, rhyolite, andesite and rhyolite tuff in the river sand, leading to deterioration level 2 in the petrographic scale. The reactive minerals cryptocrystalline quartz, chalcedony and volcanic glass were confirmed in rhyolite, but none of the highly reactive opal or cristobalite were identified. In the present survey, the surface cracking area increased to level B in this structure. In addition, ASR gel formed from andesite expanded into the cement paste and filled the air voids, leading to ASR deterioration level 4 in the petrographic scale. In the future, there is a strong probability that surface cracking will progress in this structure.

In Figure 4 (6) from structure *i*, severe ASR cracking classified as level A, has been already observed 10 years ago and highly reactive andesite was found in river gravel and river sand in the thin section observations. In addition, ASR gel expanded into the cement paste and a wide crack net was formed, leading to a deterioration level 3 in the petrographic scale. Cristobalite and volcanic glass reactive minerals were identified in andesite. In the current survey, crack formation in the structure did not show a significant change, thus maintaining the deterioration at level A, but ASR gel and severe cracking occurred in the cement paste observed by polarizing microscope, upgrading the deterioration level to 4, in the petrographic scale.

The careful evaluation of these cases has shown that, there is a similar relationship between the deterioration level observed in the field survey and that estimated from the polarizing observation of thin sections, although in some cases, the deterioration level in the petrographic scale was higher than that of the field survey. Therefore, we consider that ASR deterioration can be predicted by carrying out regular thin section observations.

3.3 Verification of the residual expansivity of concrete cores

Relationship between the time lapse and the residual expansivity of cores

The residual expansivity of concrete cores was evaluated by Canadian method. The comparison with the expansion ratio observed 10 years ago is shown in Figure 5. The current residual expansion ratio of structures with deterioration level A has became less than half the residual expansion observed 10 years ago, meaning that ASR expansion tended to recess. On the other hand, the residual expansion ratio in structures with field ASR deterioration level B have steadily increased, which indicates that this behavior is expected to continue in the future. However, because the residual expansion test of concretes cores is conducted under accelerated environmental conditions, which may not necessarily match the actual conditions of the structures, a special attention should be paid in interpreting the test results [4]. Therefore, despite the valuable information for maintenance provided by accelerated expansion tests and thin section observations, actual inspection of the structures, conducted on regular basis, should never be neglected.

Relationship between the expansion behavior of structures and residual expansivity of cores

In structures were ASR is in progress, with the total sum of expansion already occurred and residual expansion ratio deducted by reinforcement steel restraint expansion, it is possible to predict the future expansion [4]. The relationship between the time-changes in surface expansion ratio of the structures and the residual expansion ratio obtained is shown in Figure 6. Ten years ago, structures *b* and *c*, revealed expansion ratios of less than 0.1% at 21 days in the Canadian method test, but this expansion behavior of structures almost stopped afterwards. Based on the results of thin section observations, the structures were also expected to continue expanding in the future, but these predictions were completely ruled out in the current survey. On the other hand, structures *h* and *i* showed 10 years ago large residual expansions in the range of 0.5% at 21 days, also in the Canadian method, but this expansion ratio significantly decreased in the recent study, showing that ASR was in a recession trend. However, in structures *d* and *k*, despite the good aggreement between Canadian method expansion ratio and field surface expansion ratio at the time, both expansions are currently almost the same as 10 years ago. ASR progress was predicted to continue.

Relationship between alkali content and residual expansivity of concrete cores

The results of alkali content for each cement in Figure 5 are shown in Figure 7. As previously mentioned, in structures *d* and *k* the residual expansion ratio determined at 21 days by Canadian method remained unalterable. This phenomenon occured because the alkali content of cement was below 2kg/m^3, which caused ASR to consume only small amounts of Si and would, expectly, turn ASR progress into a long term process. In this regard, useful information for maintenance of ASR damaged structures was regularly gathered in field surveys (expansion behavior of the structures), residual expansivity of cores determined by Canadian method and thin section observations by polarizing microscope. In the cases where the expansion ratio at 21 days exceeded 0.1%, it was also necessary to determine the alkali content and mineral composition to properly interpret the expansion test results.

3.4 Chemical composition of ASR gel determined by EPMA analysis

After determining the reactive aggregate by polarizing microscope observations, the chemical composition of ASR gel was quantitatively analyzed by EPMA. The analysis targeted andesite rocks from Jyouganji riverbed (structures *d*, *e*, *h*, *i* and *k*) and Kuzuryu riverbed (structures *q* and *s*). In each analysis, ASR gel occurrence was investigated in 5 to 10 points including, inside the andesite particles (gravel and sand), cement paste, interface between aggregates and cement paste, cracks and air voids. The average values of each analysis are shown in Table 2 and Table 3. From these results, a tendency of silica (SiO_2), alumina (Al_2O_3) and alkalis (Na_2O, K_2O) in the coarse aggregates decreasing towards the cement pastes was observed. On the other hand, calcium (CaO) tended to increase in the reverse direction. This phenomenon showed that alkalis in ASR gel were replaced by calcium from the cement paste. This finding is in aggreement with past research [7] that concluded that CH both acts as a buffer to maintain a high OH^- concentration in the pore solution and exchanges for alkalis in the ASR gel, leading to alkali release and further production of swelling alkali silicate gel. It has also been reported in another study that gels in aggregate in a 7-year-old concrete have constant Ca/Si ratios of ~ 0.25 and K/Si ratio of 0.1~0.3, whereas gels in the paste of the same concrete have higher Ca/Si ratios, up to 1.3, and lower K/Si ratios [8]. [Ca / Si] and [Ca /(Na+K)] ratios [9] in ASR gel are shown in Figure 8. Both relationships are characterized by an almost linear distribution. The chemical composition [Ca/Si and Ca/(Na+K)] of andesite from gravel tended to be smaller than that of andesite from sand. Because of the large surface area of sand compared to that of gravel, ASR occurs from the early stages and, in the reaction process, Ca particles from the cement paste are absorbed into the interface with sand particles. However, there is a suggestion that this reaction will slowdown in the long term.

The relationship between the chemical composition [Ca/Si and Ca/(Na+K)] of andesite from gravel and the expansion ratio at 21 days determined by Canadian method is shown in Figure 9. All plotted points are under the [Ca/Si=0.25] line, which suggests a highly hygroscopic expansive gel. In addition, the reinforcement steel stresses measured in structure *e* were 370kN/mm^2 (strain=1798μ, D16) in the vertical bars and 178N/mm^2 (strain=864μ, D19) in the horizontal bars, which indicates that stress is building up in the reinforcement bars due to ASR progress. The corresponding strains are shown in Figure 10. The test results show that the strain has gradually increased over time, but this is related to seasonal changes in temperature, rather than ASR progress itself. Also, there was no inconsistency with the chemical composition of ASR gel and residual expansion test results, either. Particularly for structures *s* and *q*, with no residual expansivity, the Ca/Si mol ratio of highly hygroscopic expansive ASR gel was considered to be less than 0.15 to 0.2.

From the overall results of the present study, the authors found out that, for these structures now over 30 years in service, there is a high probability that ASR is likely to progress in those built with Jouganji river gravels. On the other hand, there are strong indications that ASR is in recession in those structures with Kuzuryu river gravels.

4 CONCLUSIONS

The main concluding remarks are drawn from by this study, are as follows:

(1) Severe ASR deterioration occurred in some of the structures built with river sand and river gravels from Jouganji river (Toyama Prefecture) and Kuzuryu river (Fukui Prefecture) in Hokuriku district. Andesite was found to be the main reactive mineral in these aggregates of the region.

(2) Thin section observation by polarizing microscope was a more effective method of detecting ASR deterioration than visual inspection of the structures. In addition, ASR deterioration progress was accurately predicted by regularly carrying out thin section observations and residual expansivity tests of concrete cores drilled from the structures.

(3) Valid data for maintenance purposes could be gathered by measuring the expansion of the structures on the field and conducting residual expansivity tests in accordance with the Canadian method. In the cases of expansion ratios exceeding 0.1%, alkali content and mineralogical composition analysis should also be performed.

(4) The results of chemical composition of ASR gel showed that in the cases of reactive river sand, ASR progress was fast in the early stages, but eventually slowed down in the long term.

(5) The results of chemical composition of ASR gel, residual expansivity of concrete cores and strain of reinforcement steels bars revealed that, for these structures now over 30 years in service, there is a high probability that ASR is likely to progress in those built with Jouganji river gravels. On the other hand, there are strong indications that ASR is in recession in those structures with Kuzuryu river gravels.

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TABLE 1: Comparison with data 10 years by severity of ASR in the field and severity of ASR in the petrography

Structure	Part	1998-1999 research		2008-2010 research	
		Severity of ASR in the field ‡	Severity of ASR in the petrography #	Severity of ASR in the field ‡	Severity of ASR in the petrography #
a	Abutment 1	OK	1	OK	1
	Abutment 2	B	-	B	3
b	Abutment	OK	1	OK	1
c	Abutment	OK	1	C	2
d	Abutment	B	3	B	4
e	Pier 1	C	-	A	4
	Pier 2	C	-	A	4
f	PC Girder	OK	-	C	1
	Abutment	OK	-	C	1
g	Abutment	Ok	1	OK	1
h	C-Box	A	-	A	4
i	Abutment	A	3	A	4
j	Abutment 1	C	-	C	3
	Abutment 2	B	-	B	3
k	Abutment	C	3	B	4
l	Slab	B	-	B	3
	Abutment	B	-	B	3
m	Abutment	OK	-	OK	1
n	Abutment	C	-	C	1
o	Abutment	B	-	B	2
p	Abutment	OK	1	OK	1
q	PC Girder	B	-	B	3
r	Abutment	C	-	C	2
s	Abutment	A	4	A	4
t	Abutment	OK	-	OK	1
u	Abutment	OK	-	OK	1
v	Abutment	OK	1	OK	1
w	Abutment	OK	-	OK	1
x	Abutment	OK	-	OK	1

‡ : Severity of ASR in the field
OK : No clack due to ASR
C : Cracks in all over the structure
B : Cracks in more than 1/3 of structure
A : Cracks all over the structure

: Severity of ASR in the petrography
1: reaction rim & gel-exudation
2: gel-fill crack in aggregate
3: gel-fill cracks in cement paste
4: gel-fill void in cement paste
-: No date

TABLE 2: The average ASR gel at each analysis position

Structures		d (Jouganji river)				e pier 1 (Jouganji river)				h (Jouganji river)				
Position analysis of ASR gel*		Gr	Gr-Cp	Sa	Cp	Gr	Gr-Cp	Cp	Air	Gr	Gr-Cp	Sa	Cp	Air
SiO_2		40.81	38.78	38.86	39.03	50.40	45.80	36.89	38.94	50.37	48.04	35.41	40.09	37.29
Al_2O_3		10.44	8.61	6.73	8.68	13.66	7.71	7.44	6.20	11.25	11.32	7.70	8.53	6.77
MgO		1.57	2.18	1.85	1.31	1.98	1.80	1.33	1.55	2.11	1.60	1.43	1.55	1.12
CaO		7.60	9.86	11.54	13.31	5.08	10.63	12.21	13.92	5.96	9.57	14.68	13.41	14.51
Na_2O		4.57	3.89	3.27	4.40	7.17	5.07	3.94	4.32	5.82	6.17	3.89	4.40	4.30
K_2O		2.00	2.10	1.60	1.68	2.94	2.60	1.70	1.55	2.54	2.32	1.78	1.99	1.50
SO_3		0.13	0.14	0.19	0.14	0.04	0.14	0.14	0.30	0.06	0.14	0.28	0.22	0.21
P_2O_5		0.18	0.07	0.00	0.15	0.19	0.07	0.11	0.12	0.27	0.15	0.07	0.08	0.10
Total		67.30	65.62	64.04	68.71	81.47	73.82	63.76	66.90	78.40	79.31	65.24	70.27	65.80
Atomic ratio	Ca/Si	0.20	0.27	0.32	0.37	0.11	0.25	0.37	0.39	0.13	0.21	0.45	0.36	0.43
	Ca/(Na+K)	0.71	1.03	1.48	1.36	0.31	0.87	1.42	1.47	0.45	0.69	1.63	1.31	1.57

*Position analysis of ASR gel
Gr : In the gravel
Gr-Cp : Boundary between the gravel and cement oaste
Sa : In the sand
Cp : In thr cement paste
Air : In the air

TABLE 3: The average ASR gel at each analysis position

Structures		i (Jouganji river)				k (Jouganji river)					q (Kuzuryu river)					s (Kuzuryu river)				
Position analysis of ASR gel*		Gr	Gr-Cp	Sa	Cp	Gr	Gr-Cp	Sa	Cp	Air	Gr	Gr-Cp	Sa	Cp	Air	Gr	Gr-Cp	Sa	Cp	Air
SiO_2		52.48	41.88	39.56	36.24	46.61	41.12	31.14	39.03	34.50	39.18	38.96	34.55	38.50	35.96	39.68	38.94	40.92	37.27	33.80
Al_2O_3		9.08	7.60	8.70	7.57	9.79	9.37	6.37	8.68	6.79	7.68	7.59	5.87	5.45	5.65	7.95	8.59	6.46	6.72	4.82
MgO		0.35	0.72	1.56	1.29	1.58	1.37	1.79	1.31	1.15	1.71	1.38	0.70	1.01	0.99	1.44	1.64	1.05	1.21	1.04
CaO		2.93	10.64	10.95	12.63	6.12	11.07	15.21	13.31	14.79	7.13	9.90	15.75	15.28	14.42	7.94	9.72	12.70	14.38	15.43
Na_2O		5.07	3.75	4.19	3.96	5.95	5.03	3.47	4.40	3.71	4.13	3.98	3.90	2.83	1.48	5.63	5.23	3.11	3.09	2.50
K_2O		2.81	1.70	1.39	1.19	2.97	2.48	1.43	1.68	1.26	2.72	2.60	0.97	1.53	1.28	2.87	1.95	3.03	1.60	1.36
SO_3		0.04	0.08	0.14	0.38	0.03	0.09	0.16	0.14	0.16	0.05	0.04	0.09	0.12	0.14	0.09	0.08	0.07	0.09	0.07
P_2O_5		0.12	0.09	0.16	0.09	0.18	0.15	0.12	0.15	0.10	0.18	0.09	0.03	0.08	0.02	0.09	0.13	0.08	0.13	0.08
Total		72.88	66.45	66.64	63.34	73.23	70.68	59.69	68.71	62.47	62.78	64.54	61.87	64.80	59.94	65.69	66.29	67.41	64.48	59.10
Atomic ratio	Ca/Si	0.06	0.25	0.30	0.37	0.15	0.29	0.52	0.37	0.46	0.20	0.27	0.49	0.43	0.44	0.22	0.27	0.33	0.42	0.50
	Ca/(Na+K)	0.23	1.01	1.21	1.54	0.44	0.92	1.91	1.36	1.80	0.67	0.96	1.92	2.27	3.53	0.59	0.82	1.36	1.98	2.55

Structures	Part	Constuction year	Aggregate Source	Severity of ASR in the field
a	Abutment 1	1983	Kurobe river	OK
	Abutment 2	1983	Jouganji river	B
b	Abutment	1983	Kurobe river	OK
c	Abutment	1983	Kurobe river	C
d	Abutment	1980	Jouganji river	B
e	Pier 1	1980	Jouganji river	A
	Pier 2	1980	Jouganji river	A
f	PC Girder	1980	Jouganji river	C
	Abutment	1980	Jouganji river	C
g	Abutment	1980	Jouganji river	OK
h	C-Box	1975	Jouganji river	A
i	Abutment	1975	Jouganji river	A
j	Abutment 1	1975	Jouganji river	C
	Abutment 2	1975	Jouganji river	B
k	Abutment	1973	Jouganji river	B
l	Slab	1973	Jouganji river	B
	Abutment	1973	Jouganji river	B
m	Abutment	1973	Syo river	OK
n	Abutment	1973	Syo river	C
o	Abutment	1985	Syo river	B
p	Abutment	1972	Tedori river	OK
q	PC Girder	1973	Kuzuryu river	B
r	Abutment	1973	Kuzuryu river	C
s	Abutment	1975	Kuzuryu river	A
t	Abutment	1976	Kuzuryu river	OK
u	Abutment	1977	Crush Stone	OK
v	Abutment	1977	Crush Stone	OK
w	Abutment	1980	Unidentified	OK
x	Abutment	1980	Unidentified	OK

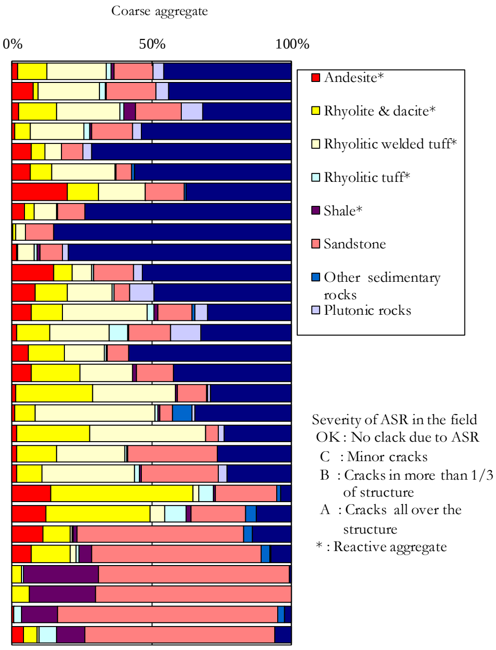


FIGURE 1: The surveyed structures and rock types found in their coarse aggregates

Structure e

Structure h

Structure s

FIGURE 2: Deterioration due to ASR

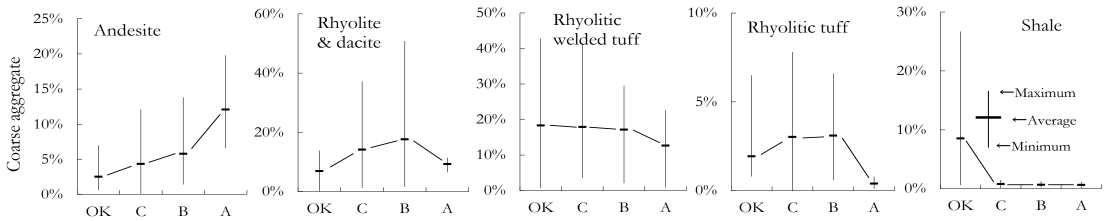
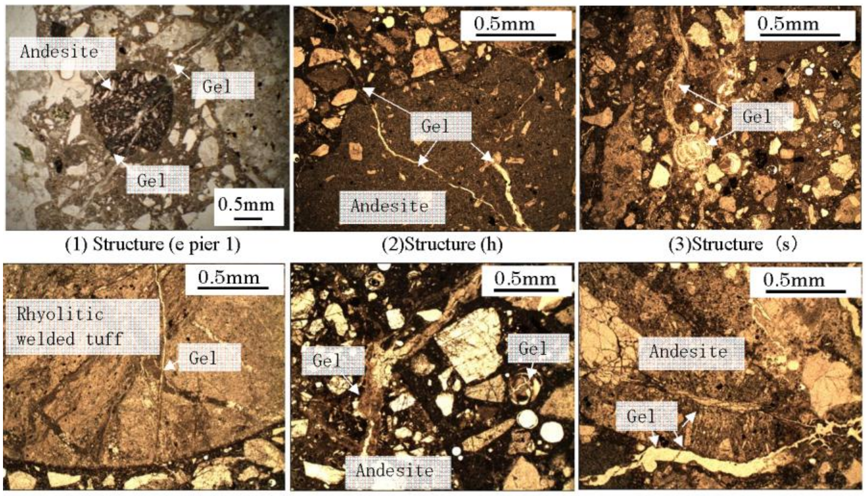


FIGURE 3 : Correlation between the rock types and the severity of ASR degradation in the field survey



(1) Structure (e pier 1) (2)Structure (h) (3)Structure (s)

(4) Structure (c) (5)Structure (k) (6)Structure (i)

FIGURE 4 : Observation of concrete thin sections by polarizing microscope (Open Nicole)

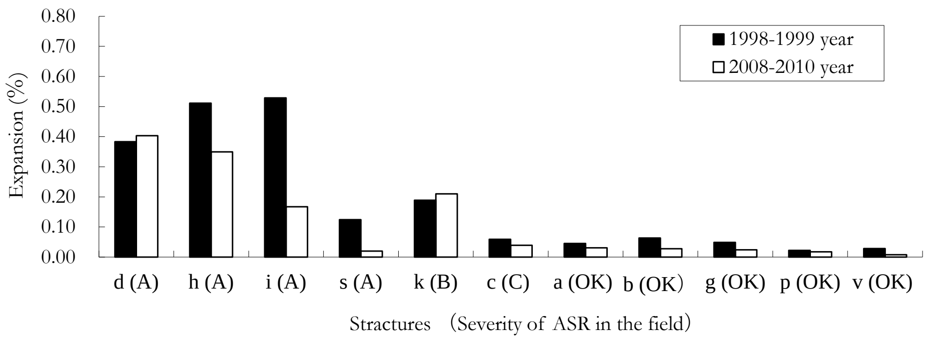


FIGURE 5 : Comparison between the field expansion ratio of the structures and the residual expansion ratios obtained by Canadian method

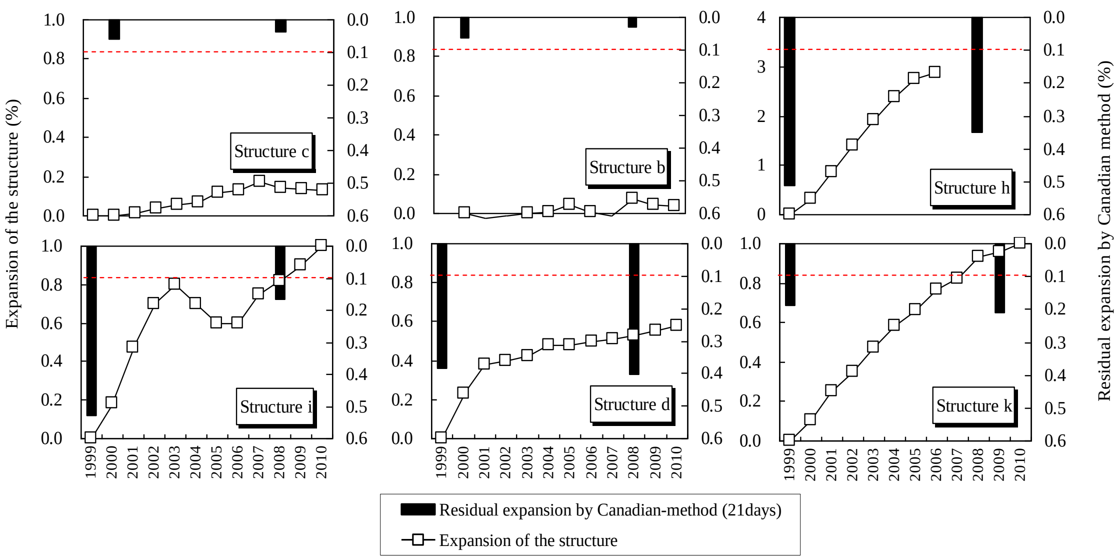


FIGURE 6 : Relationship between the field expansion ratio of the structures and the residual expansivity of concrete cores ratios

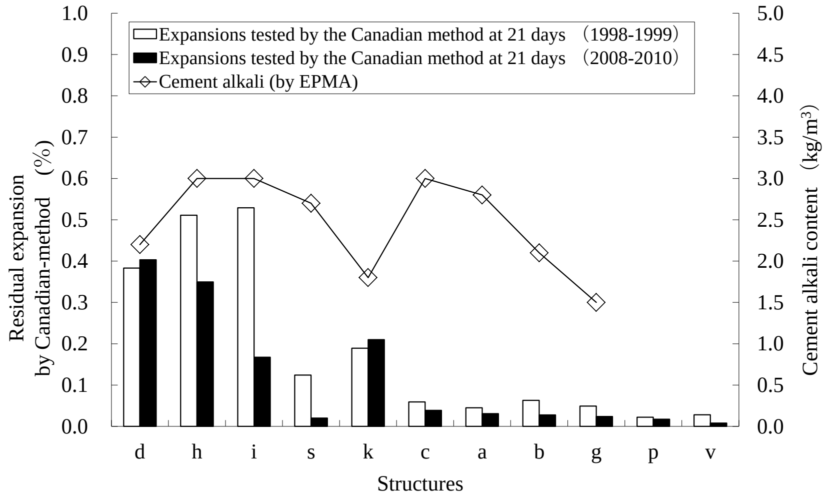


FIGURE 7 : Relationship between the alkali content and residual expansivity of cores

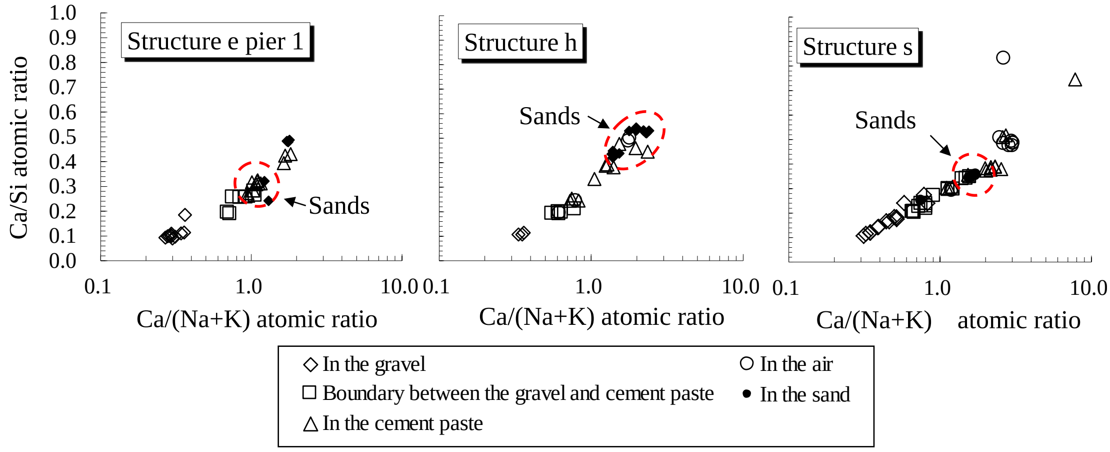


FIGURE 8 : Compositional trends of ASR-gels in concrete as determined by EPMA (EDS)

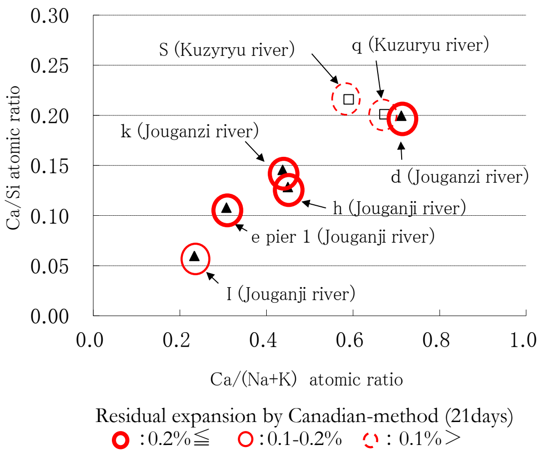


FIGURE 9: Relationship between the chemical composition [Ca/Si and Ca/(Na+K)] of andesite in gravels and the residual expansion ratio measured by Canadian method at 21 days

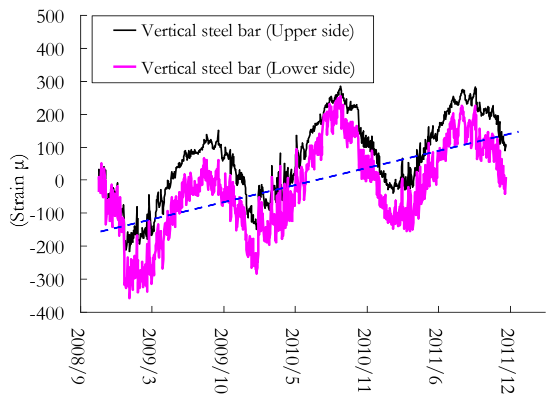


FIGURE 10: Strain of steel reinforcement due to ASR progress