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Alkali-Silica Reaction in Japan

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ABSTRACT: Alkali-Silica Reaction (ASR) has attracted considerable attention since the 1980s as one of the main causes of concrete deterioration in Japan. Defects caused by ASR are seen in various reinforced concrete structures such as viaduct piers, but there are no reports of ASR deterioration of large concrete dams. Possible reasons for the absence of ASR in large dams include low cement content and usage of fly ash blended cement compared with other concrete structures in Japan. On the other hand, deterioration of general concrete structures in Japan has significantly decreased since 1987 when provisional mitigation methods for ASR were introduced. However ASR is still seen in some concrete structures excluding dams despite the application of mitigation methods. In this paper, the results of long-term outdoor exposure test of concrete specimens with low total alkali are introduced to promote awareness of ASR.

1 DETERIORATION OF CONCRETE STRUCTURES DUE TO ASR IN JAPAN

1.1 *Deleterious rock types associated with ASR*

Various types of rocks are used as aggregate for concrete in Japan due to the region's complex geotectonic environment and many of the types used can cause ASR in concrete. The Public Works Research Institute (PWRI) collected samples of aggregate from quarries throughout Japan and examined their alkali reactivity using the ASTM C 289 standard test method. The results are shown in Figure 1 (Wakizaka 1998). Volcanic rock, especially andesite, is widely used in Japan. The andesite contains cristobalite, tridymite and volcanic glass, which can have significantly high alkali reactivity. Chert, which contains cryptocrystalline quartz, is another typical aggregate with high alkali reactivity. Other sedimentary rocks, such as sandstone can also cause ASR.

Deleterious and potentially deleterious aggregates are distributed throughout Japan (Wakizaka 1998). Hence, deterioration due to ASR can occur almost anywhere in the region.

1.2 *Deterioration due to ASR and mitigation measures*

Alkali-silica reaction (ASR) has attracted considerable attention since the 1980s as one of the main causes of concrete deterioration in Japan. Defects caused by ASR are seen in various reinforced concrete structures such viaduct piers.

From the data on bridge inspections conducted by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), it is estimated that 2% of bridges built before 1987 are affected by ASR (Fig. 2, Kawano & Koga 2005). Cracking due to ASR was mainly observed in piers and abutments.

A report on ASR deterioration states that there has been a dramatic reduction in damage since 1987 when provisional measures for ASR mitigation set by the Ministry of Construction became effective. Provisional mitigation methods consisted of the following four options: (1) Use of certified safe aggregate, (2) Use of low alkali portland cement, (3)Use of blended cement with controlling effect, and (4) Control of the total alkali content in the concrete.

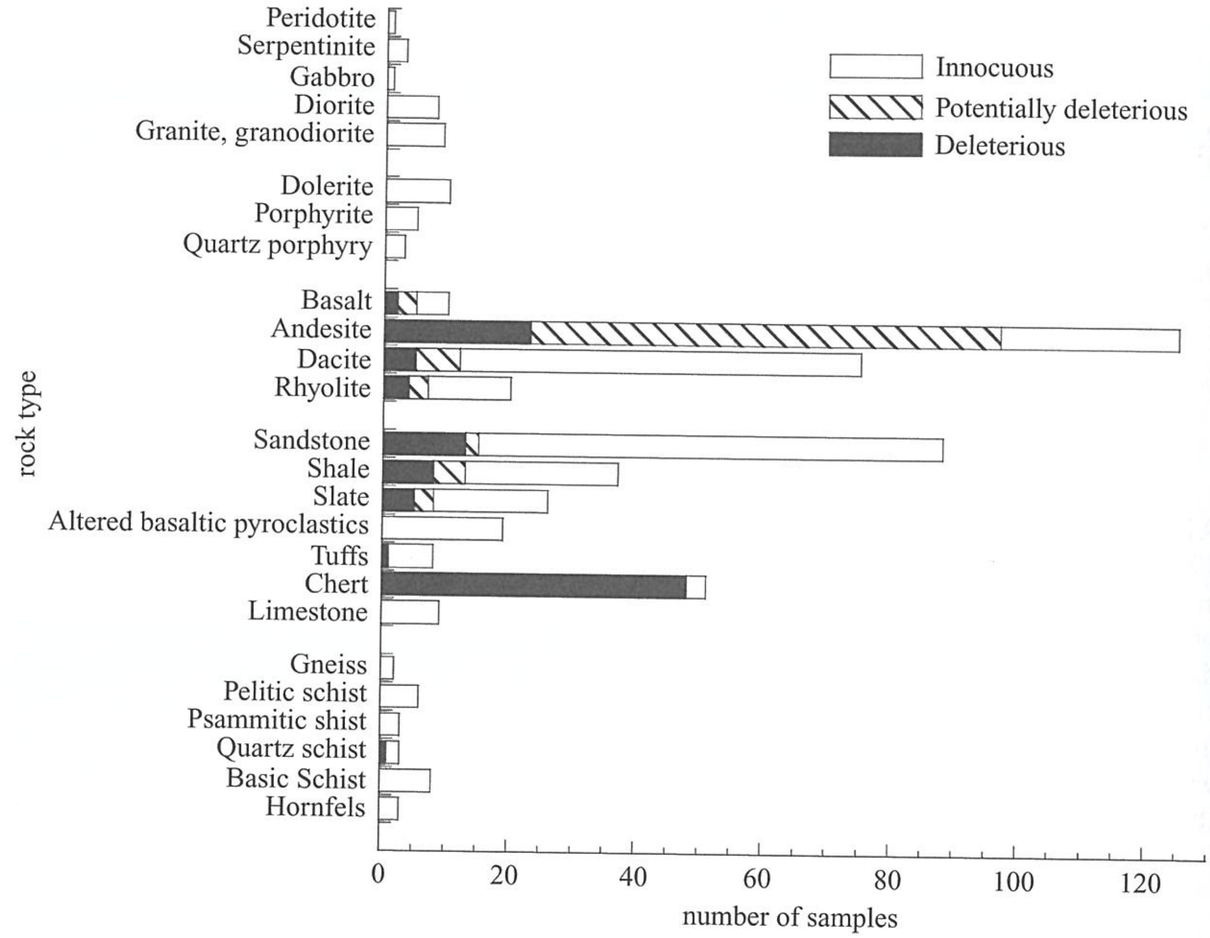

Figure 1. Reactivity of aggregates in Japan (from Wakizaka 1998).

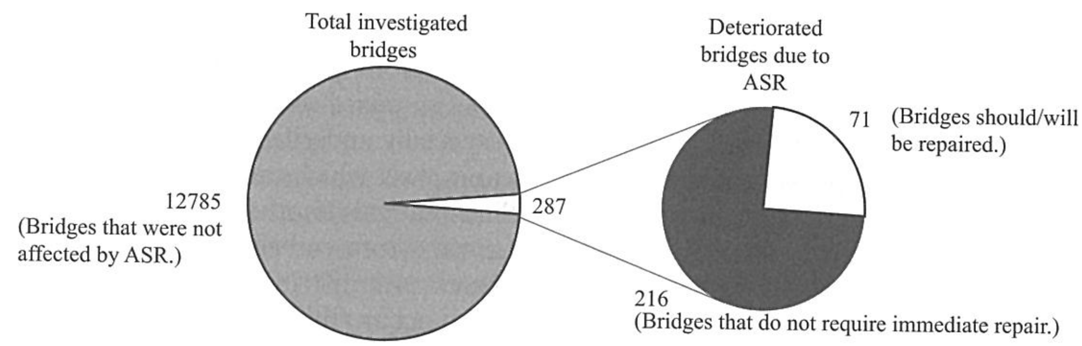

Figure 2. Number of highway bridges with deterioration due to ASR (Kawano & Koga 2005). * This figure was drawn using only the data on bridges managed by MLIT.

These measures were revised in 1989 and 2002. In the revised 2002 version, reference allowing the use of low-alkali portland cement was deleted mainly because of its limited marketability. One of the alternatives listed in Table 1 shall be chosen to prevent ASR, according to the revision in 2002.

2 MIX DESIGN OF DAM CONCRETE IN JAPAN

ASR is a major deterioration factor in Japan and its effects are seen in many different structures. However, there have been no reports of ASR causing damage to Japan's large dams. For instance, Kobayashi (1986) reported the absence of ASR deteriorated dams as

Table 1. Mitigation methods for ASR in Japan.

Control of the total alkali content in the concrete	The alkali content (based on Na_2Oeq) per cubic meter of concrete must be 3.0 kg or less. Portland cement with known alkali content should be used.
Use of blended cement with controlling effect	Use of blast-furnace cement conforming to JIS R 5211 or portland fly-ash cement conforming to JIS R 5213 or the use of binding material with verified suppressing effect on ASR added to portland cement In this case, blast-furnace slag in the blast-furnace cement should be 40% or more in mass and fly-ash in the fly-ash cement should be 15% or more in mass.
Use of certified innocuous aggregate	Use of aggregates that have been certified as innocuous according to alkali-silica reactivity tests (chemical method or mortar-bar method)

Table 2. Typical mix proportions of concrete used in large dams (Kano et al. 2005).

Type of dam	Type of concrete	Name of dam	Completion year	Gmax (mm)	W/B (%)	s/a (%)	Quantity of materials per unit volume of concrete (kg/m³)				Type of cement**
							W	B*	S	G	
Gravity Dam	Inner (conventional block)	Ikari	1956	150	62.9	27.8	104	170	584	1520	M
					56.8	26.2	114	200	535	1508	
		Sonohara	1964	150	56.3	25	90	160	540	1627	BB
		Shimokubo	1967	150	75.8	27	114	150	570	1565	BB
					68.6	27	110	160	568	1581	
		Ishidegawa	1972	150	69	24.5	110	160	523	1672	BB
		Ohishi	1978	150	68.7	23	110	160	490	1650	M
		Ohdo	1982	150	65	24	98	150	521	1662	M
		Hitokura	1983	150	75	27.1	105	140	612	1657	BB
		Kyuragi	1987	150	72.5	25	116	160	535	1616	BB
	Inner (ELCM)	Nunome	1991	150	88	26	115	130	560	1617	M+F
		Miharu	1997	150	80	23	112	140	501	1725	M+F
		Hinachi	1998	150	87.8	26	114	130	533	1580	M+F
		Nakasujigawa	1998	150	73.3	29	110	150	615	1527	M+F
	Inner (RCD)	shimajigawa	1981	80	87.5	34	105	120	752	1482	O+F
		Tamagawa	1990	150	73	30	95	130	657	1544	M+F
		Mano	1991	80	85.8	33	103	120	735	1520	M+F
		Nunome	1991	150	79.2	27	95	120	608	1670	M+F
		Miyagase	1998	150	73.1	30	95	130	652	1568	M+F
	Exterior	Ikari	1956	150	48.7	25.2	112	230	535	1508	M
		Sonohara	1964	150	42.5	23	85	200	474	1563	BB
		Shimokubo	1967	150	52.4	25	110	210	516	1570	BB
		Ishidegawa	1972	150	48	23.5	105	220	494	1662	BB
		Ohishi	1978	150	50	23	110	220	436	1610	M
		Ohdo	1982	150	50	23	105	210	483	1631	M
		Hitokura	1983	150	50	25.3	105	210	549	1657	BB
		Kyuragi	1987	150	54.5	23	120	220	477	1608	BB
		Tamagawa	1990	150	48	22	115	240	440	1572	M+F
		Miyagase	1998	150	50	26	108	216	537	1535	M+F
Arch		Naruko	1958	150	55.3	26	105	190	528	1504	M
		Amagase	1964	150	48.6	26.2	107	220	528	1525	M

(Continued)

Table 2. (Continued).

Yagisawa	1967	150	46	25	105	230	495	1504	M
Hoheikyo	1972	150	47.6	24	100	210	490	1527	M
Managawa	1977	150	51	26.5	107	210	550	1543	M
Kawaji	1983	150	43	25	100	230	520	1615	M+F

* B: binder; total of cement and admixture materials, such as blast furnace slag and fly-ash.
** Abbreviation used as types of cement; M: moderate heat portland cement, BB: blast furnace -slag cement, O: ordinary portland cement, F: fry-ash.

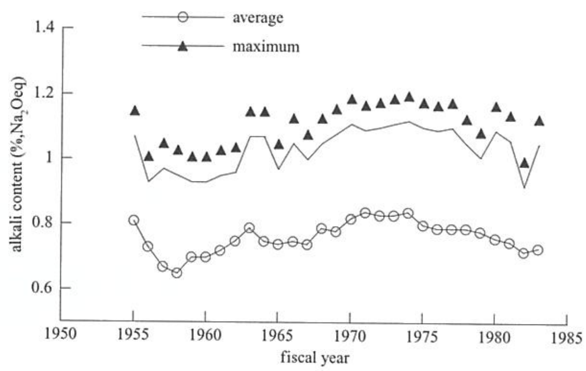

Figure 3. Alkali content of ordinary portland cement in Japan (Japan Cement Association, 1983).

the result of a document based survey of over 400 Japanese concrete dams with a height of 15 m or more.

The reason for this is considered to be the minimal amount of cement used in large dams in Japan. Typical mix proportions of concrete used in Japanese dams are listed in Table 2 (Kano et al. 2005). The amount of binder for dam concrete was usually set at less than 230 kg/m^3.

On the other hand, the maximum total amount of alkali in ordinary portland cement produced between 1955 and 1984 was approximately 1.2% (Na_2Oeq) according to Fujii (1949) and a report by the Japan Cement Association (1983, Fig. 3). Alkali content of cement has been reduced since the 1980s due to growing concern over ASR (Kobayashi, 1986). Although there was no detailed information on the alkali content of moderate heat portland cement, it is estimated to be almost the same as that of ordinary portland cement.

The total alkali content of dam concrete, therefore, should be less than 2.6 kg per cubic meter of concrete. In addition, the use of fly-ash or blast-furnace slag cement has been common in dam concrete since the 1980s,. The ratio of fly-ash in the mass of blended cement is usually between 20% and 40%, which should be enough to control ASR.

3 RECENT RESEARCH TOPICS ON ASR IN JAPAN

3.1 *Examples affected by ASR in recent concrete structures*

According to visual observations of recently built concrete structures in Japan, the number of the structures affected by ASR has decreased significantly, however, the problem has not been eliminated.

Although, it is difficult to identify the main cause of ASR in recent structures, a defect in the mitigation method using certified safe aggregate has been pointed out in several reports. For instance, Hayashi et al. (2009) reported the deterioration of a prestressed concrete bridge. ASR of the bridge was caused by opal and chalcedony produced by hydrothermal alteration in andesite, but this aggregate was judged as innocuous by the mortar-bar method normalized as the Japanese Industrial Standard testing method (JIS A 1146). Yoshizawa & Okazazi (2009) reported the deterioration of an expressway viaduct caused by fine aggregate that was certified as innocuous by the mortar-bar method. In each of these cases, ASR was caused by a small amount of a substance having high reactivity and the ASR risk could not be accurately judged by the JIS mortar-bar method.

On the other hand, a number of researchers have stated that the control of total alkali content at 3.0 kg/m^3 or less would not necessarily mitigate ASR. For instance, Katayama et al. (2008) reported the deterioration of structures in the Okinawa Expressway where total alkali content of concrete is estimated at between 2.2 and 3.5 kg/m^3 depending on the structures. They also pointed out that alkali reactivity of crypto- to microcrystalline quartz contained in imported sand and sea-dredged sand from Okinawa cannot be detected by the mortar-bar method or chemical method (JIS A 1146 & 1145). Hayashi et al. (2009) reported that the total alkali content of concrete used for the prestressed concrete bridge mentioned above was 2.6 kg/m^3 according to the concrete manufacturer. Obana & Torii (2008) reported ASR in prestressed concrete pavement having an estimated alkali content of 2.2 kg/m^3.

3.2 *Twenty-two-year exposure test*

3.2.1 *Test procedures*

In 1987, the PWRI initiated exposure tests on concrete specimens in which various types of coarse aggregate of Japan were mixed. Ninety-five samples of coarse aggregate, about two-thirds of which were volcanic rocks, were collected throughout Japan. The purpose of the research test was to provide data for the development of improved ASR mitigation measures.

The mix proportion for the concrete specimens is shown in Table 3. Four specimens were made for each coarse aggregate: two specimens with 3 kg/m^3 and two specimens with 5 kg/m^3 of total alkali content in concrete. The alkali content of specimens was controlled by adding NaOH to the mixing water.

The specimens are prisms with dimensions of 150 mm in width and depth, and 800 mm in height. Two re-bars 13 mm in diameter were embedded in each specimen as reinforcement. A third part of the specimen was buried in the ground as shown in Figure 4. The specimens were exposed for 22 years in the test field, unsheltered grassland, of PWRI (Tsukuba, Japan).

Table 3. Mix proportion of concrete used for exposure test.

Gmax (mm)	W/C (%)	s/a (%)	Quantity of materials per unit volume of concrete (kg/m^3)			
			W	C	S*	G**
25	50	44	177	354	780	from 866 to 1114

* Innocuous crushed limestone was used as fine aggregate in all specimens.
** Amount of coarse aggregate was varied depending on the density.

Figure 4. Outdoor exposure condition.

Table 4. Tentative results of visual observation.

Alkali content in concrete	Number of samples possibly affected by ASR		
3 kg/m³ (Na_2Oeq)	Total:	8	
		Andesite:	6
		Dacite:	1
		Dolerite:	1
5 kg/m³ (Na_2Oeq)	Total:	38	
		Andesite:	21
		Sandstone:	5
		Dacite:	4
		Slate:	2
		Rhyolite:	1
		Basalt:	1
		Dolerite:	1
		Shale:	1
		Hornfels:	1
		Andesitic pyroclastic rocks:	1

Table 5. Results of petrographic observation.

		Petrograhic observation		
Sample	Appearance	Rock types	Substances that have reactivity	ASR stage*
A	Cracking	Andesite 1	Cristobalite Volcanic glass	4
		Andesite 2	Volcanic glass	2 or 3
		Pelitic schist	Cryptocrystalline quartz	None
B	Cracking	Andesite	Tridymite Volcanic glass	4
C	No cracking	Andesite	Cristobalite Volcanic glass	2

* ASR stages are judged based on the classification by Katayama et al. (2008).
stage 1: Formation of reaction rims and exudation of ASR sol/gel around the reacted aggregate.
stage 2: Formation of gel-filled cracks within the reacted aggregate.
stage 3: Propagation of gel-filled cracks from the reacted aggregate into the surrounding cement paste.
stage 4: Migration of ASR gel into air voids.

3.2.2 *Visual observation after approximately 22 years*

In 2009, we conducted visual observation of cracks on the specimens and estimated whether or not ASR was the major cause. When there were differences in the condition of two specimens made with the same aggregate and total alkali content, it was estimated as a possible deteriorated case.

The tentative results of visual observation are shown in Table 4. Eight samples of coarse aggregate were suspected of causing ASR. Cracking on specimens with 3 kg/m³ alkali content was less significant than that on specimens with 5 kg/m³ alkali content.

3.2.3 *Detailed examination of three selected specimens*

Petrographic investigation was carried out using three specimens having 3 kg/m³ alkali content in the concrete. The results are shown in Table 5. Samples A and B that consist of crushed andesite stone contain cristobalite, tridymite and volcanic glass. In sections of concrete with

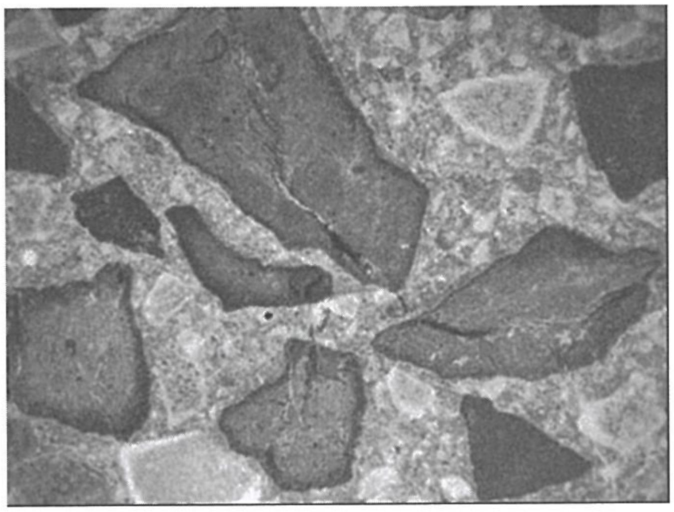

Figure 5. Cracks observed in a section (Sample A).

Samples A and B, the formation of reaction rims and cracks filled with ASR gel were identified, which is characteristic of ASR (Fig. 5).

Sample C also caused significant cracking in specimens with 5 kg/m^3 alkali content. However, in specimens with 3 kg/m^3 alkali content, while there is slight evidence of reaction by petrographic investigation, there is no significant cracking to indicate expansion of concrete. It is judged that the reactivity of Sample C was sufficiently mitigated by controlling the total alkali content at Na_2Oeq 3.0 kg/m^3.

However, it is difficult to explain why there is a difference in ASR stages between Samples A, B and C in the concrete with Na_2Oeq 3 kg/m^3 total alkali content.

4 CONCLUSION

Despite the wide distribution of aggregates with high alkali reactivity, there are no reports of ASR deterioration in Japanese large dams. It is assumed that this is due to the small amount of cement used in dam concrete and the use of fly-ash or blast-furnace slag cement. However, recent research has shown that some aggregates can cause expansion of concrete even at a total alkali content of less than Na_2Oeq 3.0 kg/m^3. To ensure the success of ASR mitigation, further research is necessary on all concrete structure including large dams whose alkali content of concrete is relatively small.

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