

**ALKALI-AGGREGATE REACTIVITY IN JAPAN—A REVIEW**

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INTRODUCTION

Recently, cracking damage to concrete structures due to alkali-aggregate reactions (AAR) have been increasingly found in Japan.

Active investigation and research on alkali-aggregate reactions started in Japan in the early 1980's. A number of research organizations have dealt earnestly with the difficult AAR problem for about ten years now, and the level of research in our country has come lately to rank among the world.

This paper reviews various aspects of research on AAR, including such basic studies as the mechanisms of AAR, the microstructure of reaction products and petrographic study, effect of mineral and chemical admixtures on AAR, standard and new rapid testing methods, preventive measures for AAR, and inspection and repair of damaged concrete structure due to AAR.

Research concerned with AAR dates back to the 1950's. Investigations were made using the Chemical Method and the Mortar Bar Method according to ASTM Standards on the approximately 100 kinds of river aggregate throughout the country. At that time, only two or three kinds of aggregate that consisted with chert and shale were evaluated to be potentially alkali reactive.

In 1965, an investigation of an accident in which the parapet of a building in Yonago, Tottori, spalled and fell off, approximately 35 years after construction, revealed the cause to be alkali-silica reaction between andesite, containing a large quantity of tridymite, and cement, showing typical reaction rings.

Since then, however, nothing whatsoever has been reported about cracking damage due to reactions until the 1980's, where damage due to AAR was observed in reinforced concrete structures of Hanshin Expressway, Osaka. After this case of damage was reported, other investigations revealed that there were a number of such cases of damage, mainly in western Japan. Types of reactive rock in Japan are limited at present to andesites, cherts, and slates.

The reasons why AAR has occurred so often recently in Japan the same as in other countries around the world. The main reasons in Japan can be explained as follows:

(1) Many kinds of crushed stone have been used as aggregates without checking for reactivity, because of the lack of the commonly used river aggregate.

(2) The alkali content of cement has become higher and cement content tends to be increasing, particularly to improve the pumpability of concrete.

(3) The use of marine sand as fine aggregate as a replacement for commonly

used river sand has increased, resulting increasing alkali content in concrete.

## REVIEW OF THE RESEARCH ON AAR IN JAPAN

It has been only a short time since research on AAR has started regularly, as mentioned above. Fifty or more experimental results on AAR were reported every year in the annual meeting held by JSCE, JCI, the Cement Association, or other societies or associations.

Such reports can be roughly classified into basic studies on AAR, such as mechanisms, microstructure, and petrographic and mineralogical studies, testing methods, including standard, rapid, and accelerated tests, and controlling methods, which consists of the countermeasure of prevention for structures in the future and repairs to damaged concrete structures due to AAR.

### 1. BASIC STUDY

#### (1) Mechanisms

Studies on the mechanisms of AAR can be divided roughly into before and after damaged concrete structures due to AAR were actually found in Japan.

Research concerning the mechanisms of AAR had already been conducted by the group headed by Professor Kawamura, Kanazawa University, before AAR was found. The following findings were reported in a series of papers between 1979~83 by Kawamura<sup>1), 2), 3)</sup>.

(a) The alkali concentration within the peripheral layer of opal grains embedded in cement paste rapidly increases, and the microhardness in the region decreases, with time. The thickness of the soft region increases as the alkali-silica reactions occurring within the opal grain proceed. The hardness decreases as water gradually penetrates into the reacting region.

(b) The solidification after 14 days of the softened region within about 50 microns from the interface that was found in coarse opal grains embedded in cement paste appears to relate to the intrusion of a relatively large amount of  $Ca^{++}$ .

(c) The flyash used in these studies did not inhibit ASR at all, but facilitated the mobilization of  $Ca^{++}$  ions into reacting with the aggregate grains. These results led to the proposal of a concept of the mechanisms responsible for the preventive effects exerted by flyash in ASR.

With increases in AAR problems in Japan, the interest of researchers has been focused on elucidation of the mechanisms of the inhibition of AAR by flyash, blast furnace slag, and silica fume, as described later.

#### (2) Microstructure of Reaction Products and Petrographic Studies

Andesitic rocks were the aggregates considered to be responsible for deterioration due to AAR in Japan. The reactive components in the rocks were cristobalite, tridymite and volcanic glass<sup>4)</sup>. Later, affected concrete structures, including cherty rocks, were found in several regions in Japan<sup>5)</sup>. Several researchers<sup>5), 6), 7)</sup> who conducted petrographic examinations on cherty rocks in the affected concrete identified cryptocrystalline quartz, chalcedony and strained coarse quartz as potential alkali reactive components. They also investigated the microstructure of reaction products by means of SEM, polarizing microscope, and X-ray diffractometer.

The reaction products on the fractured surfaces of aggregate grains in concrete cores drilled from a damaged structure were classified into three types: ①  $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{SiO}_2$ , ②  $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{SiO}_2$  and ③  $(\text{Na}_2\text{O})-\text{K}_2\text{O}-\text{CaO}-\text{SiO}_2$ . The reaction products of Type ① and ② are jelly-like, while the appearance of Type ③ reaction product is rosette-like. Such rosette-like reaction products were also found in other affected concrete<sup>5)</sup>.

### (3) Effect of Mineral Admixtures on Alkali-Aggregate Reactions

The effect of mineral admixtures such as blast furnace slag and flyash, to counteract AAR has been especially investigated, because these materials are produced as byproducts in very large quantities in Japan. Quality data on slags and flyashes indicate that the total alkali content ranges from 0.4 to 0.7 % for slag and 0.8 to 3.5% for flyash. Silica fumes are also almost all imported and are only rarely produced in Japan. Counteraction effect testing of these mineral admixtures on AAR shows that slag and flyash exert counteraction effects when portland cement is replaced 40% or more by slag and 20% or more by flyash<sup>8), 9), 10)</sup>.

The major results obtained between 1983~88 in Japan are as follows:

- (a) The enhancement of expansion in opal mortars containing silicafume is attributable to the delay in softening of the gels formed in the mortar<sup>11)</sup>.
- (b) Some factors other than the reduction in alkalinity in pore solutions are related to the prevention of expansion due to the ASR caused by the incorporation of pozzolans and slag<sup>12), 13)</sup>.
- (c) Different silica fumes vary widely in their preventive effects on alkali-silica expansion of mortars with opal aggregate<sup>14)</sup>.
- (d) The effectiveness of flyashes in inhibiting the expansion of mortar with a siliceous aggregate which reacts very quickly varies widely, depending on their alkali content and pozzolanic activity<sup>15)</sup>.

### (4) Influence of Cements and Chemical Admixtures on Alkali-Aggregate Reactions

#### (a) Influence of Cement

The total alkali content of normal portland cement is less than 1.07%  $\text{Na}_2\text{O}$  equiv. at most, and has been gradually reduced between 1983 and 1988. The total alkali content of normal portland cement averaged 0.60% with a maximum of 0.69%, according to statistics on cement quality in Japan collected in 1987. The degree of alkali-silica expansion affected by the alkali content in normal portland cement has been investigated by many researchers. The results indicate that the expansion of mortar bars using typical andesitic reactive aggregate and cherty reactive aggregate do not occur when the total alkali content is less than 0.6%<sup>10), 16)</sup>. On the other hand, the expansion of concrete using the same aggregate does not occur in concrete with less than 3  $\text{kg/m}^3$   $\text{Na}_2\text{O}$  equiv. total alkali, thus, 3  $\text{kg/m}^3$  is judged to be the critical content for alkali-silica expansion.

#### (b) Influence of Chemical Admixtures

The influence of air entraining agents, water reducing agents, superplasticizers, etc., differs with the kind of chemical admixtures. It is considered that the factors of chemical admixtures which influence the alkali-silica expansion are the alkali content of the admixtures and the dispersing power of the cement particles. For this reason, chemical admixtures having a high alkali content and high dispersing power sometimes show a high possibility of promoting ASR<sup>17)</sup>.

#### (5) Influence of Environmental Conditions on Alkali-Aggregate Reactions

Expansion caused by AAR is affected by temperature, humidity and externally supplied alkali. Typical results obtained in recent investigations are as follows.

##### (a) Influence of Temperature

Alkali-silica expansion depends on the temperature. The pessimum temperature exists in relation between temperature and expansion. Results of mortar bar tests with typical andesitic reactive aggregate indicate that the temperature at the maximum expansion of the mortar bar is 40°C. At 60°C, the expansion is small and saturates at an early stage. At 20°C, however, although expansion starts after a delayed time, it occurs more at a later stage than at 40°C<sup>18)</sup>.

##### (b) Influence of externally supplied alkali

In general, alkali-silica expansion is said to be accelerated by sea water or by alkali sulphate in soil but the degree of expansion varies over a very wide range, depending on the conditions. From the results of testing of concrete specimens made with andesitic reactive aggregate, it was discovered that when specimens were exposed in a half immersed condition in sea water, the expansion was extremely accelerated.

## 2. TEST METHODS - STANDARDS AND NEW RAPID TESTS - AND PREVENTIVE MEASURES FOR ALKALI AGGREGATE REACTION IN JAPAN

### (1) Standard Test Method

The standard test method which has been tentatively established by the Japan Concrete Institute (JCI) is composed of the Chemical, Mortar bar, and Concrete specimens tests<sup>19)</sup>.

#### (a) Chemical test

In the chemical test method in Japan, it was considered that the accuracy of test results would be improved by changing the method of drying by evaporation to the method of dehydration uses with perchloric acid for the determination of the dissolved silica content (Sc), for which errors had been comparatively large, and also by the combined use of the gravimetric method and atomic absorption spectroscopy.

#### (b) Mortar bar method

Using several test results as references, and broadly conforming to the ASTM specifications, the following test conditions were provided for the mortar bar testing method:

- 1) Specimen size = 4 × 4 × 16cm, as specified in the Japanese Industrial Standard (JIS) for the cement mortar tests ;
- 2) Total alkali content = 1.2% Na<sub>2</sub>O equiv. (adjusted by NaOH) ;
- 3) Water cement ratio = 0.50.

The ASTM testing conditions and expansion limits were adopted as test conditions. However, it was recommended that the minimum period of measurement shall be one year, because some aggregates showed large expansion after longer periods of curing.

#### (c) Concrete specimens method

Testing of the concrete specimens has as its objectives the evaluation of the reactivity of aggregates and the estimation of the cracking damage due to

AAR under conditions of actual use. At present, studies are mainly being made of the shape and dimensions, the storage conditions, the unit cement content and the total alkali content of the test specimens, comparisons of the test results obtained from mortar bars, and investigation of the relationship between length change, total alkali content (or cement content), and strength.

The items measured were the length change, the dynamic modulus of elasticity and the ultrasonic pulse velocity and crack growth pattern.

## (2) New Rapid Testing Methods

The mortar bar method is considered to be the most reliable method for evaluating the reactivity of aggregate, at present. However, this method is time consuming. Therefore, it is of practical importance to develop a rapid, simple, and reliable method of determining the reactivity of an aggregate.

Several types of rapid test methods have been proposed in Japan to rapidly identify the alkali reactivity of an aggregate and to clarify the expanding behavior and cracking characteristics of concrete.

### (a) Takenaka Komuten Co. LTD.<sup>20)</sup>

The method of immersing specimens in NaOH solution at early age and then sustaining them under high temperature and high humidity is effective to accelerate the reaction and the expansion of mortar bars. The temperature is 80°C, the immersion period is 24 hours and the concentration of the NaOH solution is 1 N. The results of the rapid test have a good correlation, which with those of the mortar bar method and the reactivity of the aggregate, can be evaluated at 7 days.

### (b) General Building Research Co. LTD.<sup>21)</sup>

Mortar specimens (Dimensions = 4 × 4 × 16cm, S : C = 1 : 1, W/C = 0.50, alkali content = 2.5% Na<sub>2</sub>O equiv.), after 3 days of curing, are placed in boiling water in a pressure vessel (0.5 kgf/cm<sup>2</sup>, 110°C) for two hours. Cracking, changes in the ultrasonic pulse velocity and the dynamic Young's modulus of the specimens are inspected just before and after boiling. The aggregate is evaluated as innocuous, when the pulse velocity or the dynamic Young's modulus is less than 5% or 15%.

### (c) Tottori University<sup>22), 23), 24)</sup>

Mortar specimens (Dimensions = 4 × 4 × 16cm, C/S = 1/2.25, W/C = 0.45, total alkali content = 2.0% Na<sub>2</sub>O equiv. (by NaOH)) are subjected to autoclave treatment. The test conditions based on the results of several experiments, are as follows:

Pressure in the autoclave kiln = 0.1 Mpa, duration of the autoclave treatment = 4 hours, age of the specimen = 24 hours after casting, measurement of the length change = 24 hours after autoclave treatment. The expansion that occurred during the autoclave treatment corresponds to about 30% of that of the normal storage condition. The expansion limit of 0.02% is proposed as the standard for evaluation the activity of aggregate.

Concrete specimens (Dimensions = 10 × 10 × 40cm) are subjected to repeated cycles of immersion in a testing bath (20°C) and drying in an oven (60°C). The length change, the reduction in the dynamic Young's modulus and, the ultrasonic pulse velocity are measured until 50 cycles in order to determine the degree of deterioration due to AAR. When the expansion is greater than 0.1% and the reduction in the dynamic Young's modulus is less than 80%, it must be evaluated that injurious cracking damage has occurred in the concrete.

### (d) Kyoto University<sup>25)</sup>

Concrete specimens (Dimensions = 10 × 10 × 40cm) are subjected to repeated cycles of 40°C, RH 100%, 12 hours, and 20°C, RH 60%, 12 hours. This wetting

and drying exposure simulates the most severe exposure conditions anticipated in Japan. Under these test conditions, the effects of various repair systems (both the waterproofing type and the water repellent type) are examined for quality in the actual exposure conditions in Japan.

### 3. PREVENTION OF ALKALI-AGGREGATE REACTIONS IN NEW CONSTRUCTION

One of the following measures should be taken for the prevention of AAR in new concrete structures, according to the tentative recommendations proposed by the Ministry of Construction:

- 1) Use of aggregate considered innocuous by means of either the chemical method or the mortar bar method;
- 2) Use of low-alkali portland cement, i.e. less than 0.6% Na<sub>2</sub>O equiv.;
- 3) Use of an appropriate blended cement, such as blast furnace slag cement of Type B and C with a slag content of 30 to 60% or 60 to 70%, and flyash cement Type B and C with a flyash content of 10 to 20% or 20 to 30%, or admixture such as blast furnace slag and flyash;
- 4) Control of the total alkali content in concrete. The total alkali content of the concrete mix shall not exceed 3 kg/m<sup>3</sup> of Na<sub>2</sub>O equiv., when portland cement is used.

### 4. DAMAGED CONCRETE STRUCTURES DUE TO ALKALI SILIKA REACTION AND THEIR REPAIR

#### (1) Field Investigation

Investigation of damaged concrete structures is carried out generally on cores drilled from the structures. Investigations include measurement of core expansion at 40°C and 100% RH, rock identification by mineralogical inspection, measurement of alkali content, measurement of crack width and depth, checking the corrosion of the reinforcing bars, compressive strength and Young's modulus of the cores, ultrasonic velocity of the structures, etc. Reactive aggregates found in the damaged structures are Bronzite Andesite, Chert, Slate etc. Bronzite Andesite is most popular reactive aggregate in Japan.

Some results of the field investigation are as follows:

The degree of damage or cracking due to ASR depends upon the mix rate of Bronzite Andesite in the total coarse aggregate and the alkali content. The amount of expansion of the cores from the concrete structures with significant cracking exceeded  $500 \times 10^{-6}$ . There is a tendency for wider cracks to be deeper, but the crack depth in most reinforced concrete structures investigated remained within a range of the concrete cover. The compressive strength of concrete drops due to ASR, but Young's modulus estimated from the deflection of the beam measured at the loading test was not so low<sup>(2,6)</sup>. The low Young's modulus measured by the core may be due to the release of restriction existed in the structure.

#### (2) Repair by Coating

An efficient method to inhibit AAR has not been established yet. Since AAR requires water for the reaction, it is inferred that waterproofing might be effective to inhibit AAR.

Various types of coating materials have been tested in Japan. Some of the materials have been applied to bridge substructures damaged by ASR. Poly-

urethane resin and epoxy resin were selected as waterproofing coatings. Polybutadiene resin, silane resin and polymer cement were selected as aeration coatings. Cracks wider than 0.3mm were normally injected before coating. Before repair by coating, crack width and depth, corrosion of steel, reactive aggregate used, expansion of core drilled from the structure, etc. were investigated. After coating, strain measurement is carried out periodically on the surface of the structure.

Residual expansion of the core at the time of coating as well as the total expansion should be taken into account when judging the efficiency of the coating by the degree of the strain after coating.

The following statements can be made from the field tests:

(a) Waterproofing coatings are not very effective, as the piers expanded greatly after coating and cracked again.

(b) The effect of polybutadiene cannot be determined at this stage since the residual expansion of the abutment is very little, although the abutment has not re-cracked after coating.

(c) Silane resin looks effective for the pier. However, the coating was applied at the rate stage of the expansion. Therefore, more information is required to determine the efficiency of silane resin.

(d) Polymer cement appear to work well for the pier. The strain occurring in the pier appears only due to temperature change, although the residual expansion of the core is very large. However, this result is limited to within a year after coating. Therefore, more observation is required before judging the efficiency.

Dr. Ono will offer some examples of the field investigation and repair, in his key note lecture.

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