Suppressing Effect of Alkali Silica Reaction in Chloride Attack Environment by Classified Fine Fly ash

Makoto TSUDA¹, Amin Khalili AHMAD RIZAL², Yuka NAKATA³ and Kazuyuki TORII⁴

¹ Department of Civil Engineering, National Institute of Technology, Ishikawa College, Kitacyujo, Tsubata, Ishikawa, 929-0392 Japan, m-tsuda@ishikawa-nct.ac.jp
² Architecture and Civil Engineering, Toyohashi University of Technology, 1-1 Hibi-riaoka, Tempaku, Toyohashi, Aichi, 441-8580, Japan
³ Department of Civil Engineering, National Institute of Technology, Ishikawa College, Kitacyujo, Tsubata, Ishikawa, 929-0392, Japan
⁴ Central Nippon Highway Engineering Nagoya Company Limited, 1-8-11 Nishiki, Naka-ku, Nagoya-shi, 460-0003, Japan, torii@se.kanazawa-u.ac.jp

ABSTRACT

In the Northernmost area of Noto Peninsula, Ishikawa Prefecture, Japan, ASR occurs even in structures conforming to the current JIS. This has been attributed to airborne salt and deicers. On the other hand, recent research reports that fly ash has an ASR-suppressing effect, with regional implementation being under way. In this research, expansion tests are conducted under multiple conditions to investigate the ASR-suppressing effect of classified fly ash in mixtures containing regenerated aggregate in salt-laden environments, demonstrating its sufficient effect even when using aggregate with high ASR reactivity and recycled aggregate.

INTRODUCTION

Crushed volcanic rocks, such as andesite, and river gravel from neighboring prefectures have been used as important aggregate resources for concrete in the northernmost area of Noto peninsula, Ishikawa Prefecture, in short supply of gravel resources. On the other hand, deterioration due to serious alkali-silica reaction (ASR) has been posing problems in concrete structures made using aggregate from these volcanic rocks.

Miocene volcanic rocks referred to as the Anamizu Formation, which mainly comprises andesitic lava and pyroclastic rocks, account for the largest part in the geology of the northwestern part of the Noto Peninsula. These volcanic rocks generally contain volcanic glass, cristobalite, etc., causing deterioration by ASR when used as aggregate for concrete.

In addition, although ASR suppression measures in Japan are based on the total alkali control value (3 kg/m³)(Alkali aggregate reaction restraint measure, 2002), it is also pointed out that ASR may progress over a long period of time due to the effect of alkalis eluted from the aggregate (Nomura, et al., 2006). On the other hand, although the total alkali amount regulation is observed as one of the ASR control measures, concrete structures in which ASR is still occurring have been recognized. As shown in Figure 1, aggregate that have been judged “innocuous” can cause ASR, presumably due to the effects of alkali elution from the
aggregate and the chloride environment of the structure, such as the use of deicers and airborne salt from the sea.

However, due to the requirement for local production for local consumption, mitigation of environmental load and current social conditions, it is not realistic to select aggregate with no risk of ASR. It is rather important to effectively utilize locally produced aggregate and formulate rules of control measures suitable for the aggregate to be used in respective areas to construct concrete structures without ASR-induced deterioration.

As shown in Figure 2, Neogene and Quaternary volcanic rocks containing rapidly expanding reactive minerals are distributed all over Japan, posing potential risk of ASR anywhere in the country. Therefore, there are many potentially ASR-degraded structures in Japan, even in areas where ASR has not been reported so far, with research on risk management for ASR-deterioration being underway (Tori, et al., 2014) (Katayama, et al., 2012) (Yamada, et al., 2014) (Kawabata, et al., 2007). Hence, reduction of the ASR risk is required in various environments of structures while effectively utilizing resources available.

In this study, tests were conducted using fly ash (FA), which is reported to have an ASR-suppressing effect, with the aim of making various aggregates produced in Japan safely usable without the risk of ASR, assuming a chloride attack environment, which is one of the harshest conditions for concrete. To investigate the ASR-suppressing effect of classified FA, expansion test specimens were fabricated using mortar and concrete containing FA, as well as aggregate with high ASR reactivity. These were cured in salt water and a sodium hydroxide solution. Based on the results, the authors verified the ASR-suppressing effect of FA in chloride attack environments.

Figure 1. Overview of ASR-deteriorated structure (Used non active aggregate)
EXPERIMENTAL DETAILS

Expansion tests were conducted on concrete specimens as ASR reactivity testing of aggregates. Eight cases were tested using mixtures shown in Table 1. Both coarse and fine aggregates for ASR-reactive specimens were those from Joganji River in Toyama prefecture. Reference specimens were fabricated using gravel and sand from the Tedori River, Ishikawa Prefecture, which are regarded as non-reactive aggregates. Classified FA produced at the Nanao-Ota Thermal Power Plant of Hokuriku Electric Power Co. was used as a supplementary cementitious material. Table 2 gives the physical properties of FA. 15% by weight of cement was replaced with FA as a percentage with sufficient field experience in the Hokuriku district.

Cylindrical specimens with a diameter of 100 mm and a height of 200 mm were prepared for the tests. After standard curing in water for 28 days, moist-cured specimens were placed in a thermostatic chamber at 40°C. Brine-cured specimens were immersed in a 1 mol NaCl solution in the thermostatic chamber at 40°C. The expansion of both moist- and Brine -cured specimens was then measured in accordance with the mortar bar method specified in JIS A1146. Measuring chips were attached after fixing stainless-steel bands to each specimen at intervals of 100 mm for measurement using a contact gauge. Compression tests were also conducted after standard curing.
The aggregates used for test concrete were subjected to testing by the chemical method (JIS A1145) and mortar bar method (JIS A1146), which are the standard judgment criteria in Japan. SSW tests involving chloride permeation as a curing condition were also conducted in accordance with JIS A1146 to simulate a chlorine attack environment. In these tests, mortar bars fabricated in accordance with JIS A 1146 were wrapped with absorbent paper impregnated with a 20% aqueous NaCl solution and stored to be kept in the presence of the NaCl solution.

Meanwhile, accelerated mortar bar tests (ASTM C1260) were conducted as a method of judging conformity to the ASTM standard. The specimen size and aggregate grading were selected to conform to the mortar bar method of JIS A1146. According to ASTM C1260, specimens with an expansion coefficient of <0.1% at 14 days is judged “innocuous” in regard to ASR. With an expansion coefficient of ≥0.1% and <0.2%, specimens are judged “indistinct” with a mixture of “innocuous” and “not innocuous” conditions. Specimens with an expansion coefficient of ≥0.2% are judged “not innocuous”. ASTM C1260 does not require control of the total alkali content at the time of specimen fabrication.

Table 1. Mix proportions of concrete

<table>
<thead>
<tr>
<th>Marks</th>
<th>Aggregate</th>
<th>Curing method</th>
<th>W/B (%)</th>
<th>Air (%)</th>
<th>s/a (%)</th>
<th>Gmax (mm)</th>
<th>Replacement ratio (%)</th>
<th>Unit content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-OPC</td>
<td>River</td>
<td>40°C moisture</td>
<td>55</td>
<td>5.0</td>
<td>43.5</td>
<td>25</td>
<td>-</td>
<td>Water: 168, 305, 769, 1006, 0.405, 0.0122</td>
</tr>
<tr>
<td>N-OPC-S</td>
<td>(non-reactive)</td>
<td>40°C NaCl solution</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Cement: 15, 152, 35, 235, 41, 792, 1035, 0.365, 0.11</td>
</tr>
<tr>
<td>N-FA</td>
<td>River</td>
<td>40°C moisture</td>
<td>15</td>
<td>15</td>
<td>23</td>
<td>35</td>
<td>168</td>
<td>Ad1: 1006, 0.405, 0.0122</td>
</tr>
<tr>
<td>N-FA-S</td>
<td>(reactive)</td>
<td>40°C NaCl solution</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Ad2: 1006, 0.405, 0.0122</td>
</tr>
<tr>
<td>R-OPC</td>
<td>River</td>
<td>40°C moisture</td>
<td>15</td>
<td>15</td>
<td>23</td>
<td>35</td>
<td>168</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Ad2: 1006, 0.405, 0.0122</td>
</tr>
</tbody>
</table>

Ad1 Air-entraining and Water-reducing Admixture
Ad2 Air-entraining Admixture for fly ash

Table 2. Physical proportions of fly ash

<table>
<thead>
<tr>
<th>Type of Fly ash (JIS A6201)</th>
<th>Density (g/cm³)</th>
<th>Blaine fineness (cm²/g)</th>
<th>45μm sieve remains ratio (%)</th>
<th>Percent flow (%)</th>
<th>Activity index Date28days (%)</th>
<th>Date91days (%)</th>
<th>Methylene Blue absorption (mg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type II</td>
<td>&gt;1.95</td>
<td>&gt;2,500</td>
<td>&lt;40</td>
<td>&gt;95</td>
<td>&gt;80</td>
<td>&gt;90</td>
<td>—</td>
</tr>
<tr>
<td>Nanto ota Type II</td>
<td>2.45</td>
<td>4770</td>
<td>1</td>
<td>111</td>
<td>91</td>
<td>105</td>
<td>0.34</td>
</tr>
</tbody>
</table>
TEST RESULTS AND DISCUSSION

Results by the chemical method (JIS A1145). Figure 3 shows the test results by the chemical method. Coarse and fine aggregates from Joganji River, which are highly ASR-reactive, were judged “not innocuous”, and the other aggregates were judged “innocuous”. However, coarse and fine aggregates from Tedori River were judged “quasi-not-innocuous” according to the judgment criteria by East Japan Railway Company.

![Figure 3. Results by the chemical method (JIS A1145)](image)

Results by the mortar bar method (JIS A1146). Figure 4 shows the test results by the mortar bar method. Though the curing period is 1/3 of the prescribed 180 days, all specimens scarcely expand, including those made using aggregate from Joganji River, which was judged “not innocuous” by the chemical method and regarded as highly ASR-reactive.

![Figure 4. Results by the mortar bar method (JIS A1146)](image)
Results by the mortar bar method (SSW method). Figure 5 shows the results of SSW tests. The curing period is 1/3 of the prescribed 180 days, similarly to the JIS mortar bar method mentioned above. However, fine aggregate from Joganji River, which was judged “not innocuous” by the chemical method, showed expansion behavior. These results suggest that chlorides can accelerate ASR.

![Figure 5. Results by the mortar bar method (SSW method)](image)

Results by the accelerated mortar bar method (ASTM C1260). Figure 6 shows the results of accelerated mortar bar tests. Specimens made using fine aggregate from Joganji River without FA replacement show large expansions from the beginning, exceeding 0.4%, twice as large as the standard value of 0.2% for judging “not innocuous”, at the number of days for judgement of 14 days. The expansion continues to linearly increase thereafter.

![Figure 6. Results by the accelerated mortar bar method (ASTM C1260)](image)
demonstrating high ASR reactivity. On the other hand, in the case where 15% of cement is replaced with FA as a supplementary cementitious material, no expansion is found in all the specimens, with the value being less than 0.1%, the value for judging “innocuous”, even at 28 days, which is twice as long as the number of days for judgment. A significant ASR-suppressing effect of FA is therefore demonstrated even with aggregate with high ASR reactivity.

As to fine aggregate from Tedori River, which is regarded as nonreactive, the expansion at 14 days, which is the number of days for judgment, is in the range of “indistinct”. During the extended test period of 14 to 28 days, however, the expansion exceeds 0.2%, the value for judging “not innocuous”, with the increase in the expansion during this period being as large of 70% of that during the period from 0 to 14 days. In addition, the amount of dissolved silica, Sc, by the chemical method of JIS A 1145 exceeds 50 mmol / l. This aggregate can therefore be judged “not innocuous” by the mortar bar method, as previously pointed out(Tsuda, et al., 2015).

The results of recycled fine aggregate, which was judged “innocuous” by the chemical method, are nearly the same as those of the above-mentioned fine aggregate from Tedori River. Therefore, there is a risk in judging recycled fine aggregate by the chemical method. Furthermore, specimens in which FA is mixed with recycled aggregate show little expansion, demonstrating a significant ASR-suppressing effect of FA. From these results, the use of FA as a supplementary cementitious material can be an effective means to reduce the risk of ASR when using recycled aggregate for concrete.

Figure 7 and 8 compare specimens made using reactive aggregate with and without FA replacement after accelerated mortar bar tests. Whereas map cracking is densely distributed on the surfaces of specimens with no FA replacement (Figure 7) due to ASR expansion, no cracking is observed on specimens with FA replacement (Figure 8). The ASR-suppressing effect of FA is therefore evident on the surfaces. The uniform distribution of map cracking suggests constant expansion throughout the test period.

Figure 7. Situation of After ASTM C1260 method teste (Reactive aggregate • Only as for the cement)

Figure 8. Situation of After ASTM C1260 method teste (Reactive aggregate • Containing fly ash)
Expansion test results of concrete specimens. Figure 9 shows the results of expansion tests on concrete specimens. The triangular and circular pointers express the reactive and non-reactive aggregates, respectively. The broken and solid lines represent specimens with and without FA replacement, respectively. These results reveal that specimens containing reactive aggregate with no FA replacement lead to significant expansion beginning immediately after curing. In contrast, expansion is suppressed in specimens with FA replacement, even with reactive aggregate and curing in salt water.

![Figure 9. Expansion behaviors of concrete test specimen](image_url)

However, the expansions of specimens with FA replacement are greater than those of specimens without FA replacement at an early stage of curing, contrary to the expectation, similarly to the above-mentioned results of mortar bar tests. This is presumably due to the difference in the compressive strength at the beginning of accelerated expansion testing as shown in Table 3. The degree of the progress of pozzolanic reaction in standard-cured concrete containing FA is lower than without FA. The denseness of microstructure at this stage is therefore presumed to be lower. In addition, the fraction of C-S-H with a low Ca/Si ratio, which is considered to adsorb alkali ions (Tsuda et al., 2014), is not sufficiently formed by pozzolanic reaction by this stage in concrete containing FA. These are presumably the reasons for the greater expansion of concrete containing FA at an early stage of curing.

On the other hand, the expansion of brine-cured specimens made using non-reactive aggregate rapidly increases after 28 days, suggesting the possibility of chloride-accelerated ASR. This agrees with the above-mentioned results of mortar bar testing.
Accordingly, even aggregate judged “innocuous” by the current JIS can cause ASR in an environment laden with external chlorides including air-borne salt and deicing salt. For this reason, the use of “innocuous” aggregate is not sufficient as a measure to cope with ASR. When FA was used in place of part of cement, expansion scarcely occurred similarly to the case of using non-reactive aggregate, demonstrating the ASR-suppressing effect of FA.

CONCLUSIONS

The main results obtained from this study are summarized as follows:

1. As a result of accelerated mortar bar tests using reactive aggregate, specimens made using fine aggregate from Joganji River with no FA showed large expansions more than double the reference value from the initial stage of the testing, demonstrating the high ASR reactivity of the aggregate. On the other hand, when 15% of cement was replaced with FA as a supplementary cementitious material, no expansion was observed in all specimens, with the results at the number of days twice as many as the specified test period being lower than the criterion value for “innocuous”. The ASR-suppressing effect of FA was thus confirmed even with aggregate with high ASR-reactivity.

2. As a result of accelerated mortar bar tests using aggregate that is regarded as non-reactive, its expansion was in the “indistinct” region. Moreover, the expansion during the 14 days after the judgment day exceeded the “not innocuous” value. Tests on concrete specimens also showed that chlorides accelerated ASR. Accordingly, even aggregate judged “innocuous” by the current JIS can cause ASR in an environment laden with external chlorides including air-borne salt and deicing salt. For this reason, the use of “innocuous” aggregate on its own is not sufficient as a measure to cope with ASR.

Table 3. Compressive strength of concrete test specimen

<table>
<thead>
<tr>
<th>Test piece</th>
<th>Aggregate</th>
<th>Compression strength (Curing time for 28 days) (N/mm²)</th>
<th>Compared with the compression strength (Standard: River sand·gravel(Tedori)N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>River sand·gravel(Tedori)N-OPC</td>
<td>Non-reactive</td>
<td>44.3</td>
<td>1.0</td>
</tr>
<tr>
<td>River sand·gravel(Tedori)N-FA</td>
<td></td>
<td>31.4</td>
<td>0.71</td>
</tr>
<tr>
<td>River sand·gravel(Jogojjiri)R-OPC</td>
<td>Reactive</td>
<td>32.3</td>
<td>0.73</td>
</tr>
<tr>
<td>River sand·gravel(Jogojjiri)R-FA</td>
<td></td>
<td>26.8</td>
<td>0.60</td>
</tr>
</tbody>
</table>
(3) As a result of ASR expansion tests on concrete specimens, those made using reactive aggregate with no FA replacement showed expansion beginning immediately after curing. In contrast, expansion was suppressed in specimens containing FA even with reactive aggregate and brine curing, demonstrating the ASR-suppressing effect of FA.

(4) When using recycled aggregate as aggregate for concrete, the use of FA as a supplementary cementitious material can be regarded as a means to reduce the risk of ASR.

REFERENCES