Recycling concrete rubbles with reactive aggregates from ASR-affected bridge pier

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ABSTRACT: A large number of bridge piers on the Noto highway are now suffering from serious damages caused by alkali-silica reaction (ASR). The Kashima Bridge with a 2-span steel girder structure was constructed in 1978. However, in the inspection carried out in 2004, it was found that half of stirrup steel bars in the pillow beam fractured at the bending corner of steel bar due to the excessive ASR expansion of concrete. For this reason, the pillow beam of the Kashima Bridge was completely reconstructed by removing all the concrete in 2005. In the first part of the paper, the execution procedure of reconstruction of pillow beam and the strengthening of column in ASR-affected RC pier were introduced. In the second part of the paper, in order to recycle concrete rubbles from the Kashima Bridge, the possibility of recycled aggregates for residual ASR reactivity and its some countermeasures were also discussed.

1 INTRODUCTION

A large number of bridge piers, which were mostly constructed in the 1970s or 1980s, are suffering from serious damages caused by ASR; for example, the peeling off of cover concrete, the reduction in compressive strength of concrete, and in the most serious case, the yielding or fracturing of steel bar (Torii 2003). In the 1990s, these RC piers were repaired by both the epoxy injection into large cracks and the surface coating using epoxy resin and/or polymer cement mortar. This approach was not effective in controlling the expansion of concrete, resulting in breaking off of the surface coating within 5 years after repairing. Also, recent investigations have revealed new type of deterioration. That is to say, the embrittle fracture of steel bars at the bending corner of stirrup or bent-up steel bars due to the excessive ASR expansion of concrete occurred in the pillow beam or the footing of RC pier, leading to the significant loss of structural integrity of concrete elements (Torii et al. 2004).

In Japan, during the past 20 years, recycled concrete has been actively studied, and in 2005, the recommendation of recycled aggregate for the use of concrete, JIS A5021, has been established (Japanese Industrial Standards Committee 2005). When recycling concrete rubbles as an aggregate, two important problems should be taken into considerations in durability aspects of concrete; one is freezing-thawing durability and the other is ASR. The freezing-thawing durability of recycled concrete has been actively studied and almost clarified. However, there are very few studies concerning the susceptibility towards ASR of recycled aggregate (Nielsen et al. 1992, Desmyter et al. 2000).

The objective of this paper is to make sure whether or not recycled aggregate produced from concrete rubbles containing reactive aggregates can use for making a new concrete. In the first part of the paper, the execution process of reconstruction of ASR-affected RC pier was introduced. In the second part of the paper, in order to recycle concrete rubbles from the Kashima Bridge, physical and mineralogical properties of recycled aggregates were examined with the special interest to the residual ASR reactivity of recycled aggregates.

2 OUTLINE OF ASR-AFFECTED BRIDGE

2.1 *Outline of Kashima Bridge*

Kashima Bridge with a 2-span steel girder structure was constructed in 1978, as shown in Figure 1. Its T-shaped RC pier is 42 m high. The location of Kashima Bridge on the Noto highway is presented in Figure 2. A recent research has clarified that 230 bridges out of a total of 620 bridges in the north district of Noto peninsula in Ishikawa Prefecture, which is about 40 percent, are judged as ASR-affected ones in the inspection carried out in 2004. The Kashima Bridge is located in the center of the Noto highway which is running in the mountain area from Kanazawa to Anamizu (Torii et al. 2006).

Figure 1. Overview of Kashima Bridge.

Figure 2. Location of Kashima Bridge in Noto Highway.

The concrete used in the Kashima Bridge was made of the non-reactive river sand and the reactive crushed andesite stone. It is recognized that the crushed andesite stone produced in the Noto peninsula is one of the most reactive aggregates in Japan, which contains both the cristobalite and the volcanic glass as reactive components.

2.2 *Investigation on ASR deterioration of Kashima Bridge pier*

2.2.1 *External observation and non-destructive inspection*

Figures 3 and 4 show the cracking of pillow beam of the Kashima Bridge. It is observed that there are large horizontal cracks with width of 5 to 8 mm on the side of pillow beam beneath the shoes, and that the cover concrete at the end of cantilever partially peels off due to the rainfall water with deicing salts. On the other hand, the cracking of column and footing is not so significant, although there are some vertical cracks with width of 1 to 2 mm on the column and the partial map cracking on the footing. In order to evaluate the deterioration of the inner part of pillow beam due to ASR, the ultrasonic wave method was applied to the side surface of pillow beam of 2.5 m wide, where the feature of wave pattern with the passing time of elastic wave from one side to opposite was measured. Figure 5 shows the results of ultrasonic wave method of pillow beam. Ultrasonic wave velocity ranged from 3000 m/sec to 4000 m/sec, which corresponds to the degree of deterioration of concrete due to ASR. Importantly, at the end of cantilever where the cover concrete peeled off, the ultrasonic wave could not propagate at all. Also, the frequency at average peak, which is calculated from the analysis of total wave energy, also shifted toward the lower value as the deterioration due to ASR proceeded.

2.2.2 *Monitoring of crack progress using sensors*

In order to investigate the propagation of cracking, and to guarantee the daily safety of the Kashima Bridge until the strengthening work has finished,

Figure 3. Large horizontal cracks in center of pillow beam.

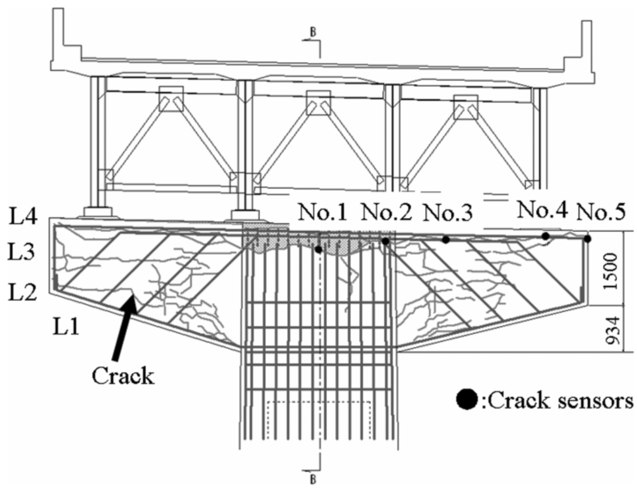


Figure 4. Schematic diagram of cracking of pillow beam.

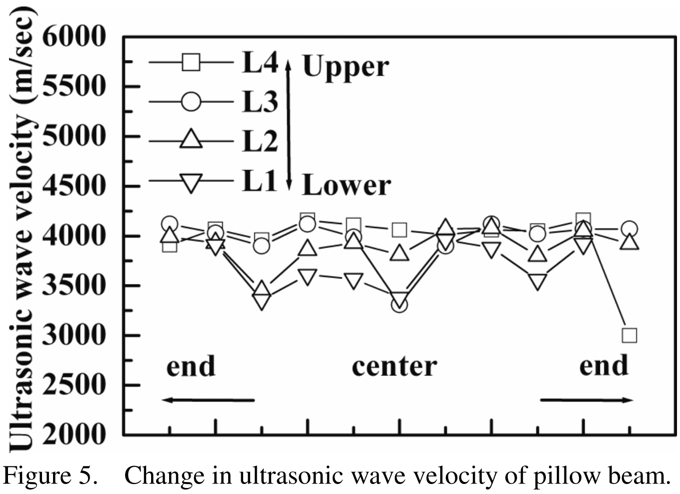


Figure 5. Change in ultrasonic wave velocity of pillow beam.

a large number of crack sensors, in which the sensitivity of sensor is 1/1000 mm and the total capacity is ± 5 mm, were attached on the surface of concrete, as shown in Figure 6. All monitoring data can be logged twice a day by using the computer system connected with the sensors. Figure 7 shows variations in crack width of various portions of RC pier and abutment for the past two years, where the change in temperature is automatically compensated. The monitoring result indicates that the crack width of pillow beam increases at a very high rate of about 10 percent a year especially at the center portion beneath the shoes, although changes in crack width of column of RC pier or abutment are marginal. Interestingly, the crack width increases significantly from the spring to the summer, and it almost stops during the winter, which corresponds to seasonal changes in temperature and moisture supply. From the results of this monitoring, it is considered that the pillow beam of bridge pier should be reconstructed, and that the column of bridge pier should be strengthened with the steel plate bonding along with the countermeasure for earthquake force. After the reconstruction of pillow beam and the strengthening of the column, some crack sensors have been attached again along the boundary between the pillow beam and the column. The monitoring of behavior of concrete after strengthening is still going on.

3 RECYCLING OF CONCRETE RUBBLES FROM KASHIMA BRIDGE

3.1 *Production of recycled aggregates and properties of recycled aggregates*

In the process of producing recycled aggregate, concrete rubbles from the Kashima Bridge were firstly crushed using a jaw crusher and sieved at the grain size of 40 mm or less. Furthermore, in order to satisfy the quality requirement of recycled aggregate class H according to JIS A5021, adhesive mortars of recycled aggregate were removed through the process of screw abrasion, and sieved again at the grain size of 25 mm or less, as shown in Figure 8. Recycled aggregates produced by crushing process and followed by screw abrasion process are classified to class L and class H recycled aggregate, respectively. Physical properties of two types of class L and class H recycled aggregates and original andesite aggregate are presented in Table 1. Mixture proportion of concrete using recycled aggregate is presented in Table 2. Ordinary Portland cement was used for making concrete. Coarse and fine aggregates used were class H recycled aggregate and non-reactive river sand, respectively. The water-cement ratio and sand-aggregate ratio of concrete were 50% and 46% for each mixture. An alkali ($Na_2Oeq.$) of 5.06 kg/m^3 was added to the concrete mixture as the NaOH solution or NaCl solution. The size of concrete specimens was 75 mm × 75 mm × 400 mm. The change in length and dynamic elastic modulus of concrete specimens were periodically measured until 6 months under the storage condition at 40 °C and RH 100%. A 15 % fly ash or 40 % blast-furnace slag was replaced as a percentage of total cement in order to examine the preventive measure in controlling ASR expansion.

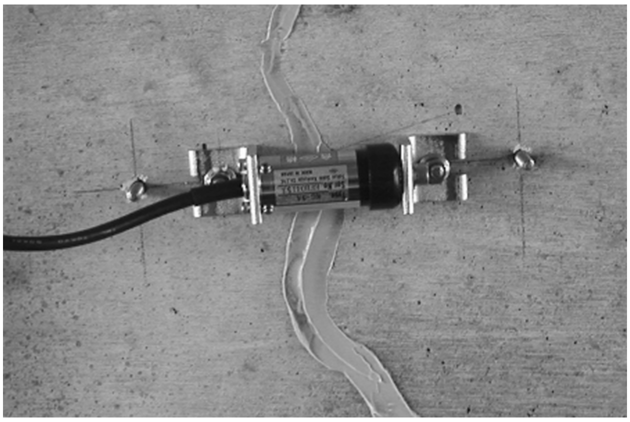


Figure 6. Sensor attached across cracks on surface of pillow beam.

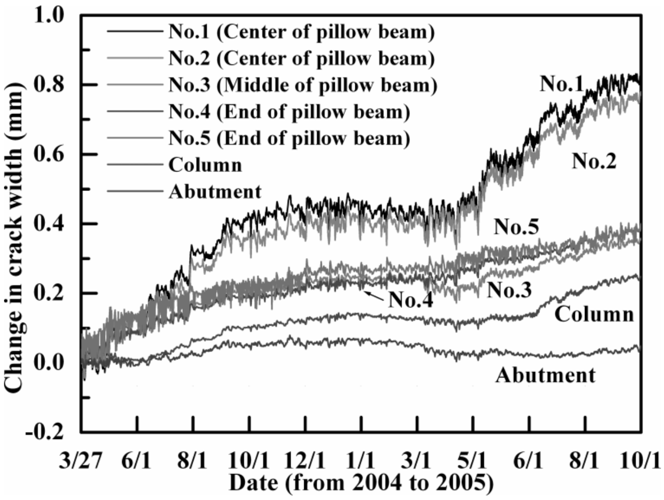


Figure 7. Variations in crack width of RC pier and abutment.

Figure 8. Recycled aggregate production apparatus.

Table 1. Physical properties of recycled aggregate and original andesite aggregate.

Type		Class H	Class L	Original
Aggregate size	mm	25	25	25
Density	%	2.51	2.24	2.64
Absorption	%	2.77	6.27	1.30
Adhesive mortar	%	23.2	56.8	—

Table 2. Mix proportion of concrete.

W/C	s/a	Water	Cement	Sand*	Gravel**
%	%	kg/m^3	kg/m^3	kg/m^3	kg/m^3
50	46	160	320	879	986

* River sand **Recycled aggregate (class H)

3.2 *Alkali-silica reactivity of recycled aggregates*

3.2.1 *Evaluation by chemical method*

The alkali-silica reactivity of recycled aggregate was accessed according to the chemical method (JIS A1145). The results of chemical method according to JIS A1145 are shown in Figure 9. The recycled aggregate treated with HCl solution and original andesite aggregate were assessed as "deleterious", while the recycled aggregate (class H) was assessed as "innocuous". In the evaluation of alkali-silica reactivity of recycled aggregate according to JIS A1145, there is a tendency that the reduction in alkalinity (Rc) increases and the dissolved silica (Sc) decreases, as the amount of adhesive mortar increases. This is why CSH and calcium carbonate contained in adhesive mortar may consume the OH^- ion by reacting with NaOH solution in the chemical method. In JIS A5021, it is specified that when the chemical method is applied to the recycled aggregate, the adhesive mortar is totally removed by the treatment with HCl solution. However, as shown in Figure 9, when treated with HCl solution, both the reduction in alkalinity (Rc) and the dissolved silica (Sc) also increase to a significant degree. From the results, it is apparent that the chemical method may not be appropriate to assess the alkali-silica reactivity of recycled aggregate.

3.2.2 *Evaluation by mortar bar methods*

Three types of mortar bar methods (JIS A1146, ASTM C1260, Danish method) were carried out in order to assess the alkali-silica reactivity of recycled aggregate. The results of three types of mortar bar methods are shown in Figures 10-12, respectively. In the evaluation according to JIS A1146, both the recycled aggregate (class H) and the original andesite aggregate were assessed as "deleterious". On the other hand, in the evaluation according to ASTM C1260 and Danish method under the severe curing condition which the alkali was always supplied from the outside, expansion behaviors of mortars with recycled aggregate and original aggregate were almost similar, which were assessed as "deleterious". From the results, it is considered that the alkali-silica reactivity of recycled aggregate is almost the same as the original andesite aggregate, although the Kashima Bridge passed about 30 years after the construction.

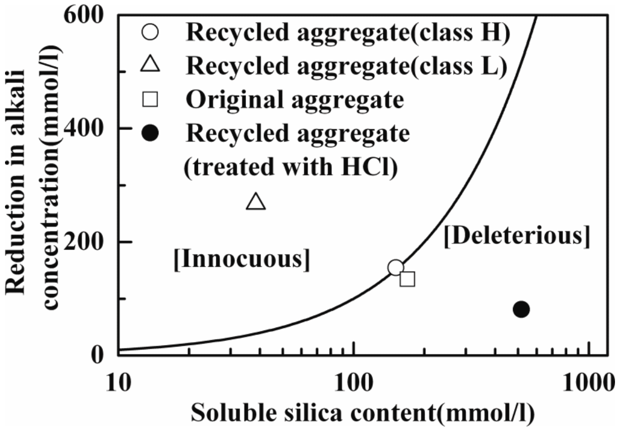


Figure 9. Results of chemical method of recycled aggregate and original aggregate (JIS A1145).

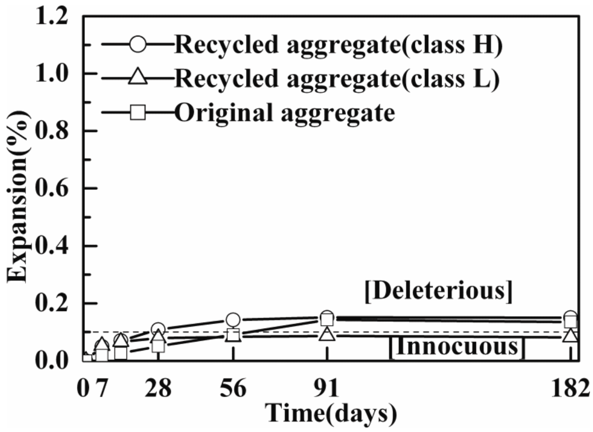


Figure 10. Expansion behaviors of mortars using recycled aggregate and original aggregate (JIS A1146).

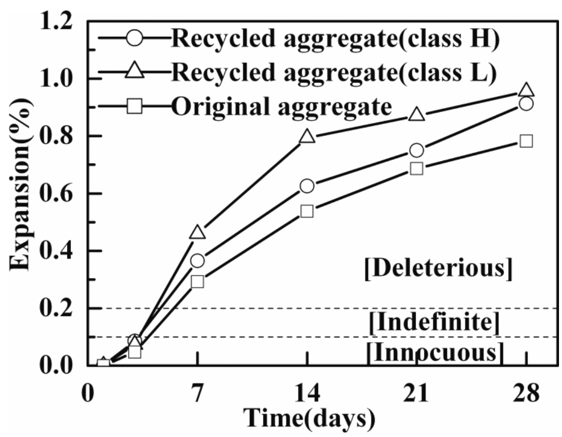


Figure 11. Expansion behaviors of mortars using recycled aggregate and original aggregate (ASTM C1260).

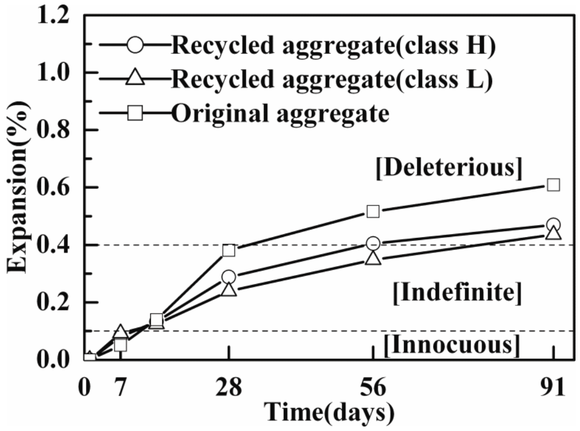


Figure 12. Expansion behaviors of mortars using recycled aggregate and original aggregate (Danish method).

Figure 13 shows the schematic diagram of fragments of crushed coarse aggregate with reaction rim. From the results of EPMA analysis of polished surface of recycled aggregate, it is estimated that the reaction region of a dense andesite coarse aggregate is limited only to the surface of 1 to 2 mm. So, in the mortar bar method, the recycled aggregate and original andesite aggregate show almost the same expansion behavior, because the new surface of crushed aggregate fragment can easily react with the alkaline solution, resulting in forming ASR gel again.

3.3 *Alkali-silica reactivity of concrete using recycled aggregates*

3.3.1 *Expansion behavior of concrete using recycled aggregates*

When using the concrete made with reactive aggregate where the reaction is still going or where the reaction has not yet started because the concrete is placed in a dry environment with insufficient alkali and moisture, it is obvious that a further precaution for ASR is needed in recycling. For this reason, JIS A5021 recommends the preventive measure of using the blended cement such as fly ash cement or blast-furnace cement. The expansion behaviors of concrete bar using recycled aggregates are shown in Figures 14, 15. When concrete bars are stored in a fog box, concrete using recycled aggregates shows a rapid expansion after the age of 2 months. Also, concerning the influence of type of alkalis added, the expansion of concrete with the addition of NaOH solution is slightly larger than that with the addition of NaCl solution. It has been pointed out that the degradation caused by ASR can be separated in the different two processes; the first process in which the chemical reaction occurs and ASR gel forms, and the second process in which ASR gel swells the pore solution. Also, ASR gel must have been formed to some degree in order to generate the expansion of concrete. From the test results, it is suggested that the expansion of concrete using recycled aggregates may retard to some degree. This may be attributed to the buffer effect of adhesive mortar and reaction rim of recycled aggregate against the attack of OH- ion. The use of blended cement is very effective in reducing the expansion of concrete using recycled aggregates, as it is expected. In this study, a 15 % fly ash or 40 % blast-furnace slag replacement is selected according to the specification of JIS A5308. However, it seems that the replacement percentage by fly ash and blast-furnace slag should be increased depending on the alkali-silica reactivity of original aggregate itself and the environmental condition of concrete.

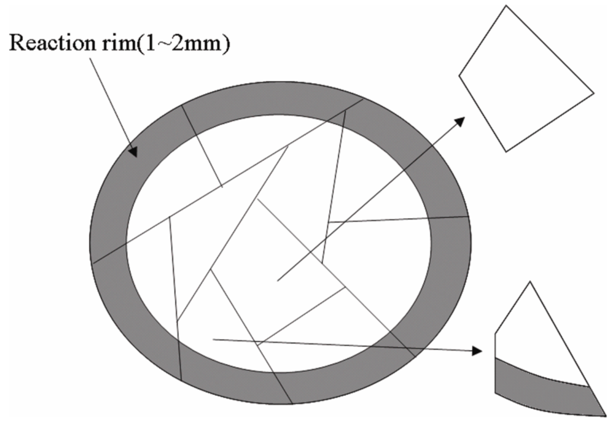


Figure 13. Schematic diagram of fragments of crushed aggregate with reaction rim.

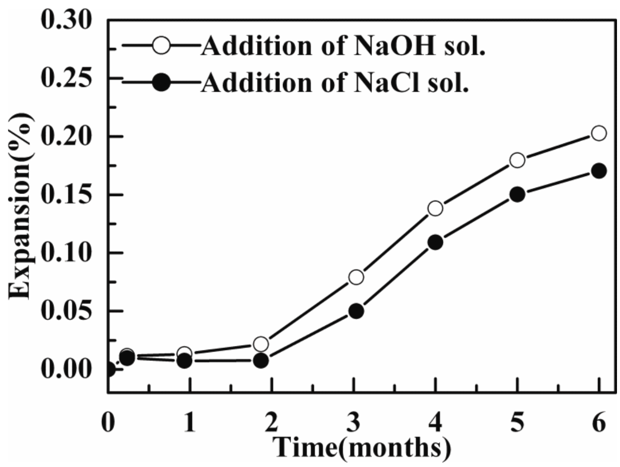


Figure 14. Expansion behaviors of concretes using recycled coarse aggregate and river sand with addition of NaOH solution and NaCl solution.

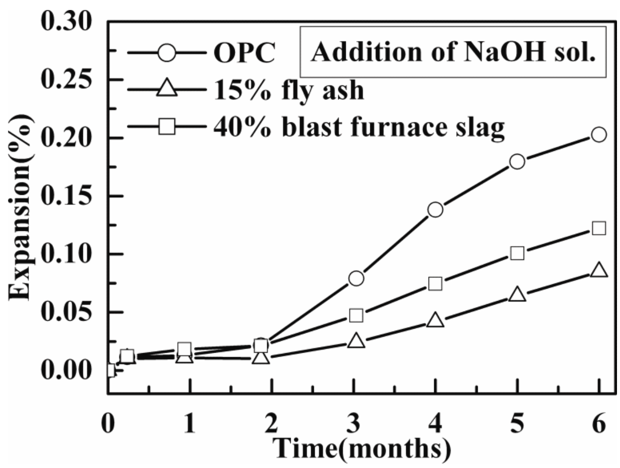
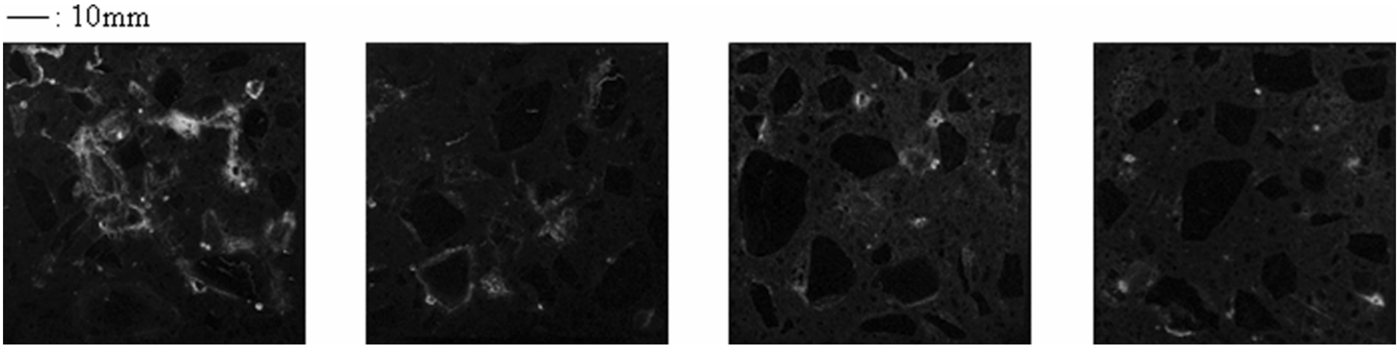


Figure 15. Expansion behaviors of concretes using recycled coarse aggregate and river sand with 15 % fly ash and 40 % blast furnace slag.



(a) Addition of NaOH solution. (b) Addition of NaCl solution. (c) 15 % fly ash. (d) 40 % blast furnace slag.

Figure 16. ASR gel observed in cross section of concrete in fog box curing.

3.3.2 *Observation of ASR gel formed by uranyl acetate fluorescence method*

After the concrete bar test, the amount of ASR gel formed was observed by uranyl acetate fluorescence method, where the fluorescent coloring of yellow green shows the generation of ASR gel. The results of uranyl acetate fluorescence method are shown in Figure 16. It is observed that there is a distinct fluorescent coloring around recycled aggregates, and that the area of fluorescent coloring is more significant in concrete with the addition of NaOH solution than in that with the addition of NaCl solution. This indicates that a further alkali-silica reaction may occur around recycled aggregate by the supply of alkalis in concrete. On the other hand, the formation of ASR gel in concrete with both blended cements was very small.

4 CONCLUSIONS

The pillow beam of RC pier in the Kashima Bridge was reconstructed in 2005 based on the results of the non-destructive testing and monitoring using crack sensors. Although the Kashima Bridge passed about 30 years after construction, it was judged that ASR of concrete with the reactive andesite coarse aggregate has not stopped due to the lack of reactive silica in aggregate and/or alkalis in concrete. For this reason, accelerated mortar bar and concrete bar tests were carried out to examine the residual expansion capacity of recycled aggregate.

Main results obtained from accelerated mortar bar and concrete bar tests are as follows;

1 From EPMA analysis, the reaction region of dense andesite coarse aggregate was limited near surface of 1 to 2 mm, even if concrete was about 30 years old.
2 Both the chemical method and mortar bar method were not appropriate to assess the alkali-silica reactively of recycled aggregate because crushed aggregate fragments must be used in these tests.
3 The concrete bar method was more preferable to evaluate the alkali-silica reactivity of concrete using recycled aggregates.
4 The expansion of concrete using recycled aggregates was retarded by the buffer effect of adhesive mortar and reaction rim around recycled aggregate.
5 The use of blended cement, a 15 % fly ash or 40 % blast-furnace slag replacement, was very effective in reducing the expansion of concrete using recycled aggregates.

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