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Quantitative Evaluation of Multiplier Effect of Concrete Expansion and Reinforcement

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ABSTRACT

Many concrete structures deteriorated by Alkali Silica Reaction (ASR) are still found in Japan. In fact, the continuous propagation after being repaired has been also reported. The solution for the ASR expansion mechanism and the confinement effect of reinforcements might contribute to the reasonable repair and economical design in the future. This research focused on the effect of the reinforcement on ASR. The experimental and analytical studies provided the evidence that the size and shape of the specimens and the direction of the arrangement of reinforcements might affect the amount of expansion and crack patterns. The chemical analysis was performed by X-ray equipment and the possibility of this technique was indicated to make clear the ASR expansion mechanism.

INTRODUCTION

The deterioration caused by ASR in concrete structures was discovered in 1983 in Japan and it has been increasing severer than expected. Some concrete structures are still expanding even after being repaired by the steel jackets. The most difficult situations when solving the ASR expansion mechanism are caused by the diversity of environmental conditions and the reactivity and variety of aggregates on the structures.

The stirrups play an important role restricting the expansion in the reinforced concrete deteriorated by ASR. However, quantitative evaluation of reinforcement against ASR expansion is not clarified yet. Therefore, it is important to make clear the resistance of reinforcements to the ASR expansion.

In this research, the experiments and analyses were conducted to study the effects of the stirrups on the ASR expansion mechanism. Moreover, the chemical analysis by the use of X-ray was made and the possibility of solving the ASR expansion mechanism was suggested.

RESEARCH OUTLINE

Three types of methods were selected to investigate the effect of the reinforcement on reinforced concrete structures deteriorated by ASR. Hence, this paper consists of three parts, the experimental study, analytical study by finite element method (FEM) and the chemical analysis by X-ray. Figure 1 shows the outline of this research and its objectives for each method.

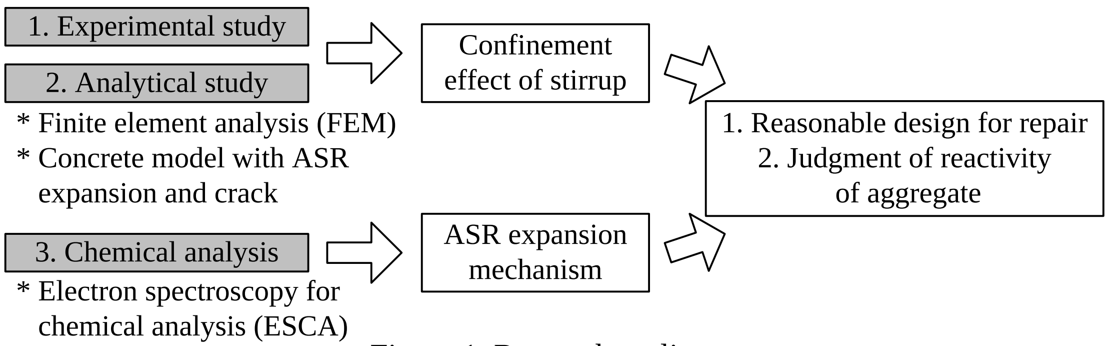

Figure 1 Research outline

EXPERIMENTAL STUDY

Specimen preparation

Figure 2 shows the sizes of the specimens and Table 1 lists the factors of three types of the

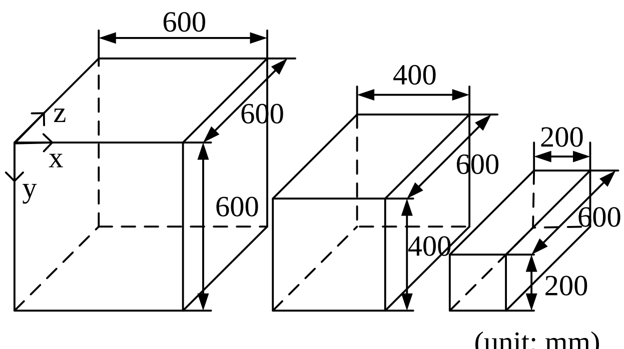

Figure 2 Sizes of the specimens

Table 1 Factors of the specimen

specimen	size x× y ×z, mm	type of reinforcement (reinforcement ratio, %)		
		upper	lower	stirrup
S-200	200×200×600	D6 (0.189)	D10 (0.420)	D6 (0.122)
S-400	400×400×600	D10 (0.102)	D19 (0.409)	D6 (0.079)
S-600	600×600×600	D16 (0.127)	D29 (0.412)	D10 (0.095)

specimens. The length was 600mm for all the specimens and the cross section area was changed. All specimens had similar longitudinal and shear reinforcement ratios.

The mix proportion of the concrete is shown in Table 2. In this study, andesite aggregates were used as reactive aggregates and its alkali-silica reactivity was tested following the JIS A 1145 method. After the measurement of the Pessimum percentage, the ratios of reactive aggregate and non-reactive aggregate were determined as; 50 : 50 for coarse aggregate and 40 : 60 for fine

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aggregate. The specimens were cured in a room at 40℃ and 100% RH in order to accelerate the ASR expansion.

Results and discussions

Figure 3 shows the crack patterns on the axis Z. The straight lines represent a crack with more than 0.20mm wide and the dotted lines represent a crack with less than 0.20mm wide. Cracks with cross stripes spread over the whole surface in all specimens. The cracks on the specimen S-

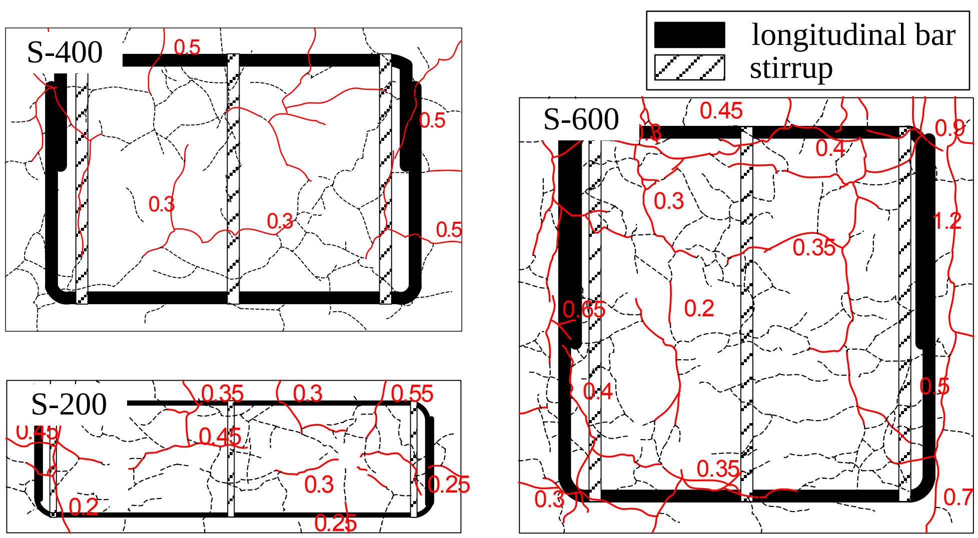

Figure 3 Crack patterns

600 were remarkably extended above the longitudinal bars. On the other hand, the specimens S-200 and S-400 had cracks in random directions.

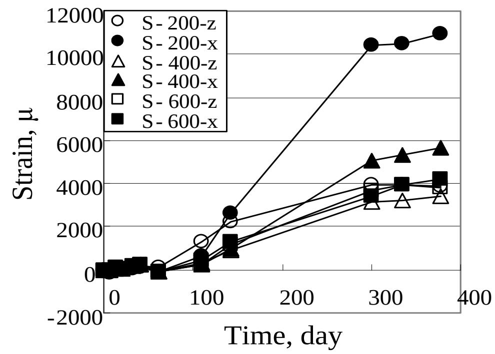

Figure 4 Relationship between expansion and time

The relationship between expansive strain and time is shown on Figure 4. The expansive strain on the surface was measured with a contact strain gauge on axes X and Z. The expansive strain on X was larger than on Z for the specimens S-200 and S-400. However, the expansive strains on both axes were almost the same in case of the specimen S-600. The ratios of the strains on X and Z were approximately; 3 : 1 for the specimen S-200, 3 : 2 for the specimen S-400 and 1 : 1 for the specimen S-600. The difference might be caused by the shape of the specimens.

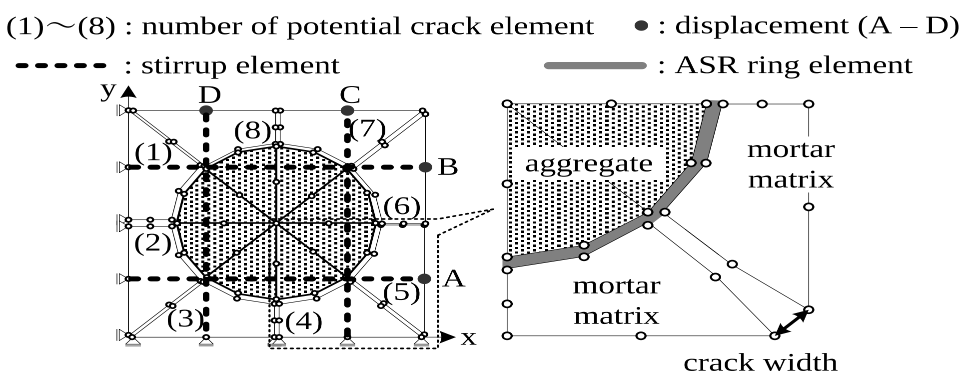

Figure 5 Concrete element

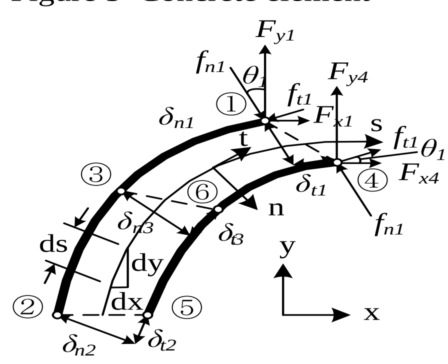

Figure 6 Interfacial element

ANALYSIS BY FEM

FEM model of concrete deteriorated by ASR

Figure 5 shows an ASR concrete model proposed analyze the expansive process induced by ASR. This concrete element consists of aggregate and mortar matrix. The quadratic triangle elements with 6 nodes were used for aggregate. The mortar matrix was represented by a quadratic quadrilateral element with 8 nodes. Additionally, Figure 5 shows the stirrup elements and its boundary condition.

The interfacial elements between all elements were inserted in advance (see Figure 6). The interfacial elements are composed of two liner elements with 3 nodes. In this analysis, two types of interfacial elements were used. The first is the ASR ring element between the mortar matrix and the aggregate elements which represents the expansion caused by ASR. The second is the potential crack element between two mortar matrix elements.

Generally, the normal stress, σ_n and shear stress, τ_t are acting across a crack plane, and normal and tangential displacement, δ_n and δ_t occur. The relationship between these stresses and displacements can be expressed as shown on Equation (1).

$$\{\sigma\} = \begin{Bmatrix} \sigma_n \\ \tau_t \end{Bmatrix} = \begin{bmatrix} C_{nn} & C_{nt} \\ C_{tn} & C_{tt} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_t \end{Bmatrix} = [C]\{\delta\} \quad (1)$$

In the analysis, a constant value of $C_{nt}=C_{tn}=0N/mm^3$ was assumed. C_{tt} was also constant equal to G/t, where G is the shear modulus of elasticity and t=10mm is the thickness of ASR concrete element. On the other hand, the tension softening curve was introduced into C_{nn} in the potential crack element and the modulus of elasticity of the ASR ring element was assumed to be $1.0\times E_{c0}$, where $E_{c0}=3.0\times 10^4 N/mm^2$ referring to a normal concrete.

The stirrup element was represented by a liner element connecting both sides of the ASR concrete element with 2 nodes. The number of stirrup elements was two in each direction. The amounts of expansion in X and Y were the averages of the displacements at A and B, and C and D, respectively.

Analytical outline

The analysis was conducted as follow;

1) An arbitrary amount of expansion is given in δ_n in the ASR ring element.

2) The calculations are repeated up to the σ_n - δ_n relationship of the potential crack element fits the given tension softening curve.

3) Steps 1 and 2 are iterated.

The relationship between the expansion, δ_{rn} and the time, t was assumed as shown on Equation (2).

Table 3 Analytical cases

Case	arrangement of stirrup		diameter, mm
	X	Y	
I	○	—	6
II	○	○	
III	○	—	13
IV	Non		

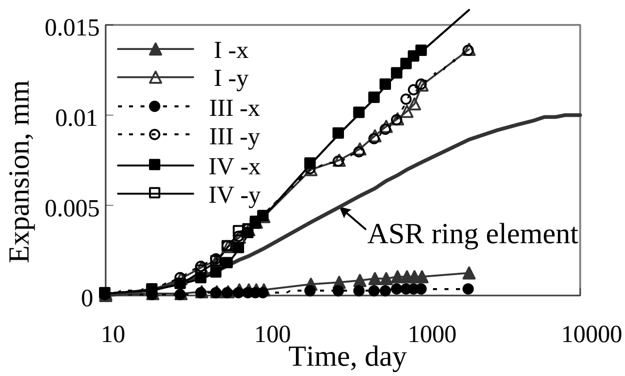

Figure 7 Relationship between expansion and time

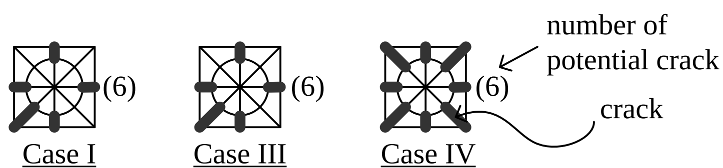

Figure 8 Crack patterns

$$\delta_{rn} = \frac{1}{2700}\left(2T^3 + 15T^2 - 24T + 1\right) \quad (2)$$

where $T=\log_{10}t$.

Table 3 summarizes four kinds of the analytical cases. The main factors of this analysis were the arrangement and diameter of the stirrups.

Results and discussions

Figure 7 shows the relationship between the expansion and time and Figure 8 shows the crack patterns after 2000 days. The comparisons between Case I, III and IV indicate the effect of diameter of the stirrup.

In Case IV, the ASR concrete model expanded uniformly. The amount of expansion on X was similar as that on Y and it was the double of the amount given in the ASR ring element. Additionally, the radial cracks around the aggregate were simulated and the width of all potential

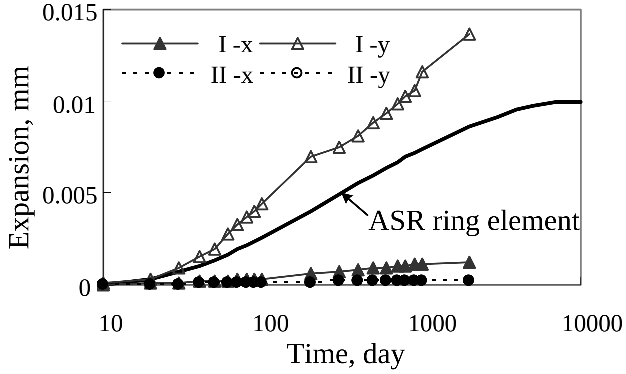

Figure 9 Relationship between expansion and time

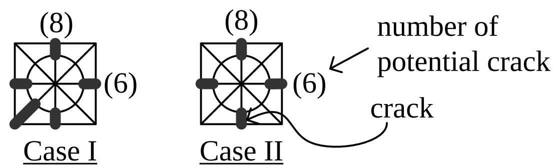

Figure 10 Crack patterns

crack elements between the mortar matrix elements was approximately 0.007mm after 2000 days.

In Case I and III, the arrangement of the stirrups made great contribution to decrease the amount of expansion on X. In fact, the number of cracks in the mortar matrix decreased. On the other hand, the diameter of the stirrups did not have a relevant effect on the expansion and number of cracks. However, the maximum crack width of the potential crack element (6) was 0.03mm and it was larger than that in Case IV without stirrups.

Figure 9 shows the relationship between the expansion and time and Figure 10 represents the crack patterns after 2000 days. On these figures, the effect of the arrangement direction of stirrups was observed.

The stirrups confined and restricted the expansion of concrete due to the arrangement of the stirrups in X and Y in Case II. The expansion and number of cracks decreased more than those in Case I. The maximum crack width of (6) and (8) in Case II was approximately 0.0027mm.

CHEMICAL ANALYSIS

Sampling

Figure 11 shows a reinforced concrete specimen degraded by ASR. It was cut at the A-A section and some powder samples were collected from each portion of the cross section in as shown on Figure 12. In this study, the chemical analysis was performed by ESCA (Electron spectroscopy for chemical analysis) for five samples as follow; (1) inside of the reactive aggregate, (2) surface of the reactive aggregate, (3) cement paste, (4) non-reactive aggregate and (5) reactive aggregate before use.

Principle of ESCA

This is a method to measure the kinetic energies of photoelectrons emitted by monochromatic X-ray irradiation. Since they are directly related to the binding energies of core electrons of elements contained in a sample, it is a useful tool for elemental analysis.

Results and discussions

Figure 13 shows the ESCA spectra from several portions of the reinforced concrete specimen. All the samples contain Ca, O, Na, Si and Al, as well as contaminated C. The atomic composition ratios were estimated by considering the sensitivity of each sub-shell peak as listed on Table 4.

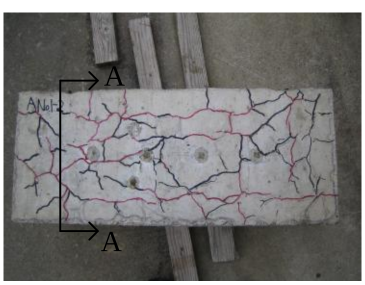

Figure 11 Specimen

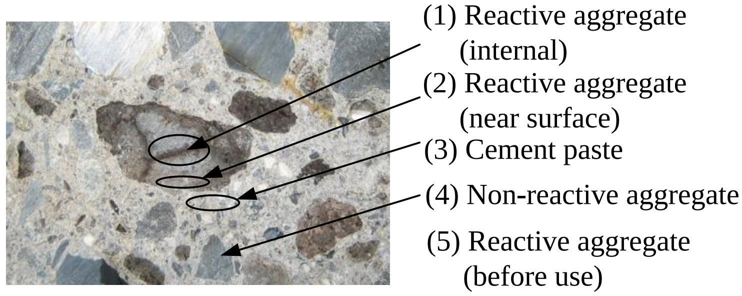

Figure 12 Sampling points (A-A section)

These results give some suggestions for the ASR expansion mechanism. The Na content of the ASR deteriorated portion (1) is much more than that of the aggregate before being used (5). This indicates clearly the increase of Na in the ASR process. Although there is no big difference of the Na amount between the reactive and non-reactive aggregates, the Ca content of the non-reactive aggregate is almost double of the reactive one. These results suggest that the Ca content might play an important role in the ASR process. The Si content in reactive aggregate (4) was more than that of non-reactive aggregate (5). This result might be general trend of a reactive aggregate.

CONCLUSIONS

(1) The size and shape of a reinforced concrete deteriorated by ASR might have an effect on the amount of expansion and crack pattern.

(2) The arrangement of the stirrups can lead to the resistance of the ASR expansion and decrease

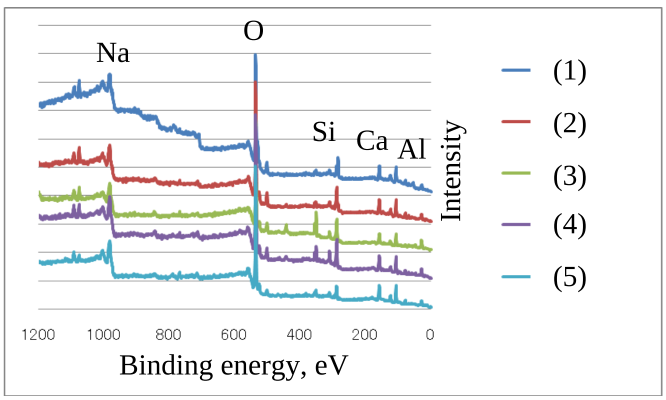

Figure 13 Results by ESCA

Table 4 Elemental ratio by ESCA

	Ca	O	Na	Si	Al
(1)	3.09	64.58	3.95	21.36	7.00
(2)	2.41	67.36	3.31	21.12	5.78
(3)	7.61	68.46	2.49	16.09	5.33
(4)	4.09	71.09	1.73	17.94	5.14
(5)	2.17	70.29	1.15	20.04	6.33

* Where an elemental ratio means a relative ratio.
Each element might contain other elements.

the number of cracks. The crack might be wider for reinforced concrete members without any stirrups.

(3) The information obtained from the chemical analysis of an element using the X-ray (ESCA) might give some suggestions for the ASR expansion mechanism in the future.

ACKNOWLEDGEMENTS

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