INFLUENCE OF ALKALI CONCENTRATION DISTRIBUTION OCCURRING
IN CONCRETE MEMBERS ON EXPANSION AND CRACKING
DUE TO ALKALI–SILICA REACTION

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1. INTRODUCTION

The cracking behavior of concrete structures affected by ASR will differ greatly depending on the type and dimensions of the structures, the internal and external restraints to which the structures is subjected, and the degree of water supply to the structure, and it has become known that there are the cracking properties specific to ASR. Large cracks having widths of 10 mm and depths as much as 30cm from the surface have occurred in structures with small degree of restraint by reinforcement and unreinforced concrete structures , while it has been pointed out that in case of reinforced concrete structures the depth have been limited mostly to parts of cover by concrete [1],[2].

ASR cracking is said to be caused by execessive expansion acompanying absorption of water by gel formed in reaction of the alkalis in the pore solution of a concrete with reactive substances in the aggregate, but there has been almost no explanation given regarding the mechanism by which cracks occur due to this expansion. The authors have ascertained through area analyses(color mapping) of EPMA that concentration of alkali differ between the surface and central portion of concrete members kept in an environment of high humidity, and have studied the mechanism by which cracking is produced
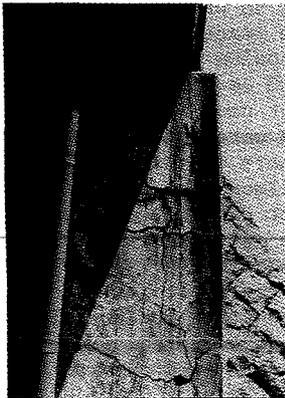

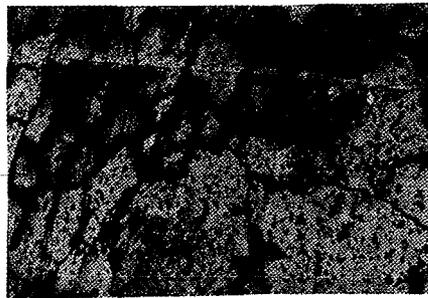Fig.1 ASR cracking in an abutment
     of bridge

Fig.2 ASR cracking in retaining
     wall

2. CRACKING OF CONCRETE STRUCTURES DUE TO ASR

Fig.1 shows ASR cracking in the abutment of a bridge, while Fig.2 shows ASR cracking in a retaining wall, which are commonly called " map cracking". Fig.3 shows the pattern of ASR cracking produced at the surface of a concrete prism (7 × 7 × 40 cm) stored in an environment of 20°C and 100 % RH.

What should be noted in this figure are the direction of the cracks and the sequence of occurrence. At first, cracks perpendicular to the longitudinal direction of the prism occur, followed by cracks in the longitudinal direction connecting these first cracks. Such a cracking pattern is not of expansive cracking, but rather of shrinkage cracking.
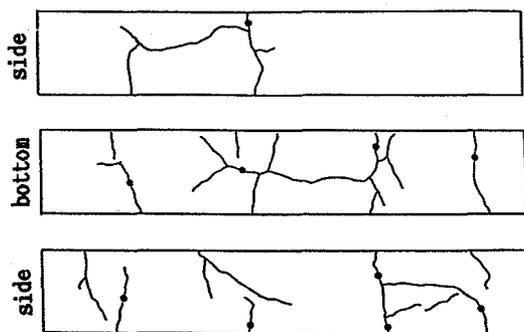

Fig.3 ASR cracking on a concrete prism
(W/C = 0.50, R_2O = 1.46 %, glassy andesite aggregate)

3. CONCENTRATION DISTRIBUTION OF ALKALI OCCURRING IN CROSS SECTION OF CONCRETE MEMBER

Fig.4 shows the relative concentration distribution of sodium and potassium in the cross section of cylindrical mortar specimens 5 cm in diameter. The mix proportion of the mortar were W : C : S = 0.5 : 1.0 : 2.25, while as cement an ordinary portland cement of R_2O = 0.57 % to which NaOH was added to attain R_2O =1.56 % was used. Chert was used as the reactive aggregate. Fig.5 shows the relative concentration distribution of sodium and potassium at the cross section of a cylindrical concrete specimen 10 cm in diameter. The concrete had a water cement ratio of 0.60, and cement used was an ordinary portland cement of R_2O = 0.52 % to which NaOH and KOH were added at the ratios of Na_2O and K_2O contained to obtain R_2O = 1,46 %. Chert was used as the reactive aggregate for both fine and coarse sizes. The specimens, upon holding in an environment of 20°C and 100 % RH for 24 hours after casting, were stored for 56 weeks in an environment the same as that of the acceleration conditions specified in ASTM C 227(Mortar-Bar Method) in case of mortar, and 61 weeks in a fog room of 40°C in case of concrete, followed by element analyses by EPMA. These figures show that alkali concentration are lower at peripheral portions. The question is how such alkali concentration change occurred. The key for solving the problem is shown in the analysis results of the mortar specimens in Fig.4. It may be seen in the figure that there are parts of considerably high concentration of both sodium and potassium in the peripheral parts of the specimens. Chemical analyses for sodium and potassium show approximate agreement of the concentrations of these elements with the values calculated based on

the alkali conctents of the cement and the mix proportions, and quantitative
analyses by EDX if the alkalis in these peripheral portions are as much as 3
times the calculated values. The results of analyses for total alkali contents
in the mortar specimens show that it is not possible alkali was leached out
from the mortar. Based on the above results, we concluded that the decreases
in alkali concentration at the surface portions were caused by precipitation
of Na_2CO_3 and K_2CO_3 through reaction of sodium and potassium ion migrating from
the interior to the surface portion by concentration diffusion to react with
carbon dioxide in air and hydrogen carbonate ion in water supplied from the
exterior. In the case of the concrete specimens in Fig.5, increases in alkali
concentration at the peripheral portions can hardly be recognized as in the
mortar specimens. This is thought to have been because the concrete specimens
were stored in a fog room so that carbonates which had first been leached out.
Such variations in the alkali concentrations at the cross sections of mortar
and begin from around the age of 4 days, and at 7 days fairly distinct concen-
tration distribution can be recognized. This suggests that occurrence of al-
kali concentration distribution is not restricted only to specimens in the
" Mortar Bar Method ", but also can be found in cross sections of concrete
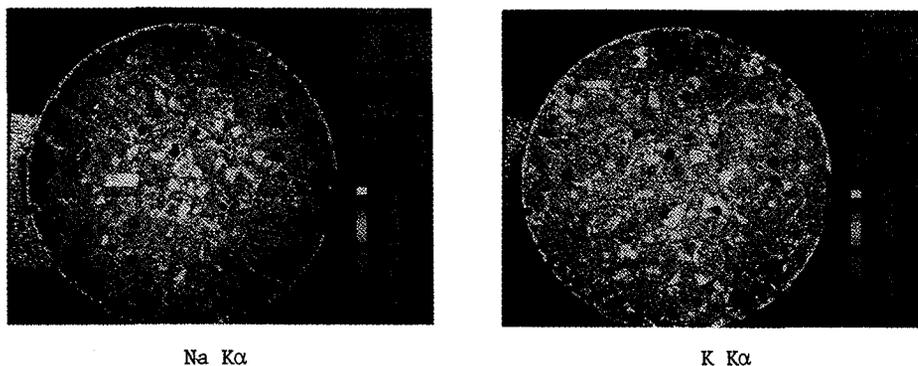structures in genaral. The reason for this is that concrete structures are

Na Kα   K Kα

Fig.4   Stage-scanned image of mortar sample (55 × 55 mm)

Na Kα   K Kα

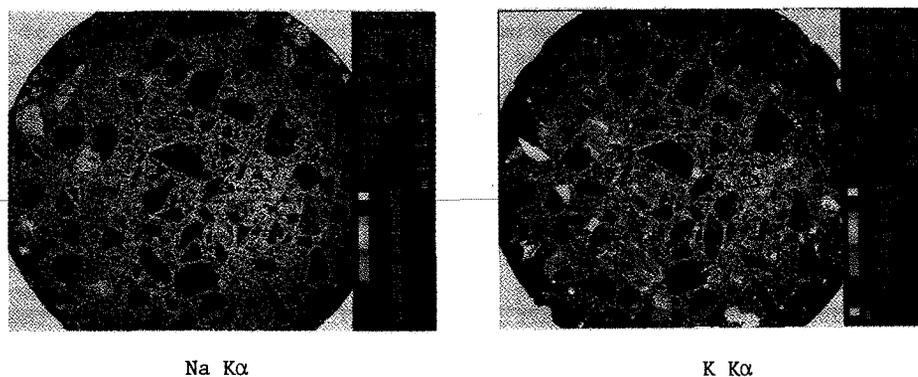Fig.5   Stage-scanned image of concrete sample (88 × 88 mm)

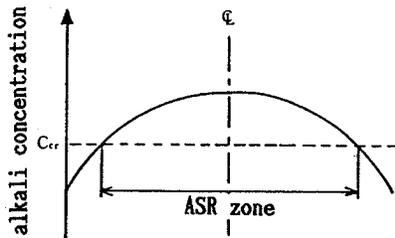subjected to moist curing at least 4 days after placement of concrete.

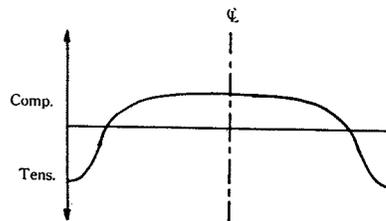Fig.6 Schematic alkali concentration distribution in a section of concrete member

Fig.7 Schematic stress distribution in a section of concrete member preceding the expansive cracking

4. ALKALI CONCENTRATION DISTRIBUTION AT CONCRETE MEMBER CROSS SECTION AND OCCURRENCE OF CRACKING DUE TO ASR

It has been shown that alkalis in concrete involved in ASR are not distributed uniformly in the cross section of a member, but have lower concentrations at the peripheral parts of the member. This means that ASR does not occur over the entire cross section of a member, but only in an area at the center portion where concentrations of alkalis exceed certain limits (Fig.6). This mean, in effect, that excessive expansion due to ASR does not occur over the entire cross section of the member, but only in the area shown in Fig.6. When expansion of concrete due to ASR occures locally in the member cross section in this manner, a stress distribution such as shown in Fig.7 occurs. That is, as ASR progresses, compressive stresses occur at the interior and tensile stresses consequentially at the peripheral portions, and when expansion at the interior reaches a certain extent, the concrete at the periphery reaches the limit of tensile strain, and cracking occurs. Such a limit of tensile strain is about 0.05 % in case of concrete of ordinary quality.

Fig.8 is a micrograph of a specimen sampled from the central portion of a concrete cylinder in which chert was used as reactive aggregate, and shows an example of the numerous minute cracks formed at the interior of concrete. The cylinder had been stored for 6 months in an environment of 40°C and 100 % RH and expansion of approximately 0.3 % had occurred. As is clearly seen in this figure, cracks occurring at the interior have developed unrelated to the two phases of cement paste and aggregate particles. Such minute cracks are extremely scarce in specimens sampled from the peripheral portions of the cylinder. In this figure, one more thing that should be noted is where fine aggregate particles contact cement paste. The boundaries with the cement paste are indistinct with the appearance being that of particles dissolved in the cement paste portion. In effect, this part is where silica minerals comprising the particles are decomposed by ASR. Such parts exist in greater number the closer it is to the center with hardly any seen in the peripheral portions. Instead, there are wide cracks at the periphery extending towards the exterior as shown in Fig.9, and most of these cracks are filled by gel which has become carbonated.
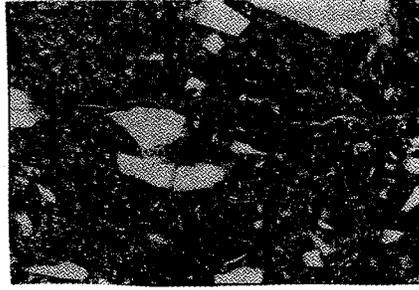
Fig.8 Microcracks in a section sampled from the central portion
       of a concrete cylinder, magnification × 200
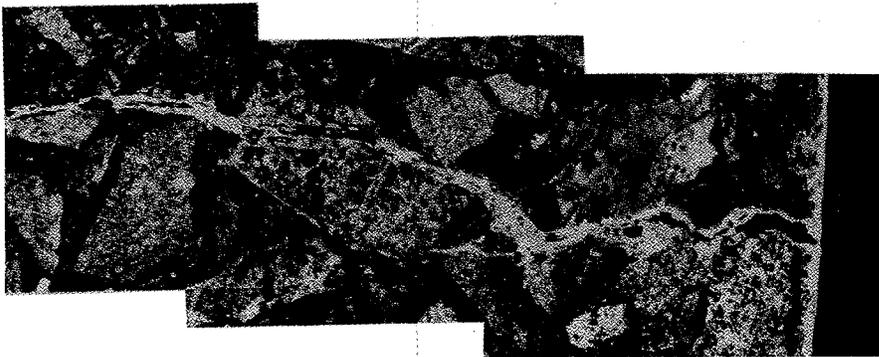

Fig.9 Macrocracks in a section sampled from the peripheral portion
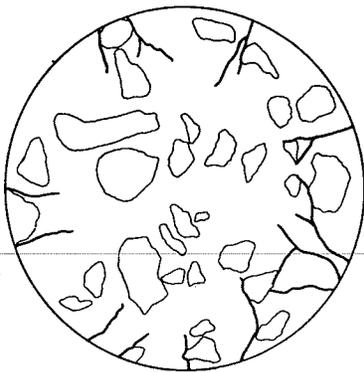   of a concrete cylinder, magnification × 40

Fig.10 Macrocracks at the surface
        layer of a concrete cylinder