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Cement & Concrete Composites 26 (2004) 47–56

Cement & Concrete Composites

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ASR gel composition and expansive pressure in mortars under restraint

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Accepted 6 November 2002

Abstract

It is significant for deeper understanding of features of ASR damages of concrete structures to reveal relations between expansive pressure under restraint and free expansions of mortars in the laboratory. One of the purposes of this study is to estimate the amount of ASR gel produced within mortars by the combination of EDS analysis for the gels and pore solution analysis. In addition, this study aims at elucidating relations between expansive pressure measured under a restraint condition, and the amount and composition of gels. The expansive pressure was approximately proportional to the amount of ASR gel formed, when alkali contents of ASR gels formed were less than a critical value. However, mortars containing ASR gels with higher alkali content than the critical value showed extremely low expansive pressure, even when they greatly expanded in expansion tests without restraint. These results suggest that, in existing ASR affected concrete structures containing gels with higher alkali content than a critical value, damages due to the secondary stresses caused by restraint might not be so significant, even if reactive aggregates used in the concrete have showed great expansions in mortar bar test in the laboratory.

Keywords: ASR; Expansive pressure; ASR gels; Pore solution; EDS analysis

1. Introduction

Expansion and cracking in ASR damaged concretes are caused by the osmotic pressure due to the imbibition of pore solution by ASR gel produced by the alkali–silica reaction. However, it is difficult to calculate the osmotic pressure by the use of the physico-chemical equation, because we cannot estimate the vapor pressure over the gel [1]. Stresses induced on concrete by restraint of expansion mainly depend on the composition and the amount of ASR gel produced within the concrete. Effects of ASR gel composition on the osmotic pressure due to the absorption of solution into the insoluble gel have been extensively studied. However, relationships between the amount of ASR gel produced in concrete and the overall stress induced across a section of concrete and mortar specimens have not been discussed, probably because it may be difficult to quantitatively obtain the amount of ASR gel within concretes and mortars.

It has been reported that the measured expansive pressure for a synthetic gel exceeded 10 MPa [2]. The expansive pressures measured for mortars confined in a special metal container ranged from 2.5 to 14 MPa [3]. Expansive pressures of 2.5 and 4 MPa were also obtained by constraining the expansion of concretes with reinforcing steel bars [4,5]. Recently, expansive pressures were measured by restraining mortar cylinders with the steel frame immersed in 1 N NaOH solution [6]. In the study by Ferraris et al. [6], the values of 9 and 2 MPa were obtained for two mortar mixes containing aggregates with high and low reactivity levels, respectively. Wide variations of measured expansive pressures may be derived not only from differences in the measuring method and the degree of restraint to free expansion of specimens, but also from differences in the amount and the composition of ASR gels produced in mortars and concretes.

In the existing ASR damaged concrete structures, the degree and the configuration of restraint of concrete members vary widely. Crack patterns are greatly

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doi:10.1016/S0958-9465(02)00135-X

conditioned by the restraint produced by reinforcing steel, prestressing applied, and arrangements of concrete members. Thus, a systematic study for revealing relationships between free expansion of mortars and expansive pressure under a certain degree of restraint is needed for deeper understanding of the process of damaging of concrete due to ASR.

The purpose of this study is to reveal relationships between expansive pressure and free expansion, reactive aggregate and alkali content in mortars by measuring the expansive pressure exhibited by mortar prisms restrained under the steel frame which is similar to the apparatus used in the study by Ferralis et al. [6]. In this study, a method of the estimation of ASR gel volume fraction in mortars by the combination of BSE–EDS analysis for gels and pore solution analysis was proposed. A qualitative consideration was also given to the mechanisms of damages of concrete members due to the alkali–silica reaction from a point of view of the relationships between the expansive pressure, and the ASR gels volume fraction and composition.

2. Outline of experiments

2.1. Materials

Three types of reactive aggregate used were a calcined flint (C.F.), which was produced by Blue Circle Cement Ltd., Yoro chert (a crushed rock produced in Gifu in Japan, Y.C.) and Pyrex glass (P.G.). The reactive components in the calcined flint and the chert were cristobalite and microcrystalline quartz, respectively. The size of the reactive aggregates ranged from 0.6 to 2.5 mm. The Japanese standard sand was used as a non-reactive aggregate. The dissolved silica (Sc) and the reduction in alkalinity (Rc) of the reactive aggregates are given in Table 1. Cements with an equivalent percentage of Na_2O of 1.06 and 0.72 were used for making a series of mortars with various amounts of ASR gels. Furthermore, NaOH was added in the production of mortars at a high dosage level of alkalis equivalent to 1.5%, 2.0% and 2.5% Na_2O in cement. The chemical compositions of cements are presented in Table 2.

Table 1
Dissolved silica and reduction in alkalinity of reactive aggregates

	Dissolved silica (mmol/l)	Reduction in alkalinity (mmol/l)
Calcined flint	1063	70
Yoro chert	391	88
Pyrex glass	1075	27

2.2. Mix proportions of mortars

All the mortars were made with a water:cement ratio of 0.5 and a cement:aggregate ratio of 0.5. A series of mortars were produced with the replacement of the calcined flint of 15%, 30%, 60% and 100% for aggregate. In order to increase the amount of ASR gels produced in mortars, a mortar was made with a cement:aggregate ratio of 1.0 maintaining a water:cement ratio of 0.5 and a reactive aggregate replacement level of 60%. The replacement of Yoro chert and Pyrex glass (pessimum contents) were 30% and 60%, respectively. Only in mortars with the replacement of the calcined flint of 15% and 30% for aggregate, prescribed amounts of NaOH were added to make mortars with an equivalent Na_2O percentage of cement of 1.5%, 2.0% and 2.5% for increasing the amounts and alkali contents of ASR gels produced in mortars.

2.3. Measurements of expansive pressure and free expansion

Mortar prisms, 40 mm by 40 mm by 160 mm, were set in the stainless steel frame at one day after placement of mortars. The schematic diagram of the apparatus is presented in Fig. 1. The force generated by restraining expansion of a mortar prism was transmitted to the load cell through the bearing. The expansive force was recorded by the use of a computer once a day. The frame with a mortar specimen was placed in a moist atmosphere at 38 °C (>95% R.H.). Free expansions of mortars were measured for specimens placed in the same moist container as used in measurements of the expansive pressure. Duplicate or triplicate measurements of expansive pressure were made only in some mortars, as shown in Fig. 2. As shown in Fig. 2, difference in expansive pressure between the three different measurements for the same mortar was very small. Measured free expansions are the average of three measurements.

Table 2
Chemical compositions of cement

	ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Medium alkali cement (%)	1.73	20.9	4.96	2.91	64.48	1.26	2.00	0.48	0.36
High alkali cement (%)	1.32	19.26	6.03	2.01	62.27	2.82	3.64	0.30	1.15

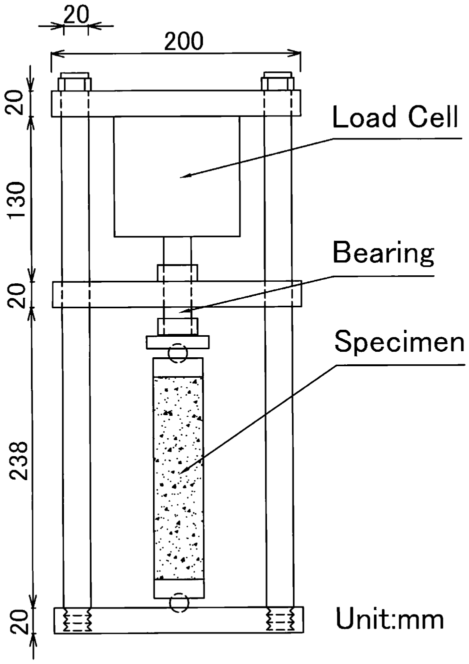

Fig. 1. Schematic diagram of the steel frame for measuring expansive pressure.

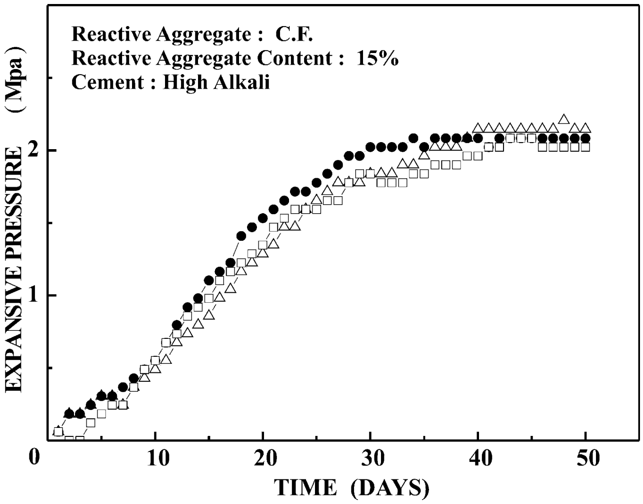

Fig. 2. Expansive pressure curves for a mortar in three different measurements.

2.4. BSE–EDS analysis

Immediately after the completion of measurements of expansive pressure, mortar slices 5 mm in thickness were cut for BSE–EDS analysis from middle portions of mortar specimens. They were dried by ethanol replacement. After that, they were placed in the vacuum drying container at room temperature overnight. The dried slices were impregnated with an ultra-low viscosity epoxy resin under vacuum, and then polished using silicon carbide abrasive papers. The polished surface was sputter coated with a 30 nm thick layer of gold–palladium alloy. BSE–EDS analyses on ASR gels produced in mortars were made only for mortars containing the calcined flint aggregate (C.F.). The polished mortar samples were examined by the use of a Hitachi S-2250N SEM equipped with a back scatter detector and Horiba EMAX-5770W energy dispersive X-ray analyzer. The SEM was operated at 25 KeV. A standard magnification of 500× was used in EDS analyses at 10–20 spots selected within gel areas, 10–20 μm wide and about 150 μm long, within cracks in reactive aggregate particles in mortars. Averages of results of EDS analyses made for 10–20 spots in each gel area for five different reactive aggregate particles were used for the calculation of ASR gel volume fraction in mortars by the use of Eq. (1), the derivation of which is stated in Section 2.7.

2.5. Measurements of amounts of pore solution and its analysis

The quantity and composition of pore solutions and the composition of ASR gels are required for calculating the ASR gel volume fraction in mortars by Eq. (1). Mortar cylinders, 40 mm by 100 mm, used for expressing pore solutions were cured in the same container as used in measurements of expansive pressure. Pore solutions were extracted from 3 days, 7 days and 28 days old mortars with and without reactive aggregate.

We regarded the residual free water content of mortars without reactive aggregate obtained by using mortar samples cured in a moist environment for a prescribed period as equivalent to the amounts of the pore solution in reacting mortars. Considerable parts of alkalis in the pore solution leaked with time from unsealed specimens stored in a moist environment at 38 °C. However, taking into consideration the facts that the gel volume fraction was estimated by the use of amounts of alkalis consumed by ASR by the early time of 7 days, and differences in alkalis concentrations of pore solutions between companion mortars with and without reactive aggregate were regarded as the amount of alkalies consumed by ASR, the effects of the leakage of alkalis from specimens on the estimation of amounts of ASR gels in mortars may not be significant.

2.6. Analysis of pore solution

Mortar cylinders were stored in a moist environment at 38 °C (>95% R.H.). After the prescribed periods of 3 days, 7 days and 28 days, pore solutions were extracted from the mortar specimens by the high-pressure apparatus which was fabricated according to Barneyback and Diamond's description [7]. The Na^+, K^+, Ca^{2+} ion concentration in pore solutions were determined by atomic absorption; the OH^- and SO_4^{2-} ion concentration by titration with HCl and ion chromatography, respectively. All the ions concentrations have been adjusted for bound water to obtain amounts of alkalis ions removed by ASR [7].

2.7. Estimation of the amount of ASR gel produced in mortars

The following equation for estimating the ASR gel volume fraction produced within mortars was derived on the assumption that the difference in the amount of Na^+ and K^+ ions in the pore solution between mortars with and without reactive aggregate was equal to the amount of alkalis ions consumed by the formation of ASR gels in the mortars.

$$\frac{V_g}{V} = \frac{\rho_m w C_s}{\rho_w \rho_g} \frac{A_{Na} A_K}{G_{Na} A_K + G_K A_{Na}} \tag{1}$$

where w is water content of mortar (%), ρ_w: density of pore solution, ρ_m: density of mortar, ρ_g: density of ASR gel, V: volume of specimen (l), V_s: volume of pore solution (l), V_g: volume of ASR gel (l), G_{Na}: Na content in gel (by weight) (%), G_K: K content in gel (by weight) (%), A_{Na}: atomic weight of Na, A_K: atomic weight of K, C_s: difference in Na^+ and K^+ ion concentration in the pore solution between mortars with and without reactive aggregate at 7 days.

The process of the alkali–silica reaction is divided into two stages. The first stage is neutralization of the acidic silanol groups by OH^- ions. In the second stage, excess hydroxyl ions in pore solutions attack the siloxane bridges in the silica structure [12]. The silica structure loosens progressively, resulting in the formation of ASR gel. Since the Na^+ and K^+ ions consumed in the first stage cannot be separately taken into consideration in the derivation of Eq. (1), the equation overestimates the amount of ASR gel in mortars. Thus, in this paper, only a qualitative discussion will be given to the results obtained by the use of the equation.

3. Results and discussion

3.1. Free expansion and expansive pressure in mortars under restraint

Fig. 3 shows free length changes of mortar prisms with time. It is found from Fig. 3 that all the mortars with C.F. have started expanding around 7 days, and expanded only a little after 28 days with the exception of most mortars with empty symbols for which expansion was still increasing to some extent after 28 days. Free length changes with time of mortars containing P.G. and Y.C. are given in Fig. 4. As expected from the dissolved silica for these reactive aggregates (Table 1), mortars with P.G. expanded rapidly, but the ultimate expansion for mortars with Y.C. was as small as about 0.1%.

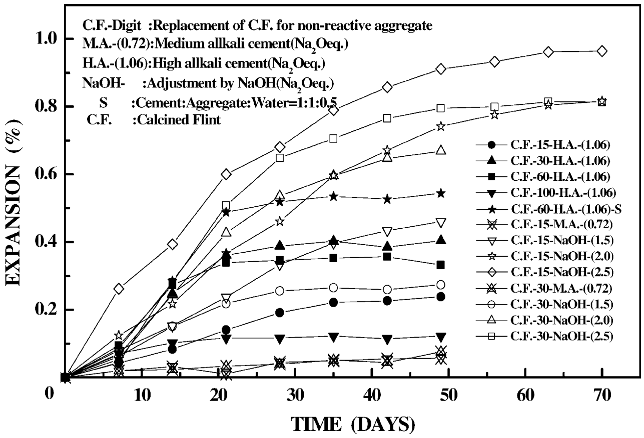

Fig. 3. Free length changes in mortars with calcined flint.

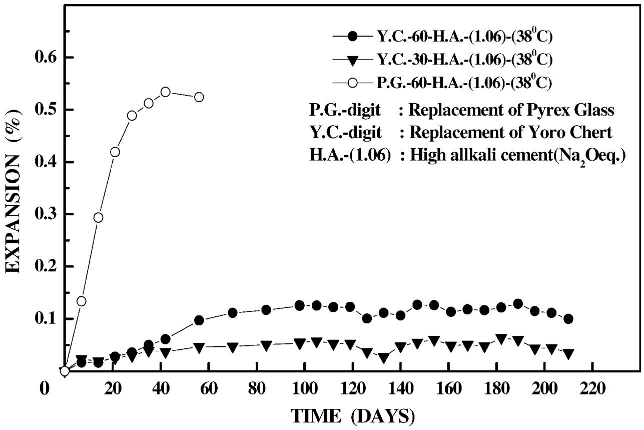

Fig. 4. Free length changes in mortars with Pyrex glass and Yoro chert.

Ultimate expansions for mortars with various C.F. contents were plotted in Fig. 5. The pessimum content for C.F. is found to be between 30% and 60% in the mix proportion of mortars.

Expansive pressures measured by the load cell arranged in the steel frame are plotted against time, as shown in Fig. 6. The expansive pressure of mortars started developing several days after the mortar prisms were fixed in the frame. At 20–30 days after the initiation of expansive pressure tests, ultimate expansive pressures were attained, and thereafter maintained up to at least 50 days. The shapes of expansive pressure curves for mortars were found to be similar to those of their corresponding free expansion curves (Fig. 3).

3.2. Relationships between expansive pressure and free expansion

As presented in Fig. 7, expansive pressures for various mortars with three different reactive aggregates were plotted against their free expansions. All the plots were

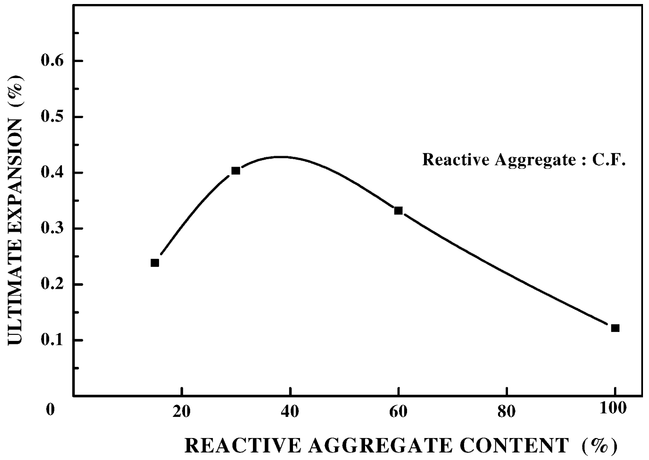

Fig. 5. Relation between ultimate expansion and reactive aggregate content for calcined flint mortars.

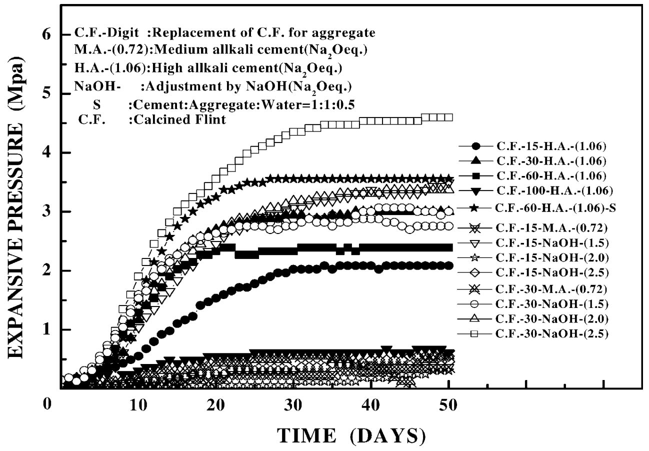

Fig. 6. Expansive pressure of mortars under the steel frame.

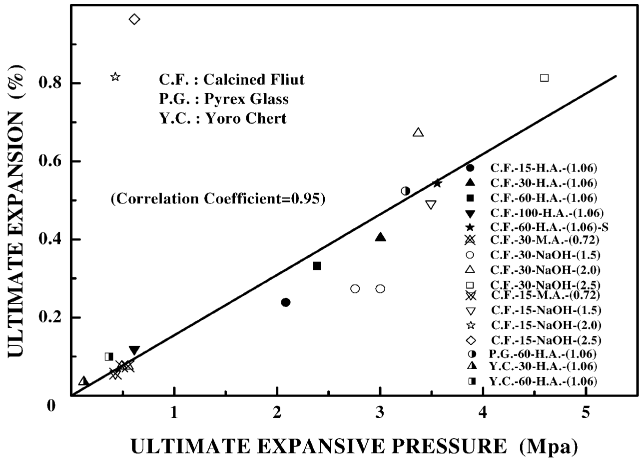

Fig. 7. Relation between ultimate expansive pressure and ultimate expansion.

around a straight line, except that the 15% C.F.-containing mortars with added alkali hydroxide contents to 2.0% and 2.5% when expressed as Na_2O equivalent, showed very high free expansions of 0.8% to 1.0%, respectively, but very low expansive pressures of about 0.5 N/mm^2. It has been pointed out that the correlation between expansions calculated from the mean number and width of cracks and measured expansions for mortars produced with an opaline aggregate was good [8]. The number of cracks caused by the expansive pressure due to ASR gels is supposed to be proportional to the amount of ASR gel produced in mortars. Therefore, the excellent correlation between the expansive pressure and free expansion in most mortars suggests that the viscosity of gels and the osmotic pressure caused by the imbibition of water by the gels were not so greatly different from one mortar to another. However, as discussed below, the compositions of gels produced in the two high alkali mortars showing the exceptional expansive behavior might be different from the compositions of gels in other mortars.

As shown in Fig. 8, the relation between reactive aggregate content and the expansive pressure in a series of mortars made with a high alkali cement and C.F. were almost the same as the relation between reactive aggregate content and free expansion shown in Fig. 5.

Ultimate expansive pressures and expansions for a series of mortars with a reactive aggregate content of 15% and 30% were plotted against the alkali content of mortars as the equivalent percentage of Na_2O, as shown in Figs. 9 and 10, respectively. It was found from Fig. 10 that the ultimate expansion of mortar increased with increasing alkali content in both series of mortars. A conspicuous difference between both series of mortars was found in the development of expansive pressure. In mortars with a reactive aggregate content of 30%, the expansive pressure increased with increasing alkali content (Fig. 9). However, in mortars with a reactive

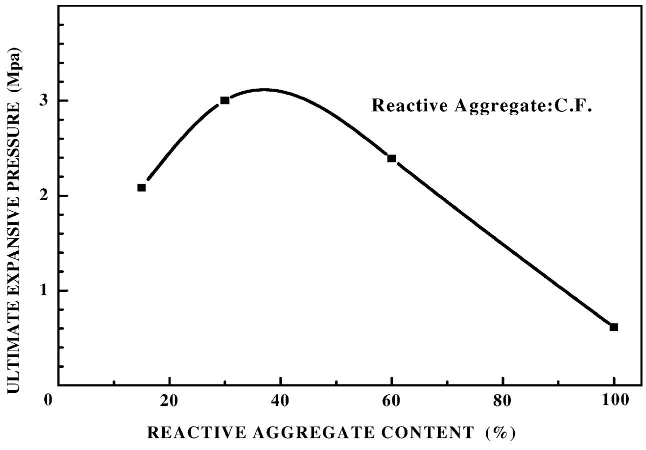

Fig. 8. Relation between ultimate expansive pressure and reactive aggregate content for calcined flint mortars made with high alkali cement.

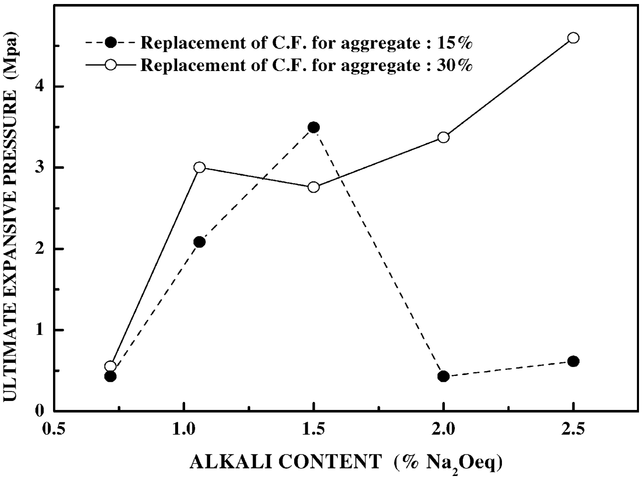

Fig. 9. Relation between ultimate expansive pressure and alkali content in mortars with 15% and 30% replacement of calcined flint.

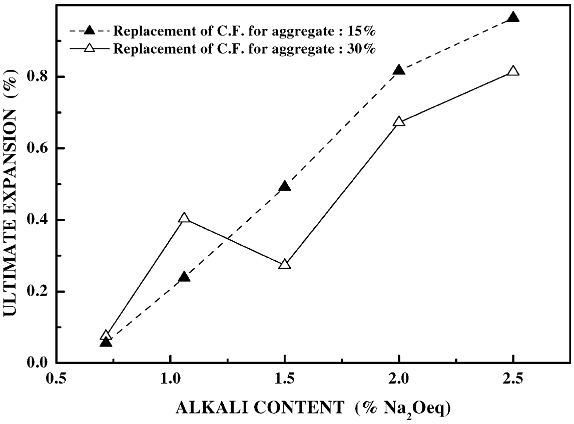

Fig. 10. Relation between ultimate expansion and alkali content in mortars with the replacement of 15% and 30% replacement of calcined flint.

aggregate content of 15%, the expansive pressure increased with increasing alkali content up to the alkali content of 1.5%, followed by a great reduction in the expansive pressure for the alkali content of 2.0% and 2.5%.

3.3. Process of the alkali–silica reaction, pore solution analysis and composition of ASR gels

SEM examinations were conducted on the polished surfaces of a mortar sample taken from a mortar prism after the completion of the expansive pressure test. It was found from the SEM examinations that 10–20 μm wide cracks existed within reactive aggregate particles, as shown in Fig. 11(a). Fig. 11(b) shows an enlarged BSE image for parts of the wide cracks. The wide cracks are found to be impregnated with massive ASR gel. From the results of SEM examinations and EDS analyses for the massive ASR gel areas, the following supposition may be proposed for the process of the alkali–silica reaction in mortars with the calcined flint [9].

As the pore solution intruded into reactive aggregate particles through cracks which had existed in the original reactive aggregate particles [10,11], the alkali–silica reaction must have taken place on silica surfaces along cracks. As a result, ASR gels were produced within the cracks. The expansion of gels widened fissures, some of which might expand to significantly wide cracks. Osmotic pressure due to the imbibition of pore solution by ASR gels within reactive particles lead to the expansive pressure caused by mortar prisms restrained in the steel frame.

Fig. 12 shows time-dependent changes in the difference between Na$^+$ and K$^+$ ion concentration of pore solutions extracted from mortars with and without the reactive aggregate. Since differences in Na$^+$ and K$^+$ ion concentration of pore solutions between mortars with and without reactive aggregate are considered to be the amounts of alkalis consumed by the alkali–silica reaction, the results obtained in this study show that all the ASR gels appear to have been produced by the age of 7 days. The amounts of alkalies which had disappeared from pore solutions by the age of 7 days, and the volume of pore solution in mortars at 7 days were used for calculating the volume fraction of ASR gels in the mortars by the use of Eq. (1).

The average compositions of gels in each reactive aggregate particle are plotted in the ternary phase diagram, as shown in Figs. 13–15. As shown in Fig. 13, the

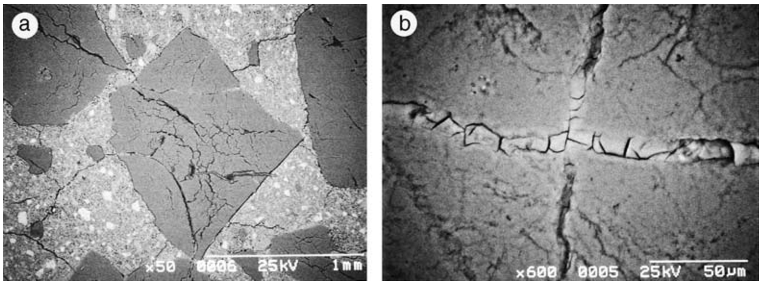

Fig. 11. BSE micrograph for several reactive aggregate particles (a) and the massive ASR gel areas within the aggregate particle (b) in a mortar sample (C.F.-60-H.A.-S) taken after the completion of the expansive pressure test.

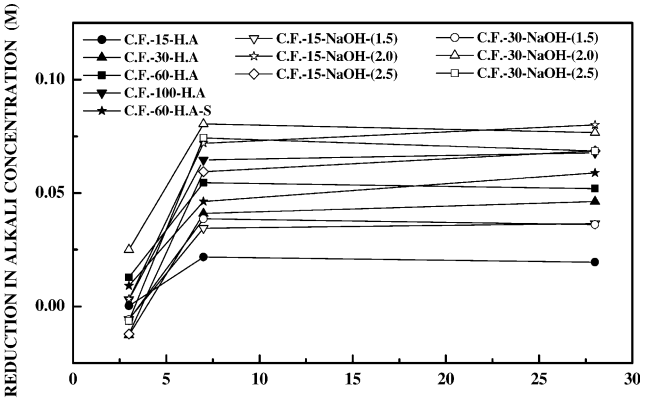

Fig. 12. Time-dependent changes in difference in alkali concentration of pore solutions between mortars with and without reactive aggregate.

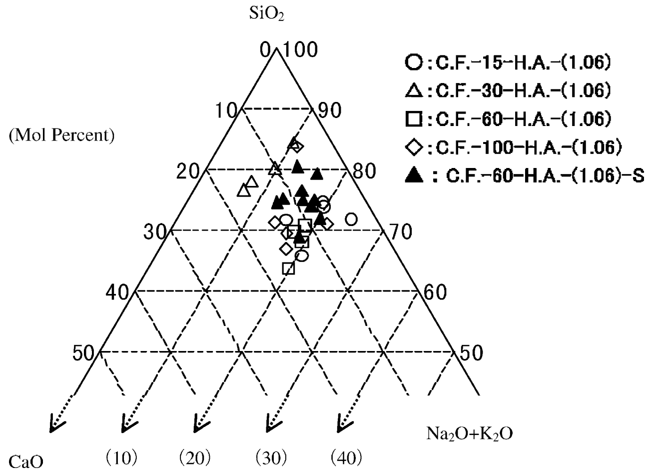

Fig. 13. Ternary phase diagram for ASR gels in reactive aggregate particles in mortars with various reactive aggregate contents.

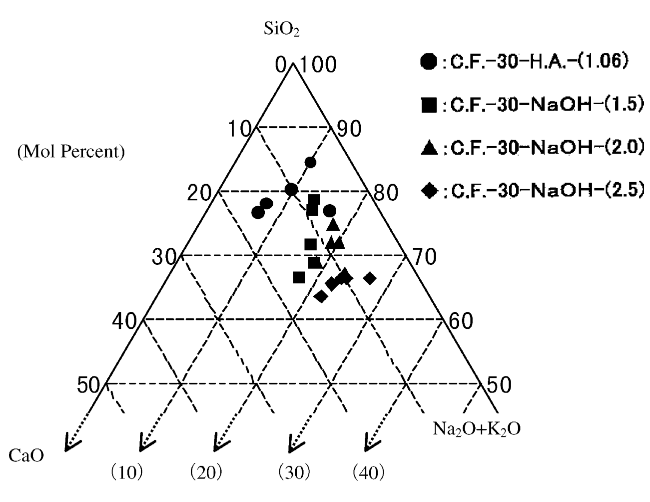

Fig. 14. Ternary phase diagram for ASR gels in reactive aggregate particles in mortars with various alkali contents at a reactive aggregate content of 30%.

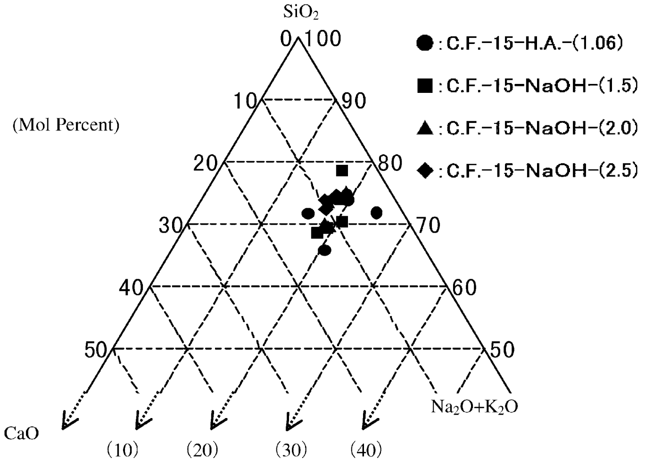

Fig. 15. Ternary phase diagram for ASR gels in reactive aggregate particles in mortars with various alkali contents at a reactive aggregate content of 15%.

compositions of ASR gels produced within reactive aggregate particles are found to vary to a considerable extent within a particle as well as between particles. It should be noted that the alkali content of ASR gel in mortars with a C.F. content of 15% was approximately twice as high as that in mortars with a C.F. content of 30%.

Figs. 14 and 15 show the compositions of ASR gels produced in mortars with different alkali contents at a C.F. content of 15% and 30%. Fig. 14 indicates that, at the C.F. content of 30%, the alkali content of the gels generally increased with increasing alkali content of mortars. As shown in Fig. 9, the ultimate expansive pressure for mortars with a C.F. content of 30% increased with increasing alkali content of mortars. Taking into consideration the general concept that viscosities of low Na_2O/SiO_2 ratio gels are much higher than high Na_2O/SiO_2 ratio gels [12], the increase in expansive pressure with increasing alkali content in the mortars may be attributed to the increase in amount of ASR gels.

However, as shown in Fig. 9, only small expansive pressures occurred, but free expansions were very great at the alkali content of 2.0% and 2.5% in a series of mortars with a reactive aggregate content of 15%. The compositions of ASR gels produced in these two mortars, as shown in Fig. 15, are not so different from those of mortars with the alkali content of less than 1.5%. However, incidentally we found some ASR gel of a very high alkali content within an air void. Fig. 16 shows a BSE micrograph for the massive gels in an air void and the compositions of the gel. A characteristic of the BSE image for ASR gel areas in the air void was that parts of the gel areas were darker than the other parts. The results of EDS analyses made at about 12 spots in the darker and lighter gel areas in the BSE image are given

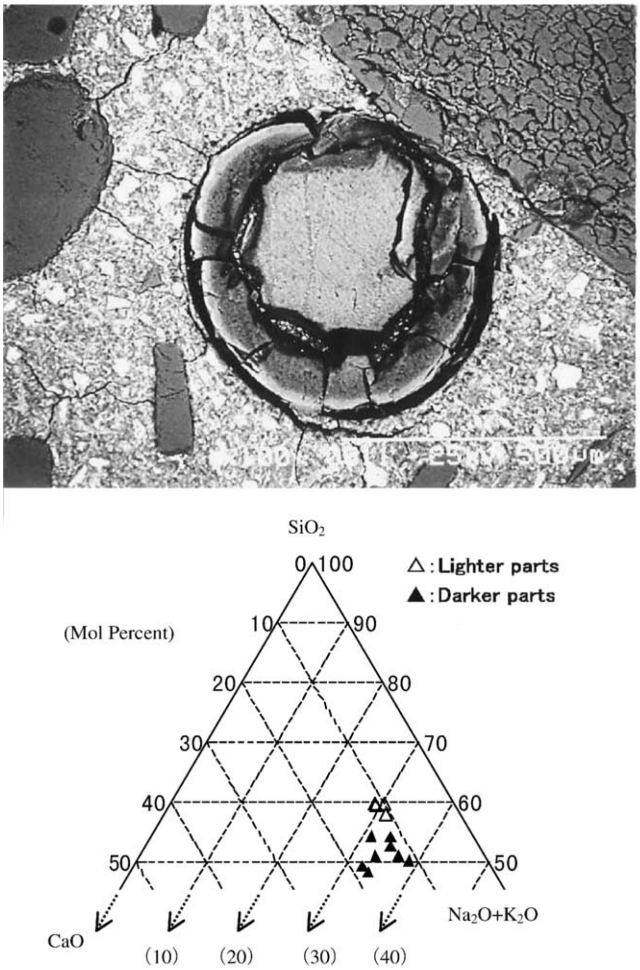

Fig. 16. BSE micrograph for ASR gels deposited in an air void and their composition in the mortar of C.F.-30-NaOH-(2.0).

in the ternary diagram in Fig. 16. It is found from the ternary phase diagram in Fig. 16 that both the alkali and calcium contents of the darker areas are greater than those of lighter areas. The alkali contents of the darker gel areas were about 35%; their calcium contents were about 15%. The alkali contents of these gels contained in the air voids are found to be considerably greater than those of gels found within reactive aggregate particles. Thus, we assumed that the gels of very high alkali content might be incidentally deposited in an air void without transport through the matrix of cement paste. In fact, in the upper right corner in the BSE micrograph in Fig. 16, a reactive aggregate particle was contiguous to an air void.

We also found the exudation of great amounts of gels through cracks on the surfaces of only the mortars prisms made with an alkali content of 2.0% and 2.5%, as shown in Fig. 17. Such exudations were not found with other mortars of lower alkali content. From these experimental results, we presumed that gels with very high alkali contents had been produced within reactive aggregate particles in these mortars, and then dissolved into the cement paste matrix and/or microcracks, finally appearing on the surfaces of mortar prisms. The viscosity of alkali-rich gels in the mortars must be so low even at relatively low water content that they could not exhibit a high expansive pressure under restraint. However, even in the mortars, the osmotic pressure due to the imbibition of water by gels may be high enough to cause cracks leading to great free expansions of the mortar prisms.

Fig. 17. Exudation of ASR gels on the surfaces of a mortar prism.

3.4. Relations between the amount of ASR gel and expansive pressure

The Na and K contents of gels used for calculating the volume fraction of gel are presented in Table 3. The measured free water contents for mortars with a cement:aggregate ratio of 0.5 and 1 were 7.63% and 13.01%, respectively. The density of gel was assumed to be 2.09 (g/cm^3) [12]. In Fig. 18, measured ultimate expansive pressures for mortars are plotted against the volume fraction of ASR gels produced in the mortars. As shown in Fig. 18, the expansive pressures have a tendency to increase with increasing volume fraction of ASR gel, but are not so closely correlated with it.

It was stated above that very low expansive pressures in the mortars corresponding to the two points at the volume fraction of gel of about 2.0% and 1.7% may be due to the formation of very alkali-rich gels. The other point far away from the trend represents the mortar made with 100% replacement of C.F. Despite a relatively large amount of gel produced in this mortar, only a low expansive pressure occurred under restraint. The deviation of this point from the trend line may be due to overestimation of the volume fraction of gel by the use of Eq. (1). A great amount of alkalis was consumed in the first reaction stage (neutralization) of the alkali–silica reaction process on the great internal and external reactive silica surface areas in this reactive aggregate; this surface reaction, not leading to the formation of ASR gels.

Taking account of the result that differences in expansive pressure between different measurements for the same mortar were very small (Fig. 2), the reliability of the measured expansive pressures in this study is considered very high. Therefore, the scatter of the plot in Fig. 18 may be attributed to uncertainly in the estima-

Table 3
Na and K content of ASR gels and C_S values used for calculating ASR gel volume fraction in mortars

	G_{Na} (%)	G_K (%)	C_S (mol/l)	V_g/V (%)
C.F.-15-H.A.-(1.06)	6.930	0.590	0.043	0.588
C.F.-15-NaOH-(1.5)	7.179	9.186	0.069	0.999
C.F.-15-NaOH-(2.0)	8.777	7.453	0.144	1.993
C.F.-15-NaOH-(2.5)	8.476	6.917	0.119	1.726
C.F.-30-H.A.-(1.06)	4.160	1.990	0.082	1.988
C.F.-30-NaOH-(1.5)	6.680	8.918	0.077	1.179
C.F.-30-NaOH-(2.0)	8.550	8.738	0.161	2.142
C.F.-30-NaOH-(2.5)	12.488	6.277	0.149	1.674
C.F.-60-H.A.-(1.06)	6.410	1.550	0.109	1.545
C.F.-100-H.A.-(1.06)	5.650	2.080	0.129	2.079
C.F.-60-H.A.-(1.06)-S	5.597	8.652	0.092	2.323

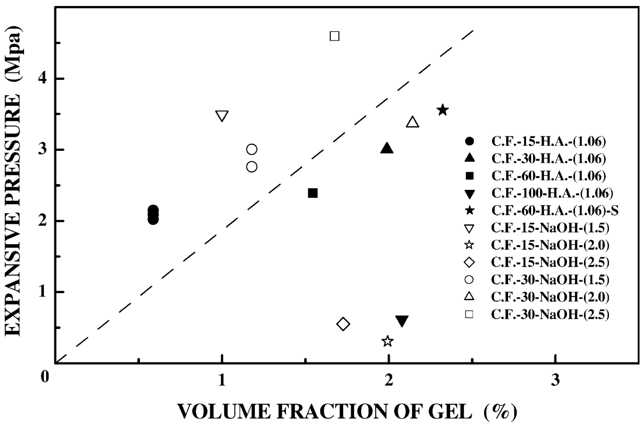

Fig. 18. Relation between expansive pressure and volume fraction of ASR gel.

tion of the volume fraction of the gel. However, it may be concluded that the expansive pressure induced in mortar prisms under restraint is generally approximately proportional to the volume fraction of ASR gel except for mortars with especially alkali-rich gels.

3.5. Consideration on ASR damages in concrete structures from the viewpoint of expansive pressure under restraint

The degree of restraint of members in existing ASR affected concrete structures may vary widely. Furthermore, as shown in Fig. 6, even under such an arbitrary degree of restraint as the steel frame used in this study, measured expansive pressures ranged widely, depending on the amount of reactive aggregate and cement, and on the alkali content in mortars. The expansive pressure generated in most mortars used in this experiment appears to depend on the amount and composition of gel. However, ASR gels with high alkali contents can be produced by particular combinations of reactive aggregate and alkali content and these do not generate high expansive pressure. Even if concretes containing ASR gels with high alkali contents (i.e. alkali contents higher than about 25%) exhibit great expansion in a free expansion test, the damages to concrete members caused by secondary stresses under a considerable degree of restraint may not be so significant.

4. Conclusions

The major results obtained in this study are summarized as follows;

(1) The shapes of expansive pressure curves were similar to those of their corresponding expansion curves.
(2) The expansive pressure generated under longitudinal restraint was in proportion to free expansion except that the 15% C.F.-containing mortars with a high Na_2Oe of 2.0 and 2.5% showed high expansions (0.8–1.0%), but low expansive pressures (about 0.5 MPa). This exceptional behavior of the alkali-rich mortars appears to be due to the production of alkali-rich ASR gels.
(3) The relationships between reactive aggregate content and expansive pressure in a series of mortars without added NaOH were almost the same as the relationships between reactive aggregate content and free expansion.
(4) The results obtained in this experiment suggest that, even if concretes containing ASR gels with a high alkali content exhibit great expansions in laboratory expansion tests, damages due to secondary stresses induced by the expansive pressure in concrete members under restraint may not be significant.

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