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Estimation of critical free expansions related to surface cracking in ASR-affected concretes

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Abstract

This paper proposes a simple procedure to determine the critical free expansion for macro-surface cracking in ASR-affected model concrete cylinders. It is assumed that the non-reactive near-surface concrete regions act as restraint against uniform expansion of the inner core due to ASR. The critical free expansion is calculated assuming that a longitudinal crack forms when the maximum circumferential tensile stress in the concrete cylinder reaches the tensile strength of the material. The expansive pressure that causes the tensile stress depends on degree of restraint, as determined from measured expansive pressures and free expansions. The calculated critical free expansions for concretes with various strengths at various depths of the non-reactive concrete cylinders can be used to qualitatively interpret the significance of suppression of ASR macro-cracking by drying and relatively lower probability of surface cracking in structures in indoor rather than outdoor environments. It appears the proposed procedure can be used for estimating critical free expansions independently of temperature.

Keywords: ASR; Critical free expansion; Expansive pressure; Non-reactive layer

1. Introduction

Overall expansions of ASR affected-concretes originally arising from swelling of ASR gel in the concretes are restrained by the non-reactive near-surface layers and reinforcement, resulting in the induction of secondary stresses. Differential expansions and movements between separate parts of concrete that expand at different rates also induce secondary stresses.

The presence of reactive silica in the aggregate, sufficient amounts of alkali, and sufficient moisture contents are required for expansive ASR in concrete. Absence of any one of these requirements results in little expansion. A series of mortar bar tests indicated that the threshold relative humidity (RH) above which expansive ASR can occur is 80% [1]. The extensive field investigations [1] revealed that depths of near-surface layers with relative humidity values below the 80% threshold level varied widely in existing ASR-affected concretes structures. The non-reactive layers restrain expansion of the inner cores, and thus, tensile stresses are induced in the layers. These tensile stresses can become large enough to cause surface cracking.

It was found that a considerable amount of expansion can frequently be observed before cracks become visible to the unaided eye in concrete cube tests at outdoor exposure sites [2]. This finding suggests that the surface cracking may be due to the existence of non-reactive near-surface layers in the concrete cubes.

It has been reported that the expansive pressure induced in ASR-affected concrete under restraint depends considerably on the degree of restraint [3]. Furthermore, measured expansive pressures for expanding mortars under a certain degree of restraint were far smaller than those estimated from measured free expansions by regarding the mortars as elastic materials [4]. However, we indicated that expansive pressures induced by restraining free ASR expansions

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in mortars were proportional to free expansions with a few exceptions in one dimensional expansive pressure tests [4]. Thus, we can calculate the ultimate tensile stresses induced in the non-reactive surface layers in unreinforced concrete bodies by a simple procedure based on the assumption that expansive pressures are proportional to free expansion under a given degree of restraint. In this paper, critical free expansions for surface cracking in ASR-affected model concrete cylinders made with various strengths are estimated by calculating the maximum tensile stresses induced in the non-reactive layers. We review the significance of empirical preventive measures for ASR damage in concrete by the use of the calculated critical free expansions. Expansion of ASR-affected concretes is greatly influenced by temperature. The effect of temperature on the relationship between expansive pressure and free expansion will be also discussed.

2. Estimation of critical free expansions in model concrete cylinders

In addition to reductions in relative humidity in concretes to lower than 80%, carbonation and fixation of alkali hydroxide by repeated drying also influence the formation of the non-reactive near-surface regions in ASR-affected concretes [5,6]. In estimation of critical free expansions for surface cracking in this study, depths of the non-reactive surface layers are assumed to be controlled only by the 80% threshold level of relative humidity.

The non-reactive layer in a model concrete cylinder, which is shown in Fig. 1, restrains an expansive core to induce expansive pressure. It is assumed that the uniform ASR expansive pressure acts on the internal surface of non-reactive layer as in a cylindrical pressure vessel. The state of stress in the cylinder is treated as a problem of the plane strain. The maximum circumferential tensile stress ($\sigma_{\theta t}$) at the inner surface of cylinder is greater than the longitudinal normal tensile stress [7]. Thus, in this study, critical free expansions are calculated, assuming that a longitudinal crack forms when the maximum circumferential stress reaches the tensile strength of the material. However, creep processes would reduce the tendency for cracking.

It has been accepted that the first chemical reaction process producing ASR gels was followed by the physicochemical process of expansion [8]. Based on this concept, after cease of the chemical reaction process, the expansive pressure induced under restraint should increase with increasing free expansion of concrete for relatively long times up to accomplishment of the ultimate equilibrium state between tensile stresses in non-reactive surface layers and internal compressive stresses. The ultimate maximum circumferential stress ($\sigma_{\theta t}$) at the inner surface of the non-reactive layer in an ASR-affected model concrete cylinder with free ends at a sufficient distance from the ends, which is free from external forces, is given by Eq. (1). (Fig. 1) [7]

$$\sigma_{\theta t} = p_i\{r^2 + (r-\delta)^2\}/\{r^2 - (r-\delta)^2\} \quad (1)$$

where $\sigma_{\theta t}$: the circumferential tensile stress, δ: depth of the non-reactive layer, r: the radius of cylinder, and p_i: the expansive pressure.

Expansive pressure caused by restraining free expansion due to ASR is proportional to free expansion [4]. Thus, the expansive pressure (p_i) induced within an ASR-affected concrete core in the model concrete under restraint of the non-reactive layer is

$$p_i = \alpha_i \cdot \epsilon_f \quad (2)$$

where p_i: expansive pressure, α_i: coefficient of the degree of restraint, and ϵ_f: free expansion.

Experimental data of the relationships between expansive pressure (p_i) and free expansion (ϵ_f) have been measured by some workers [4,9]. As shown in Fig. 2, measured expansive pressures for concrete–steel bar composite specimens with four different amounts of steel at 40 °C are presented as the four marks at a free expansion of 0.6% [9]. The bold line in Fig. 2 is the regression line for the data of measured expansive pressures for various mortars prisms restrained under a steel frame and their measured free expansions at 38 °C [4]. The linear regression coefficient for the bold line is 0.95, indicating a close fit of the data.

The relationship between coefficients of the degree of restraint (α_i) and amounts of steel (β_s) (degree of restraint) is expressed as a curve in Fig. 3. The curve indicates that coefficient of the degree of restraint (α_i) increases with increasing amount of steel (β_s). Above the amount of steel of 0.4%, however, the increasing rate of $\dot{\alpha}_i$ rapidly decreases with increasing amount of steel.

In order to estimate the tensile stress induced in the non-reactive layers in the ASR-affected concrete cylinder with

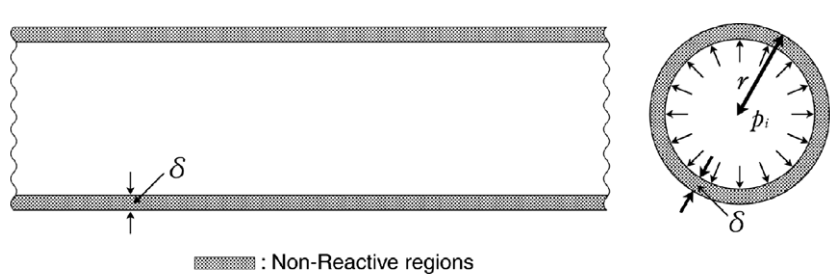

Fig. 1. Schematic diagram of ASR-affected model concrete cylinder.

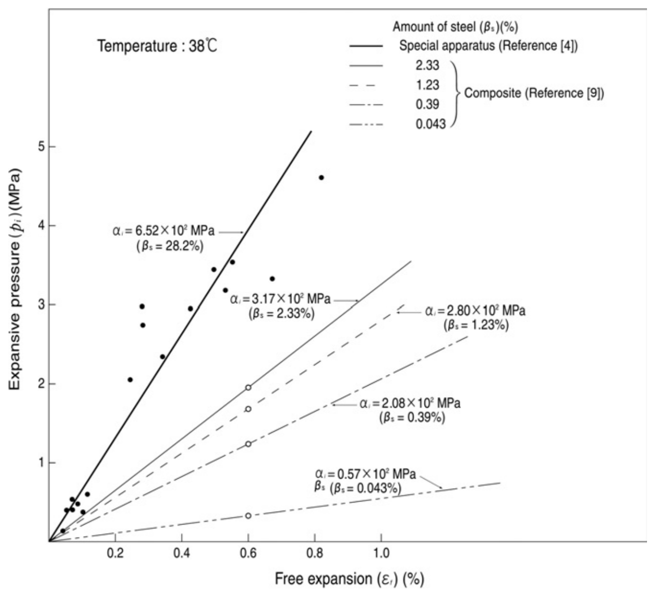

Fig. 2. Relationships between expansive pressure and free expansion at 38 °C.

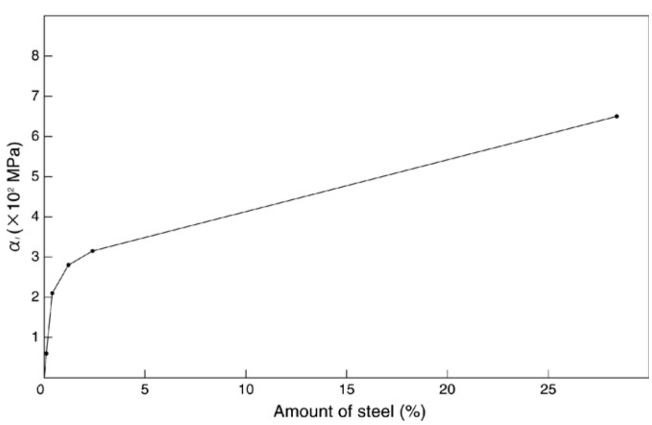

Fig. 3. Relationship between coefficient of restraint and amount of steel at 38 °C.

Eqs. (1) and (2), the degree of restraint imposed on the internal expanding core by the external non-reactive layer should be evaluated. This degree of restraint depends on the depth of the layer and modulus of elasticity of the material. It is difficult to measure expansive pressures in concrete cylinders with various depths of the non-reactive layer. However, the relationship between coefficient of the degree of restraint (α_i) and amount of steel (β_s) given in Fig. 3 is available. Namely, in the calculation procedures, the degree of restraint imposed by the non-reactive layer can be estimated with the curve in Fig. 3. For the purpose of using the curve for the calculations, the equivalent amount of steel of the non-reactive concrete layer (β_{se}) is defined in Eq. (3) assuming that the degree of restraint of the layers around expanding concrete cores is proportional to sectional area of the layers and modulus of elasticity of the materials.

$$\beta_{se} = (A_n/A_0)(E_c/E_s), \tag{3}$$

Table 1
Tensile strength and modulus of elasticity of various concretes and steel[a] used for calculating critical free expansions (ϵ_{fc})

Compressive strength (MPa)	24	30	40	100
Modulus of elasticity (GPa)	25	28	31	40
Tensile strength (MPa)	2.4	3.0	4.0	6.0

[a] Es = 200 GPa.

Table 2
Critical free expansions of model concretes cylinders with various compressive strengths at $\delta/r = 0.4$, 0.3, 0.25, 0.10 and 0.05

Compressive strength (MPa)	24	30	40	100
$\delta/r = 0.4$				
β_{se} (%)	22.2	24.9	27.6	35.6
α_i ($\times 10^2$ MPa)	5.93	6.21	6.49	7.39
ϵ_{fc} (%)	0.19	0.23	0.29	0.38
$\delta/r = 0.3$				
β_{se} (%)	13.0	14.6	16.1	20.8
α_i ($\times 10^2$ MPa)	4.71	4.98	5.18	5.75
ϵ_{fc} (%)	0.17	0.21	0.26	0.37
$\delta/r = 0.25$				
β_{se}(%)	9.72	10.9	12.1	15.6
α_i ($\times 10^2$ MPa)	4.35	4.48	4.62	5.10
ϵ_{fc} (%)	0.15	0.19	0.24	0.33
$\delta/r = 0.1$				
β_{se}(%)	2.93	3.28	3.64	4.69
α_i ($\times 10^2$ MPa)	3.29	3.37	3.43	3.58
ϵ_{fc} (%)	0.077	0.093	0.12	0.18
$\delta/r = 0.05$				
β_{se} (%)	1.35	1.75	1.94	2.50
α_i ($\times 10^2$ MPa)	2.87	3.00	3.18	3.22
ϵ_{fc} (%)	0.043	0.051	0.065	0.095

where β_{se}: equivalent amount of steel, A_n: sectional area of the non-reactive layer, A_0: sectional area of expanding concrete core, E_c: modulus of elasticity of concrete, E_s: modulus of elasticity of steel.

Measured depths of the non-reactive layers in existing ASR-affected concrete structures ranged from 2.5 to 20 cm [1]. Supposing an ASR-affected model concrete cylinder with radius 50 cm (Fig. 1), critical free expansions for concretes with compressive strengths of 24, 30, 40 and 100 MPa can be calculated at depths of the non-reactive layer of 20, 15, 12.5, 5 and 2.5 cm with Eqs. (1)–(3). The moduli of elasticity and tensile strengths of concretes used in the calculations are tabulated in Table 1. The calculated critical free expansions (ϵ_{fc}), equivalent amounts of steel (β_{se}) and coefficients of restraint (α_i) at various values of δ/r are presented in Table 2.

3. Significance of empirical preventive measures in view of the critical free expansions

Several concepts concerning empirical preventive measures of ASR are reviewed using the calculated critical free expansions.

Comparisons of the values of ϵ_{fc} at $\delta/r = 0.1$ and 0.05 in Table 2 explicitly show that, at a depth of the non-reactive layer (δ), the value of ϵ_{fc} can be reduced by about half by doubling the radius of cylinder (r). This result is consistent with the general concept that the more massive the ASR-affected concrete structures, the more serious are the ASR damages [10]. If we suppose an ASR-affected concrete cylinder with radius 50 cm, an increase in depth of the non-reactive layers from 2.5 to 5.0 cm ($\delta/r = 0.05$–0.10) in the cylinder approximately doubled the critical free expansions in the various concretes (Table 2). Generally, the probability of macro-surface cracking in ASR-affected concrete structures can be reduced by drying. Interior relative humidities measured in massive field structures are high enough to maintain expansive ASR [1]. Thus, it is by increasing depth of the non-reactive layers by drying that the probability of surface cracking can be reduced. Naturally, shrinkage stresses are intermittently added to the tensile stresses due to ASR in concrete members, which are exposed to repeated wetting–drying environments.

Stark [1] has measured relative humidity (RH) values at different depths and locations in field ASR-affected concrete structures. The data for the pavement concretes indicated that, at all locations regardless of climate, RH values exceeded the 80% threshold level at depths greater than about 5 cm. Similar results were obtained from the data collected for thinner concrete members, such as parapet walls, walkways and spillway piers, in concrete dams in various climates in the United States. However, depths at which measured RH values exceeded the 80% threshold level, ranged from 15 to 20 cm in the interior walls in a hydroelectric dam power house. Summarizing the results obtained in the investigations [1], depths of the non-reactive layers ranged from 15 to 20 cm in indoor concrete members, being between 2.5 and 12.5 cm in outdoor ones.

Judging from the criterion of expansion of 0.1% at six months in ASTM mortar bar test generally used, free expansions of ASR-affected concretes in fields may exceed 0.1%. Calculated critical free expansions indicate that most values of ϵ_{fc} for the model concretes cylinders with radius 50 cm at depths of the non-reactive layers of 15–20 cm in indoor members ($\delta/r = 0.3$–0.4) are greater than about 0.2% (Table 2). This result suggests that the risk of surface cracking in ASR-affected indoor concrete members is relatively low. In fact, in the German guideline for alkali-aggregate reactions in concrete [11], preventive measures against alkali-aggregate reactions are not taken for interior components of buildings. However, supposing ASR-affected model concrete cylinders with radius 50 cm that are exposed to outdoor precipitation [1], the values of ϵ_{fc} range from about 0.04% to about 0.3% at depths of the non-reactive layers of 2.5 to 12.5 cm ($\delta/r = 0.05$–0.25) (Table 2). Risk of surface cracking in outdoor concrete members may be relatively high.

4. Effect of temperature on the coefficient of restraint (α_i)

Critical free expansion depends on the coefficient of the degree of restraint (α_i) (Eqs. (1) and (2)). However, ASR expansion of concrete varies with temperature. Measurements of expansive pressures and free expansions for some mortars used in expansive pressure tests at 38 °C [4] were also carried out at 20 °C [12]. A series of mortars were prepared with a water/cement ratio of 0.5 and aggregate/cement ratios of 2.0 and 1.0 (indicated as N and S, respectively, in the legends of Figs. 4–8). The alkali content (equivalent percentage Na_2O) of the cement used was 1.06%. The calcined flint (C.F.) produced by Blue Circle or Pyrex glass (P.G.) and the Japanese standard sand were used as a reactive and a non-reactive aggregate, respectively. Figs. 4 and 5 show free length changes of mortars prisms with C.F. and P.G. at both temperatures with time, respectively. Measured expansive pressures for the mortars are presented in Figs. 6 and 7. Free expansions and expansive pressures measured at 20 °C are found to increase far

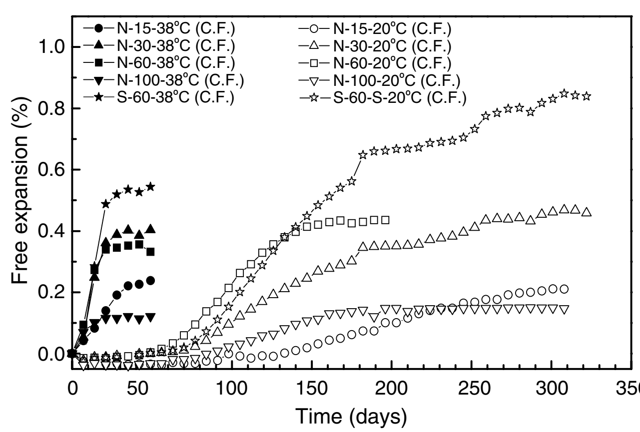

Fig. 4. Free length changes in C.F. mortars with time at 20 °C and 38 °C.

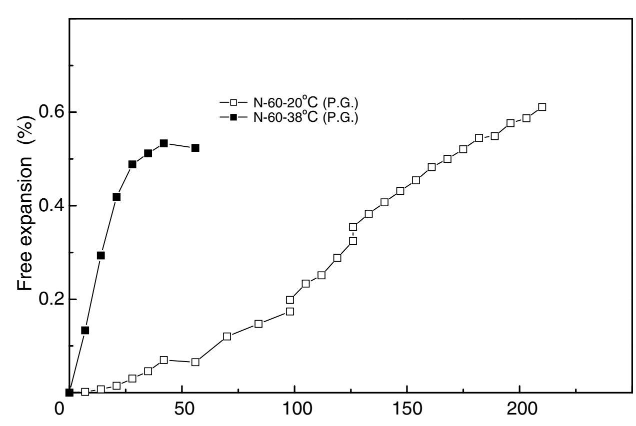

Fig. 5. Free length changes in P.G. mortars with time at 20 °C and 38 °C.

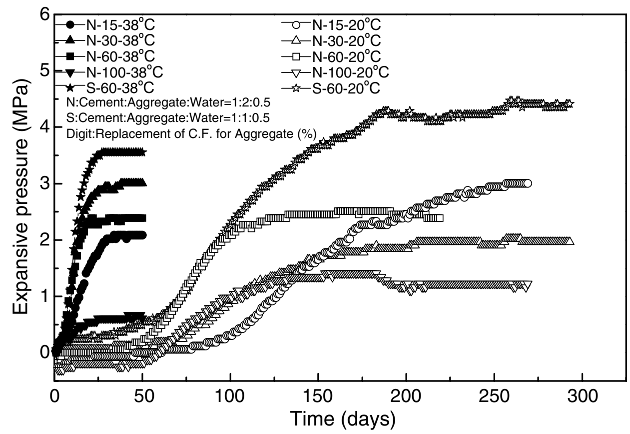

Fig. 6. Expansive pressures measured for C.F. mortar prisms restrained in a steel frame at 20 °C and 38 °C [4,12].

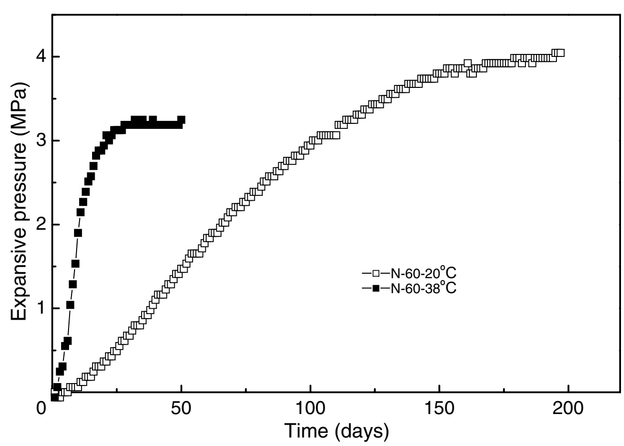

Fig. 7. Expansive pressures measured for P.G. mortar prisms restrained in a steel frame at 20 °C and 38 °C [4,12].

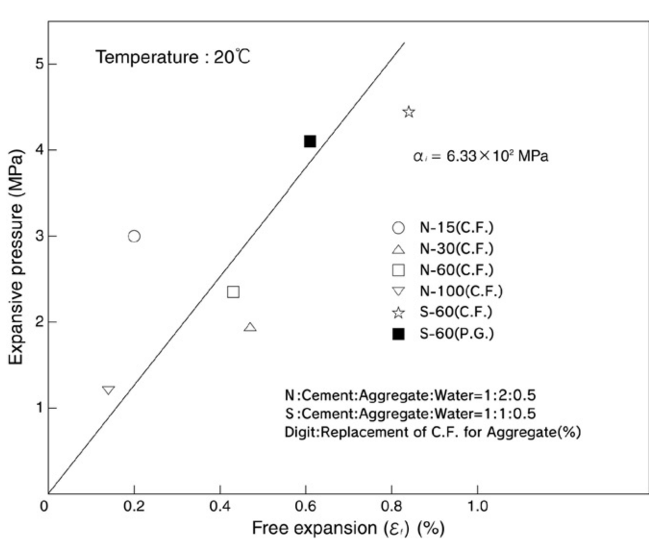

Fig. 8. Relationship between expansive pressure and free expansion at 20 °C [12].

more slowly with time than those measured at 38 °C. As shown in Fig. 8, measured expansive pressures for the mortars were plotted against their free expansions at 20 °C [12]. The coefficient of the degree of restraint (α_i) calculated from the slope of the regression line was 6.33×10^2 MPa [12]. The linear regression coefficient was 0.80, attesting to considerably good fit of the data. The value of $\dot{\alpha}_i$ (6.33×10^2 MPa) at 20 °C is little different from the value of α_i (6.52×10^2 MPa) at 38 °C (Fig. 2). Coefficient of the degree of restraint changes little with temperature. This result suggests that the procedure for estimating critical free expansions proposed in this paper is applicable for predicting surface cracking even in concrete cylinders exposed to outdoor environments.

5. Conclusions

We obtained an experimental result that expansive pressure induced by restraining free expansion due to ASR was proportional to free expansion with a few exceptions [4]. On the assumption that expansive pressure is proportional to free expansion, and the non-reactive near-surface layers restrain expansions of inner cores, critical free expansions for surface cracking in ASR-affected unreinforced concretes can be calculated by a simple procedure, if the strength and modulus elasticity of concrete, cylinder dimensions, and depth of non-reactive layer are given.

Using this procedure, it is seen that reductions in tensile strength in ASR-affected concretes would reduce critical free expansions. The results of calculations also indicate that increasing depth of the non-reactive layers by drying can reduce the probability of surface cracking. Furthermore, it appears the procedure can be used for estimating critical free expansions independent of temperature.

References

[1] Stark D. The moisture condition of field concrete exhibiting alkali–silica reactivity. In: Proceedings of the second international conference on durability of concrete (ACI SP-126), 1991, Montreal, Canada. p. 973–87.
[2] Grattan-Bellew PE. Evaluation of test methods for alkali-aggregate reactivity. In: Proceedings of the sixth international conference on alkalis in concrete, 1983, Copenhagen. p. 303–14.
[3] Doran DK. (Chairman of Task Group), Structural effects of alkali silica reaction. Institute of Structural Engineers, 1992. p. 45.
[4] Kawamura M, Iwahori K. ASR gel composition and expansive pressure in mortars under restraint. Cement Concrete Comp 2004;26(1):47–56.
[5] Diamond S. Alkali silica reaction – some paradoxes. In: Proceedings of the tenth international conference on AAR in concrete, 1996, Melbourne. p. 3–14.
[6] Hagelia P. Origin of map cracking in view of the distribution of air voids, strength and ASR-gel. In: Proceedings of the twelfth international conference on alkali-aggregate reaction in concrete, vol. II. 2004, Beijing. p. 870–81.
[7] Timoshenko S, Goodier JN. Theory of elasticity. McGraw-Hill, Inc.; 1951. p. 53–60.
[8] Diamond S, Barneyback RS, Struble LJ. On the physics and chemistry of alkali–silica reactions. In: Proceedings of the fifth international conference on alkali-aggregate reaction in concrete, 1981, Cape Town, South Africa. S252/22.

[9] Committee on AAR of the Hanshin expressway public corporation. Report of investigation of alkali-aggregate reaction, Hanshin Expressway Public Corporation, 1986, Osaka, Japan. p. 339 [in Japanese].

[10] Flanagan JC. Alkali-aggregate reaction: practical, preventive and remedial measures. In: Proceedings of the fifth international conference on alkali-aggregate reaction, 1981, Cape Town, South Africa. S252/17.

[11] German committee for reinforced concrete, guidelines for alkali-aggregate reactions in concrete, German Building Standards, Committee of the Deutsches Institute fur Normunge eV, December 1986.

[12] Iwahori K. A study on expansive pressure due to ASR, MS Thesis, Kanazawa University, 2001, 92 pp [in Japanese].