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A study on the alkali-aggregate reaction in high-strength concrete with particular respect to the ground granulated blast-furnace slag effect

Young-jin Kwon*

Fire Fighting Engineering, Hoseo University, Korea

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Abstract

The alkali-aggregate reaction (AAR) in high-strength concrete and the effect of ground granulated blast-furnace slag (GGBFS) were studied in this paper. From the results of this study, following conclusions can be drawn:

(1) In high-strength concrete, because of high alkali content, the possibility of alkali-aggregate reaction is much higher than conventional concrete.
(2) The occurrence of large expansion can be prevented by using nonreactive aggregate, which has been judged according to the mortar bar and chemical method's as specified in JIS A 5308, in high-strength concrete.
(3) The replacement of cement by 30% of blast-furnace slag and using low-alkali cement can prevent the alkali-aggregate reaction from causing large expansion in high-strength concrete.

Keywords: Alkali-aggregate reaction; Expansion; Aggregate; Cement; Granulated blast-furnace slag

1. Introduction

Deterioration of concrete due to alkali-aggregate reaction (AAR) is known to be closely related to the total alkali content of concrete. In order to inhibit deleterious expansion induced by AAR, the following measures have been exercised [1–3]:

- Use of aggregate that is judged as innocuous by the chemical method and mortar bar method.
- Use of low-alkali cement with an alkali (R_2O) content of 0.6% or less.
- Use of blended cement having an effect of inhibiting AAR.
- Proportioning to reduce the total alkali content to 3.0 kg/m^3.
- As suggested by these measures, the major source of alkali supply to concrete is cement.

High-strength concrete, which was recently put to practical use, is made with a high cement content to achieve a low water/cement (W/C) ratio, entailing high cement-derived alkali content. Although this is a disadvantage in regard to AAR, the high strength of the concrete may restrain the expansion. Investigation into AAR of high-strength concrete is a prerequisite for its use on a commercial scale [4–7].

The JCI concrete bar method was proposed in 1991 by the Japan Concrete Institute as a method of testing the reactivity of actual concrete mixtures. In this study, the authors conducted tests in accordance with this method to investigate the following in regard to AAR of high-strength concrete:

whether or not high strength concrete with a high cement content is disadvantageous when compared with normal concrete.

* Tel.: +82 41 540 5734; fax: +82 41 540 5739.
E-mail address: refrete@lycos.co.kr.

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Table 1
Selection of aggregate

Mortar bar method total amount of alkali	Fine aggregate						Coarse aggregate									
	M	N	I	F	K2+O2	S	C	A	K	T	T2	L5	O1	R	M1	C1
1.2%	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
1.5%			○	○	○	○	○	○	○	○	○	○	○	○	○	

whether or not aggregate that shows deleterious expansion with an alkali content slightly above the value specified by the mortar bar method causes deleterious expansion in the high alkali environment of high strength concrete.

whether or not the use of ground granulated blast-furnace slag (GGBFS) which is used to inhibit AAR of normal concrete, is also effective for high-strength concrete.

2. Experiment plan

2.1. Selection of aggregate

Prior to testing of concrete, aggregates were selected for use in each test. Seventeen aggregates, 7 fine and 10 coarse, were subjected to tests by the mortar bar method and chemical method to find reactive aggregates, as well as aggregates that show deleterious expansion with an alkali content slightly above the specified value although judged as nonreactive by the normal mortar bar method (hereafter referred to as marginally reactive aggregates). This was done because it was suspected that marginally reactive aggregates could induce deleterious expansion under a high alkali condition in high-strength concrete. For this purpose, the total alkali content for the mortar bar method was set at 1.2%, the value specified in JIS A 5308, and 1.5%, a value slightly above the specification. The experiment plan is given in Table 1.

2.2. AAR in high-strength concrete

The following two experiments were conducted in regard to AAR in high-strength concrete.

2.2.1. Experiment I: effect of increasing the cement content

High-strength concrete is characterized by a high cement content with a concomitant increase in the total alkali content. In this experiment, the effect of the increase in the cement content on the expansion of concrete was investigated. Three types of concrete were used: a normal concrete with a cement content of 350 kg/m^3, high-strength concrete with a cement content of 650 kg/m^3 containing an air-entraining and high-range water-reducing admixture, and concrete with the same cement content but with no admixture. A 2-N solution of reagent-grade sodium hydroxide (NaOH) was used for increasing the alkali content to accelerate the reaction. Four and five levels of additional alkali content were selected for concretes with a cement content of 350 and 650 kg/m^3, respectively, up to around 6 kg/m^3 in terms of total alkali content including that from cement. The experiment plan is given in Table 2. Normal portland cement with a specific gravity of 3.16 and R_2O content of 0.58% was used as the cement. Fine aggregate N (sea sand) and coarse aggregate C (crushed andesite) were used as reactive aggregates, while fine aggregate M (river sand) and coarse aggregate T (crushed andesite) were used as nonreactive aggregates. The differences in the expansiveness by different combinations of these aggregates were also investigated.

2.2.2. Experiment II: safety confirmation of nonreactive aggregate

Aggregates judged as nonreactive by the mortar bar method are normally used without precautions against AAR. However, an alkali content slightly above the specification can cause certain types of aggregates to exhibit deleterious expansion. Whether or not these aggregates can be safely used for high-strength concrete with a high alkali content was investigated in this experiment using concretes with a cement content of 350, 500, and 650 kg/m^3. The experiment plan is given in Table 3. Granular industrial sodium

Table 2
Effects of the increase in unit cement weight (Experiment I)

Unit cement weight (kg/m^3)	Fine aggregate	Coarse aggregate	Addition amount of alkali (kg/m^3)							High-range AE water reducer
			0.0	0.6	1.2	1.8	2.4	3.0	3.6	
350	Nonreactive aggregate M*	Reactive aggregate C				○	○	○	○	None
	Reactive aggregate N	Nonreactive aggregate T*				○	○	○	○	None
650	Nonreactive aggregate M*	Reactive aggregate C	○	○	○	○	○			None
	Reactive aggregate N	Nonreactive aggregate T*	○	○	○	○	○			None
	Nonreactive aggregate M*	Reactive aggregate C	○	○	○	○	○			Use
	Reactive aggregate N	Nonreactive aggregate T*	○	○	○	○	○			Use

Table 3
Confirmation of safety in nonreactive aggregate (Experiment II)

Unit cement weight (kg/m^3)	Fine aggregate	Coarse aggregate (relatively reactive nonreactive coarse aggregate)	Addition amount of alkali (kg/m^3)					High-range AE water
			0.0	0.6	1.2	1.8	2.4	
350	Nonreactive aggregate	A*	○		○	○	○	None
			○		○	○	○	Use
		K*	○		○	○	○	None
			○		○	○	○	Use
500		A*	○	○	○	○		Use
		K*	○	○	○	○		Use
650		A*	○	○	○			Use
		K*	○	○	○			Use

hydroxide (NaOH) was added afterward as additional alkali for accelerating the reaction. Four levels of alkali content were selected in the range of up to 6 kg/m^3 in terms of total alkali content including that from cement. The cement was a high-alkali-type normal portland cement with a specific gravity of 3.15 and R_2O content of 0.94%, an alkali level similar to that used by the Research Committee on Test Method for Judgment of AAR by the Concrete Method organized in JCI. This value exceeds 0.75% the JIS upper limit of R_2O content for normal portland cement. The aggregates were nonreactive fine aggregate (M) and marginally reactive coarse aggregates (A and K) found in the experiment stated in Section 2.1.

2.3. AAR-inhibiting effect of GGBFS in high-strength concrete

2.3.1. Experiment III: AAR-inhibiting effect of GGBFS

GGBF slag is used as a means to inhibit AAR in normal concrete. An experiment was conducted to investigate if a similar effect is obtained when GGBFS is used for high-strength concrete. Only high-strength concrete with a cement content of 450 kg/m^3 was used in this experiment. Reagent-grade NaOH was used as an alkali for accelerating the reaction. Normal portland cement with a specific gravity of 3.17 and R_2O content of 0.68% for AAR testing by the Japan Cement Association was used as the cement. The aggregates were nonreactive fine aggregate M and reactive coarse aggregate C1, whose source is the same as coarse aggregate C used in Experiment I. Due to the difference in time of delivery, the expansion coefficient of C1 by the mortar bar method was approximately 1/2 of that of C. Three types of GGBFS with a fineness of 4000, 6000, and 8000 cm^2/g were used. The specific gravity of each was 2.91, while the R_2O content was 0.45%, 0.47%, and 0.43%, respectively. These were used in place of 0%, 30%, 45%, or 60% of cement. Because some of the slags contained gypsum, its effect on AAR was also investigated using the type with a fineness of 6000 cm^2/g, the generally used fineness. The experiment plan is given in Table 4.

3. Experiment procedure

3.1. Alkali-aggregate reactivity test on aggregate

The reactivity of aggregate was judged by the chemical method in accordance with Appendix 7 of JIS A 5308 and the mortar bar method in accordance with Appendix 8, ibid. When testing by the mortar bar method, a total alkali content

Table 4
Inhibiting effect of GGBFS

Unit cement weight (kg/m^3)	GGBFS Fineness (cm^2/g)	GGBFS (%)	Fine aggregate	Coarse aggregate	Addition amount of alkali (kg/m^3)									Alkali type
					1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.2	8.0	
450	4000	0	Nonreactive aggregate M*	Reactive aggregate C1	○	○	○	○	○					NaOH
		30					○	○	○	○	○			
		45						○	○	○	○	○		
		60							○	○	○	○	○	
	6000	0			○	○	○	○	○					
		30					○	○	○	○	○			
		45						○	○	○	○	○		
		60							○	○	○	○	○	
	8000	0			○	○	○	○	○					
		30					○	○	○	○	○			
		45						○	○	○	○	○		
		60							○	○	○	○	○	

Table 5
Mix proportion and compressive strength of concrete (Experiment I)

Unit cement weight (kg/m^3)	Total alkali content (kg/m^3)	W/C (%)	S/a (%)	Coarse aggregate ratio (%)	Absolute volume (ℓ/m^3)			AE water reducer (c×%)	Compressive strength (MPa)
					Cement	Sand	Crushed gravel		
350	1.8	52.9	47.0	195	111	321	363	–	33.8
	2.4								30.1
	3.0								29.4
	3.6								29.4
650	0.0	36.3	38.9	236	206	208	340	–	62.7
	0.6								60.3
	1.2								59.0
	1.8								54.8
	2.4								52.7
	0.0	26.0	40.0	169		241	363	2.3	89.9
	0.6								89.6
	1.2								84.0
	1.8								79.3
	2.4								77.1

of 1.5% was also tested in addition to 1.2% specified in JIS A 5308, in order to find nonreactive aggregates with a relatively high reactivity.

3.2. Alkali-aggregate reactivity test using concrete

Alkali-aggregate reactivity tests on concrete were conducted in accordance with the JCI concrete bar method [2], which examines the reactivity of a concrete mixture, whereas the chemical and mortar bar methods examine the reactivity of aggregate. A Hobart-type forced action mixer was used for mixing concrete. Specimens were beams measuring 7.5×7.5×40 cm, with gauge bolts embedded in the centers of both ends for measuring length change. Specimens were demolded after 20 or 48 h after placing. After measuring the datum length, each specimen was wrapped with two sheets of water-retaining paper wetted with water to a weight of approximately 100 g, placed in a mesh bag, and individually sealed in a plastic bag. Specimens were then transferred to a curing box maintained at 40±2 °C and 100% RH. On the day before the test age, they were transferred to a thermo-hygrostatic room at 20 °C and 60% RH, and their length was measured 20 to 24 h later. Length measurement was repeated at ages of 2 weeks, 4 weeks, and at 1 or 2 month intervals thereafter. Judgment for deleterious expansion was made at an age of 6 months. Tables 5–7 give the mixture proportions and compressive strength of concrete for each experiment. Concrete mixture proportions were determined based on trial mixtures with a target slump and air content of 18 cm and 4%, respectively. The compressive strength tended to slightly decrease by the alkali addition, being in the range of 300–400 kgf/cm^2 with

Table 6
Mix proportion and compressive strength of concrete (Experiment II)

Unit cement weight (kg/m^3)	Total alkali content (kg/m^3)	W/C (%)	S/a (%)	Coarse aggregate ratio (%)	Absolute volume (ℓl/m^3)			AE water reducer (c×%)	AE admixture (c×%)	Compressive strength (MPa)	
					Cement	Sand	Crushed gravel			A*	K*
350	0.0	52.9	46.0	185	111	319	375	–	–	40.8	40.8
	1.2									39.6	38.2
	1.8									38.1	38.1
	2.4									38.6	35.0
	0.0	45.7	47.8	160		329	360	0.4	0.01	42.3	40.0
	1.2									42.2	39.4
	1.8									39.3	35.7
	2.4									35.3	33.1
500	0.0	32.0	43.5	160	158	279	363	1.4	0.01	66.5	65.9
	0.6									64.6	57.9
	1.2									60.5	51.1
	1.8									61.6	54.9
650	0.0	24.8	40.8	160	204	243	353	3.1	0.02	81.3	72.4
	0.6									72.0	60.0
	1.2									69.0	64.9

Table 7
Mix proportion and compressive strength of concrete (Experiment III)

Unit cement weight (kg/m^3)	GGBFS/B (%)	Total alkali content (kg/m^3)	W/C (%)	S/a (%)	Unit water content (kg/m^3)	Absolute volume (ℓ/m^3)				High range AE water reducer (c×%)	AE admixture (c×%)	Compressive strength (MPa)
						Cement	GGBFS	Sand	Crushed gravel			
450	0	1.6	35.8	44.0	160	143	0	289	368	1.3	0.01	51.2*
		2.4										
		3.2										
		4.0										
		4.8										
	30	3.2				100	46	288	366			
		4.0										
		4.8										
		5.6										
		6.4										
	45	4.0				79	69	287	365			
		4.8										
		5.6										
		6.4										
		7.2										
	60	4.8				57	93	286	364			
		5.6										
		6.4										
		7.2										
		8.0										

* Compressive strength of base concrete (replacement ratio of GGBFS: 0%, total alkali content: 0 kg/m^3).

a cement content of 350 kg/m^3. With a cement content of 450 and 500 kg/m^3, the compressive strength ranged between 500 and 600 kgf/cm^2. When the cement content was 650 kg/m^3, the compressive strength was from 800 to 900 kgf/cm^2 and from 500 to 600 kgf/cm^2 with and without an air-entraining and high-range water-reducing admixture, respectively.

4. Results and discussion

4.1. Reactivity of aggregate

Table 8 tabulates the results of physical tests and tests by the chemical and mortar bar methods on the aggregates. At an age of 6 months, some of the aggregates showed

Table 8
Result of alkali-aggregate reaction

Symbol		Surface dried specific gravity	Mortar bar method expansion factor		Result of chemical method			Total result	Experiment
			Total alkali content		Sc	Rc	result		
			1.2%	1.5%					
Fine aggregate	M	2.69	0.022	–	32.0	50.0	harmlessness	○	I, II, III
	N	2.62	0.310	–	194.0	103.0	harm	×	I
	I	2.66	0.102	0.326	37.7	174.3	harmlessness	×	
	F	2.60	0.043	0.129	44.0	114.7	harmlessness	△	
	K2	2.58	0.048	0.160	95.3	137.3	harmlessness	△	
	O2	2.61	※ K2 : O2= 2 : 8 mix		41.3	83.0	harmlessness	△	
	S	2.65	0.681	0.830	77.7	109.7	harmlessness	×	I
Coarse aggregate	C	2.65	0.679	0.794	461.3	140.0	harm	×	II
	A	2.64	0.046	0.351	480.7	222.0	harm	△	II
	K	2.68	0.031	0.132	130.7	196.0	harmlessness	△	I
	T	2.66	0.052	0.130	34.3	198.3	harmlessness	△	
	T2	2.64	0.255	0.745	538.7	196.3	harm	×	
	L5	2.63	0.679	0.794	212.0	82.7	harm	×	
	O1	2.64	0.042	0.178	29.7	55.3	harmlessness	△	
	R	2.61	0.614	0.873	565.7	212.7	harm	×	
	M1	2.64	0.056	0.136	31.7	50.0	harmlessness	△	
	C1	2.65	0.342	–	578.4	167.5	harm	×	III

expansion coefficients at an “innocuous” level of less than 0.1% with a total alkali content of 1.2% specified by the mortar bar method, but the coefficients exceeded 0.1% when the total alkali content was slightly higher at 1.5%. These include F, K2, O2, A, K, T, O1, and M1. Aggregates A and K were therefore adopted for Experiment II. Aggregates C and C1 were adopted for Experiments I and III, respectively, as highly reactive coarse aggregates.

4.2. AAR of high-strength concrete

4.2.1. Comparison between expansion coefficients of high- and normal-strength concretes

The expansiveness of high-strength concrete with a low water/cement ratio was compared with that of normal concrete, using nonreactive M and reactive C as fine and coarse aggregates, respectively. The relationship between the total alkali content and expansion coefficient at 6 months is shown in Fig. 1(a). It appears that AAR-induced expansion is inhibited more in high-strength concrete than in normal concrete with the same total alkali content. According to Ref. [3], however, alkali from NaOH increases the development of expansion by around 30% compared with alkalis from cement [3]. When converting the total alkali content of cement to incorporate this effect, the relationship between the total alkali content and the expansion coefficient changes to Fig. 1(b). This figure indicates that expansion is closely related to total alkali content and that the expansion of normal- and high-strength concretes are equivalent under the same total alkali content conditions. This suggests that high strength concrete with a high cement content entailing a high total alkali content is disadvantageous in regard to AAR.

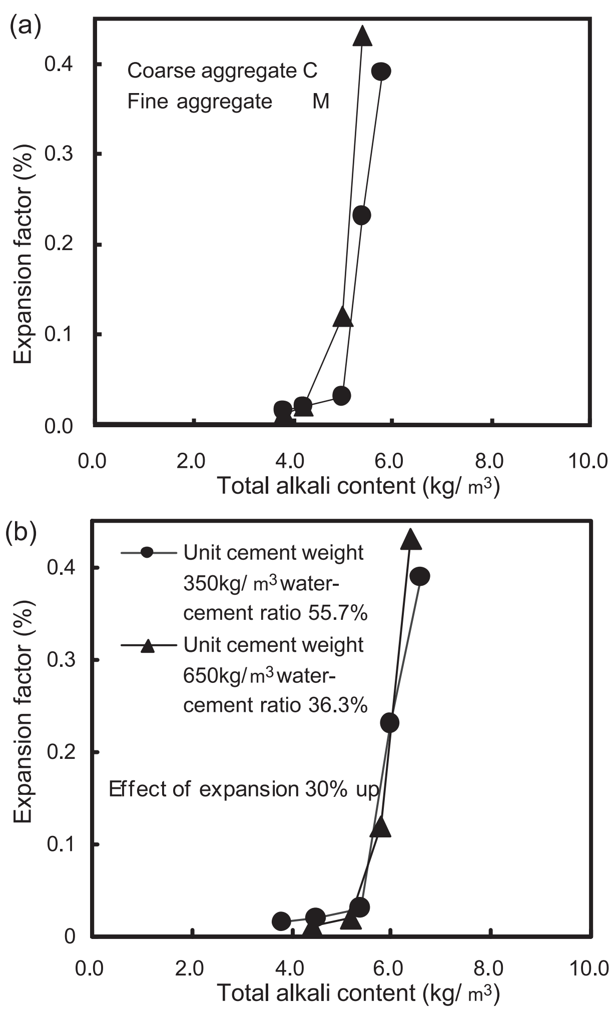

Fig. 1. Expansion factor comparison of normal- (a) and high-strength (b) concrete (curing 6 months).

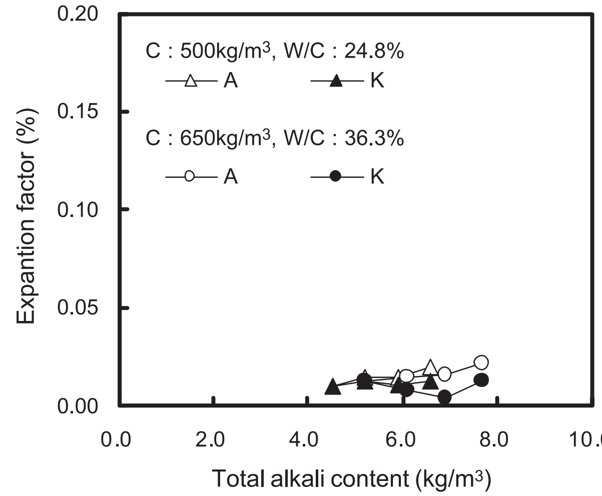

Fig. 2. Expansion factor comparison of high-strength concrete used nonreactive (relatively high) aggregate (curing 6 months).

In concretes made using reactive fine aggregate N and nonreactive coarse aggregate T, no deleterious expansion exceeding 0.1% occurred even at 6 months, exhibiting no significant tendencies.

4.2.2. AAR in high-strength concrete made using marginally reactive aggregate

In Section 4.2.1, high-strength concrete having a high cement content was found to be disadvantageous in regard to AAR. Therefore, AAR risk of high-strength concrete made using marginally reactive aggregate was then investigated. The relationship between the total alkali content and the expansion coefficient at 6 months is shown in Fig. 2. No expansive tendency was observed either in high strength concrete with a cement content of 500 kg/m^3 and NaOH addition of 1.8 kg/m^3 to a total alkali content of 6.5 kg/m^3 or in high-strength concrete with a cement content of 650 kg/m^3 and NaOH addition of 1.2 kg/m^3 to a total alkali content of 7.3 kg/m^3. These total alkali contents are much higher than the case of using cement with a R_2O content of 0.75%, the upper limit specified in JIS. It is therefore considered that no deleterious expansion occurs in general high strength

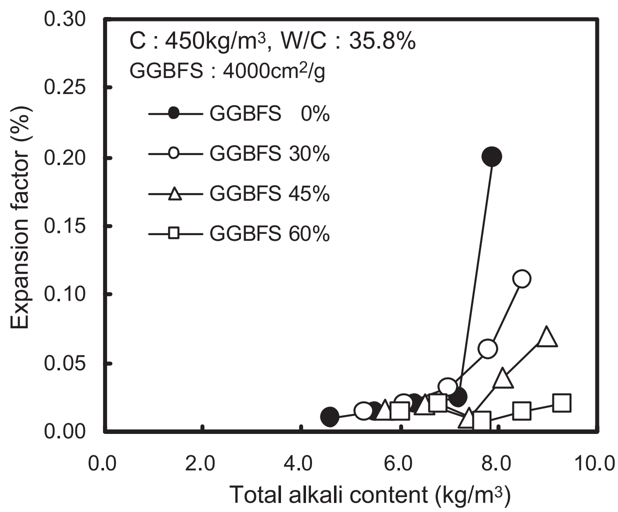

Fig. 3. Effect of GGBFS replacement ratio (curing 6 months).

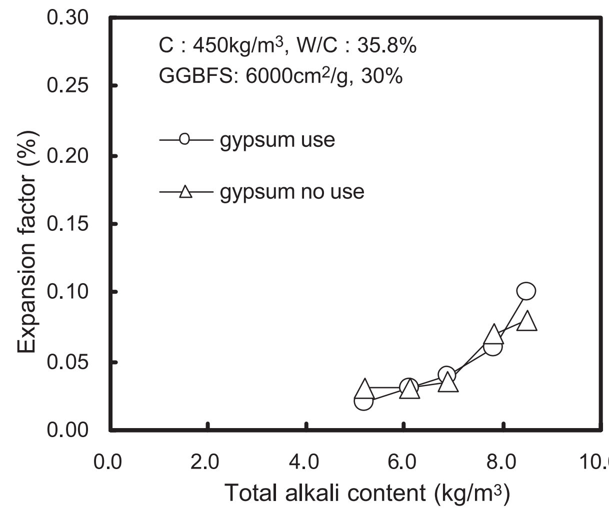

Fig. 5. Effect of GGBFS (curing 6 months).

concrete with a cement content of around 500 kg/m^3 when using aggregate judged as being nonreactive by testing in accordance with the chemical method and mortar bar method with a total alkali content of 1.2%.

4.3. AAR inhibition by GGBFS

4.3.1. Effects of various factors

The effects of the replacement ratio, fineness, and powder composition of GGBFS in high-strength concrete were investigated. Fig. 3 shows the effect of replacement ratio. The expansion coefficient was lowest with a GGBFS replacement ratio of 60%, followed by 45%, 30%, and 0% in this order, indicating the AAR-inhibiting effect of GGBFS in this order [8–12].

Fig. 4 shows the effects of fineness. The differences were most significant when the replacement ratio was 30%. The AAR-inhibiting effect was highest with a fineness of 8000 cm^2/g, followed by 6000 and 4000 cm^2/g in this order.

Fig. 5 shows the results of comparison between the AAR-inhibiting effects produced by 6000-cm^2/g-fineness slags with and without gypsum in their powder component.

With a replacement ratio of 30%, no marked difference was observed between slags with and without gypsum regardless of the total alkali content.

4.3.2. Investigation into AAR-inhibiting effect

In the practical investigation of the AAR-inhibiting effect produced by replacement with slag, alkalis from the slag are disregarded. When part of cement is replaced with slag, the alkali content from cement decreases accordingly. If this reduction in the alkali content were the only effect brought about by slag replacement, then the relationship between total alkali content and expan-

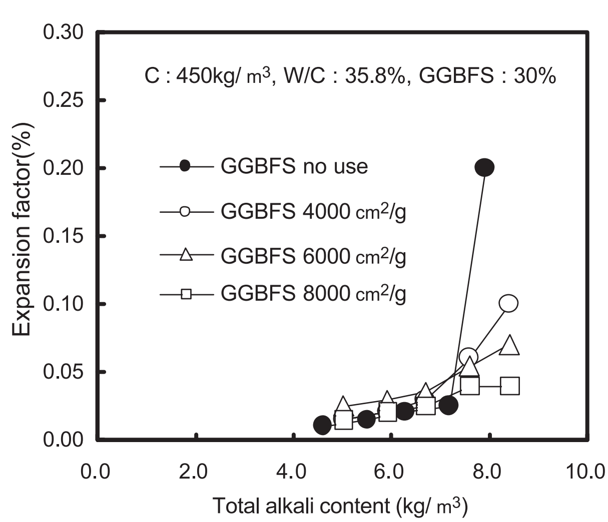

Fig. 4. Effect of GGBFS fineness (curing 6 months).

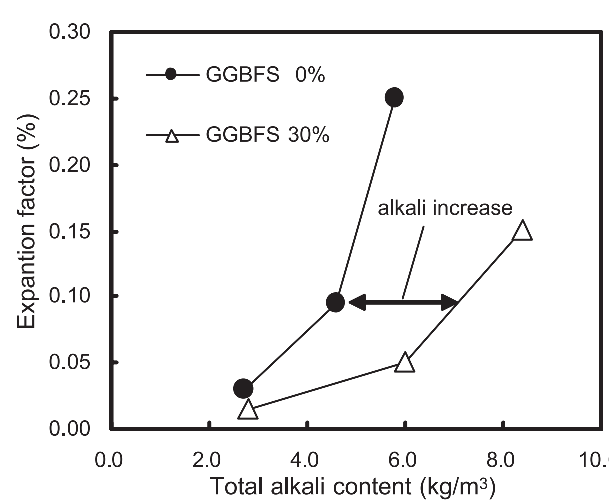

Fig. 6. Experiment method to find alkali content.

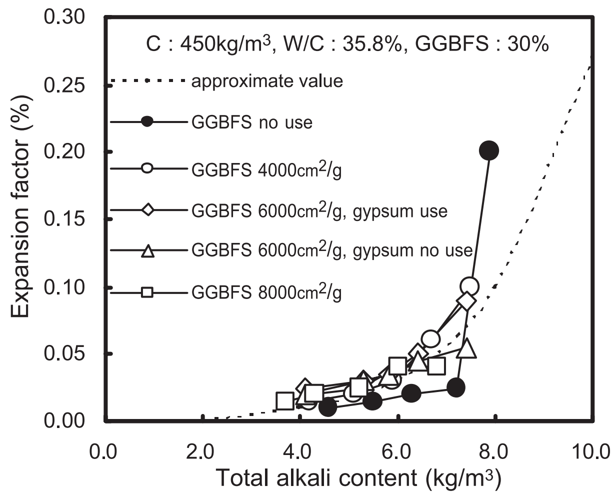

Fig. 7. Relation between total alkali content and expansion factor after correction of alkali content.

sion coefficient should have been constant regardless of the slag replacement ratio. However, as is evident in Fig. 3, the expansion coefficient of concretes containing GGBFS is lower than that of slagless concrete with the same total alkali content, suggesting the effect of slag replacement other than removal of alkalis supplied by cement [13–17]. In regard to concrete with a replacement ratio of 30%, which showed an expansive tendency, the authors calculated the alkali content at which the expansion coefficient of concrete containing slag exceeds 0.1%, the critical value beyond which the expansion is deemed deleterious. The difference between this value and the corresponding value for slagless concrete was defined as the AAR-inhibiting effect by GGBFS as shown in Fig. 6. This value was determined as alkali equivalent of cement as follows: 1.0, 1.2, and 1.7 kg/m^3 with a slag fineness of 4000, 6000, and 8000 cm^2/g, respectively. These values are regarded as the effect of slag replacement besides the alkali reduction. Assuming that GGBFS has an AAR-inhibiting effect corresponding to the alkali equivalent, the total alkali content of concrete containing GGBFS at a replacement ratio of 30% was corrected as shown in Fig. 7. This figure shows the relationship between the corrected total alkali content and the expansion coefficient and the regression curve of this relationship.

When a low-alkali cement with an R_2O content of 0.6% is used for a general high-strength concrete with a cement content of 500 kg/m^3, the alkali content from cement is 3.0 kg/m^3 without GGBFS replacement and 2.1 kg/m^3 with a 30% slag replacement. In consideration of the fact that GGBFS has an AAR-reducing effect corresponding to an alkali equivalent of 1.0 to 1.7 kg/m^3, the actual AAR-inducing effect of alkalis from cement is reduced to 0.4 to 1.1 kg/m^3, which is as low as 1/10 to 1/3 of 3.0 kg/m^3, the recommended upper limit of total alkali content for preventing AAR. Accordingly, it is judged that AAR of high-strength concrete can be inhibited by using low alkali cement and replacing 30% of cement with GGBFS.

5. Conclusions

In this study, the following were found in regard to general high-strength concrete with a cement content of around 500 kg/m^3.

(1) Although the reactivity of high-strength concrete is similar to that of normal concrete, the high alkali content of high-strength concrete can be a disadvantage.
(2) Aggregate judged as nonreactive by the conventional mortar bar and chemical methods will cause no deleterious expansion in concrete.
(3) AAR-inhibition of concrete by replacing 30% of cement with GGBFS provides an alkali-reducing effect equivalent to an alkali content of approximately 1.0 to 1.7 kg/m^3 in addition to the removal of alkalis contained in cement by replacement.
(4) It is judged that AAR of high-strength concrete can be inhibited by using low-alkali cement and replacing 30% of cement with GGBFS.

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