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The Mitigating Effect of ASR Expansion in PC Girder and PCa Product by Using High-Quality Fly Ash

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ABSTRACT

In this study, in order to effectively control the expansion of concrete due to the alkali-silica reaction (ASR) in PC girder and/or PCa product, its mitigation effect using the high-quality fly ash was investigated by the accelerated mortar bar tests according to JIS A1146, Danish method and ASTM C1260. The mortars with the reactive crushed andesite stone were prepared at the water to cement ratio of 0.35 and 0.50, where the replacement percentages by fly ash was selected at 10% and 20% by mass. In addition, after the mortar bar test, the ASR degree and cracking were comparatively examined by both the uranyl acetate fluorescence method and the polarizing microscopic observation. As a result, it was clarified that the replacement of 20% by a good-quality fly ash was effective in suppressing the total expansion of mortar independently of low and high water to cement ratio.

Keywords. ASR, High-Quality Fly Ash, PC girder, PCa product, Accelerated Mortar Bar Test, Polarizing Microscope Observation

1. INTRODUCTION

Recently, large numbers of ASR-affected PC bridge girders produced in the construction site or in the concrete factory have been discovered all over nation by the recent survey of the JCI committee on ASR Mitigation (Torii, 2010). For this reason, in the Hokuriku region and also all over the nation, a long-life for PC bridges is becoming one of the important issues. So far, the high durability PC girders have been produced by using high fineness blast furnace slag powder (6000 Blaine value) (Japan Society of Materials Science, 1998). However, the production sites of blast furnace slag powder are limited in the metropolitan and suburbs area such as Tokyo, Osaka, Nagoya and Kitakyushu. On the other hand, in the Hokoriku region, such as Toyama, Ishikawa and Fukui, coal-fired power plants are existing in each prefecture.

From this background, the effective utilization of fly ash to concrete mixture has become a new regional challenge. It becomes more important to expand the use of fly ash in concrete to “Establishing the supply system” and “Stabilizing the quality”. In addition, there was a history that concrete from the manufacturer had been avoided to use. In order to solve this problem, in January 2011,"The committee for promotion of effective utilization of fly ash to concrete in Hokuriku Region, chaired by Prof. Kazuyuki Torii (Kanazawa University)," has been launched. An active work of preparing a manual of fly ash concrete and stabilizing the supply of high quality fly ash has just started (Torii, 2012).

In this study, in order to investigate the effectiveness of a high-quality fly ash to control the expansion of concrete due to ASR in PC girders and/or PCa products, the accelerated mortar bar tests according to JIS A1146, Danish method and ASTM C1260 were comparatively conducted. In addition, the comparison of fly ash and blast furnace slag cement at the same type B experiment was also carried out (Chai et. al, 2005).

2. CRACKING OF PC GIRDER AND PCa PRODUCT

In Hokuriku region, there are records that show the reactive andesite crushed stone has been used throughout the Noto Peninsula. The serious ASR problems with a rupture of the reinforcing bar were also found on the Noto expressway and the national highway Route 249. Moreover, in the Joganji river in Toyama Prefecture, in the Tedori river in Ishikawa Prefecture, and in aggregate production from the basin of the river on top of the Kuzuryu river in Fukui Prefecture, the andesite particles contained in river sand and/or gravel show a high reactivity. In addition, the Hokoriku region has a lot of local companies that make PC Girder and PCa Product.

Furthermore, as shown by Figures 1 and 2, problems like cracking due to ASR have occurred on PCa product of concrete factory. In these cases of ASR, cracking due to ASR also occurred even by limiting the total alkali content of less than 3kg/m^3. So, a new countermeasure against ASR has become necessary. In addition, in the production of PC girders and PCa products are using a high-strength concrete around 50N/mm^2. The specification of JIS A5308 for the ready-mixed concrete as a preventive measure for ASR is also required to be implemented.

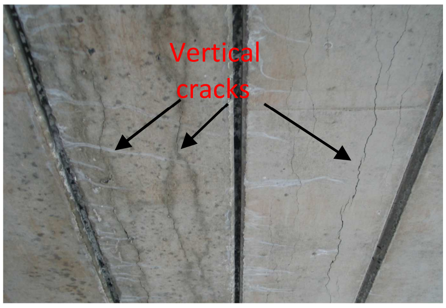

Figure 1. The Cracking of hollow-core type pre-tensioned PC girder

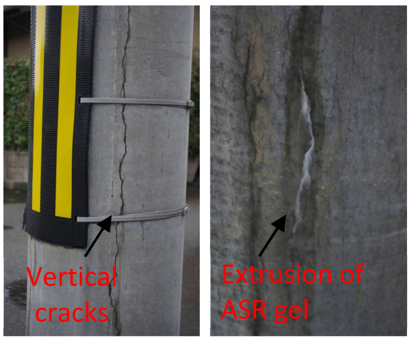

Figure 2. The cracking and ASR gel extrusion of electric utility pole

3. EXPERIMENTS

3.1 Materials and Mix Proportions of Mortars

An early strength Portland cement (HOPC) from U Co. Ltd (density: 3.14g/cm^3, Blaine specific surface area: 4300cm^2/g, Ig.loss: 0.89%) was used. As for the replacement of cement, two types of mineral admixtures were used. One is a high-quality fly ash (FA, Nanao-ohta coal thermal power plant product, I-type fly ash classified by JIS A6201, density: 2.44g/cm^3, Blaine specific surface area: 4780cm^2/g, Ig.loss: 2.0%), another is a blast furnace slag fine powder (BFS) manufactured by S Co. Ltd (density: 2.91g/cm^3, Blaine specific surface area: 6030cm^2/g, Ig.loss 1.0%). The chemical compositions of early-strength portland cement, fly ash and blast furnace slag powder are shown in Table 1.

Furthermore, the Nanao-ohta coal burning power plant has produced a high-quality fly ash with the uniform spherical particle less than 10μm (average particle size: 7.6μm) around 30.000 tons per year. The production techniques are composed of two processes: one is the selection of a good-quality fly ashes from burning the Australian bituminous coal, and the other process is the separation of ultra-fine particles of less than 10μm by a centrifugal machine. The production obtained from this process gives a satisfactory physical and chemical properties of fly ashes comply with the standard of the highest class I classified by JIS A6201. In addition, the comparison of physical and chemical properties of classified fine and original fly ashes is given in Table 2, which their particle shape of high-quality fly ashes is given in Figure 3.

As for the reactive andesite, the crushed andesite stone produced near Sapporo city in Hokkaido was selected. The alkali-silica reactivity of this stone was assessed according to JIS A1145 (Sc: 688mmol/l, Rc: 78mmol/l, Sc/Rc= 8.8). The chemical compositions and the X-Ray diffraction pattern of the referred andesite stone are shown in Table 3 and Figure 4, respectively.

Table 1. Chemical compositions of early-strength portland cement, fly ash and blast furnace slag powder (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	MnO	SO_3	Na_2O	K_2O	Total
HOPC	20.5	5.3	2.5	65.9	0.8	---	---	3.1	0.2	0.3	98.7
FA	53.6	28.9	6.7	3.2	0.8	1.4	0.1	0.2	0.3	0.7	96.2
BFS	33.0	13.6	0.1	42.6	5.8	0.6	0.2	3.1	0.2	0.2	99.3

Table 2. Physical and chemical properties of classified fine and original fly ashes

	Classified fine fly ashes	Original fly ashes
Average particle size(μm)	7.6	20.9
Crystalline quartz (%)	5.0	5.6
Mullite (%)	20.6	26.7
Silica glass (%)	73.2	65.1
Pozzolanic activity at 28days (%)	89	83
Pozzolanic activity at 91days (%)	103	95

Table 3. Chemical compositions of crushed andesite (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	MnO	SO_3	Na_2O	K_2O	Total
Crushed Andesite	61.6	20.3	6.0	5.0	1.0	0.6	0.1	0.2	2.5	2.4	99.7

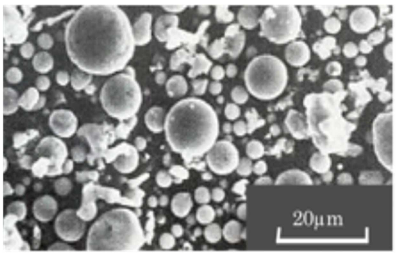

Figure 3. The particle shape of high-quality fine fly ashes

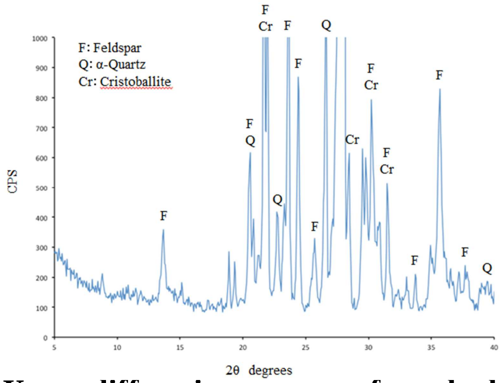

Figure 4. The X-ray diffraction pattern of crushed andesite stone

In this study, for the purpose of ASR mitigation on PC girders and PCa products, the water to cement ratio of the mortar were set at 35% and 50%. A high early strength Portland cement (HOPC) was used in both mortars of water to cement ratio of 35% and 50%. In series where mineral admixture were added, the replacement ratio of a high-quality fly ash were set at 10% and 20% by mass (FA10% and FA20%), and those by blast furnace slag was set at 50% by mass (BFS50%).

3.2 Test Methods

3.2.1 JIS A1146 method

The cement, fly ash and blast furnace slag powder are containing different forms of alkali and also have different effect on the ASR (Japan Concrete Institute, 2008). In order to adjust the mortar with equivalent amounts of 1.2% Na_2O, the addition of 1N sodium hydroxide solution was given. Mortar bar (40 × 40 × 160mm) is cured with a temperature of 40^{O}C, and more than 95% of relative humidity. Length change was measured at 20^{O}C. In JIS A1146, if the expansion ratio for 3 months is over 0.05% or for 6 months is over 0.1% indicates “deleterious”.

3.2.2 Danish method

Without adjusting the amount of alkali cement, mortar bar (40 × 40 × 160mm) immersed in saturated NaCl solution on temperature of 50^{O}C. Length change was measured at 20^{O}C. In Danish method, determines that for 3 months, the expansion ratio under 0.1% indicates "innocuous", between 0.1% and 0.4% "both innocuous and deleterious coexist" and over 0.4% considered as "deleterious". In addition, after the mortar bar test, along with checking the depth penetration of chloride ions, 0.1N silver nitrate solution was sprayed on the mortar fractured surface, and observed the formation of ASR by the uranyl acetate fluorescence method.

3.2.3 ASTM C1260 method

Without adjusting the amount of alkali cement, mortar bar (25 × 25 × 285mm) immersed in 1N NaOH solution on temperature of 80^{O}C. Length change was measured at 20^{O}C. In ASTM C1260 determines that for 14 days, the expansion ratio under 0.1% indicates "innocuous", between 0.1% and 0.2% "both innocuous and deleterious coexist" and over 0.2% considered as "deleterious".

3.2.4 Observation of polished thin section sample with polarizing microscope.

After the end of the expansion test, polished thin section samples with 20μm thickness were prepared from each mortar bar. The samples were observed to determine ASR gel and cracking by polarizing light microscopy. Classification of ASR deterioration using thin section was carried out according to the procedure shown in Table 4 with the reference by Katayama studies (Katayama et. al, 2008).

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Comparison in Three Types of Mortar Bar Tests

Using a low water to cement ratio in PC girder can change the internal part denser. Thus, the movement of moisture and alkali ions inside and the penetration of alkali ions from the outside can be reduced. So, the mitigation of ASR can be expected. Meanwhile, by increasing the volume of cement percentages (the amount of alkalis) may promote ASR on PC girders and PCa products. In accordance with that, the result of expansion behaviors of mortar bars (W/C = 35% and 50%) from various mortar bar tests (JIS A1146, Danish, ASTM C1260) can be seen in Figures 5 and 6.

Table 4. Petrographic classification of ASR severity of stages

Stages	The Progress and Severity of ASR
I	The formation of reaction rims and exudation of ASR sol/gel around the reacted aggregate
II	The formation of ASR gel-filled cracks within reacted aggregate
III	The propagation of ASR gel-filled cracks (max < 25µm) from the reacted aggregate into surrounding cement paste
IV	The formation of ASR gel-filled cracks (max 25-50µm) network and the migration of ASR gel into air voids
V	The formation of ASR gel-filled cracks (max 50µm<) network and the migration of ASR gel into air voids

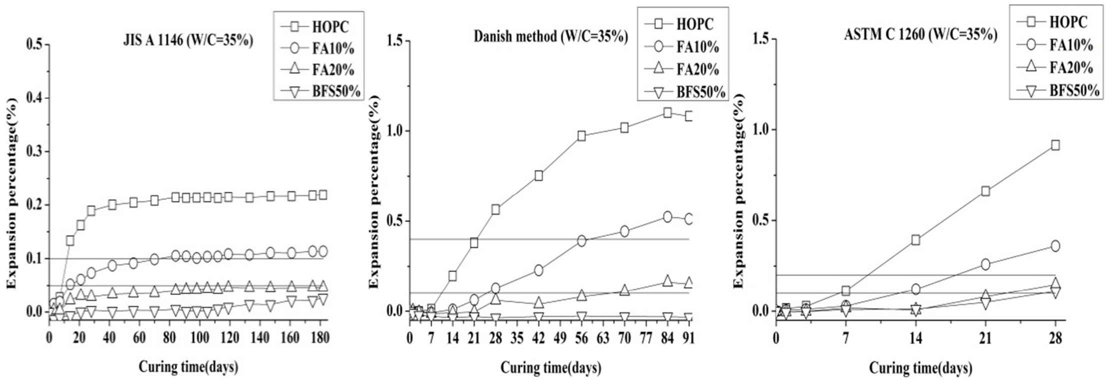

Figure 5. Expansion behaviours of mortar (W/C= 35%) using crushed sand andesite

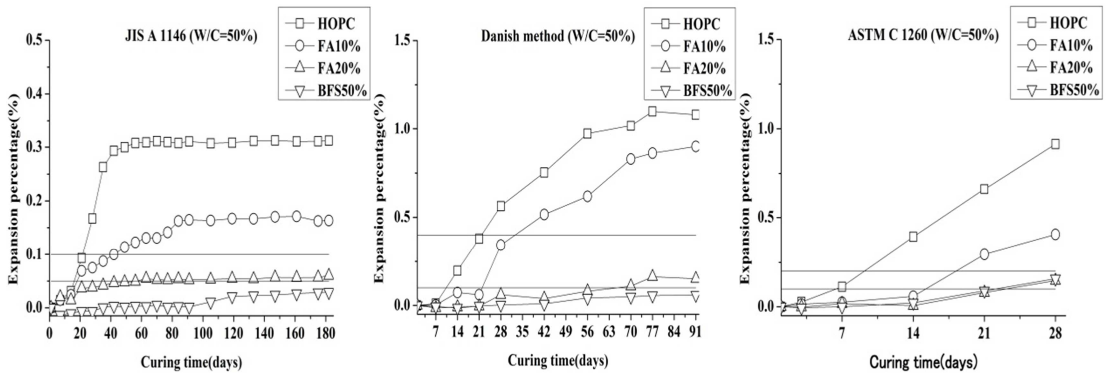

Figure 6. Expansion behaviours of mortar (W/C= 50%) using crushed sand andesite

On the other hand, in the Danish method and ASTM C1260, the expansion of mortars is gradually increased compared with JIS A1146. But, once the expansion started, it continued occurs. It is assumed that immediately after cracks occur on the surface of the mortar, alkaline solutions such as NaCl and NaOH penetrates into inside through the cracks. Moreover, because the cross section (25 × 25mm) is small for ASTM C1260 mortar bar test, the NaOH solution immediately penetrates the entire cross section. Thus, the amount of expansion was increased almost linearly until the curing time of 28 days. In this case, the effect of reducing the amount of expansion due to low water to cement ratio appears to be almost lost.

As for the result of expansion, in Danish method, HOPC and FA10% mortars (W/C= 35 and 50%) are over 0.4% of expansion for 3 months. Thus, it can then be classified as "deleterious". As seen in Figures 5 and 6, only BFS 50% can be classified as "innocuous". However, FA20% mortar is also effective enough in suppressing the occurrence of ASR compared with HOPC and FA10% mortars. After 3 months, the expansion percentages are still 0.15% for W/C=35% and 0.37% for W/C=50% that can be classified as "both innocuous and deleterious coexist". Moreover, ASTM C1260 expansion result in 14 days clearly shows the superior ASR suppressing effect for both mineral admixtures. The expansions of almost all mineral admixture at 14 days, except for FA10% mortar with W/C of 35%, are under 0.1% which is classified as “innocuous”. However, up to 28 days, the expansion is becoming larger for all mortar bars. As a result, only BFS50% and FA20% mortars are considered as “both innocuous and deleterious coexist”.

From the results of mortar bar tests, the suppressing effect of ASR for BFS50% and FA20% mortars is almost the same. The pozzolanic reaction between fly ash and portland cement that produces lower Ca/Si ratio of calcium silicate hydrates (CSH gel) might give the contribution of alkali adsorption into them. Therefore, even fly ash has a smaller replacement ratio than blast furnace slag powder, but from the experiment it shows that fly ash maybe more effective in suppressing ASR. On the other hand, in the Danish method, as those of low water to cement ratio, was able to confirm the effect of reducing the amount of expansion.

In the ASTM C1260, JIS A1146, and the Danish method, types and their supply state of the alkali in the test is quite different. These tests are to examine ASR in an extreme severe environmental condition. For this reason, ASTM C1260, JIS A1146, and the Danish method, the amount of expansion will increase until the final expansion. However, the evaluation in the early stage is possible. In this case, in relation to the suitability of the ASR test method of reactive aggregate, it is necessary to note the type of mineral component and its reactivity of the reactive aggregate rock.

For the crushed andesite was used in this study, the correlation of each result JIS A1146 at 182 days, Danish method at 91 days, and ASTM C1260 at 14 days can be confirmed. It was found that the application of ASTM C1260 and Danish method was possible to determine the inhibitory effect of ASR of both fly ash and blast furnace slag powder especially in early stages. Furthermore, in the region of cold climate such as the Hokuriku and the Tohoku, the opportunity to be exposed to a high concentrations of NaCl solution by the de-icing salt has been increasing. Under such a environment, it is expected that the effect of the addition of FA and BFS in PC girders and PCa products will be more significant. The results obtained from various mortar bar test can be summarized in Table 5.

Table 5. Comparison of assessment of results by various mortar bar tests

	W / C = 35%			W / C = 50%		
	HOPC	FA 10%	FA 20%	HOPC	FA 10%	FA 20%
JIS A1146	Deleterious	Deleterious	Innocuous	Deleterious	Deleterious	Innocuous
Danish Method	Deleterious	Deleterious	Unclear	Deleterious	Deleterious	Unclear
ASTM C1260	Deleterious	Deleterious	Unclear	Deleterious	Deleterious	Unclear

4.2 Observation of ASR Gel by Uranyl Acetate Fluorescence Method

After the Danish test, the depth of salt penetration and the uranyl acetate fluorescence method of coloring area, which ASR gel is a greenish-yellow coloration, was carried out to measure. The result of ASR gel observation was correlated with the results of expansion test that already obtained. The results shows, in FA20% mortar as those of a low water to cement ratio, large replacement ratio of FA could be confirmed to be effectively suppressed ASR over a long period of time. Besides suppressing the occurrence of ASR, the salt penetration into the mortar is also reduced by the addition of FA. The image of ASR gel observation in HOPC and FA20% mortars by uranyl acetate fluorescence method is shown in Figure 7.

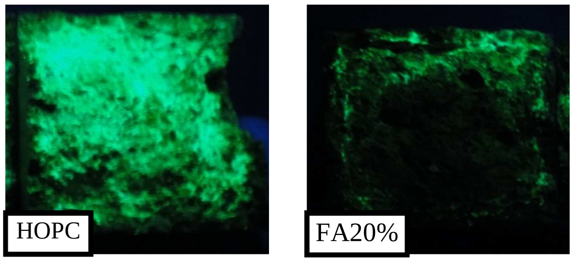

Figure 7. Observations of ASR gel formation of HOPC and FA20% mortars with W/C of 35% by uranyl acetate fluorescence method (observed area: 40 mm x 40 mm)

4.3 Observation of Cracking by Polarizing Microscope.

The image of thin section of mortar bar, HOPC and FA20% mortars with W/C of 35% are shown in Figures 8 and 9. In addition, Table 6 is showing the result of the ASR deterioration degree by the polarizing microscopic observation of thin section sample. In JIS A1146, ASR has not progressed in a lower water to cement ratio. A difference in the degree of deterioration was seen in only those with W/C of 50%. In HOPC mortar (W/C = 50%, ASR level: III) crack (less than 25μm in width) progress from the aggregate to the cement paste could be confirmed. On the other hand, for FA20% mortar (W/C= 50%, ASR level: I) the occurrence of cracks cannot be examined due to the ASR mitigation effect by FA.

In ASTM C1260, for HOPC mortar (W/C= 35%, ASR level: V) was observed a large crack in the aggregate (100μm width). A continuous network of cracks has been formed from the aggregate to the cement paste. On the other hand, FA20% mortar (W/C = 35%, ASR level: II) crack width and density was decreased together. In addition, some of the FA particles are dissolved by reaction with a solution of NaOH, FA particles can react protectively with NaOH solution.

In the Danish method, the degree of deterioration due to ASR in difference water to cement ratios could not be clearly identified. On the other hand, the degree of deterioration due to ASR in differences addition of FA is quite clear. HOPC mortar (W/C= 50%, ASR level: IV) crack (less than 25μm) is in progress from aggregate to cement paste. As for FA20% mortar (W/C= 50%, ASR level: II) there was no progress that has been made for cracking occurred in the aggregate to cement paste. This result has a high correlation with the result of ASR gel observation of the uranyl acetate fluorescence method.

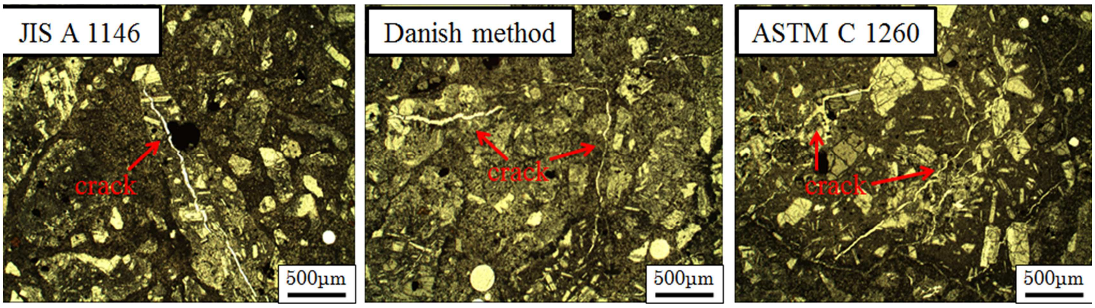

Figure 8. Observations of thin sections of mortar (W/C= 35%, HOPC) after various accelerated tests

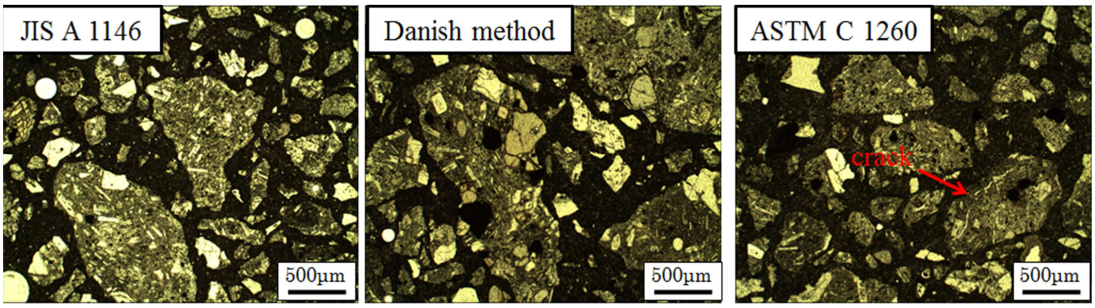

Figure 9. Observations of thin sections of mortar (W/C= 35%, FA20%) after various accelerated tests

Table 6. Comparison in ASR deterioration degree obtained from the result of thin section samples by polarizing microscope

	W / C = 35%			W / C = 50%		
	HOPC	FA 10%	FA 20%	HOPC	FA 10%	FA 20%
JIS A1146	III	II	I	III	II	I
Danish Method	IV	III	II	IV	III	II
ASTM C1260	V	IV	II	V	IV	III

5. CONCLUSIONS

The mitigation effect using the high-quality fly ash was investigated. The main concluding remarks obtained from series of tests are summarized as follows:

(1) The degree of pozzolanic activity in high-quality fly ashes used in this study was increased due to increased glass-rich phases along with its fine particle size.

(2) From the results of the mortar bar test exposed to a high alkaline solutions such as NaCl and NaOH, FA20% mortar could effectively reduce the long-term ASR expansion compared with HOPC mortar.

(3) With respect to fly ash and blast furnace slag powder of high fineness, FA20% and BFS50% mortars could demonstrate almost the same effect in controlling the ASR expansion.

(4) In the comparison of JIS A1146, Danish method, and ASTM C1260 test results, the accelerating mortar bar test took advantage of an early judgement of ASR suppression effect.

(5) After various of mortar bar test, it was able to confirm more accurately the ASR mitigation effect of fly ash by performing a thin sections observation. Among these, the Danish method shows that a high correlation could be proven.

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