THE ALKALI-SILICA REACTIVITY OF ANDESITIC RIVER AGGREGATES AND ASR MITIGATION EFFECT BY USING FINE FLY ASHES

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Abstract

In Toyama Prefecture in Japan, large numbers of concrete structures have been suffering from a combined damage caused by alkali silica reaction(ASR) and/or the chloride-induced corrosion of reinforced concrete structure. The approach to solve this problem associated with durability of concrete is effective in the following methods; one the long-life of concrete structures by the repair and strengthening, the other the preventive countermeasures of concrete itself using fly ash. In the latter case, the standard use of fly ash cement with the replacement of more than 15% has been now recommended in all ready-mixed concrete mixtures from the economical and environmental point of view in this region.

Recently, the production technique of very fine fly ash around 7 microns at average particle size has been successfully established at the Nanao-Ohta coal burning power plant in Hokuriku electric power company. It is enable to produce a highly-durable concrete, which is also related to produce a environmentally-friendly concrete matching with the regional demand. Accordingly, a joint collaborative industry-academia-government research committee, which is organized by the electric power company, the industrial association of ready-mixed concrete companies, the nation and local government and universities, has been set up in January 2011.

In this paper, the results obtained from laboratory test using reactive river sand and gravel in Toyama prefecture, and its mitigating effect by classified fine fly ashes are introduced, which has been carried out in this committee for these 4 years. Furthermore, the influence of the use of classified fine fly ash on the environmental impact in the cement and concrete industry is also discussed.

Keywords: ASR, volcanic aggregate, fly ash, assessment of ASR, mortar bar test

1 INTRODUCTION

In the Hokuriku district in Japan, large numbers of RC and PC bridges have been suffering from the combined damage caused by alkali silica reaction(ASR) and chloride-induced corrosion of steel reinforcement [1]. In the whole, in the West region in Japan, the chloride attack is related to the use of sea sand and/or sea gravel in concrete (so-called internal salt attack), but in the Hokuriku district, the chloride attack is related to both the northwest monsoon from the Sea of Japan especially in winter, and the increased scattering of deicers on road surfaces during the winter season (so-called external salt attack). On the other hand, this district is also located within some huge volcanoes, in the upstream section of main rivers, prompting the outflow and spreading of volcanic rocks such as andesite, rhyolite and tuff stones, which are the main volcanic reactive stones causing the serious damage of ASR in the entire area. Figure 1 shows the deteriorated ASR bridges map in Toyama Prefecture in Hokuriku district, Japan. Furthermore, Figure 2 shows typical features of seriously deteriorated bridge piers by ASR, where the cracking, deformation and ASR gel extrusion occurred at the same time, and in the most serious case, the steel reinforcement also were ruptured in some points of bent. In order to produce the highly durable concrete structures especially against the countermeasure of ASR problem, the standard use of a good-quality fine fly ash cement with the replacement of more than 15 %, which is the type B FA cement according to JIS A6201(Fly ash for use in concrete), was strongly recommended by the authors, which has now been spread out to about half of all ready-mixed concrete mixture plants from an economical and environmental point of view in this region [2].

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In this paper, firstly both the supply system and the quality assurance of fine fly ash developed are introduced, secondly the assessment of alkali-silica reactivity of volcanic gravel from the Jyoganji river in the Toyama prefecture, Japan, is introduced, which is considered to be the most reactive one in Japan, finally the mitigating effect of fine fly ash on ASR by using three types of mortar bar tests is introduced [3].

2 QUALITY ASSURANCE OF FINE FLY ASH PRODUCED AS CONCRETE ADMIXTURE

Amongst the important reasons for the effective utilization of fly ash in concrete in the Hokuriku District, one important reason is that there are few steel-production factories producing blast-furnace slag in the whole area facing the Sea of Japan. Most of these kinds of factories are located along the urban corridor facing the Pacific Ocean near the cities of Tokyo, Nagoya, Osaka, etc. Furthermore, the inclusion of fly ash in concrete addresses the emerging problems in older concrete structures that are now suffering from ASR and chloride attack. Further to extensive and aggressive work by the authors, it can be pointed out that both the supply of good-quality fly ash from coal burning power plants and its quality assurance are essential in the production of concrete mixtures. In the Nanao-Ohta and Tsuruga coal burning power plants in the Hokuriku District, the production technique of very fine particles has successfully been established, where two processes have been adopted; one is the selection of good-quality original fly ash (“Class II” fly ash according to JIS A6201) from only the bituminous coal from Australia, the other is the mechanical separation of ultra-fine particles less than 20 μm using a centrifuge machine with strong air flow as shown in Figure 3. The physical and chemical properties of fine fly ash produced for the most part satisfy the quality standards of the highest level (“Class I” according to JIS A6201). Additionally, when this production system in coal-burning power stations becomes operational all over the nation in the near future, it is moreover expected that the FA cement cost will be greatly reduced in addition to other advantages such as the improvement of both workability and durability of ready-mixed concretes. In order to move quickly towards the realization of these inevitable targets, a joint-collaborative research committee on “the promotion of the effective utilization of fly ash concretes in the Hokuriku district,” which is chaired by Prof. K. Torii at Kanazawa University, was set up in January 2011. Then, not long after the establishment of this committee, the 2011 Tohoku Great Earthquake and its Tsunami disaster occurred, and as a result the share of electrical power production sourcing in the Hokuriku District was drastically altered, because most of the nuclear power plants throughout the nation were shut down. There is no plan in sight for their immediate operation, as shown in Figure 4. This resulted in the importance of coal burning power plants increasing even further, and subsequently the effective utilization of fly ash, especially in the Hokuriku district, has likewise become more necessary, and the work of our committee has taken on an even greater sense of urgency.

3 PHYSICAL AND CHEMICAL PROPERTIES OF FINE FLY ASH PRODUCED

In regard to the quality assurance of fine fly ash, the production technique of very fine particles and the small variations in their physical and chemical properties has successfully been established. It has been confirmed that fine fly ash can significantly improve its pozzolanic activity itself, resulting in the strength development of concrete at early and later ages. Physical properties of fly ash can be improved from 21μm to 7μm at the average particle size, as shown in Figure 5, and chemical properties of fly ash can also be improved that the glassy phases of fly ash, which is mostly composed of silica glass or silica-alumina glass, are increased from 65 % to 73 % since the crystal phases such as quartz, mullite, magnetite and lime are reduced compared with the original raw fly ash, as presented in Table 1. This is a very successful process in the improvement in both physical and chemical properties of fly ash for admixture of concrete. Figure 6 shows the size and shape of fly ash particles by SEM-EDS observations in backscattered electron images (BEI). As it can be seen, this good-quality fine fly ash consists mainly of spherical and uniform particles with the average particle size of 7 μm, where those irregular-shaped particles containing voids are almost removed. Concerning the quality improvement of fly ash itself, amongst other properties, the ignition losses are almost constant below 2 %, although the pozzolanic activity index on the compressive strength of fly ash mortar with replacement of 25% by fly ash according to JIS A6201 is increased to over 90 % at 28 days and over 100% at 91 days at each testing age, respectively, thus fulfilling all requirements of the quality standard of the highest level “Class I” according to JIS A6201 only excepting for the Blaine fineness of more than 5000 cm^2/g. Furthermore, on the trial test in ready-mixed concrete mixture plants, it has been confirmed that in the fly ash cement concretes with the replacement of 15 % by fine fly ash, the water content of concrete can be averagely reduced by 5 kg/m^3 to 10 kg/m^3, and the compressive strength of concrete can be almost equal to the OPC concretes even at 28 days, and it can be greater at 56 days and later. Additionally, chloride diffusion coefficients of concretes with 15% fine fly ash are reduced to 1/3 to 1/4 compared with OPC concretes, although the carbonation and freezing-thawing resistance of fly ash concretes are almost equal to those of OPC concretes. These data indicate that the use of fine fly ash in concrete may be very effective in producing a highly durable concrete against both ASR and chloride attack especially in Hokuriku district.

4 MINERALOGICAL PROPERTIES AND ALKALI-SILICA REACTIVITY OF VOLCANIC RIVER AGGREGATES

The river sand and gravel in the Jyoganji river in Hokuriku district, which is considered to be the most reactive ones in Japan, was assessed by chemical method according to JIS A 1145, and the outcome of aggregate classification was 'deleterious', as shown in Figure 7, in which the alkali-silica reactivity of both the fine and coarse river aggregates is similar, in which their soluble silica content (Sc) is more than 500 mmol/l. The photomicrograph of reactive minerals and others in the Jyoganji river gravel is presented in Figure 8. In the petrographic survey on mineralogical properties of river gravel, it was found out that they were mainly constituted of granitic rocks and volcanic stones, in which the reactive minerals in typical andesite stones were cristobalite and/or tridymite, opal, small amounts of volcanic glass, as shown in Table 2. The composition ratio of 30 % on andesite stones was roughly equivalent to the pessimum content gained by the mortar bar or concrete bar test of andesite stones in the Jyoganji river. Thus, it has become very clear that the reactive river sand and river gravel especially contain Opal as the most reactive mineral, and that its content may exist around the pessimum one. Actually, the recent survey shows that in the bridges and buildings using this river sand and gravel, a severe ASR has still occurred after 2010 even in the case of total alkali content of 2 kg/m^3 and less, which is considerably smaller than the requirement value of less than 3 kg/m^3 according to JIS A5308. As the results of test, it is essential that the fly ash 15% cement should be actively applied against the countermeasure of ASR for all concrete mixture in Hokuriku district.

5 ASSESSMENT OF ALKALI-SILICA REACTIVITY BY MORTAR BAR TESTS AND MITIGATION EFFECT BY FINE FLY ASH ON ASR

Table 3 shows chemical compositions of OPC, FA and BFS used in the mortar bar test. Figures 9 to 11 show the results of the accelerated mortar tests of specimens using the Jyoganji river gravel. Concerning the mitigating effect of fine fly ash on ASR, in JIS A1146 standard mortar bar test cured in a relative humidity 100% box at 40 °C for 26 weeks (specimen size: 40mm×40mm×160mm), OPC and BFS 42 % mortars expanded with the curing time to a significant extent since FA 15 % mortar did not expand at all. Figure 12 shows C/S ratios of CSH formed around FA and BFS particles identified by SEM-EDS in thin section samples of FA15% and BFS42% mortars. The effect of FA15% mortars is mainly attributable to large amounts of CSH with low Ca/Si atomic ratio of 0.9 formed around fly ash particles on the process of their active pozzolanic reaction because this type of CSH can easily absorb and fix the alkali ions of Na^+ and K^+ in its texture, leading to the reduction of the alkali level of OH^- ion in the pore solution to a significant extent [4,5,6]. Furthermore, both in the Danish test [7,8] immersed in a saturated NaCl solution at 50°C for 13 weeks (specimen size: 40mm×40mm×160mm) and in the ASTM C1260 immersed in a 1N NaOH solution at 80 °C for 14 days (specimen size: 25mm×25mm×285mm), the OPC mortar bars expanded considerably, but also very little in FA15% mortar bars, it became very clear that total ASR expansion of both mortars was controlled over a long term by using fine fly ash. The results by accelerated mortar bar tests had a good coincidence with those by accelerated concrete bar tests according to RILEM AAR-3 and RILEM AAR-4, in which the effect of a 15 % replacement by good-quality fly ashes in mitigating ASR has been also confirmed in the field performance of concrete structures in the Hokuriku district. Furthermore, as seen in Figures 13 and 14, concerning the reaction layer of FA and BFS particles in FA15% and BFS 42% mortars, its thickness is observed to be very narrow of 1 to 2 μm even at later ages. So, it is very clear that the finer the size of fly ash particles, the larger their pozzlanic reactivity of mortars even at early ages. Furthermore, the CSH with low C/S around fly ash particles may successfully connect the internal texture by fulfilling the capillary pores, leading to the formation of very dense texture and thereby the reduction of both alkali ions and water into the texture. On the basis of these results and our another field experiences[9,10], the use of fly ash concrete using fine fly ash has now been recommended in order to solve the ASR problem in the Hokuriku district, which is in agreement with findings of Shayan et al. in Australia, and Lee et al. in Taiwan in a different manner [11,12].

6 CONCLUSIONS

In this research, it was confirmed that the mitigating effect of fine fly ash on ASR was clarified by the results of three types of the accelerated mortar bar methods using the Jyoganji river gravel, which contains opal and cristobalite of the most reactive minerals in andesite stones, and FA15%, BFS42% and OPC were more effective on ASR in good order. In the Hokuriku district, the efforts toward the production of highly durable concrete mixtures using fine fly ash from the Nanao-Ohta and Tsuruga coal burning power plants, has just started. At a present time when ASR deterioration phenomena are still progressing in some areas in the Hokuriku district after the ASR countermeasures according to JIS A5308 in 1989, the use of fly ash concrete is the most recommended in order to solve the ASR problem, based on the strong ethic.

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TABLE 1: COMPARISON IN PHYSICAL AND MINERALOGICAL PROPERTIES OF ORIGINAL AND CLASSIFIED FLY ASH.

Fly ash type	Physical properties		Mineralogical properties (%)				
	Density (g/cm^3)	Blaine fineness (cm^2/g)	Quartz	Mullite	Magnetite	Lime	Glass
Original	2.36	3390	5.4	26.7	2.0	0.8	65.1
Classified	2.43	4780	5.0	20.6	1.0	0.2	73.2

TABLE 2: LITHOLOGY OF GRAVEL IN JOGANJI RIVER DETERMINED BY PETROGRAPHIC OBSERVATION.

Rock type		Vol.%	Main constituents
Rock fragment	Granitic rocks	39	Plagioclase, Quartz, Hornblende, Biotite, Alkali feldspar, Chlorite, Epidote, Sphene, Prehnite, Opaque mineral, Pyroxene
	Andesite	36	Plagioclase, Cristobalite, Tridymite, Volcanic glass, Pyroxene, Opaque mineral, Quartz, Opal, Smectite, Biotite, Hornblende, Olivine, Apatite
	Basalt	2	Plagioclase, Pyroxene, Volcanic glass, Opaque mineral, Cristobalite
Mineral fragment		23	Plagioclase, Quartz, Alkali feldspar, Biotite, Pyroxene, Hornblende, Chlorite

TABLE 3: CHEMICAL COMPOSITIONS OF OPC, FA AND BFS USED IN THIS STUDY.

Material	LOI	SIO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO
OPC	2.67	20.10	5.31	2.97	64.70	0.82	2.09	0.21	0.38	-	-	-
FA	2.00	53.60	28.93	6.74	3.20	0.77	0.22	0.30	0.72	1.39	0.98	0.09
BFS	0.97	33.14	14.19	0.33	42.96	5.29	1.97	0.25	0.28	0.53	0.01	0.28

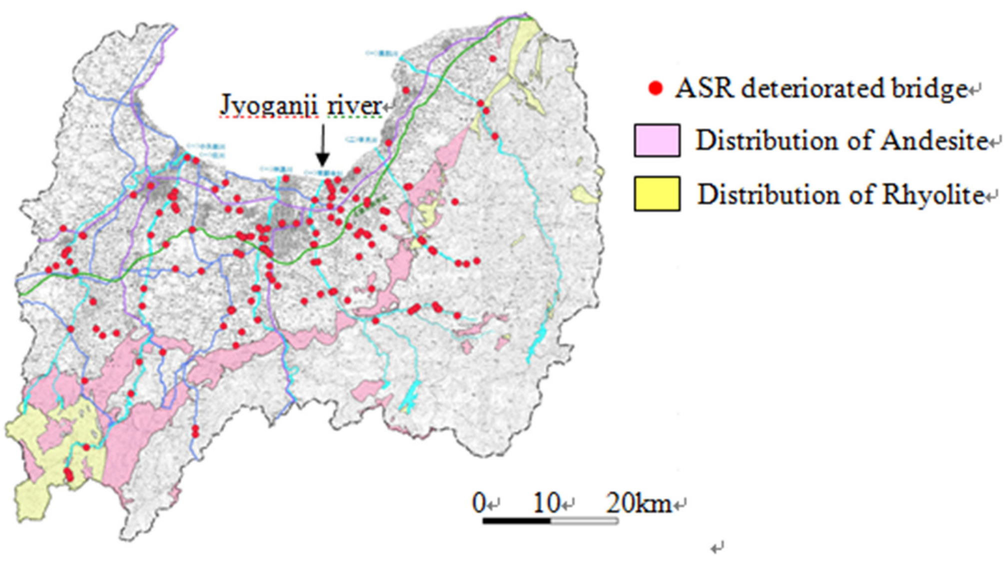


FIGURE 1: Deteriorated ASR bridges map in Toyama Prefecture.

FIGURE 2: Typical features of seriously deteriorated bridge piers.

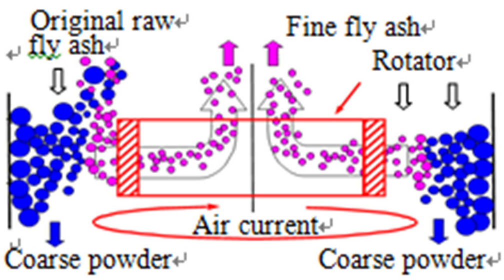


FIGURE 3: Schematic diagram of centrifugal machine in production of fine fly ash.

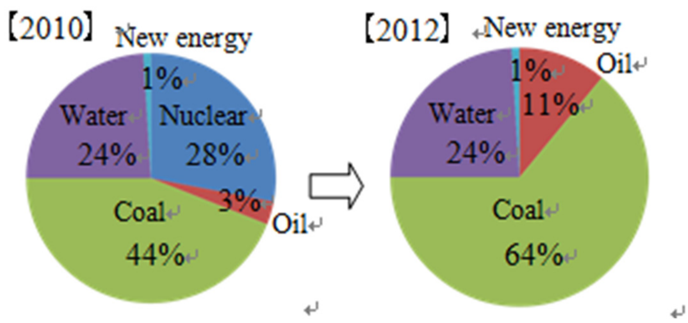


FIGURE 4: Share of electrical production source in Hokuriku district before and after the 2011 Tohoku Great Earthquake.

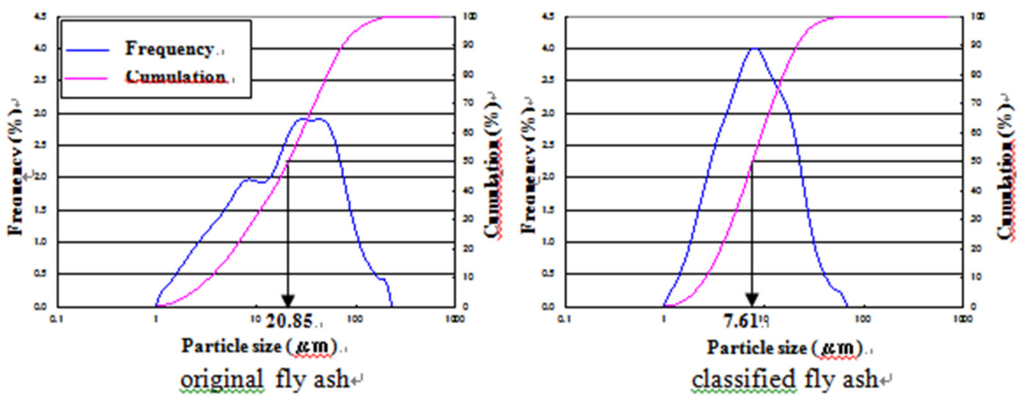
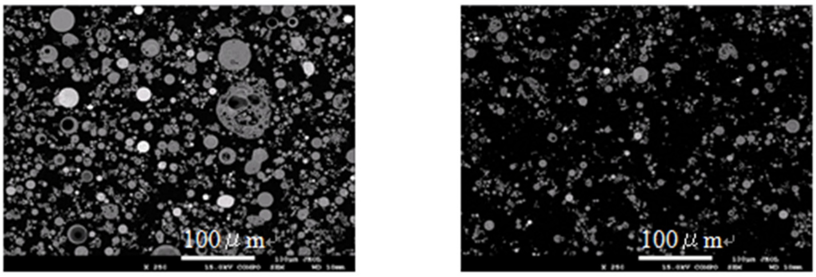


FIGURE 5: Comparison in particle size frequency of original and classified fly ash.



original fly ash

classified fly ash

FIGURE 6: Comparison in size and shape of original and classified fly ash particles.

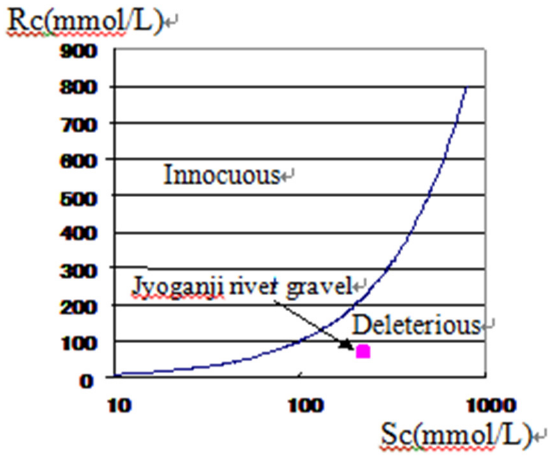
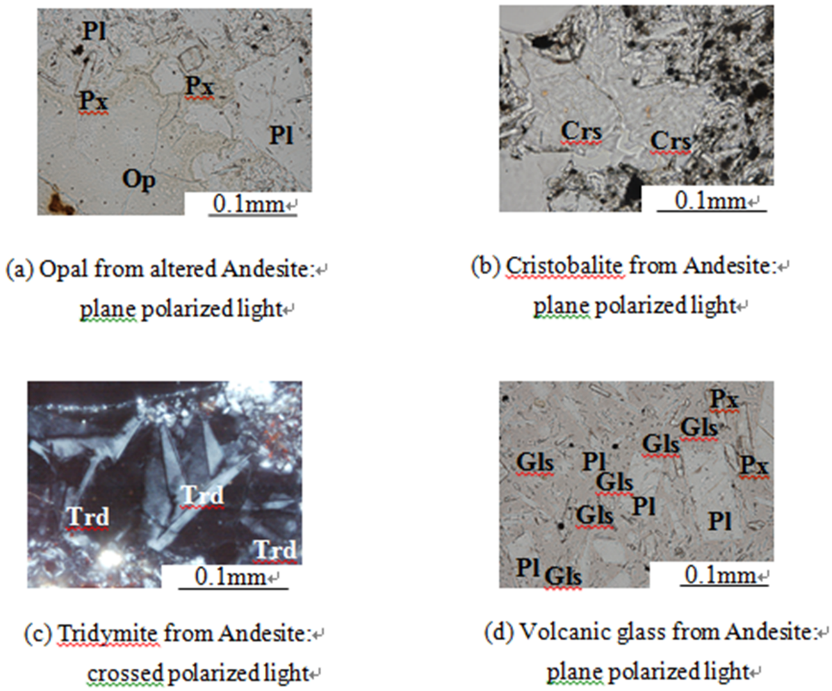


FIGURE 7: Results of chemical test method (JIS A1145) for Jyoganji river gravel.



[Op : opal; Crs : cristobalite; Trd : tridymite; Gls : volcanic glass; Pl : plagioclase; Px : pyroxene]

FIGURE 8: Photomicrographs of reactive minerals and others in the Jyoganji river gravel used in this study by polarizing microscope observation.

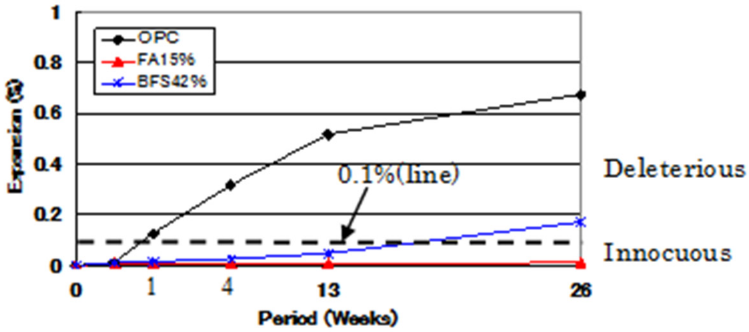


FIGURE 9: Expansion behaviors of mortars in JIS A1146 test method.

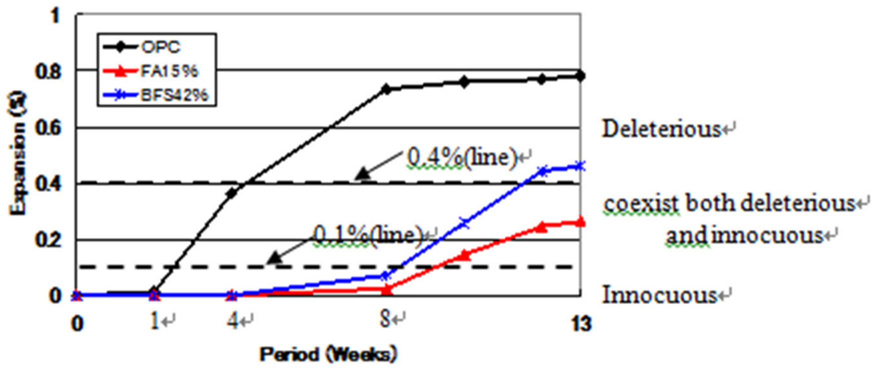


FIGURE 10: Expansion behaviors of mortars in Danish test method.

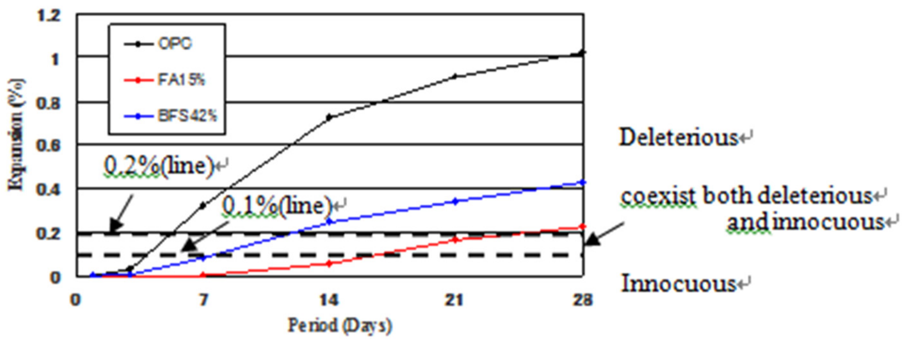
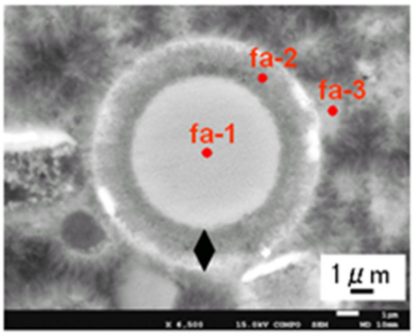
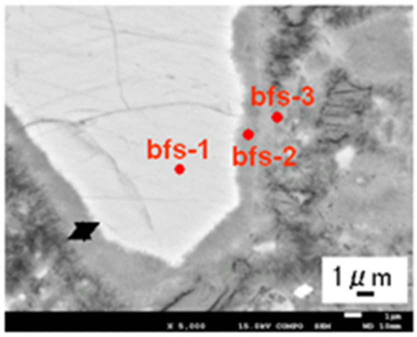


FIGURE 11: Expansion behaviors of mortars in ASTM C1260 method.





	fa-1	fa-2	fa-3
Ca/Si	0.05	0.88	1.64

	bfs-1	bfs-2	bfs-3
Ca/Si	1.39	1.47	1.58

FIGURE 12: Ca/Si ratio of CSH formed around inner and outer areas of fly ash particle after JISA1146 mortar bar test (SEM-EDS, Left: FA15% mortar, Right: BFS42% mortar).

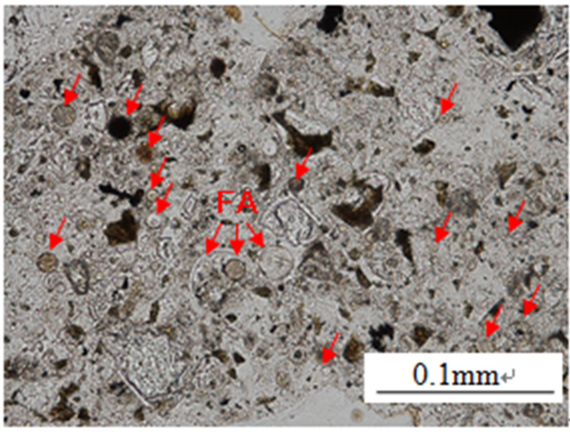


FIGURE 13: Fly ash particles in the cement paste after JIS A1146 mortar bar test (FA15% mortar) : plane polarized light.

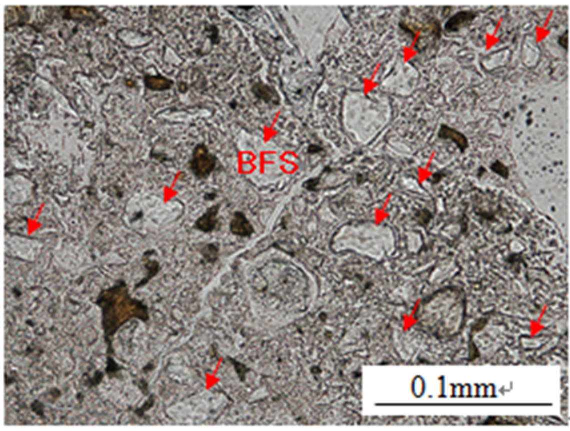


FIGURE 14: BFS particles in the cement paste after JIS A1146 mortar bar test (BFS42% mortar) : plane polarized light.