Journal of Advanced Concrete Technology
Materials, Structures and Environment

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Journal of Advanced Concrete Technology, volume 11 (2013), pp. 312-321

Journal of Advanced Concrete Technology Vol. 11, 312-321, November 2013 / Copyright © 2013 Japan Concrete Institute

Scientific paper

The Development of Highly Durable Concrete Using Classified Fine Fly Ash in Hokuriku District

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Received 7 October 2013, accepted 5 November 2013 doi:10.3151/jact.11.312

Abstract

In the Hokuriku district, the effort toward the production of highly durable concrete mixtures using classified fine fly ash has just started as a part of ongoing countermeasures for the chloride attack and the alkali silica reaction (ASR). At a time when ASR deterioration phenomena are still progressing, the use of fly ash cement in concrete should be recommended and assertively be adopted as a regional approach for the mitigation of ASR problem especially in the Hokuriku District. In order to promote this mutual understanding and cooperation among the electric power companies, the national and local governments, the industrial association of ready-mixed concrete companies and the universities are indispensable. Accordingly, a joint-collaborative industry-academia-government research committee has been set up in January 2011. This paper focuses on the drawing from the current stage of ASR problem in the Hokuriku district and the development of highly durable fly ash concretes as its countermeasures.

1. Introduction

In the Hokuriku district in Japan, as shown in **Fig. 1**, large numbers of bridges and tunnels have been suffering from the combined damage caused by the chloride-induced corrosion of steel reinforcement and/or ASR (Torii 2010). In order to produce highly durable concrete structures especially against ASR and chloride attack problems, the standard use of fly ash cement with the replacement of more than 15 % has been recommended by one of the authors, which is proposed in all ready-mixed concrete mixtures from the economical and environmental point of view in this region (Sannoh *et al.* 2008). For the achievement of this inevitable target, a joint-collaborative industry-academia-government research committee on "the promotion of effective utilization of fly ash concretes in the Hokuriku district" was also set up in January 2011.

On the approach of a promotive work, it can be pointed out that both the supply of a good-quality fly ash from the coal burning power station and its quality assurance are essential in the production of concrete mixtures. In the Nanao-Ohta coal burning power station in the Ishikawa Prefecture, as shown in **Fig. 2**, the production technique of very fine particles has successfully been established, where two processes are adopted; one is the selection of original fly ash from only the bituminous coal from Australia, the other is its mechanical separation of ultra-fine particles less than 20μm by a centrifugal machine. The physical and chemical properties of fine fly ash produced are almost well satisfied with the quality standard of the highest level "Class I" according to JIS A6201. Furthermore, on the trial test in ready-mixed concrete plants, it has been confirmed that in the fly ash concretes with the replacement of 15 % by classified 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, which is greater than them beyond 56 days.

In this paper, firstly the drawing from the current stage of a serious ASR problem in the Hokuriku district is introduced, secondly both the supply system and the quality assurance of classified fine fly ash are introduced, finally the development of highly durable concretes using classified fine fly ash as their countermeasures is introduced. (Torii *et al.* 2013)

2. Serious ASR problem in Hokuriku district and its countermeasures

In the Hokuriku district, due to the severity of both chloride attack and ASR, the development of economic and rational repair, retrofitting methods has become a top priority. In the whole, in the West Japan region (mainly in the Chugoku district), the chloride attack is related to the use of sea sand or sea gravel in concrete (internal salt attack), but in the Hokuriku district, which is rather linked to the use of river sand and river gravel in concrete, combined with the northwest monsoon from the Sea of Japan and the increased scattering of deicers on road surfaces, both in the winter season (external salt attack). On the other hand, this district is located within the huge volcanoes, such as the Hakusan and Tateyama mountains, in the upstream section of main rivers, prompting the

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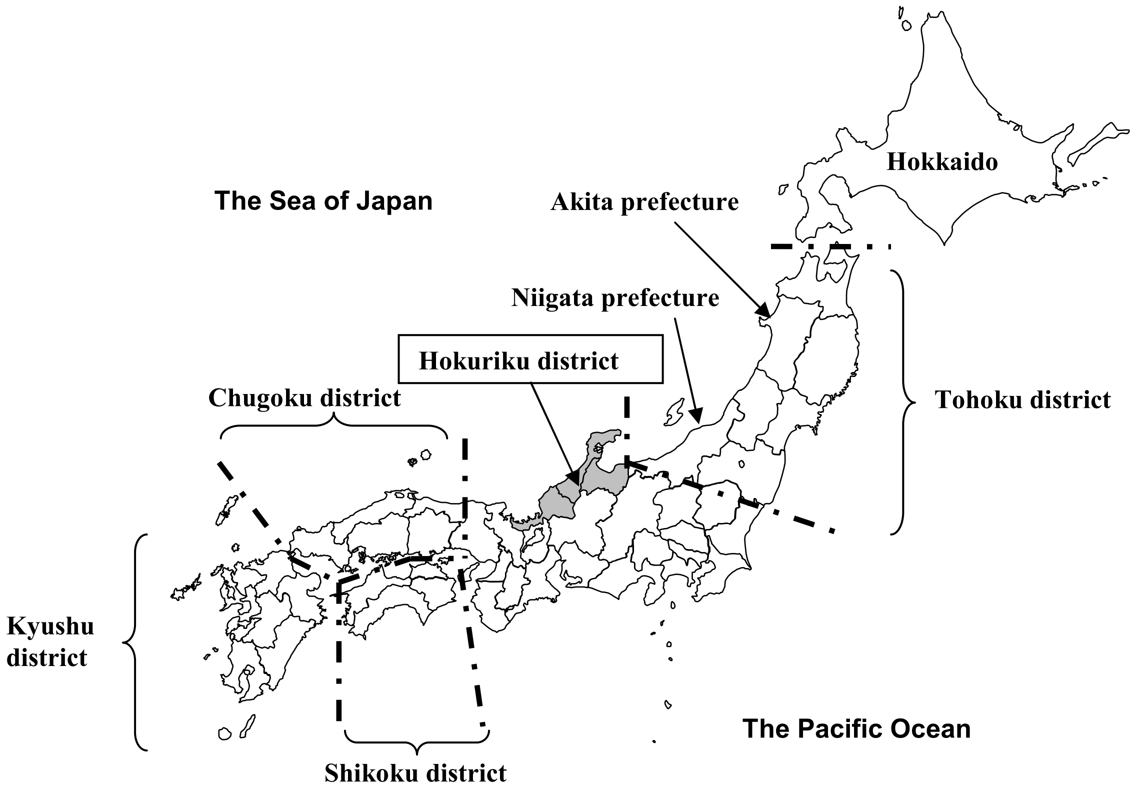


Fig. 1 Location of the Hokuriku district in Japan.

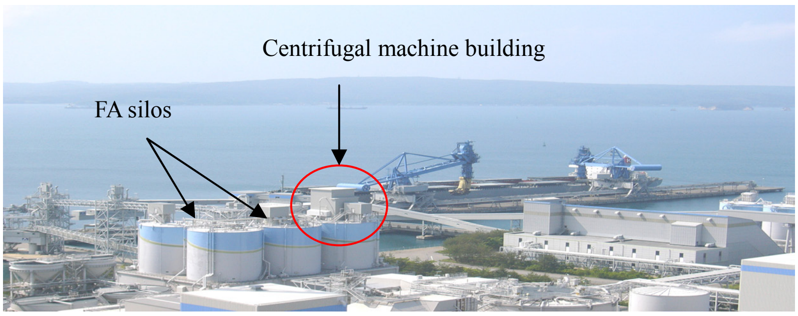


Fig. 2 Overview of centrifugal machine with fly ash silo in Nanao-Ohta coal burning power station in Ishikawa Prefecture.

outflow and spreading of volcanic rocks such as the andesite and rhyolite stones, which are the main reactive aggregates causing ASR damage in the entire area. **Figure 3** shows the deteriorated ASR bridge map in the Hokuriku district. It is a common practice in the maintenance of ASR-deteriorated bridge structures, the investigation of the relationship between the petrology of the reactive aggregates and the ASR degree of deterioration of concrete structures. However, this is a field that needs a considerable geology and petrology knowledge.

It is clarified that crushed andesite rocks from the Noto Peninsula have been used in the Noto Expressway and National Road R249 and so on, which causes a severe type of ASR including the fracture of steel reinforcing bars, as shown in **Fig. 4** (Torii *et al*. 2009; Minato *et al*. 2010). Nowadays, some ready-mixed concrete plants in the Noto Peninsula are changing the aggregate to the limestone aggregates from the Niigata Prefecture. Furthermore, through a joint-collaborative effort with the Central Nippon Expressway Company, a lot of concrete cores were drilled from approximately 30 bridge piers or abutments in the Hokuriku Expressway, thus enabling the assessment of the degree of ASR deterioration of the structures in each area (Nomura *et al*. 2012).

The results of ASR reactivity features of aggregates from river basins in the Hokuriku district has shown that particularly, the whole extension of the Joganji and Jinzu Rivers in the Toyama Prefecture, the upstream of the Tedori River in the Ishikawa Prefecture and the Kuzuryu River in the Fukui Prefecture, all aggregates possess a very high ASR reactivity, and in some cases a pessimumn content effect, because all these aggregates contain andesite particles with the opal and/or the cristobalite as a reactive component. As mentioned above, an excessive ASR expansion of concrete has led to a severe deterioration with the fracture of reinforcing steel bars and, particularly, in some bridges over the Jinzu River, the concrete bridge piers had to be completely demolished and rebuilt, as shown in **Fig. 5** (Daidai *et al*. 2008).

In order to confront the widespread ASR deterioration of concrete structures in the Hokuriku district, the problem-solving approach have considered both, the repair and retrofitting for deteriorated structures in one hand, and the use of preventive countermeasures on the other hand.

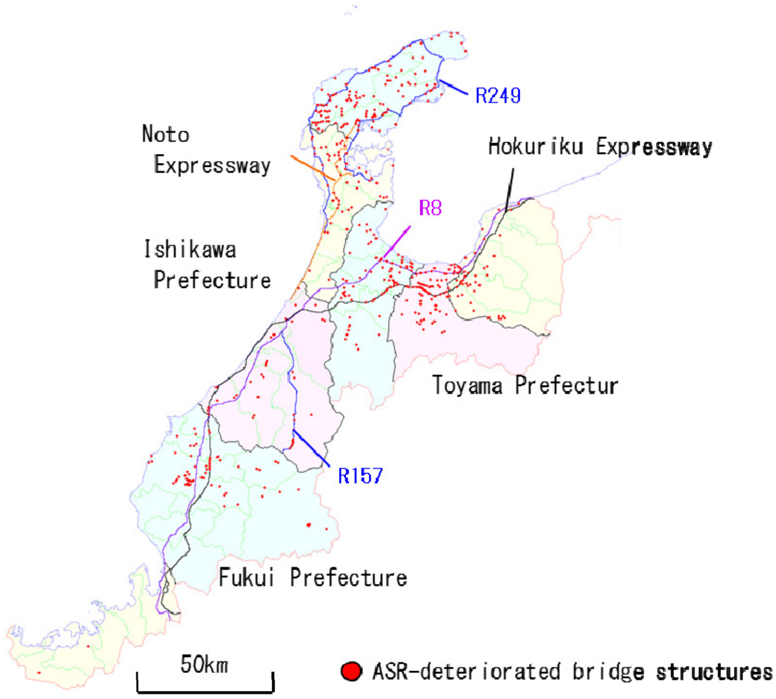


Fig. 3 Distribution map of ASR deteriorated bridges in Hokuriku district.

Fig. 4 Fracture of steel reinforcing bars in ASR-deteriorated bridge pier.

Fig. 5 Reconstruction for severely damaged ASR-deteriorated bridge pier.

3. Ineffectiveness of ASR countermeasures in Japan (JIS A5308)

According to JIS A5308 for the ready-mixed concrete, the ASR countermeasures are as follows:

(1) Use the aggregate which are judged as “innocuous” based on the chemical method (JIS A1145) or the mortar bar method (JIS A1146)

(2) Set the total alkali content in concrete below 3kg/m^3

(3) Use the blended cements using fly ash or blast-furnace slag with the ASR suppression effect

However, the order of countermeasures proposed by both the Japan Society of Civil Engineers and the Architectural Institute of Japan slightly differs. In the recent case of RC building hall in the Toyama City, as shown in **Fig. 6**, the fine and coarse aggregates from the Jinzu River have been assessed as “ Innocuous” and also the total alkali content of concrete has been kept below 3kg/m^3, presumably around 2.4kg/m^3, however the severe ASR actually occurs.

Similarly, based on the recent survey of ASR cases in the East Japan Railways, there is an evidence of ineffective countermeasures against ASR, thereby they have adopted a new strict standard in the assessment of aggregates used in concrete. On the other hand, if ASR occurs in aggregate stones, and naturally, “if the place locally changes, the quality required also changes”, then the regional deterioration phenomenon will be quite high. In terms of magnitude, the ASR problem is similar to the chloride attack, but in Japan it seems to persist a lack of awareness about this matter. It should be noted that JIS A 5308 standards and its countermeasures cannot uniformly be applicable nationwide.

When looking into the ASR countermeasures, especially in relation to (1), there are certain details that are overemphasized regarding the chemical method (JIS A1145), but the fact that the aggregate is merely judged as “innocuous” or “not innocuous”, offers little meaning in terms of engineering. In the case of ASTM C289, it is clearly stated the rocks types such as the lime stone and the stone in which contains clay mineral that cannot be appropriately assessed with the chemical method, but why this is done, we forget to inquire. In relation to (2), not only the influence of alkalis (Na^+ and K^+ ions) from the external environment and within the aggregates is not considered, but also the appropriateness of the regulation on the total alkali content has not been reexamined. Even in the Hokuriku district, where has been confirmed that differences on the rock types, the degree of ASR reactivity varies depending on the riverbeds, naturally, it is difficult to accurately assess the ASR reactivity of these aggregates only with the resort of the chemical method (JIS A1145). Especially, with such a highly reactive aggregates from the Jouganji River and Jinzu River in which contain the andesite particle with the opal and/or the cristobalite as a reactive component, even if the maximum alkali content of concrete is observed, there is a strong possibility and risk that ASR will still occur. Therefore, the countermeasures (1) and (2) should be considered for revision, while the countermeasure (3) seems to be the most effective one in the Hokuriku district. That is to say, when the reliability of the ASR test method and the variation of rock types in the aggregate mixture are considered, a countermeasure which supposes the possible presence of highly reactive rocks in the mixture is necessary. In the Hokuriku district, it translates into nothing less than “standardizing of the use of blended cements such as fly ash cement in concrete”.

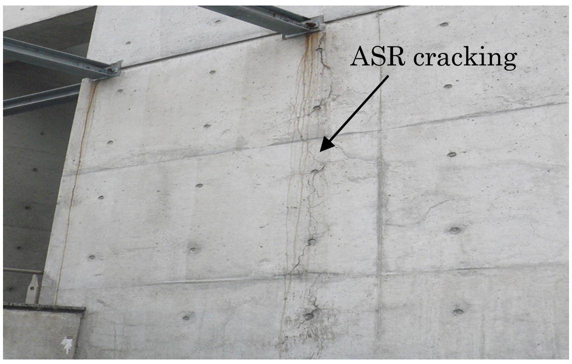


Fig. 6 Recent case of ASR cracking on wall of RC building.

4. Necessities for using fly ash in ready mixed concrete

With the introduction of a green purchase system by the Ministry of Land, Infrastructure, Transport and Tourism and other organizations, the blast furnace slag cement type B (slag replacement ratio of 30% to 60% by mass), which is one of most available blended cements, has increased up to 23 % of the whole share of cement materials. However, the production of blast furnace slug powder is limited to the national capital suburban areas, Tokyo, Osaka, Nagoya, Kitakyushu etc., but its production is completely non-existent in the Sea of Japan region. In addition, as for silica fume cement, from the results of ASR countermeasures in Iceland, it is reported that only the 5% replacement ratio is required for ASR suppression effect, but from the relationship of supply and cost, as the entire quantity would have to be imported, the use of this cement is limited to the high strength concrete of more than 100 N/mm^2. In this regard, from the viewpoint of effective utilization of available resources in the Sea of Japan region, the use of fly ash should be strongly encouraged. Actually, even in the Noshiro City in the Akita Prefecture, the northeast district of the Sea of Japan region, the ongoing application of locally produced fly ash has been reported. The common catch phrases used are “Local Production for Local Consumption” and “Reduction of Environmental Impact”.

In the 2011 Tohoku Great Earthquake and thereby Tsunami disaster, there was a lot of the human life loss, together with bridges and buildings near the seashore being destroyed and washed away by giant tsunami waves. Until now, a feeling of "Resentment" has held us back about the limits of civil engineering works and disaster prevention technology. Afterwards, most of nuclear power stations have been shutdown, and there is no plan in sight for their immediate operation. In the Hokuriku district, in the summer of this year, approximately 60% of the electricity supplied was generated by coal burning power stations. Setting apart the argument of natural renewable energy, for the time being, it is reasonable to consider that we will rely on the abundant coal reserves to meet our energy needs. In this case, also the topic of processing and the effective utilization of coal ash in cement production becomes an impending subject. Simultaneously, based on the prevailing social situation, where the reduction of general public construction works is negatively affecting the production output of cements containing coal ashes in raw materials, right now, the ability and intention of using fly ash in concrete is called into question.

Until recently, the use of fly ash in concrete has been kept at very low level around 2 %. "Why has being so poorly used?" The answer is very clear, if we look into the large quality variation of fly ash in chemical compositions and physical properties, largely due to the influence of the type of raw coal material, the type of boiler, its burning temperature, etc. Concrete manufacturers mentioned especially, the day-to-day fluctuations of residual carbon quantity as the major cause of the instability of the air content in concrete, thus refraining from using the fly ash concrete. I absolutely believe, in order to solve this problem, first, it is necessary to eliminate the "Trauma" for the concrete manufacturer and then, restore the reliability and credibility of the fly ash in concrete. This is the confidence of the author based on the experience of concrete engineer for 30 years. Actually, in Korea utilization ratio of fly ash in ready-mixed concrete was approximately 70% in 2009. (Choi and Lee 2013)

5. Supply system and quality assurance of classified fine fly ash

In January 2011, a joint-collaborative industry-academia-government research committee on "the promotion of effective utilization of fly ash concretes in the Hokuriku district" was set up. It has started the standardization of the use of fly ash concrete and consultations on the definition of a sustainable and effective supply system in the Hokuriku district. The location map of coal burning power plants currently operational in the Hokuriku district is shown in **Fig. 7**. In the Toyama, Ishikawa and Fukui Prefectures, there is one coal burning power station respectively, but those from where good quality fly ashes can be steadily supplied, judged from relationship between the type of boiler and its burning temperature, are the Nanao-Ohta coal burning power station in the Ishikawa Prefecture and the Tsuruga coal burning power station in the Fukui Prefecture. For this reason, it has been decided that both the Toyama and Ishikawa Prefectures have been supplied from the Nanao-Ota coal burning power station, while the Fukui Prefecture will be supplied from the Tsuruga coal burning power station in September 2012, thus covering all the entire Hokuriku district area, through the distribution terminals suitably located in the network of supply system. Furthermore, at the following stage, the fly ash will be directly transported to the cement factories at the Itoigawa City in the Niigata Prefecture or at the Tsuruga City in the Fukui Prefecture for the production of fly ash cement type B (fly ash replacement ratio of 10% to 20% by mass), as the supplying system is being taken under consideration. When this system becomes operational, it is more expected that cement transportation costs within the designated area can be largely reduced, including other advantages.

On the other hand, in regard to the quality assurance of fly ash, as shown in **Fig. 8**, the production technique of

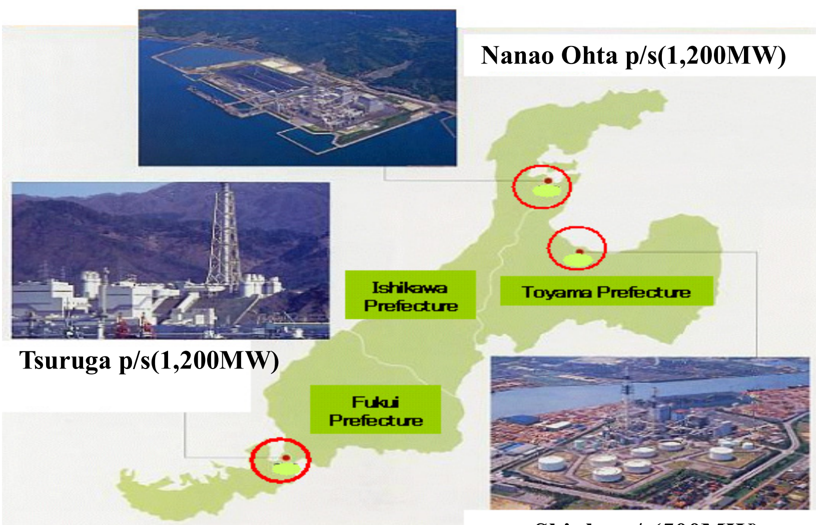


Fig. 7 Location map of coal burning power stations currently operational in Hokuriku district.

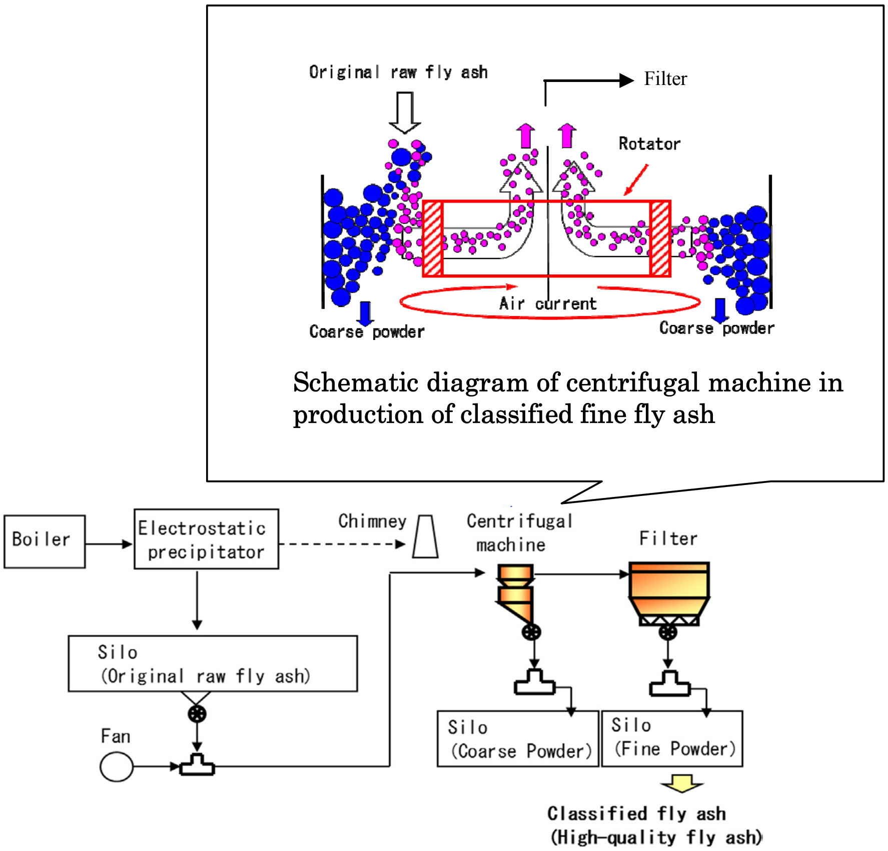


Fig. 8 Production process of classified fly ash in Nanao-Ohta coal burning power station in Ishikawa Prefecture.

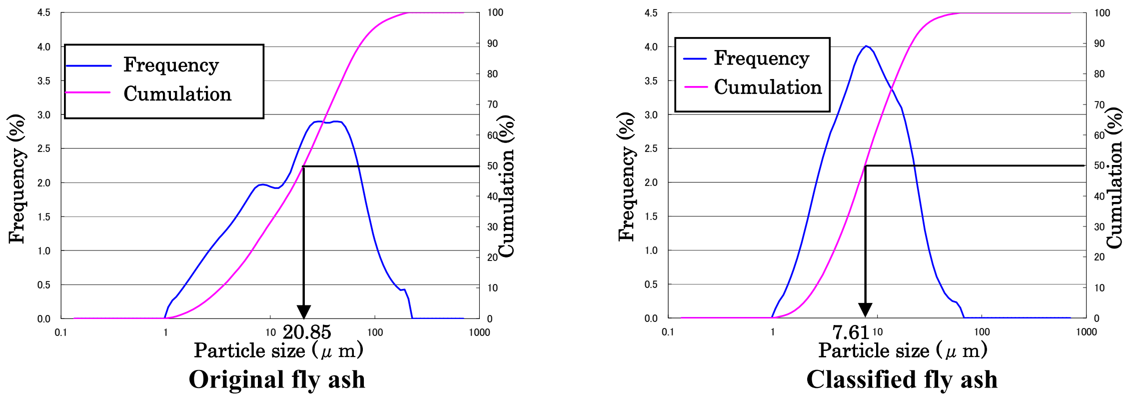
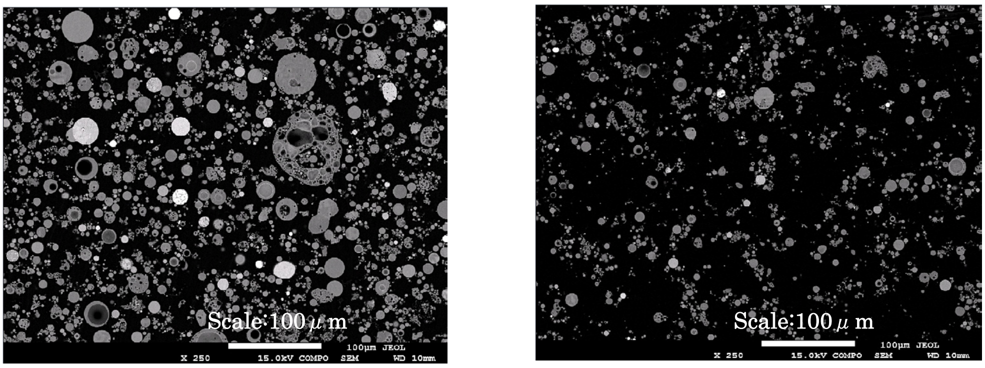


Fig. 9 Comparison in particle size frequency of original and classified fly ash (left : original fly ash , right : classified fly ash).

very fine particles and the small variations in the physical and chemical properties at the Nonao-Ohta coal burning power station has successfully been established, where two processes are adopted; one is the selection of original fly ash from only the bituminous coal from Australia, the other is its mechanical separation of ultra-fine particles less than 20μm by a centrifugal machine. Furthermore, it has been confirmed that the variations in the physical and chemical properties of fly ash itself by a centrifugal machine can significantly improve the pozzolanic reactivity. Physical properties of fly ash can be improved when the average particle size is reduced from 21μm to 8μm, as shown in **Fig. 9**, and chemical properties of fly ash can be improved when the glassy phases of fly ash, which is mostly composed of silica 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, presented as a typical sample data in **Table 1**.

In addition, **Fig. 10** shows the size and shape of fly ash particles. As it can be seen, this high quality fly ash consists mainly of spherical and uniform particles with the average particle size of 8μm, where those deformed, ill-shaped particles containing many voids are not observed. Concerning the quality improvement of the fly ash, amongst other properties, the ignition loss is almost constant below 2 %, the activity index of fly ash mortar is increased to over 90 % at 28 days and over 100% at 91



Original fly ash **Classified fly ash**

Fig. 10 Comparison in size and shape of original and classified fly ash particles (left : original fly ash , right : classified fly ash).

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

days aged, respectively, thus fulfilling all requirements of the quality standard of the highest level "Class I" according to JIS A6201 only excepting for the fineness of more than 5000 cm^2/g.

6. Advantages of highly durable concretes using classified fine fly ash

The fly ash concrete is certified for a service life that can span from 50 years to over 100 years, and the local area communities can be supplied with a highly durable concrete structure. First of all, aiming at the popularization of fly ash concrete, four representative ready-mixed concrete plants from the Toyama and Ishikawa Prefectures were selected for the production of 27N/mm^2 class concrete using their standard mix proportion. Crushed aggregates, chemical admixtures and 15% fly ash replacement from the Nanao-Ohta coal burning power station were used in the preparation of the trial mixes for subsequent laboratory tests. The test results showed that: (1) the unit water content of concrete could be reduced by 5 kg/m^3 to 10kg/m^3, thus the little bleeding and/or segregation, (2) at 28 days, the compressive strength of fly ash concrete is almost similar to those of OPC and BFS42% concretes, but at 56 days, the strength of fly ash concrete exceeded them, as shown in **Fig. 11**. Based on these trial mix results from JIS certified ready-mix concrete plants, the construction tests for retaining wall and box culvert have begun in collaboration with local construction companies.

At the same time, various experiments were simultaneously carried out at Kanazawa University and Kanazawa Institute of Technology, namely, the ASR suppression effect, chloride penetration and steel corrosion reduction effects, cracking resistance due to heat of hydration and dry shrinkage etc., leading to the establishment of a fundamental engineering database. Concerning the ASR suppression effect by fly ash, **Fig. 12** and **13** show the results of the accelerated mortar tests of specimens using the river gravel from the Jouganji River in the Toyama Prefecture, which is considered to be the most reactive one in our country. In JIS A1146 mortar bar test, OPC and BFS 42 % mortars expanded with the curing time to a significant extent since FA 15 % mortar did not expand at all. This is mainly attributable to the CSH layer with the 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 absorb the alkali ions in its texture, leading to the reduction of the alkali level in the pore solution to a significant extent, as shown in **Fig. 14** (Kawamura and Takemoto 1986; Hong and Glasser 1999; Hirono and Torii 2012, 2013). Furthermore, in the Danish test immersed in saturated

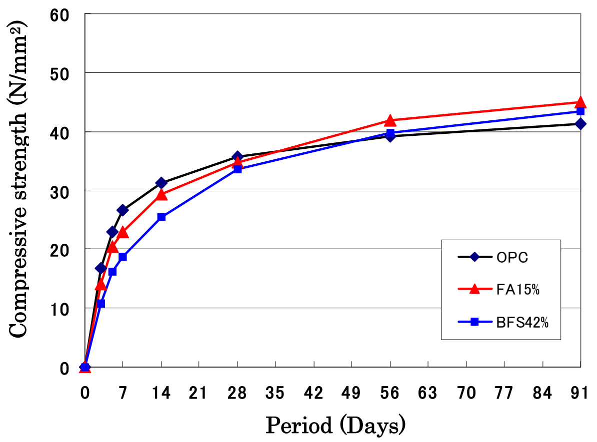


Fig. 11 Comparison in compressive strength of 27N/mm^2

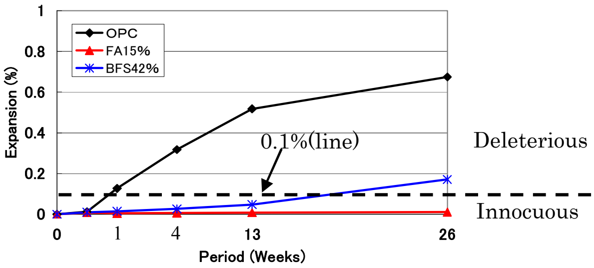


Fig. 12 Expansion behaviors of OPC,BFS 42% and FA 15% mortars in JIS A1146 method.

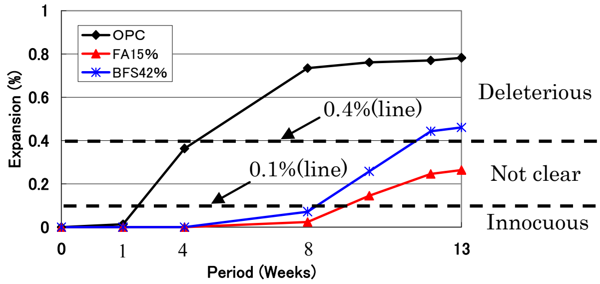
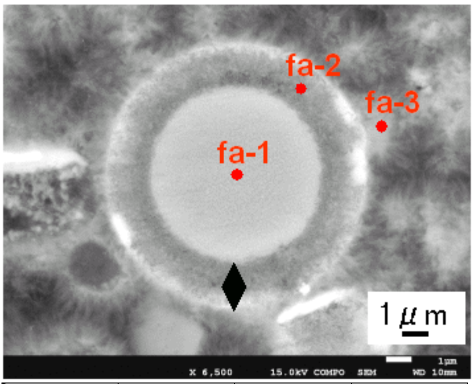
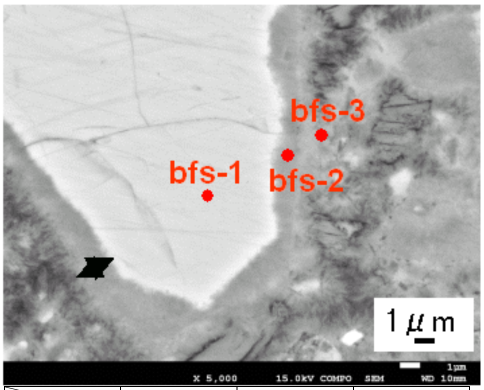


Fig. 13 Expansion behaviors of OPC, BFS42% and FA15% mortars in Danish method.

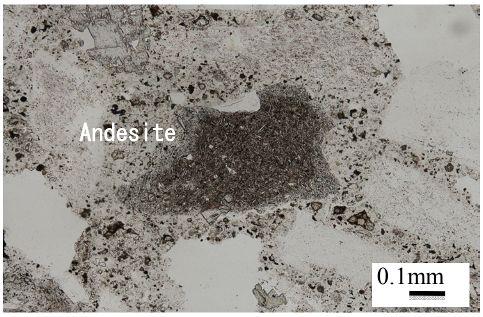


	fa-1	fa-2	fa-3
Ca/Si	0.05	0.88	1.64

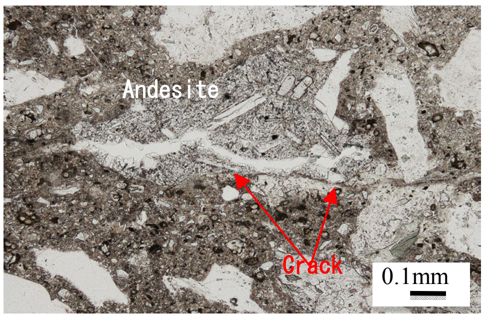


	bfs-1	bfs -2	bfs -3
Ca/Si	1.39	1.47	1.58

Fig. 14 Ca/Si ratio of CSH formed around inner area of fly ash particle after JISA1146 mortar bar test (SEM-EDS, Left: FA15% mortar, Right: BFS42% mortar).



FA 15%



BFS 42%

Fig. 15 Petrographic observations for thin section of motors aftar JIS A1146 mortar bar test (Polarizing microscope in plane-polarized light).

NaCl solution at 50°C, the mortar bars without fly ash expanded considerably, but little in FA15% mortar, it became clear that the ASR expansion of mortars was controlled over a long term by using the high-quality fly ash. **Figure 15** shows the thin section of mortars after JIS A1146 mortar bar test. It was observed that in the OPC and BFS42% mortars the cracks fulfilled with ASR gel extended around Andesite stone, while in the FA15% mortars ASR itself did not occur at all.

Concerning the effect by fly ash in the reduction of chloride ion penetration, **Fig. 16** shows the results of the test for effective diffusion coefficient of chloride ions measured by electric migration test, in which the river gravels from the Hayatsuki River, Sho River in the Toyama Prefecture, the Tedori River in the Ishikawa Prefecture and the crushed andesite rocks from the Noto Peninsula in the Ishikawa Prefecture were prepared, which are popularly and currently used for the production of 27N/mm^2 class concrete at four representative ready-mixed plants in the Toyama and Ishikawa Prefectures. In the apparent diffusion coefficient of chloride ions in concretes calculated by this test, the values obtained from FA15% concrete are less than those from OPC or BFS 42 % concrete. It has been confirmed that FA15% concrete is the most effective in the effect of chloride ion penetration mitigation. This is also attrib-

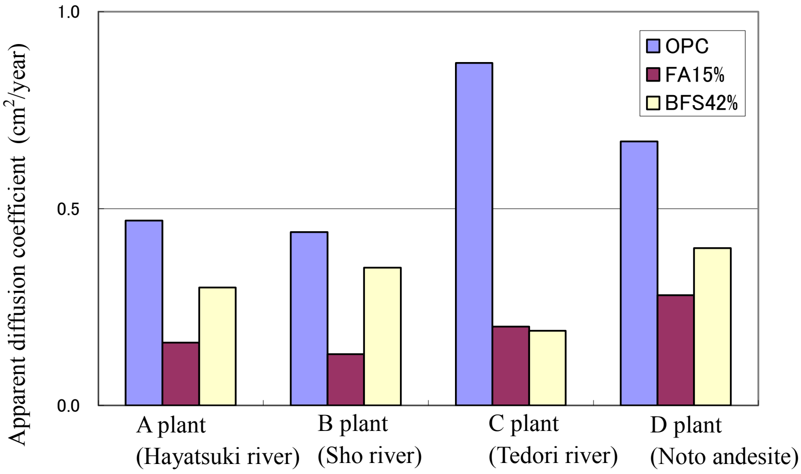


Fig.16 Comparison in apparent diffusion coefficient of chloride ions in concretes using OPC,BFS42% and FA15%.

utable to the rapid pozzolanic reaction of fine fly ashes within 28 days because the pore structure of fly ash concrete can be sifted toward the finer and discontinuous one in the process of pozzolanic reaction of fly ashes (Kawamura and Torii1989; Torii and Kawamura 1991).

In addition, there are a lot of PC bridge girders and PCa element production companies in the Hokuriku district. Accordingly, it has become a new widespread problem, the occurrence of ASR-related cracking in PC girder beams and PCa elements (Torii *et al*. 2011). Because in the PC bridges and PCa elements, high strength concrete of 40 N/mm^2 or 50 N/mm^2 with the steam or autoclave curing is executed, a different set of ASR countermeasures should be adopted, to those related to the ready-mixed concrete factories. Currently, a collaborative research work among the local companies has just started the investigation on the manufacturing technology and the performance evaluation of PC beams and PCa elements made with fly ash concrete. Therefore, the creativity and enthusiasm of all parts involved, raises no doubt that the prospects of engineering development in the field of fly ash concrete and the activation of the local concrete industry in the Hokuriku district are good.

7. Concluding remarks

In the Hokuriku district, the efforts toward the production of highly durable concrete mixture using classified fine fly ash from the Nanao-Ohta and Tsuruga coal burning power stations, has just started. At a present time when ASR deterioration phenomena are still progressing in some areas in the Toyama and Ishikawa Prefectures after the JIS A5308 ASR countermeasures in 1989, the use of fly ash concrete is the most recommended in order to solve the ASR and chloride attack problem. Fortunately, in January 2011, a joint-collaborative committee was set up. At present, a lot of trial for the target of actual use of fly ash concrete in the bridge, building and dam structure etc., are actively ongoing. We would like to propose the know-how for a further effective utilization of fly ash concrete in the Hokuriku district and other districts, based on the strong faith of “Local Production for Local Consumption” and “Reduction of Environmental Impact”.

Acknowledgment

We would like to express a lot of thanks for the committee members of a joint-collaborative industry-academia-government research committee on “The Promotion of Effective Utilization of Fly Ash Concretes in Hokuriku District”.

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