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ASR PROBLEMS IN JAPAN AND A MESSAGE FOR ASR PROBLEMS IN THAILAND

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ABSTRACT :

Alkali silica reaction, ASR is still a durability problem in Japan although countermeasures have been established since 1986. The problems of this Japanese situation are thought to be caused by lack of verification of the effectiveness of the adopted countermeasures. In this critical review, the background of the Japanese countermeasures against ASR and a new approach that Japan has to introduce are explained. It will be informative for many countries to prepare ASR countermeasures. As an example of new methodology, a case of ASR damage in Thailand was analyzed from the viewpoint of petrography using concrete thin section. The ASR found in a footing was caused by cryptocrystalline quartz in granite mylonite, which is typical mineral for late expansion. Although ettringite formation was accompanied, the major mechanism of expansion is considered as ASR judging from the texture of expansive phase produced in aggregate and cement paste. Another important highly reactive phase was identified during this analysis. Mica in granite can be altered to highly reactive opal in hot and humid climate, which is a typical mineral for rapid expansion showing compositional pessimum effect. This alteration product can be common all over Southeast Asia and considered as a possible serious cause of ASR damages.

KEYWORDS : Alkali silica reaction, Countermeasures, Petrography, Cryptocrystalline quartz, granite mylonite, Alteration, Opal.

1. Introduction

Alkali aggregate reaction, AAR is one of the durability problems of concrete. Some kinds of aggregate in concrete react with alkalis mainly from cement to produce expansive alkali silicate gels. This phenomenon was found by Stanton in 1940 [1]. After that, various methods have been introduced to detect the alkali reactivity of aggregate and to suppress AAR. Historically AAR is classified into several kinds; alkali silica reaction, ASR; alkali carbonate reaction, ACR; alkali silicate reaction. However, based on intensive petrographic study by Katayama [2], ACR expansion was not caused by the reaction of some carbonate but by the reaction of silica. Surely dolomite ($CaMg(CO_3)_2$) in argillaceous dolostone reacts to form calcite ($CaCO_3$) and brucite ($Mg(OH)_2$) or M-S-H (Mg silicate hydrate) but this reaction is volume reducing. In this rock type, cryptocrystalline quartz (SiO_2) grains are included but overlooked by its small size. This cryptocrystalline quartz was the mineral causing expansion. Therefore, ACR is a kind of ASR. Similarly, in many cases such as so-called alkali silicate reaction and the reaction of stained quartz,

ASR by cryptocrystalline quartz has been overlooked.
The above is the most recent understanding of ASR. However, not every country is considering these advanced analytical results. Canadian standard CSA A23.2 27A-09 seems to be one of the most advanced standards. Compared to CSA, JIS is far behind. Many countries desire to establish their own standards and in order to establish new standards, it is essential to understand the previous works appropriately. There are so many studies and standards which are not easy to judge whether they are important or not.

This critical review paper tries to explain the background and limitation of the Japanese standard and an ideal methodology to suppress ASR. Every time, the most fundamental difficulty for durability problems is the analysis of the local degradation and identify the exact reason. Therefore, one example of ASR diagnosis of some damaged concrete structures in Bangkok is also introduced.

2. Mechanism of ASR

ASR has been well described in various textbook already. However, there seems to be some misunderstandings. Therefore, basic mechanisms of ASR are summarized here again. Required conditions of ASR are well-known: reactive aggregate, enough alkali, and moisture. As ASR is caused by chemical reaction of silica with alkali, higher temperature is expected faster expansion. The process of ASR expansion is briefly summarized below and typical examples of ASR are shown in Fig. 1.

1) Alkalis from cement paste penetrate into aggregates.
2) Various silica or silica bearing phases in aggregate react with alkalis.
3) At inside or outside of aggregate, this reaction produces alkali silica gel containing significant amount of water with larger volume than original phases.
4) There may be a misunderstanding that reaction rim is always required for ASR expansion although reaction rim is just observed in many cases of ASR.
5) Since ASR gel is viscous but fluid and concrete is porous, so without some barriers around aggregate, the formed ASR gel just goes out from aggregate and aggregate does not expandor crack.
6) ASR gel is rich in alkalis but can change its chemical composition rich in Ca by ion exchange when it penetrates into Ca-rich cement paste and shrinks to form rigid C-S-H gel and this rigid C-S-H restrict the movement of viscous alkali rich ASR gel further.
7) When alkalis penetrate into aggregate, the texture of aggregate may be able to act as barriers against the movement of ASR gel going out. Topological effect is important and this means that petrographic observation is indispensable for ASR study.
8) With the increase in the expansive pressure inside aggregate, ASR gel makes aggregate expansive and cracks.
9) Alkalis can be supplied from some types of aggregate or environments such as deicing salt or sea salt. When NaCl is supplied to concrete, Cl reacts with monosulfate phase to form Friedel's salt and release OH^- and this reaction increases pH.
10) Temperature affects the expansive reaction in complicated ways. Higher temperature accelerates silica dissolution. However, the viscosity of ASR gel decreases and can go out from the system without expansion in an extreme case. Highly reactive chalcedony bearing chert does not show expansion by ASTM C 1260 testing at 80ºC.
11) Map/ honeycomb cracks or oriented cracks develop in non-reinforced or in prestressed concretes, respectively (Fig. 1(1), (4)).
12) There are several types of reactive aggregate; rapid expansive type showing compositional pessimum effect is mainly resulted from highly reactive opal, chalcedony, tridymite, or cristobalite, while late expansive type is mainly resulted from cryptocrystalline quartz, which is slow but continues in the order of ten years and is harmful even in limited expansion in specific structure such as dam (Fig. 1(2)).
13) In extreme cases, reinforcement can be broken (Fig. 1(3)).
14) Typically, strength decrease is limited when compared to drastic decrease in elastic modulus.

(1) Breakwater at seaside. Map cracks showing some preferred horizontal orientation because the expansion in longitude direction is restricted. Maximum opening of cracks reaches several cm partially because of almost no reinforcement.

(2) Dam gate. In the case of dam structures, only small expansion becomes problem to affect the movement of gates.

(3) Crossbeam of road bridge. Maximum opening reached 10 mm and reinforcement breakages were observed.

(4) Prestressed concrete girder. Cracks along reinforcement are characteristic appearances for this kind of prestressed structure.

Fig. 1 Examples of ASR damages

3. History of ASR research and establishment of countermeasures in Japan

In Table 1, important events relating ASR countermeasures in Japan are summarized. Similar to many other countries, before certain age, ASR was considered negligible. Once recognizing its effects, intensive researches were carried out and countermeasures were established. As aggregate tests, chemical method JIS A 1145 based on ASTM C 289 and mortar bar test JIS A 1146 based on ASTM C227 were introduced. Although the limitations of both methods were known in Japan [3], they were applied only because of the easiness of application for users. There were many simplifications in these methods such as; elimination of the boundary between harmful and potential harmful in chemical method that indicates the possibility of compositional pessimum effect, ignoring the existence of inapplicable rock types, etc. Suppression of ASR is based on three methods, i.e. control of total alkali amount to be less than 3.0 kg/m^3, use of appropriate supplemental cementitious materials (SCMs), and use of innocuous aggregates. The background data to set alkali limit is shown in Fig. 2 [4]. As shown clearly, when total alkali in concrete is less than 3.0 kg/m^3, the expansion is limited for various types of aggregates. However, the duration of experiments was only one year and continuous measurement was not carried out.

After the introduction of countermeasures, it was confirmed that the damages of ASR have been reduced drastically. However, the reduction seems to be partly due to the reduction of alkalis in cement by switching alumina source from clay to fly ash fromcoal fire electricity power plant that contains much less amount of alkalis [5]. This change of cement character just coincided with the introduction of ASR countermeasures. Certain researchers have been alerting the risks of compositional pessimum effect by highly reactive aggregate and slow expansion. Both types may pass both aggregate tests or are difficult to be controlled expansion by total alkali limit of less than 3.0 kg/m^3.

Table 1 Chronicle table of events relating ASR in Japan

Year	Event	Remarks
-1980's		ASR was not recognized as serious problems in Japan.
1983-1987	JCI research committee on ASR	Wide range of ASR were discussed including petrographic observation although the application of optical microscope was limited only for aggregate but not for degraded concrete.
1985-1987	National research project on the durability of concrete	Chloride attack and ASR were intensively researched including field survey.
1986	First national regulation for ASR	Non-reactive aggregates by chemical method and mortar bar test Low alkali cements Mineral admixtures having suppression effect Total alkalis amount limit less than 3.0 kg/m^3
2002	Revision of ASR mitigation (change in the priority order)	Total alkali limitless than 3.0 kg/m^3 Mineral admixtures Non-reactive aggregates (because of false report on the reactivity of aggregates)
2003-2005	JSCE committee on safety evaluation of rebar broken concrete structures by ASR	The effect of reinforcement breakages is limited (Chaired by Prof Miyagawa).
2006-2007	JCI research committee on the mechanism of ASR	New damages outside of traditional methodology were reported. (Chaired by Prof Torii).
2011-2013	JCI research committee on ASR diagnosis	Try to establish diagnosis procedures based on petrographic evaluation. (Chaired by Dr. Yamada).
2014-2016	Revision of JCI standards	Under discussion and preparation.

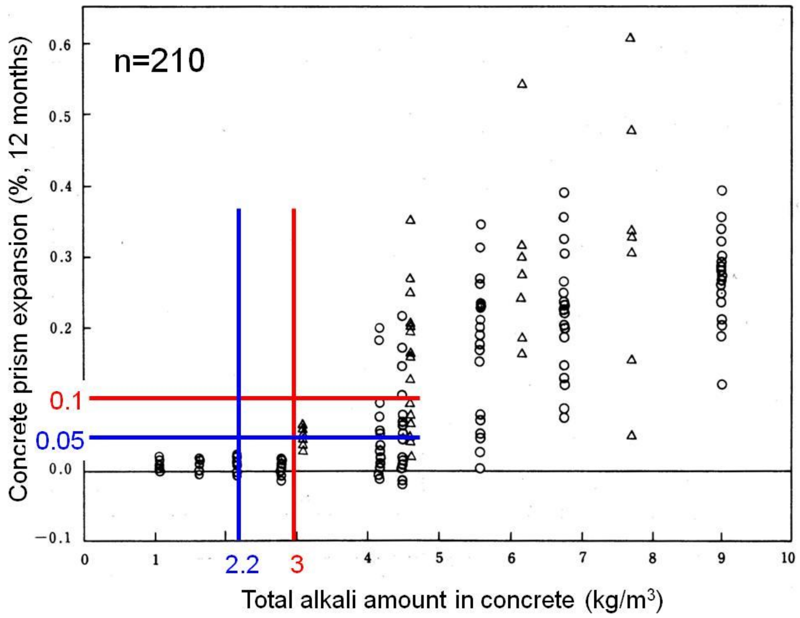

Fig. 2 Total alkali amounts and concrete prism expansions in one year [5].

Academic societies and the government have not verified the effectiveness of ASR countermeasures for long time. Recently, JCI research committee alerted the imperfectness of traditional methodology and insisted to modify the strategy [6].

One of the cases suffering serious damages by compositional pessimum effect was East Japan Railway (JR-East) and so they introduced their own methodology [7]. JR-East modified criteria of chemical method and mortar bar test. In order to introduce effective and easily applicable methods, they slightly modified existing chemical method and mortar bar test and countermeasures of alkali limit for tighter criteria. According to the category, different countermeasures are specified. For harmful aggregates, blended cement must be used. For E-harmful (semi-harmful) aggregates, total alkali must be lower than 2.2 kg/m^3 or blended cement must be used. For innocuous aggregate, no countermeasures are required. By this change, some parts of ASR will be suppressed. However, essential disadvantages of these methods have not been cleared yet.

Very recently, Public Works Research Institute reported interesting results of a 23-years exposure test indicating the limitation of chemical method, mortar bar test, and total alkali limit [8]. Now, Japan has to work to introduce new methodology [9].

4. Examples of analysis of ASR in Japan

4.1 Rapid expansion [10]

A railway bridge suffered serious ASR damages just a few years after construction. More than 15 years has passed but the expansion is still proceeding even after painting to prevent from wetting. The painted damaged member is shown in Fig. 3. This member was a prestressed panel over bridge with an oriented pattern of cracks shown in the longitude prestressing direction. Left upper part was repaired by mortar. Removed concrete (right upper) shows a typical pattern of ASR such as reaction rim. Cut surface of concrete (left lower) indicates that cracks extend into a specific type of aggregate (A). Close image of this type aggregate shows the extrusion of viscous transparent ASR gel.

In Fig. 4, microphotos by polarizing microscope are shown. The texture clearly shows that a crack comes out from andesite aggregates extending into cement paste. This is a key evidence to identify that andesite is the source material of expansion. More detailed observation reveals that the ASR gel was formed after opal vein accompanying cristobalite. The concrete used in this bridge contained only 2.2 kg/m^3 of total alkalis but these highly reactive minerals are thought to react even in such lower alkali amount.

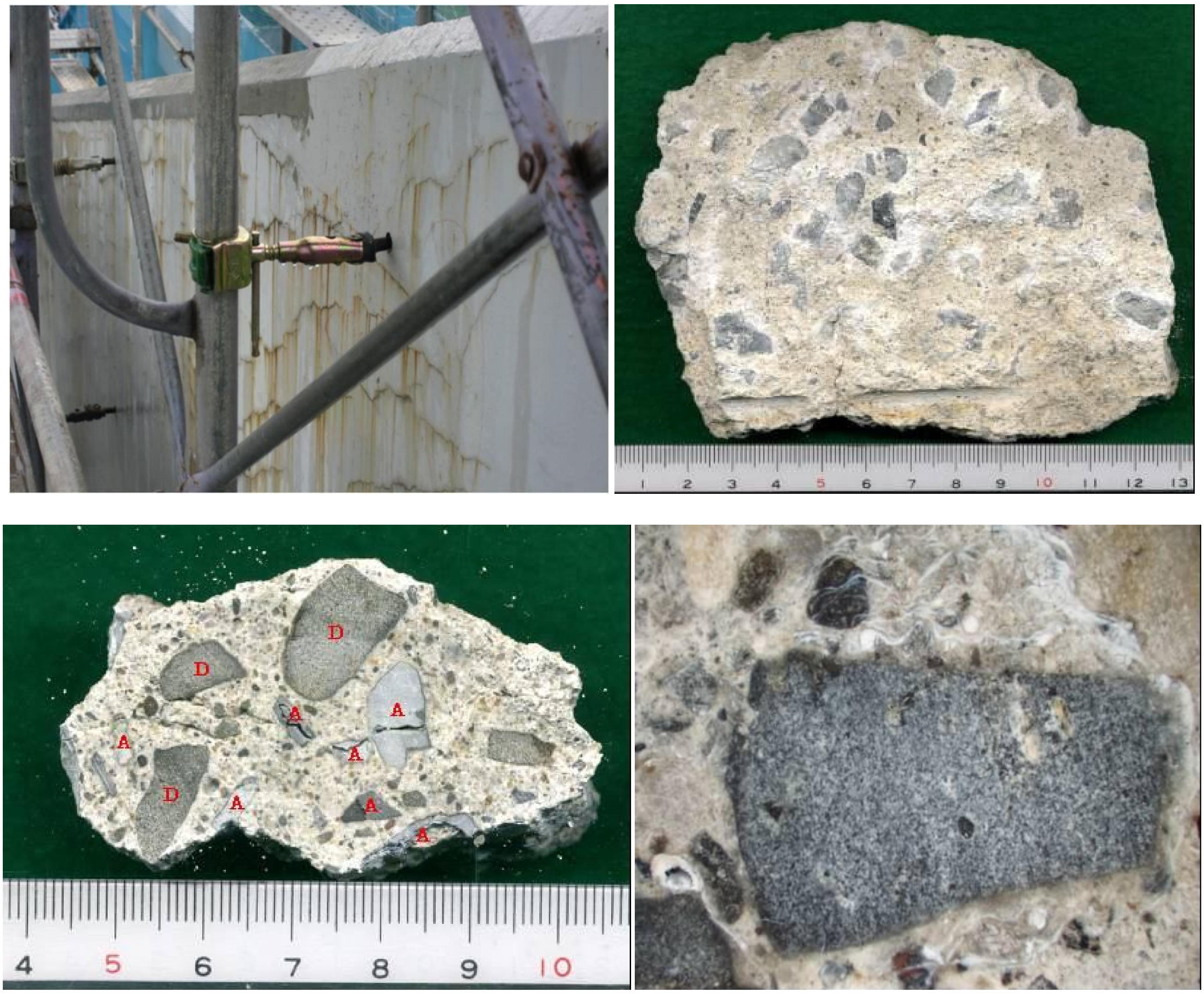

Fig. 3 Example of ASR damage by rapid expansive aggregate. Left upper: damaged member having oriented crack pattern in the direction of prestressing. Right upper: damaged concrete taken from the structure indicating white “ASR gel” residues surrounding reactive aggregate. Left lower: Cut surface of damaged concrete where cracks pass through and connecting reacted aggregate labeled as “A”. A: Andesite, D: Dolerite. Right lower: Extruded viscous ASR gel from reacted aggregate.

Similar severe ASR damages by rapid expansion were found recently around Tokyo bay area. In this area, because of the lack of source of coarse aggregate nearby, limestone aggregates have been transported from large mines in Japan by ship for hundreds km. And local sand is a little bit too fine for concrete and requires size distribution adjustment by blending with coarser aggregate. For this purpose, various kinds of aggregate were transported by sea. One kind of these aggregates contained highly reactive opal in a low ratio. This opal caused severe compositional pessimum effect even in the condition of limited alkali amount not more than 2.6 kg/m^3. According to an authority, in some extreme case, the concrete was replaced only after a few years of construction.

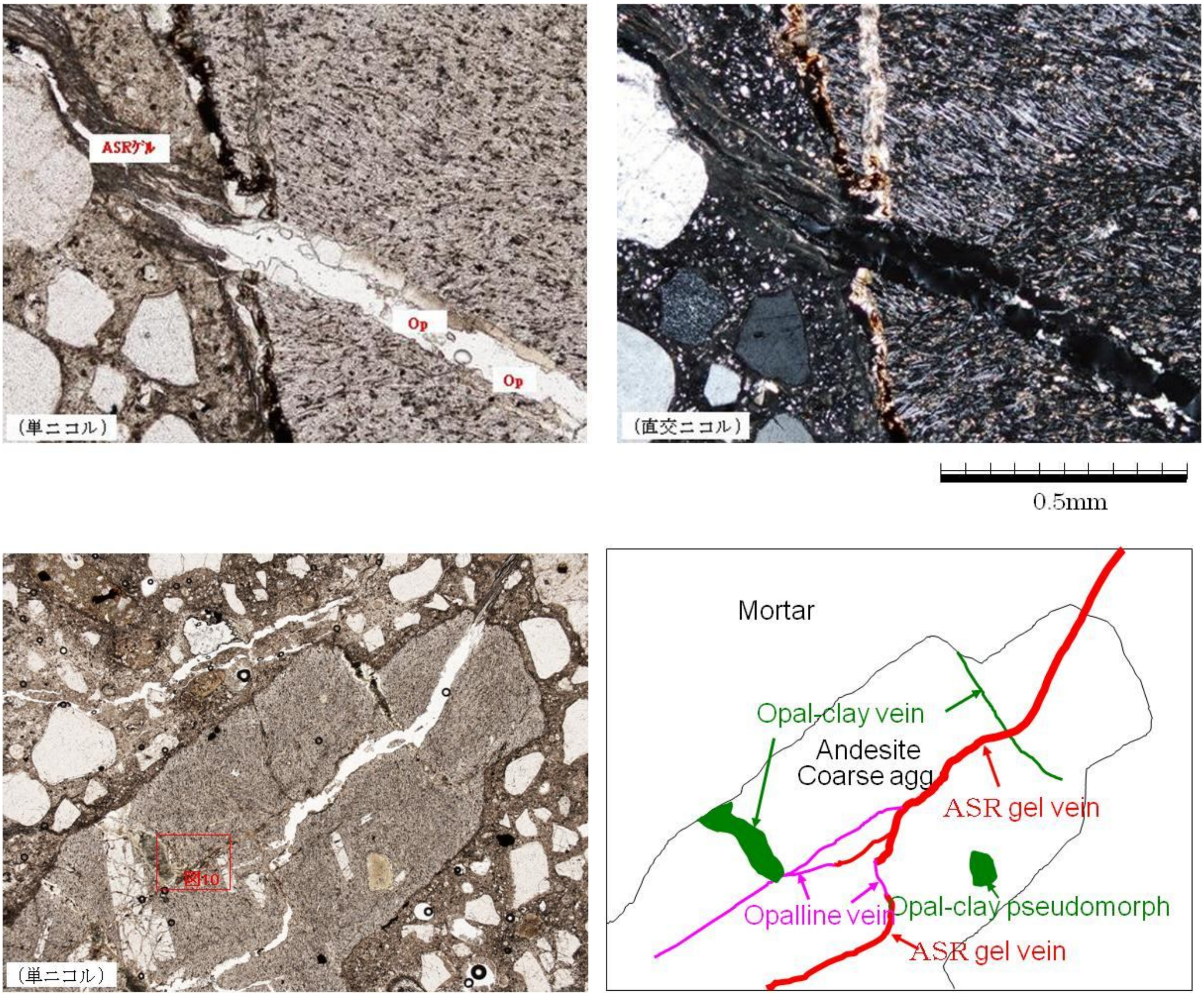

Fig. 4 Microphotos of reacted andesite by polarizing microscope

4.2 Distribution of ASR damages in Japan

In Japan, rapid expansive aggregates such as andesite or chert have caused serious damages including reinforcement breakage and they are the center of concerns. However, the detailed analyses have not been much carried out. Only recently, the importance of compositional effects and alkali released from aggregate has been emphasized based on the analysis of real damaged structures. Besides, late expansions also have caused ASR expansion even in estimated alkali amount less than 3.0 kg/m^3. This kind of study is limited possibly because there are no standardized methods for analysis and a new JCI technical committee on ASR diagnosis was started [9].

In Fig. 5 [11], a summarized map of reported ASR and geological map of important geological components having possibilities to include reactive minerals are shown. There are significant discrepancies. It is easy to imagine that many of ASR damages have not been reported yet. Even if ASR damages have not been reported in some areas, it is possible to point out the possibility of ASR based on geological knowledge and experiences in ASR.

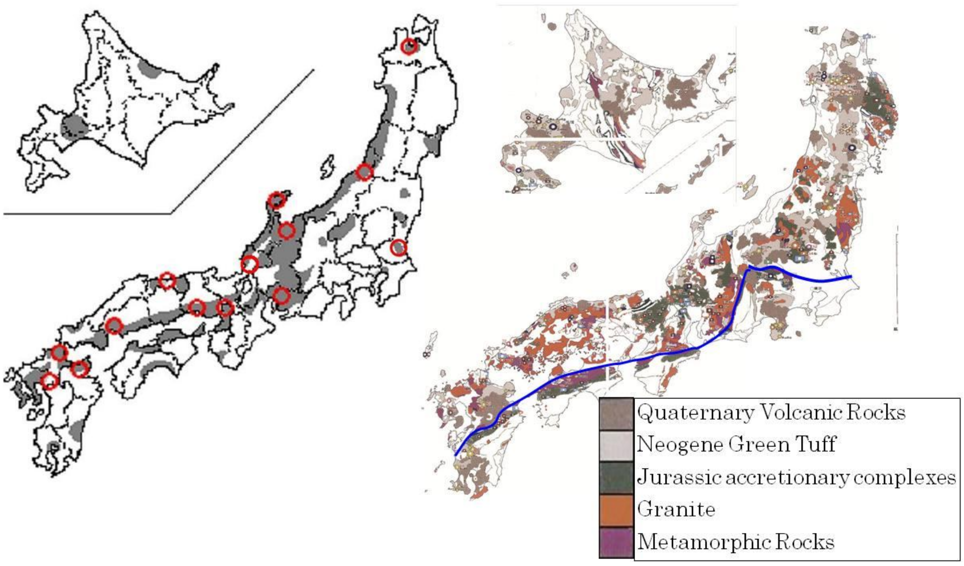

Fig. 5 Summarized map of reported ASR and geological map showing area having possibility of existence of reactive aggregate [11]

4.3 Difficulty to suppress ASR at pessimum proportion

In Fig. 6 [12] left, test results of some Japanese andesite by the chemical method are shown. They are fallen in the boundary between harmful and potentially harmful areas. By changing the ratio of this andesite (pure limestone was used as non-reactive), expansion behaviors were evaluated by mortar bar test. As are well shown in Fig. 6 right, there are clear pessimum compositions around 30%.

Pessimum phenomenon is serious because the suppressing performance of fly ash decreases. In Fig. 7 [12], the expansion behaviors of andesite at pessimum and 100% composition with and without fly ash by mortar bar test are shown. In the case of 100% reactive aggregate, FA suppressed expansion except andesite 2. However, at the pessimum composition, FA of 20 vol% did not work at all. Therefore, when highly reactive minerals are contained at compositional pessimum ratio, more amount of fly ash is required to suppress ASR.

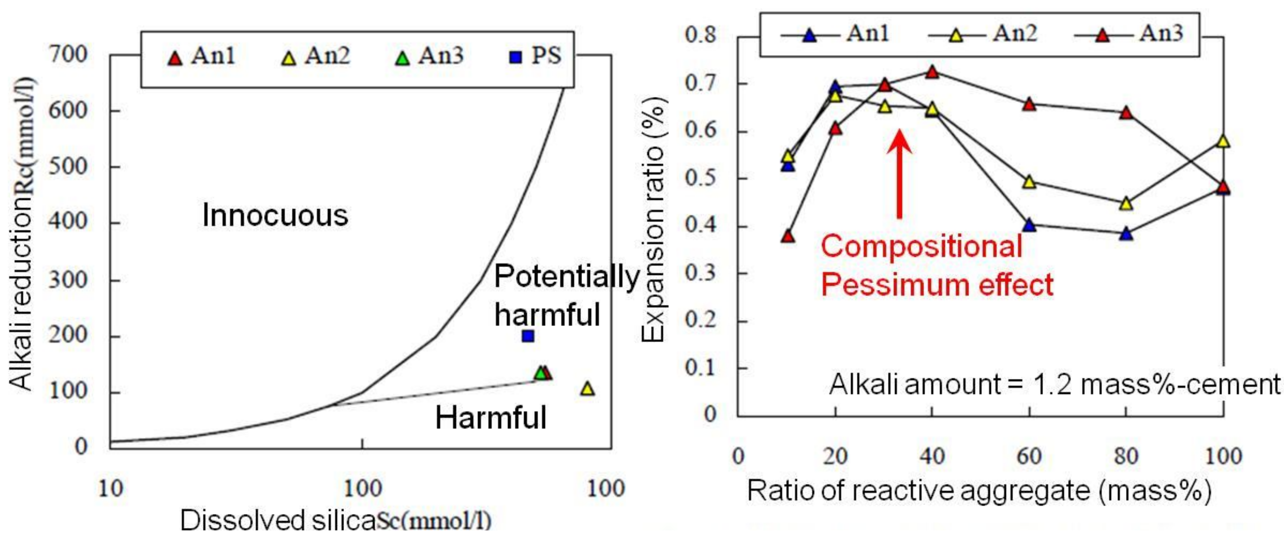

Fig. 6 Test results of chemical method (left) and compositional pessimum effect (right) of several Japanese andesite

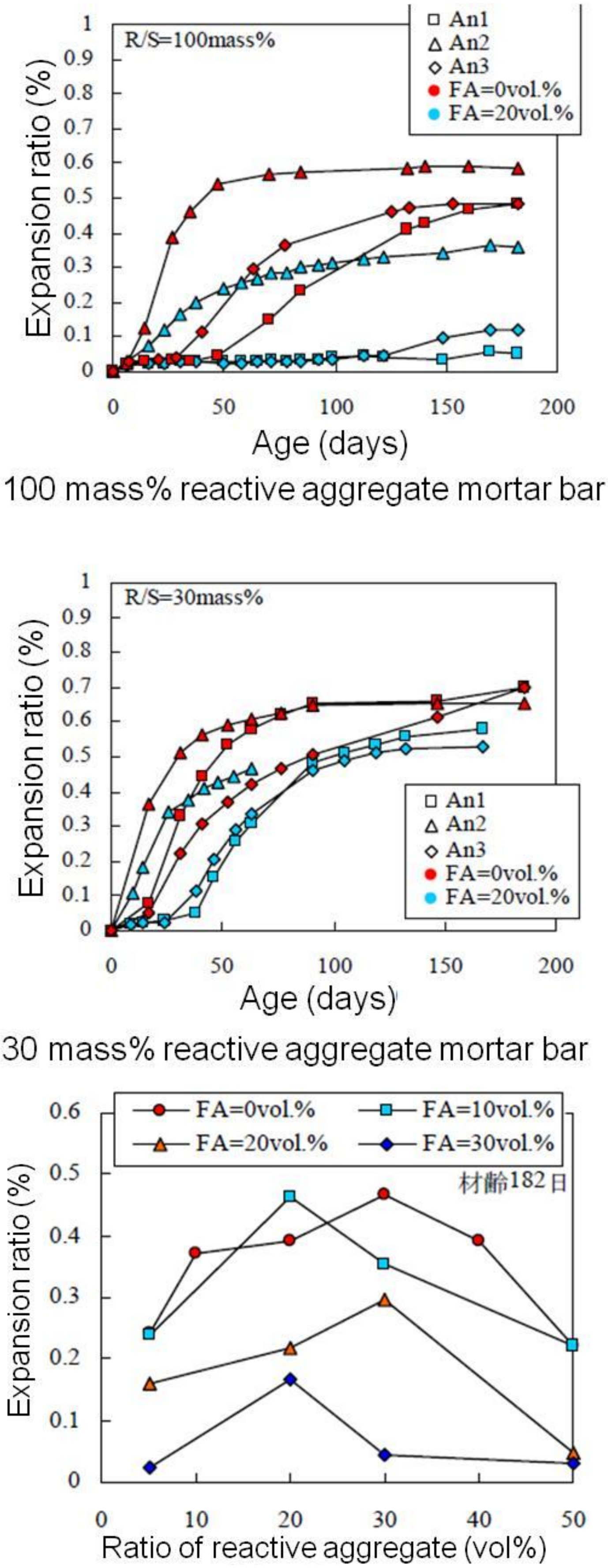

Fig. 7 Reduced effectiveness of fly ash at pessimum composition.

There are other difficult problems for the application of fly ash. As is written in Canadian standard (CSA), Ca or alkali rich fly ash has lower suppressing efficiency. In Fig. 8, back scattered electron images of cross section of fly ashes are shown. The left is siliceous Japanese one and the right is Ca rich Thai one. With more amount of Ca, Thai fly ash is rich in glass phases than Japanese and is expected more reactive, contributing to strength. However, more Ca means less suppressing effect for ASR. The fundamental role of fly ash for suppressing ASR is in decreasing pH. By calculating phase composition of cement paste and chemical composition of C-S-H, it is possible to estimate pH and suppressing performance of fly ash [13]. Based on this study, it is now possible to quantify the suppressing effect of fly ash having various chemical compositions.

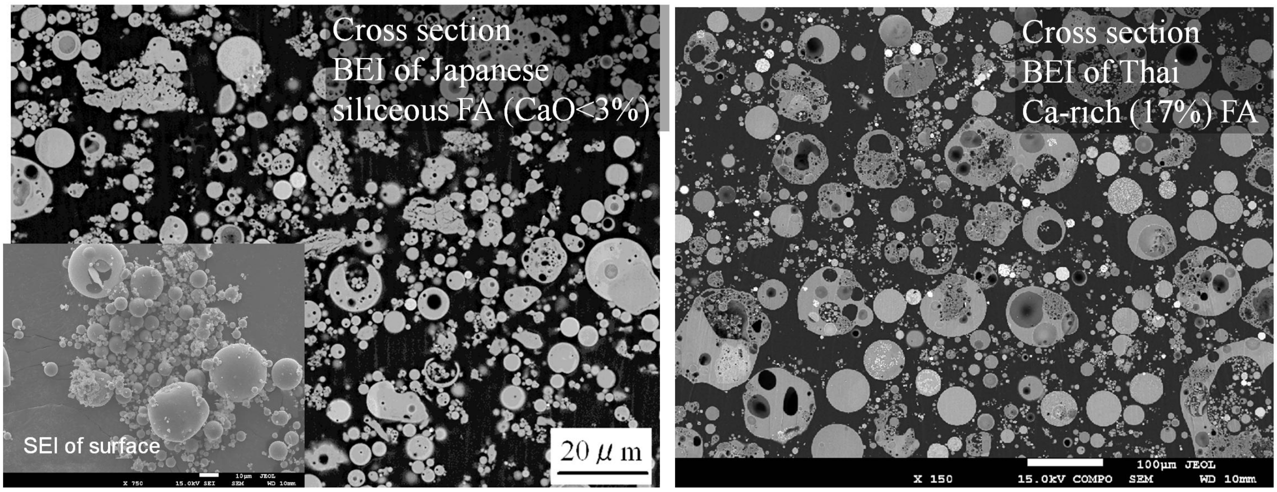

Fig. 8 Cross section photos of siliceous Japanese fly ash and Ca rich Thai fly ash under scanning electron microscope

5. An example of ASR damage in Thailand

5.1 Geological and geographical characteristics of Thailand

From geological view point, Thailand is located in Alps orogenic zone continuing from Indonesia to Alps and is divided into three areas; Shan Thai para-platform in the west; KhoratKontum platform in the east; Yunnan-Malay mobile belt in the middle. There are significant discrepancies between Japan and Thailand. Geological ages are completely different. Majority of Japan is composed of Cenozoic volcanic rocks accompanying some Mesozoic and Paleozoic metamorphic rocks. In Thailand, important characteristics are in Mesozoic and Paleozoic strata and deformation by various orogenic movements. This means every rock in Thailand has a possibility for slow expansion by crypto or microcrystalline quartz formed by metamorphism. Besides late expansion, there is some necessity to pay attention for the existence of chalcedony in every rock types. Once the general geology is understood, it is possible to predict how aggregates behave. Obviously, in order to detect alkali reactivity of aggregate in Thailand, ASTM C 1260 should be used. However, under hot and humid climate in Thailand, there is another possibility that opal is formed in some aggregates as mentioned later. For this kind of aggregate, concrete prism test such as RILEM AAR-3 or AAR-4 may be required.

5.2 Analysis of a deteriorated structure

In Table 2, analytical results of deteriorated concrete from a structure by optical microscope observation on concrete thin sections are shown. Description category of degree of ASR is shown in Table 3. Major aggregate causing ASR was granite mylonite containing cryptocrystalline quartz. Granite is coarse grained plutonic rock. When granite suffered metamorphism by orogenic movement by continental drift, its grain size decreases to invisible under optical microscope that is less than several μm. Besides, other various rock types such as limestone, hornfels, and chert contained some reactive cryptocrystalline quartz. All these rock types are expected in many places from the geology of Thailand.

Table 2 Analysis of deteriorated concrete (*Numbers in parentheses indicate progress degree of ASR about each rock types as shown in Table 3).

Sample Number	Pile cap			
	29/24	30/01	30/06	30/07
Coarse Agg.	Granite mylonite(2)※ Pelitic hornfels(2)※ Limestone～Chert(2)※	Granite mylonite(3)※	Limestone(2)※ (Cryptocrystalline quartz-bearing)	Granite mylonite(3)※
Fine Agg.	Granite(2)※	Granite(2)※	Granite(2)※	Granite(2)※
Na_2Oeq (kg/m^3)	2.02	2.53	-	2.56
ASR	Ⅱ	Ⅲ	Ⅱ	Ⅲ

Sample Number	Pier			
	29/24	30/01	30/06	30/07
Coarse Agg.	Limestone	Granite mylonite(2)※	Limestone(1) Pelitic hornfels(2)	Pelitic hornfels(2) Limestone(2) (Cryptocrystalline quartz-bearing)
Fine Agg.	Granite(2)	Granite(2)	Granite(2)	Granite(2)
Na_2Oeq (kg/m^3)	2.17	2.12	2.48	2.30
ASR	Ⅰ～Ⅱ	Ⅰ～Ⅱ	Ⅱ	Ⅰ～Ⅱ

Table 3 Category of ASR corresponding descriptions in Table 2

Progress of ASR	Petrographic severity
1 reaction rim & gel-exudation	I traceable
2 gel-fill cracks in aggregate	II minor
3 gel-fill cracks in cement paste	III moderate
4 gel-fill voids in cement paste	IV severe

In Fig. 9, microphotos of damaged concrete are shown. Cracks are originated from granite mylonite and penetrate into paste surrounding the aggregate. These cracks are filled with ASR gel in the aggregate but with ettringite in the cement paste. The chemical compositions of materials filling cracks and cement paste are shown in Fig. 10. The material in the cracks inside the aggregate shows typical chemical composition of ASR gel, rich in alkalis but poor in Ca. The chemical composition continuously changes from alkali rich material filling cracks inside the aggregate to Ca rich material near the cement paste, basically similar composition with C-S-H. Beyond some point from the aggregate, ASR gel was not observed in the cement paste at all. There is one possibility that every ASR was replaced by ettringite as suggested by the texture observed. As reported in other study [4], ettringite is detected in various places as pore or crack fillings. Also in Japan, ettringite formation was found in some voids in concrete and in ASR gel replacement texture but not so many.

In Table 4, the estimated chemical compositions of cement used in the damaged concrete and that of typical Japanese ordinary Portland cement are shown. There is a significant difference among them. Because SO_3 content is higher in Thai cement and the sulfate ion concentration in the environment where damaged structures are located is limited as reported [14], much sulfate ions in cement may be the reason why muchettringite is formed. The discrimination of the causes of cracks between delayed ettringite formation (DEF) and ASR may be difficult. As described before [15], filling patterns of cracks are the key to distinguish. Ettringite has relatively high solubility and is easy to move and re-precipitate in concrete. DEF damage is believed to occur by the ettringite formation inside C-S-H where ettringitecannot dissolve to move to other places. Many visible ettringite in many voids and cracks are secondary formed ettringite and are not the causes of DEF damage initiation. If open cracks, observed inside the aggregate, are free from ASR gel, it will be an evidence for the expansion of paste by the mechanism of DEF. In this case, it is difficult to ignore the contribution of DEF but the obvious evidence suggesting DEF was not observed in this paper.

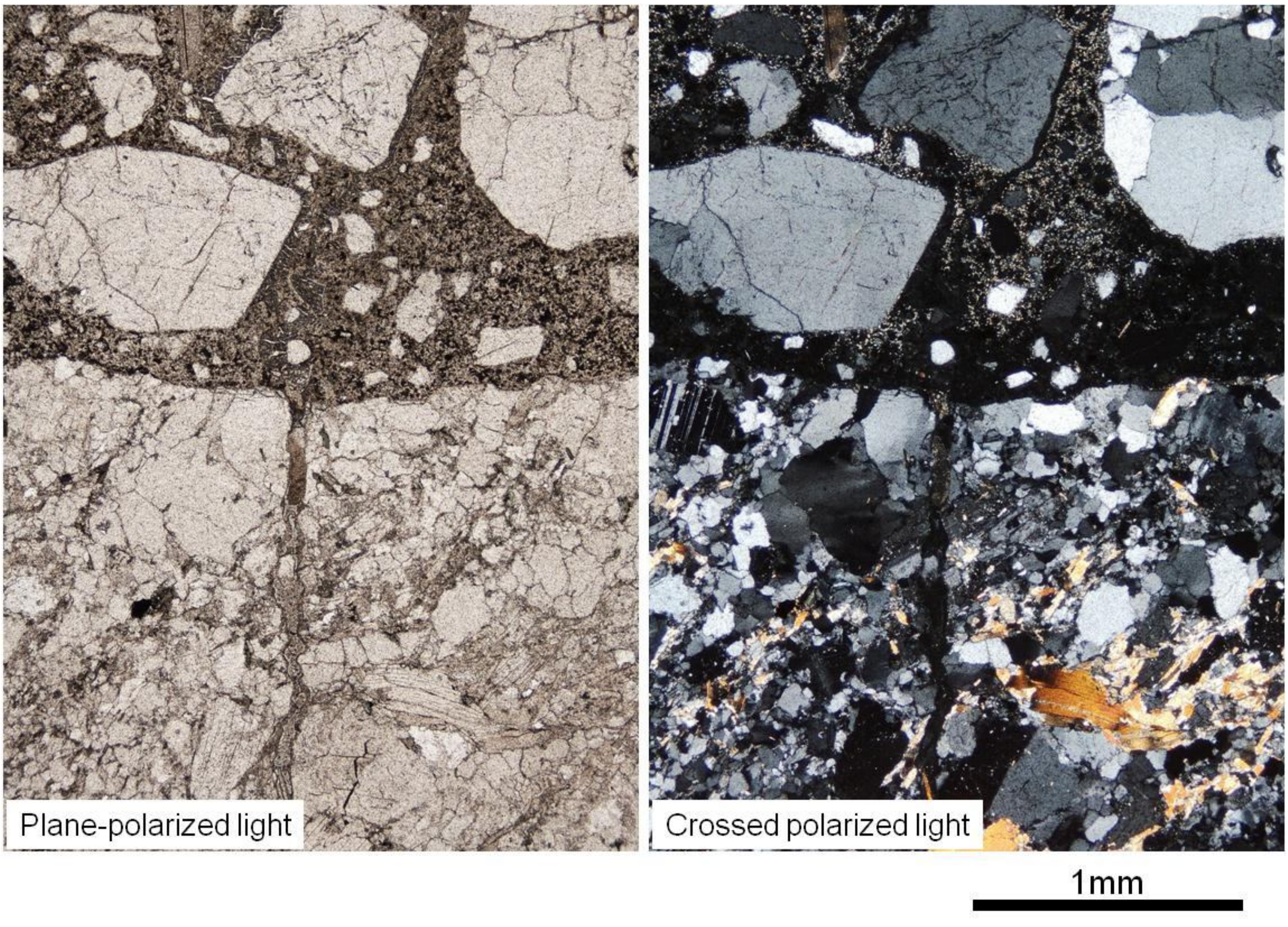

Fig. 9 Microphotos of ASR damaged concrete by polarizing microscope

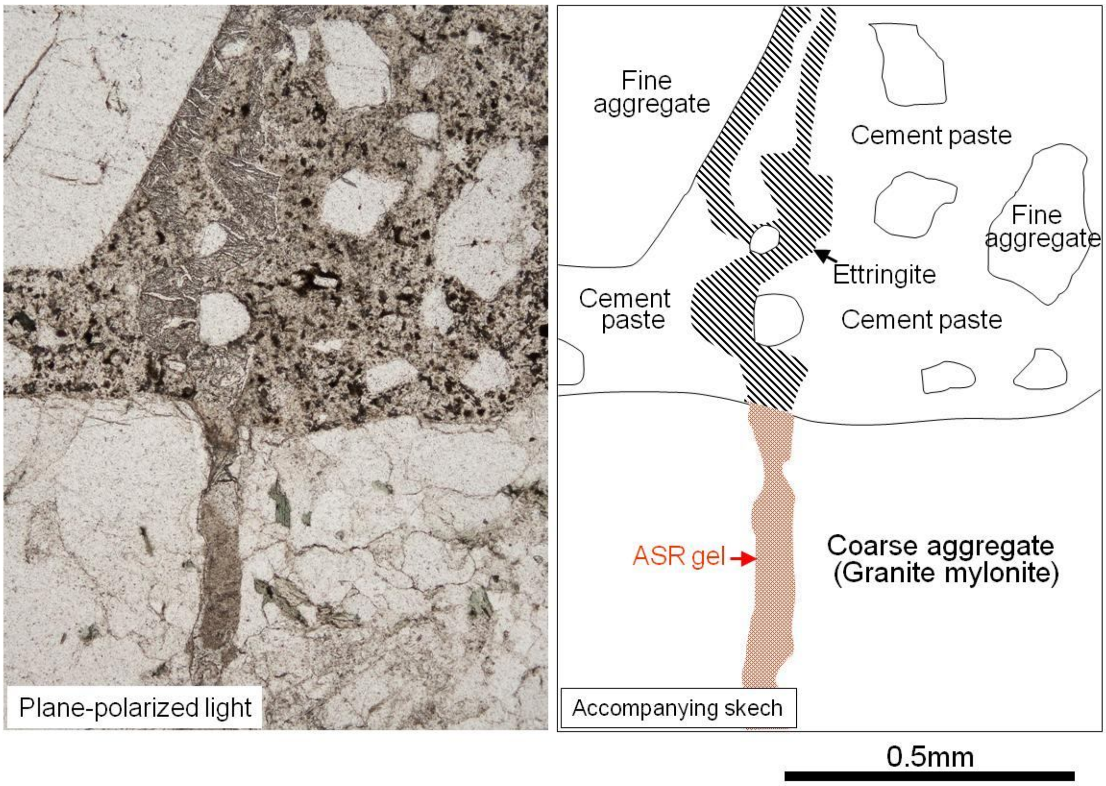

Fig. 9 (continued) Microphotos of ASR damaged concrete by polarizing microscope.

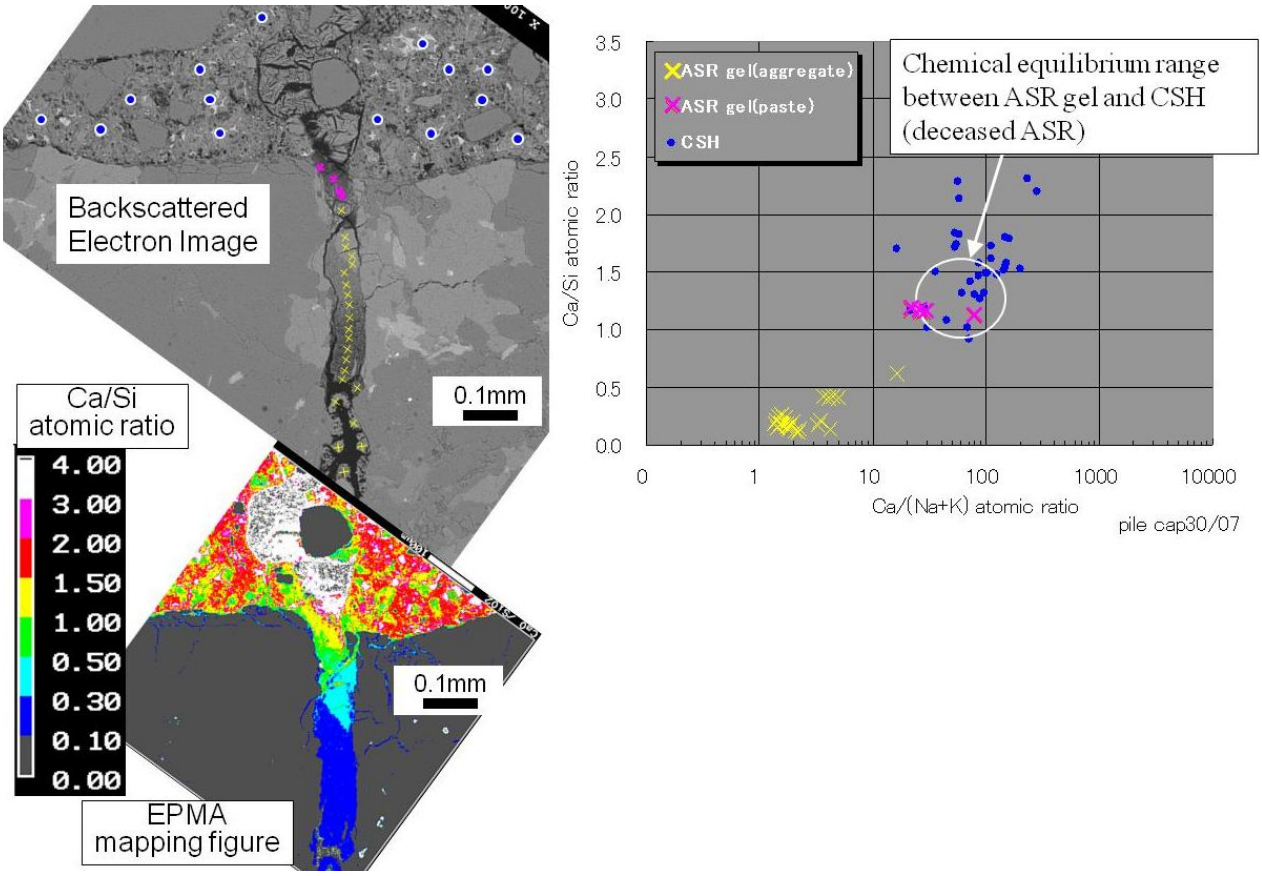

Fig. 10 Chemical composition of filling materials of crack and cement paste by electron probe micro analysis, EPMA

Table 4 Chemical composition of cement paste part

Sample	Compositions(mass%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2
1	22.0	4.9	3.0	61.5	1.3	2.9	0.5	0.6	0.2
2	21.5	4.9	3.0	61.2	1.3	3.5	0.7	0.6	0.2
OPC	21.3	5.1	2.9	64.2	1.5	2.0	0.3	0.5	0.3

OPC: Japanese ordinary portland cement

5.3 Possibility of opal formation in granite

In Fig. 11, a cut surface of the degraded concrete is shown. There are typical textures of ASR gel surrounding reactive aggregate. Surrounding parts of white granite particles look like wet by darker color than other parts. This darker part is formed by ASR gel bleeding from core aggregate. The cracks in the granite are filled with typical ASR gel as shown in Fig. 12.

There is an interesting texture in other places. One place in grain boundaries, doubted materials as opal and allophane (hydrated aluminosilicate) are observed as shown in Fig. 13. In granite, as a colored mineral, mica is generally contained. This mica is thought to be altered to form these minerals. “Alter” or “alteration” relates diagenesis and are technical terms in geology meaning the change of rock forming minerals by some action relating water such as hydrothermal activity, weathering and so on. This reaction can be expected common in hot and humid climate like Southeast Asia. The relationship between annual rainfall and change of clay minerals are shown in Fig. 14. Having more rain, aluminosilicate releases silica and alumina rich minerals are remained. This means silica will move and there is a possibility to deposit as amorphous silica such as opal. Simultaneously there may be a possibility of deposition of amorphous silica from ground water. Therefore, it is important to remind the existence of opal in any aggregate in Southeast Asian countries. Opal is an amorphous material and is impossible to be detected by X-ray diffraction. The only way to detect is the observation of thin section by polarized optical microscope. Once remembered the existence of this phenomena, it will be possible to detect this possibility during ASR diagnosis. Typical example of alkali reactive minerals and bearing rock types detected in this study are summarized in Table 5.

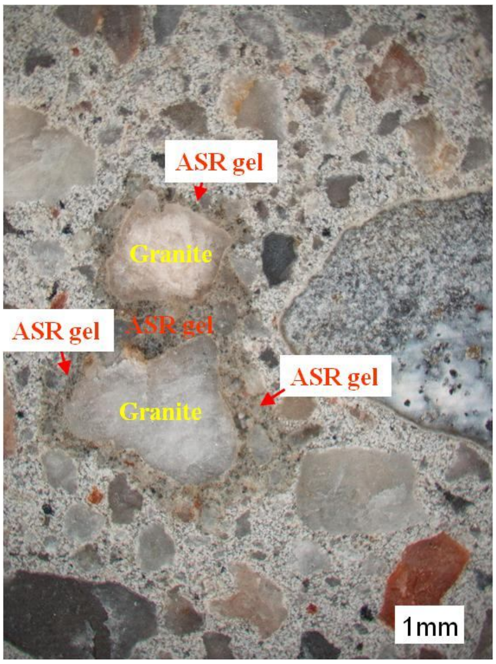

Fig. 11 Cross section of concrete showing ASR gel bleeding from granite particles

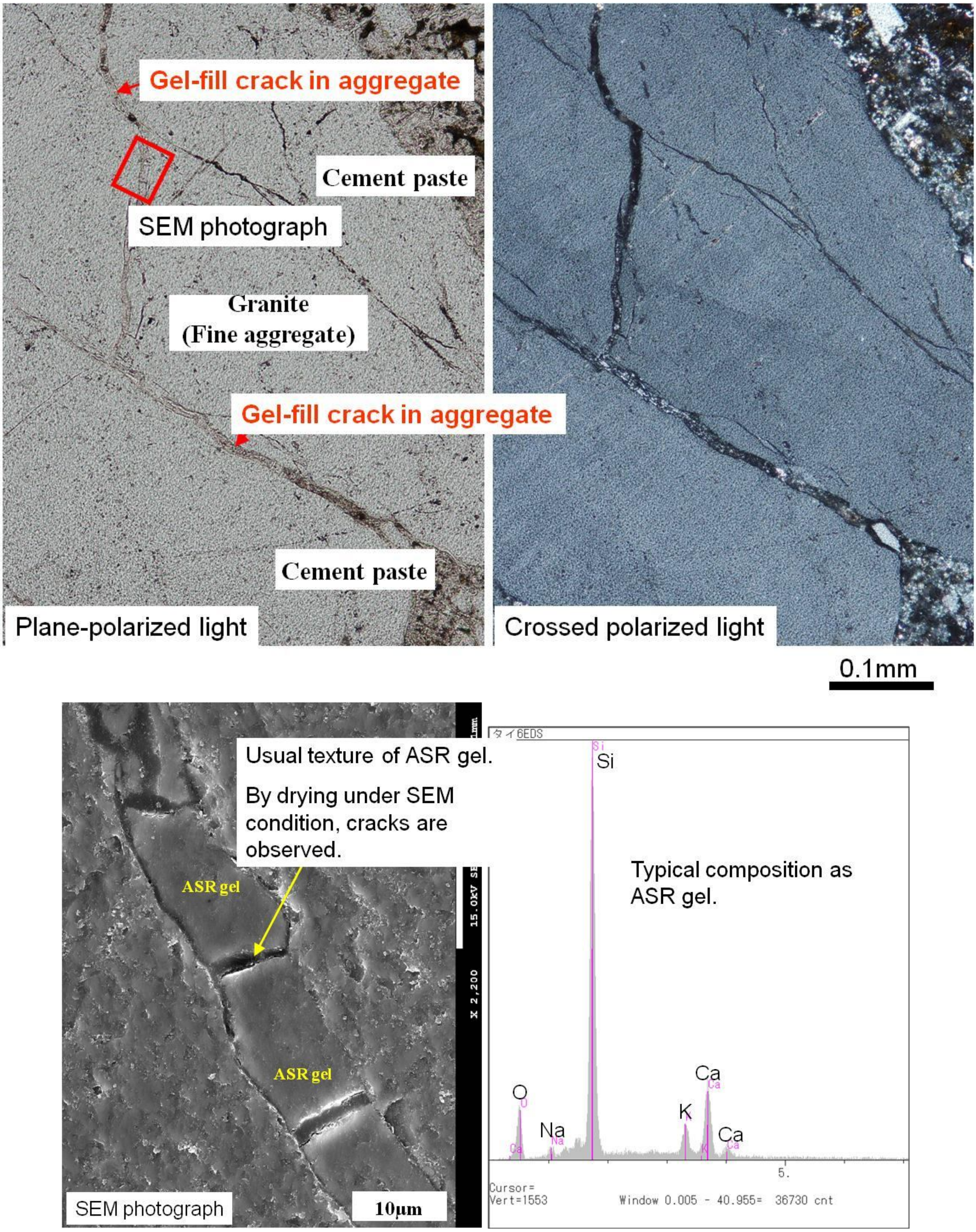

Fig. 12 Polarizing optical microscope photos of cracks in granite particle filled with ASR gel and the analysis by SEM/EDS

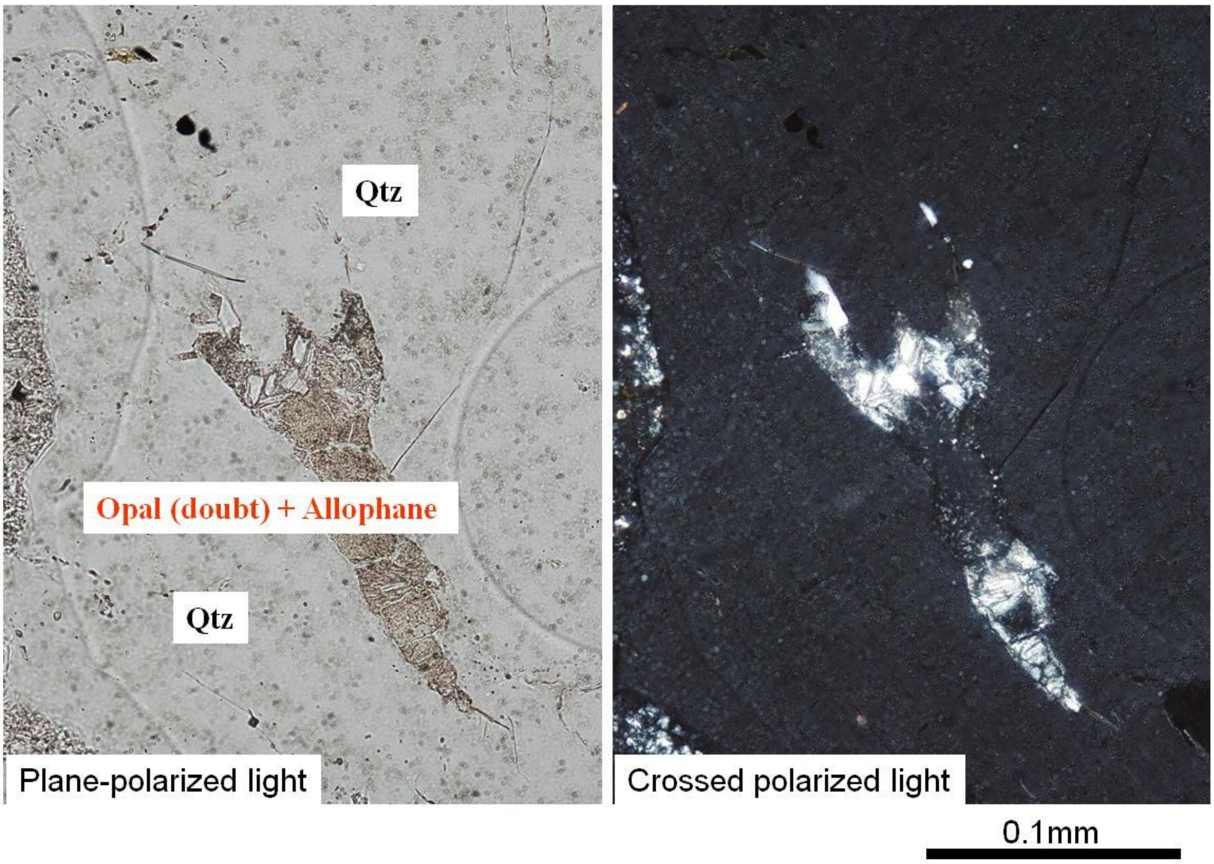

Fig. 13 Alteration products found in granite

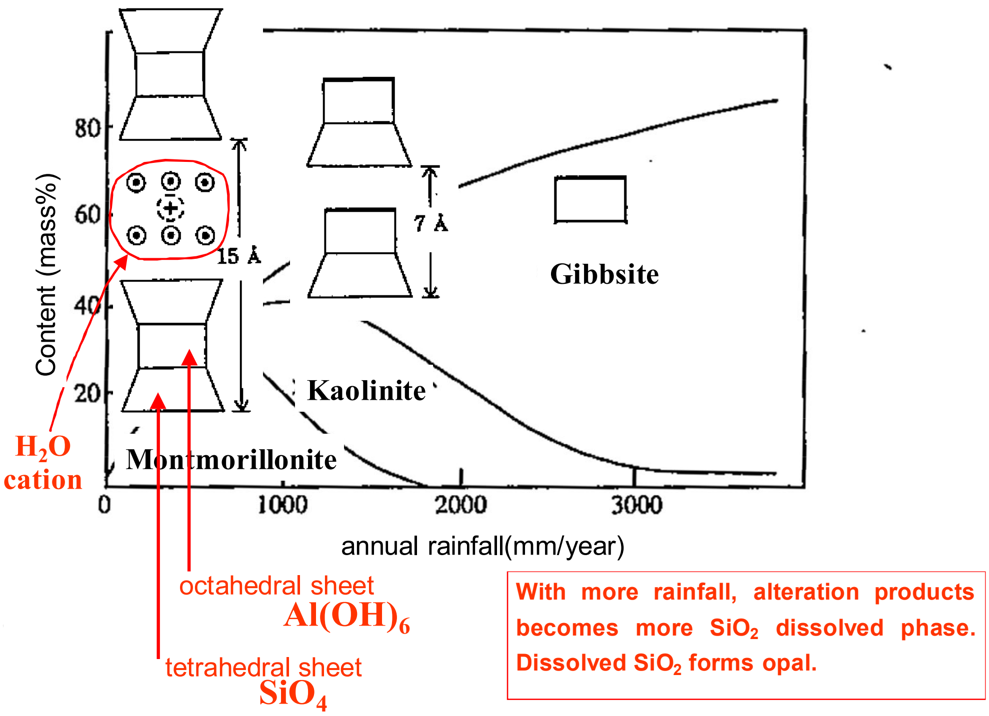

Fig. 14 Relationship between annual rainfall and clay mineral composition changes

Table 5 Alkali reactive minerals and bearing rock types.

Reactive mineral	Rock type
Cryptocrystalline quartz	Siliceous limestone
	Metamorphosed sand stone or greywacke
Opaline silica	Alternated granite
	Opal veins deposited from ground water in various rock types, which may be important in high temperature and humid climate.

6. Summary

In order to present useful information to establish local standard for mitigating ASR damages, the history and present state of Japanese testing methods of alkali reactivity of aggregates and countermeasures for suppressing ASR are explained. The major aggregates causing ASR in Japan are highly reactive andesite and chert. Therefore, old chemical method and mortar bar test have been used as test methods and total alkali limit of 3.0 kg/m^3 has been used as a major countermeasure. However, obviously there is a limitation and reconstruction is now under discussion although the activity is limited in a technical committee of the Japan Concrete Institute (JCI).

For the new countermeasures, it is essential to know the mechanism of deterioration. As an example, an ASR damaged concrete structure in Bangkok was explained from petrographic analysis. Microcrystalline quartz in granite mylonite was the major mineral of expansion. Furthermore, from the viewpoint of geology, the existence and possible damage by opal formed by alteration characteristic in hot and humid weather in Southeastern Asia are pointed out.

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