ASR FOUND IN THAILAND AND TROPICAL REGIONS OF SOUTHEAST ASIA

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Abstract

A case of ASR in Thailand was analyzed. It resulted from microcrystalline quartz in granite mylonites as coarse aggregate. Although ettringite formation was accompanied in existing cracks, the mechanism of expansion was attributed to ASR judged from the texture of expansive phases in the concrete. Another important reactive mineral was identified. Fine aggregate consisted of sand-sized granite which was free of microcrystalline quartz from secondary deformation such as mylonitization. Some micas in the granite have altered into allophane and/or opal, which could be products of weathering in hot and humid climates. Similar cases were also identified in neighboring countries, where granite that has altered to bare opal was used as crushed stone. This caused numerous pop-outs on the concrete surface. These opals are common to all tropical regions, including Southeast Asia, and various weathered rocks in tropical regions could contain potentially ASR reactive aggregates.

Keywords: alkali-silica reaction, opal, petrographic examination, weathering, granite mylonite

1 INTRODUCTION

In Thailand serious deterioration appeared in concrete of an expressway built with Japan's ODA. A research institute in Thailand had a view that it was due to both of ASR and DEF [1]. On the other hand, some researchers in Japan were commissioned to conduct an investigation into the cause of the deterioration. They performed a field survey and obtained some concrete core samples. This study was a part of the above investigation [2] using core samples and expected to clarify the cause of the deterioration. This paper describes details of petrographic examination.

2 STRUCTURES

The deteriorated expressway runs from Bangkok to Chonburi, and is 55 km long (Figure 1). It was partly opened in March, 1998, and whole line in February, 2000. The deteriorated structures comprised almost half of the viaduct piers. Cracks were found in pile caps (footings) and a number of x-shaped PC piers (Figure 2). Some footings, less than 10% of the damaged ones, had notable dense cracks involving over 3 mm width openings. Cracks had been detected since 2004 and epoxy resin was used to filled cracks in some footings. However, cracks, including those already epoxy-filled continuously expanded, resulting in re-deterioration [1].

In Thailand, expressway footings were not sealed against water such as by using epoxy resin. Furthermore, some footings were submerged during rainfall due to lack of back-filling (Figure 2-A). Therefore, footings were constantly in humid conditions. On the other hand, cracks in piers were considerably slight (Figure 2-C, D). Superstructures consisted of precast members made of different type of aggregate and were not deteriorated.

In this study, eight core samples of four sets, which were taken from footings and piers respectively in four structures were investigated.

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3 SAMPLES

The investigated structures in this study were constructed in 1998. Inspection of the concrete structures was primarily visual. Based on the visual examination, deterioration of concrete structures was classified into four levels according to appearance of crack widths and density [1]. Samples in this study were comprised of concrete cores taken from structures with each level of damage. However, without regard to this classification, deterioration of piers was generally minor.

Table 1 shows the relationship between sample names and the deterioration level (of footings).

4 METHODS FOR ANALYSIS

4.1 Petrographic examination under a polarizing microscope

Polished thin sections (15-20 μm-thick) were prepared from core samples, and observed under a polarizing microscope. Rock types of coarse and fine aggregate were analyzed. Concrete textures were observed to assess the occurrence and development of ASR and others. The degrees of ASR were classified according to Katayama et al. (2008) [3] as showed in Table 2. ASR has been confirmed to develop in order from 1 up to 4. Generally, this corresponds with appearance of structures in field.

4.2 SEM observation

Fine-grained products that were not well identified under a polarizing microscope were analyzed in a scanning electron microscope, SEM (JEOL JSM-7001F) equipped with energy dispersive spectrometer, EDS (Oxford INCA Penta FET x3). Operating conditions were set at 15 kV and 20 nA, at high vacuum (~10^{-5} Torr).

5 RESULTS

5.1 Petrographic examination under a polarizing microscope

Before the polarizing microscopy, cut surfaces of concrete cores were observed with the naked eye and a stereoscopic microscope. Coarse aggregate was crushed stone with maximum size of around 20mm, and fine aggregate was natural sand. In concrete taken from much damaged footings, some particles of coarse aggregate were cracked or exuded ASR gel or had reaction rim (Figure 3-A). Meanwhile, fine aggregate did not show remarkable signs of ASR, while some particles were observed to exude ASR gel/sol, which looked wet (Figure 3-B).

Tables 3 and 4 show results of polarizing microscopy of polished thin sections prepared from core samples. In the tables, rock types and ASR degree of each rock types and ASR degree of whole core sample are indicated. Coarse aggregate consisted of granite mylonite in certain core samples, while limestone or pelitic hornfels were abundant in the others. Among these rock types, granite mylonite was in more advanced ASR stage than others. This completely accorded with the damage levels from the visual examination of concrete structures. Figure 4 represents the texture of ASR in granite mylonite and limestone observed under polarizing microscope. ASR gel in granite mylonite produced large gel-filled cracks that extended into cement paste, while gel-filled cracks were minor and only inside of the aggregate particle in limestone. All these rocks contained as a reactive mineral microcrystalline quartz which was formed by mylonitization through fault movement in granite mylonite, and resulted from impurities such as mud in limestone. The texture of granite mylonite is shown in Figure 5. Stretched microcrystalline quartz is abundant.

Fine aggregates in all samples were common and consisted of natural sand originating from granite. There were slight signs of ASR gel surrounding the sand, which was free of secondary deformations such as mylonitization or cataclastic deformation. In Figure 3-B, surrounding parts of white granite particles appear wet, with a darker color than other parts. ASR gel/sol bleeding from core aggregate is present in this darker part. Under a polarizing microscope, these granite particles had minute veins, which were possible cracks (Figure 6-A). Amorphous or low crystallized materials that might be altered mica were also frequently found, and supposed to be or contain allophane or opal (Figure 6-B). ASR with fine aggregate was much less than with coarse aggregate, and differences among samples did not accord with the damage levels of field structures. Therefore, fine aggregate was not believed to be related to damages in field. However, granitic rocks without microcrystalline quartz are generally assumed to be non-reactive, especially in Japan, such a case has not been reported. Thus, SEM observation was conducted for identification of minute ASR products as described below.

In Footings A-D (all footings), significant ettringite formation was found in air voids and aggregate-cement paste boundary, etc (Figure 7). It had frequently much formed even inside ASR-caused cracks in cement paste as replacement from ASR gel (Figure 7-B), especially in Footing A and Footing B, in which more advanced ASR was identified.

Portland cement had been used because the cement paste did not contain any supplementary cementing materials such as fly ash, blast furnace slag or others.

5.2 SEM observation

ASR of granite mylonite

Granite mylonite, which comprises coarse aggregate, was assumed to cause ASR with remarkable damages. SEM observation was conducted to confirm the reaction site inside the aggregate and ASR gel-filled cracks that had expanded into the cement paste.

Figure 8-A shows a close-up of an ASR gel-filled crack formed inside granite mylonite. Along with ASR gel, microcrystalline quartz was present in the shape of corrosion. This means that this was a site where the reactive mineral has dissolved to form ASR gel, which has subsequently turned into rosette-like crystals.

In cement paste, most cracks concerned with ASR were presently filled with ettringite. However, the wall of the crack was partly covered with thin surviving ASR gel film, and ettringite was found to grow inside the wall, suggesting ettringite formation after ASR and replacing ASR gel (Figure 8-B).

ASR of granite

Granite particles of fine aggregate, with ASR gel/sol exudation or minute veins or amorphous to low crystallized materials possibly of altered mica as mentioned above, were analyzed by SEM-EDS. Figure 9-A shows a close-up by back scattered electron image, BEI and composition of the minute vein. Its morphology and composition represented amorphous ASR gel and suggested that most “veins” were cracks filled with ASR gel. Moreover, possible altered mica was frequently accompanied with secondary crystallized products (rosette) from ASR gel, as shown in Figure 9-B, secondary electron image, SEI and composition. Thus, it was confirmed that ASR had occurred in fine aggregate that consisted of non-deformed granite, and suggested that this ASR was attributable to altered mica.

6 DISCUSSION

6.1 Cause of deterioration

Coarse aggregate in Footings A and B consisted of granite mylonite, on the other hand, Footings C and D contained much limestone or/and pelitic hornfels. ASR gel-filled cracks that were the cause but also evidence of expansion and deterioration were confirmed to develop abundantly with granite mylonite, which corresponded to the deterioration that appeared in field structures. Granite mylonite was identified under a polarizing microscope as a reactive rock bearing much microcrystalline quartz, which is a typical late-expansive ASR-causing mineral. Therefore, it was assumed that ASR in granite mylonite dominantly contributed to the deterioration of structures.

Meanwhile, relatively rapid deterioration due to late-expansive mineral means the promotion of ASR. This suggests a more severe environment in hot and humid climate than in Japan regarding ASR, as mentioned in a previous study [3]. In addition, footings were always in humid condition due to lack of waterproofing and back filling as mentioned above. This, combined with tropical climate, also promoted ASR. Consistent waterproofing and back-filling are considered to be effective as immediate measures.

6.2 Ettringite and DEF

In all footing samples, much ettringite was found inside all sorts of voids in cement paste such as air voids, cracks, and aggregate-cement paste interfaces, etc. Especially in Footings A and B, which underwent advanced ASR, much ettringite was present even inside cracks that had surely been caused by ASR. This is because many continuous cracks which occurred inside the aggregate and expanded into the cement paste were filled with ASR gel in aggregate, but with ettringite in cement paste (Figure 7-B). This meant that the more severe ASR damage, the more ettringite was found along cracks. Ettringite formed in existing voids is considered not to cause deterioration, since expansion by delayed ettringite formation, DEF is supposed to be due to ettringite formation in C-S-H [4]. Indeed, much ettringite was observed even in the footing sample without damage in this study. Therefore, there is no evidence to suggest that ettringite was related to the deterioration. Aggregate-cement paste interfaces were sometimes gapped and filled with ettringite. These gaps were attributable to simple crossing of ASR-caused cracks or concentration of expansion stress, and later filled with ettringite.

6.3 ASR and reactive mineral in granitic rocks

Fine aggregate, which consisted of sand-sized granite, was confirmed to increase ASR, too. This ASR was so minor that it was considered to give little damage to structures. Granitic rocks without microcrystalline quartz are generally assumed to be non-reactive, although it has been reported that weathered granitic rocks caused ASR because of secondary opaline infilling in the cracks [5].

Meanwhile, within this study, ASR products in granitic fine aggregate were found along with amorphous or low crystallized substance possibly from altered mica. The identity of these substances is considered to be allophane and opal. Similar unreported cases have been also found in neighboring countries in Southeast Asia, where numerous pop-outs were produced on the surface of the concrete structures. In these cases, crushed granitic coarse aggregate had been used. Polarizing microscopy revealed that some granite particles were somewhat altered to bear aggregations of opal (Figure 10-A), which formed ASR gel-filled wide cracks that expanded into cement paste (Figure 10-B). Therefore, genesis of opal in this study is discussed as below.

Generally, it refers to hydrothermal alteration including silicification, that significantly alters rocks to bare opal. In these cases, intensive alteration such as leaching or silicification is often observed throughout the rock. But petrology of the granite in this study does not correspond with this. Thus, weathering under the tropical climate in Thailand and its vicinity is discussed. Both mica and clay minerals have basic fabrics of tetrahedral sheets composed of bidimensionally consecutive SiO_2 and octahedral sheets of similarly bidimensionally consecutive $Al(OH)_6$ (Figure 11). As regarding granite in Japan, weathering products from mica that consists of 2:1 tetrahedral sheets and octahedral sheets are observed chiefly as smectite or chlorite, which are also 2:1 type. Meanwhile, in Thailand and its vicinity, more kaolinite of 1:1 or gibbsite without tetrahedral sheets are thought to have been produced, due to the influence of hot and humid climate or water quality. As a result, the released tetrahedral sheets can help form depositions of silica minerals such as opal and so on. Generally, mineral combinations after weathering are related to the environment, especially from climatic effects. It is known that the more rainfall, the more silica is released, and alumina rich minerals dominate (Figure 12) [6]. High temperature also accelerates weathering itself. This means that silica will be removed and then deposited in another part of the rock as silica minerals such as opal. This is the supposed process of opal formation in granitic rocks, although further detailed analysis about altered mica is required for the case of Thailand. It is important to keep in mind the existence of opal in any aggregate throughout tropical regions including Southeast Asia. Therefore, weathered rocks in tropical regions contain potentially ASR reactive aggregates.

7 CONCLUSIONS

- From relationships between ASR degree in each rock type and damage levels of concrete structures, it was assumed that ASR in granite mylonite dominantly contributed to the deterioration of structures.
- In all footing samples, much ettringite was found. Samples with advanced ASR bore more, because it had grown inside cracks caused by ASR. Therefore, there is no evidence to suggest that ettringite formation contributed to the deterioration.
- Minor ASR was found along with amorphous or low crystallized products from altered mica in granitic fine aggregate. This is attributed to weathering under hot and humid climate. Therefore, weathered rocks in tropical regions contain potentially ASR reactive aggregates.
- Occurrence of ASR in tropical regions was considered to be characteristic as a relatively rapid reaction due to late-expansive minerals and weathering that might produce opal.

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8 REFERENCES

[1] Lalita, B, Warangkana, S, Pongsak, C, and Somnuk, T (2012): Diagnosis of a combined alkali silica reaction and delayed ettringite formation. Thammasat International Journal of Science and Technology (17): 22-35.

[2] Hirono, S, Aodo, Y, Yamada, K, and Torii, K (2014): ASR identified in the expressway in Thailand-example in the tropical region. Proceedings of the Japan Concrete Institute (36): 1084-1089.

[3] Katayama, T, Oshiro, T, Sarai, Y, Zaha, K, and Yamato, T (2008): Late-expansive ASR due to imported sand and local aggregates in Okinawa Island, southwestern Japan. Proceedings of the 13th International Conference on Alkali-Aggregate Reaction in Concrete, Trondheim: 862-873.

[4] Thomas, M, Folliard, K, Drimalas, T, and Ramlochan, T (2008): Diagnosing delayed ettringite formation in concrete structures. Cement and Concrete Research (38): 841-847.

[5] Thaulow, N (1983): Alkali-silica reaction in the Itezhitezhi dam project, Zambia. Proceedings of the 6th International Conference on Alkali-Aggregate Reaction in Concrete: 471-477.

[6] Barshad, I (1966): The effect of a variation in precipitation on the nature of clay mineral formation in soils from acid and basic igneous rocks. Proceedings Inter. Clay Conf., Jerusalem (1): 167-173.

TABLE 1: Correspondence between sample names and deterioration levels based on [1].

Very severe (Many wide cracks)	Severe (Many cracks)	Moderate (Few cracks)	None (No cracks)
Footing A Pier A	Footing B Pier B	Footing C Pier C	Footing D Pier D

TABLE 2: Petrographic classifications of ASR stages based on [3].

Stages	Progress of ASR
1	Formation of reaction rims and/or exudation of ASR sol/gel around the reacted aggregate.
2	Formation of ASR gel-filled cracks within reacted aggregate.
3	Propagation of ASR gel-filled cracks from the reacted aggregate into surrounding cement paste.
4	Migration of ASR gel into air voids and formation of ASR gel-filled cracks network

TABLE 3: Result of polarizing microscopy (Footing A-D).

Sample (Visual inspection)	Footing A (Very severe)	Footing B (Severe)	Footing C (Moderate)	Footing D (None)
Coarse aggregate (ASR stage)	Granite mylonite (4)	Granite mylonite (3)	Granite mylonote (2), Pelitic hornfels (2), Limestone (2), Chert (2)	Limestone (2)
Fine aggregate (ASR stage)	Granite (2)	Granite (2)	Granite (2)	Granite (2)
ASR stage of total core	4	3	2	2
Remarks	Much ettringite	Much ettringite	Much ettringite	Much ettringite

TABLE 4: Result of polarizing microscopy (Pier A-D).

Sample	Pier A	Pier B	Pier C	Pier D
Coarse aggregate (ASR stage)	Pelitic hornfels (1-2), Limestone (1-2)	Granite mylonite (1-2)	Limestone (1)	Limestone (1) Pelitic hornfels (2)
Fine aggregate (ASR stage)	Granite (1-2)	Granite (1-2)	Granite (1-2)	Granite (1-2)
ASR stage of total core	1-2	1-2	1-2	2

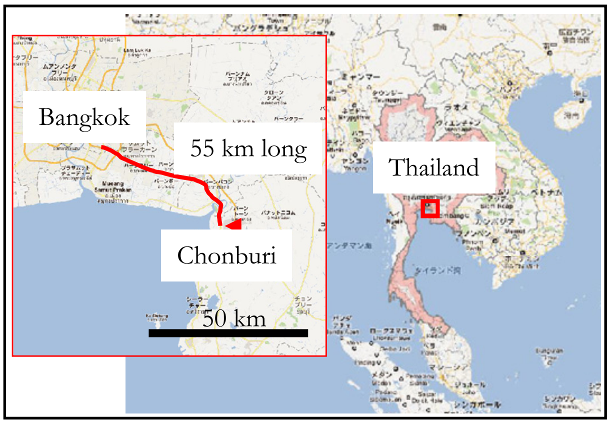

FIGURE 1: Location of investigated expressway.

FIGURE 2: Overview of ASR-deteriorated structures. A, B: Pile cap (footing). C, D: X-type PC pier.

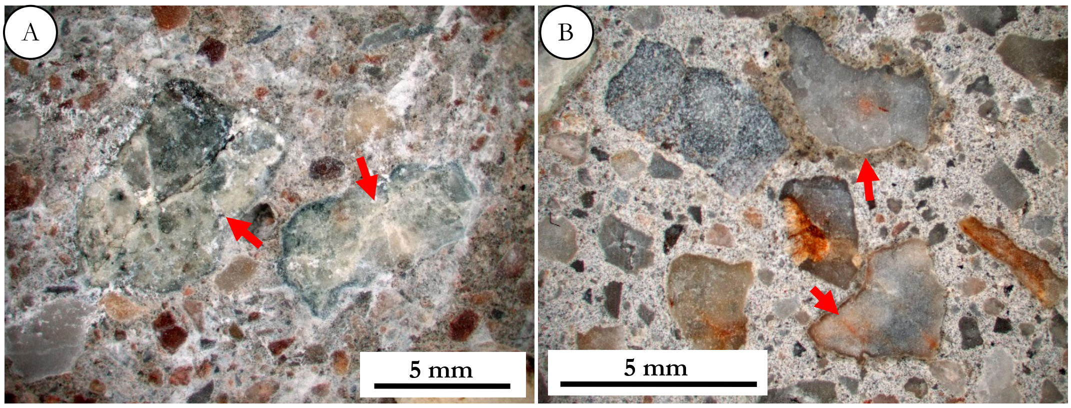

FIGURE 3: Cut surface of concrete. A: Coarse aggregate with crack, ASR gel exudation and reaction rim (Footing A). B: Fine aggregate with ASR gel exudation (Footing D).

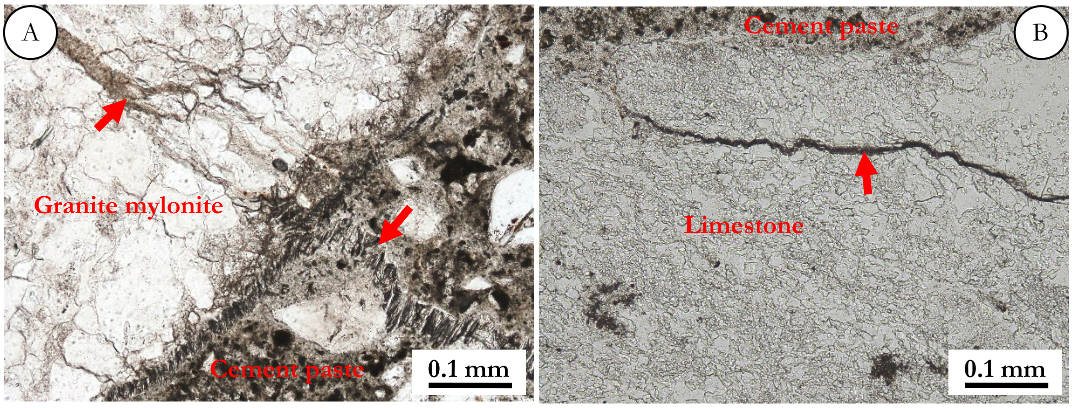

FIGURE 4: Texture of ASR damaged concrete under a polarizing microscope (plane polarized light).
A: Granite mylonite (Footing A). B: Limestone (Footing D).

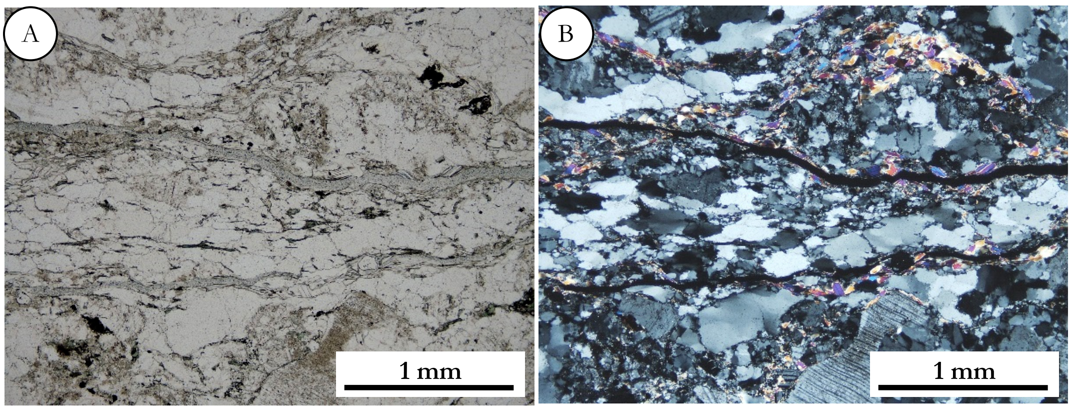

FIGURE 5: Texture of granite mylonite under a polarizing microscope.
A: Plane polarized light. B: Crossed polarized light.

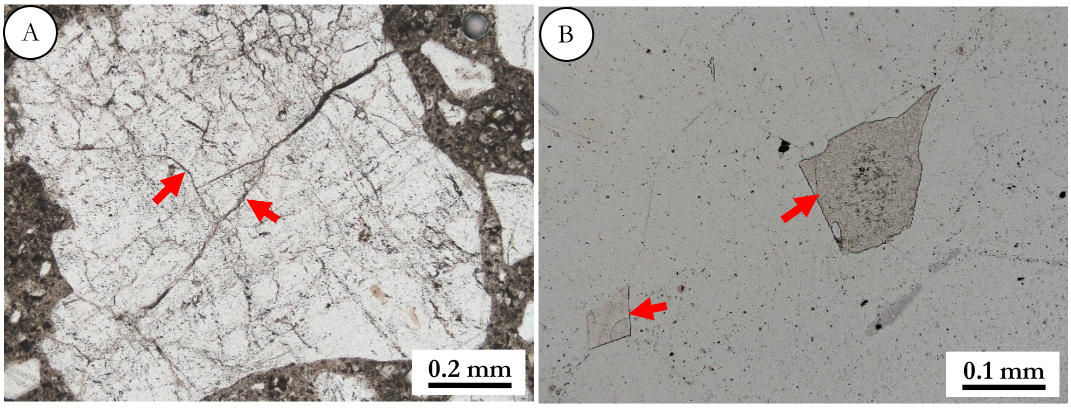

FIGURE 6: Granitic sand under a polarizing microscope (plane polarized light).
A: Minute veins (Footing A). B: Amorphous or low crystallized materials from altered mica (Footing D).

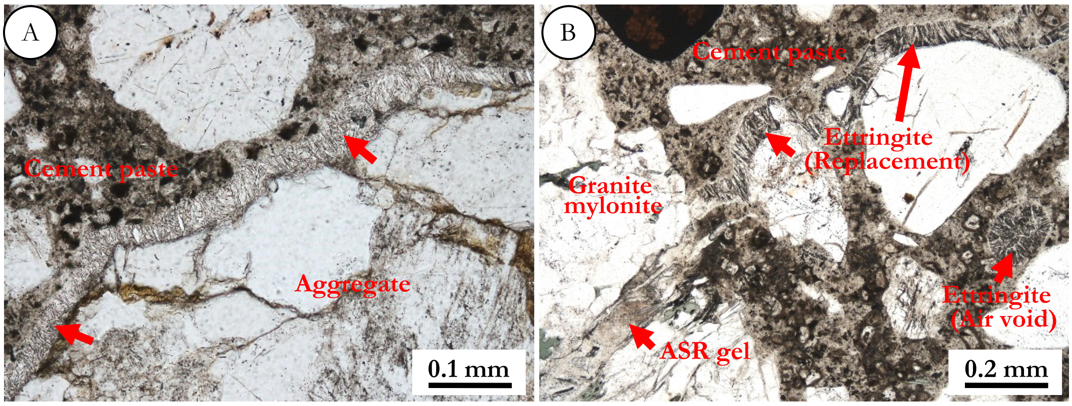

FIGURE 7: Occurrence of ettringite under a polarizing microscope (plane polarized light).
A: Aggregate-cement paste boundary (Footing A). B: Replacement from ASR gel (Footing A).

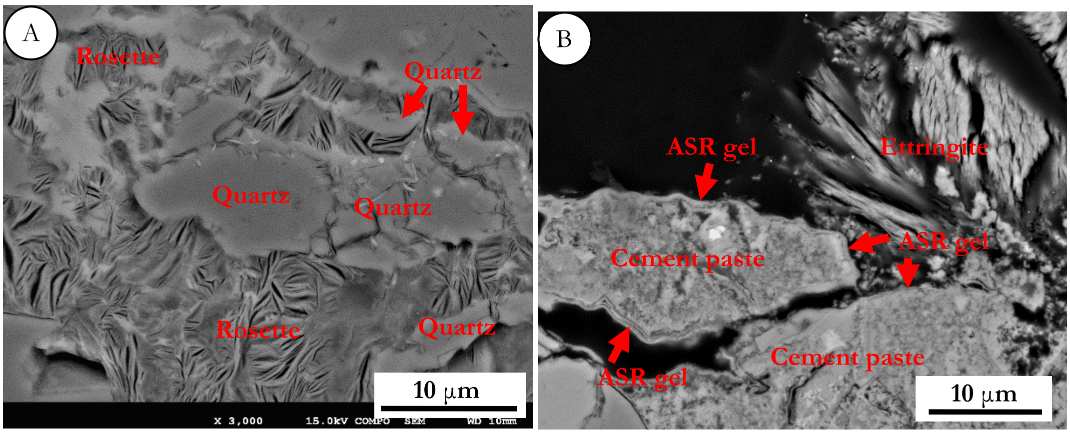

FIGURE 8: SEM photographs. A: ASR gel-filled crack inside granite mylonite (Footing A). B: ASR gel film directly on the crack wall and inner ettringite (Footing A).

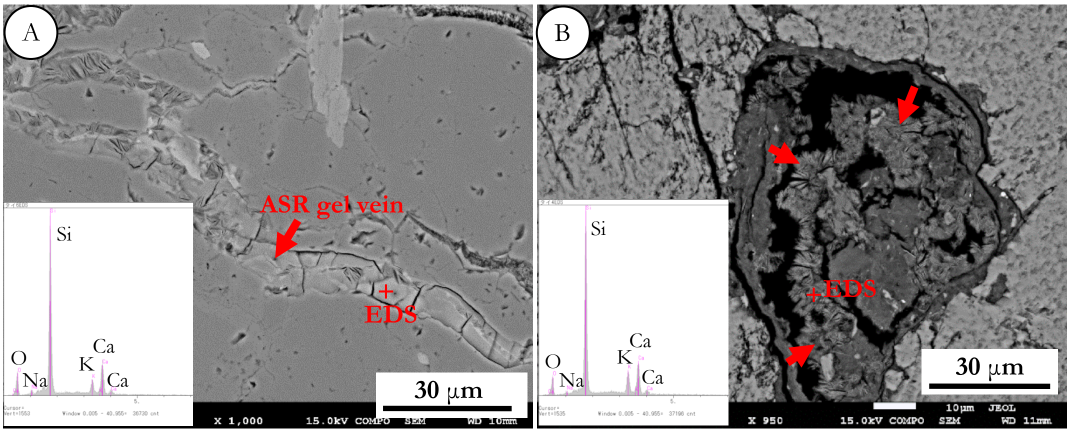

FIGURE 9: SEM-EDS of sand-sized granite.
A: Minute vein (Footing A). B: Rosette-like crystals with altered mica (Footing D).

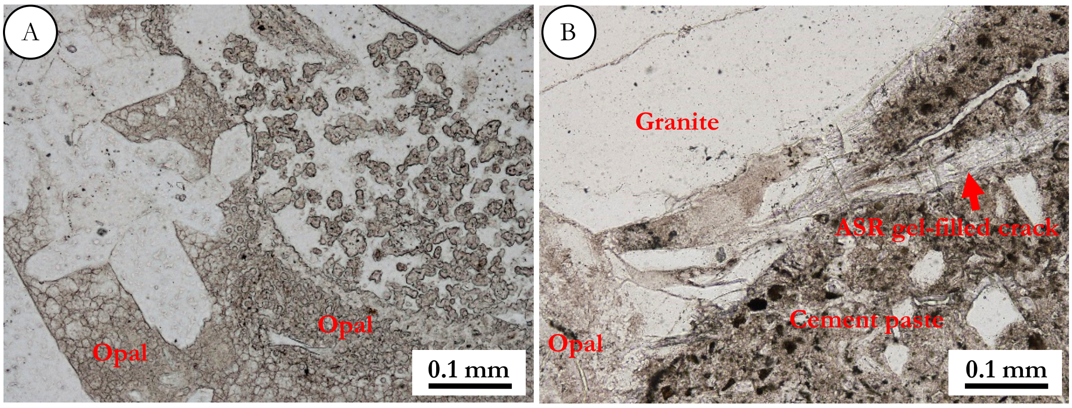

FIGURE 10: A similar ASR case in Southeast Asia under a polarizing microscope (plane polarized light).
A: Aggregation of opal in granite. B: ASR gel-filled crack from opal in granite into cement paste.

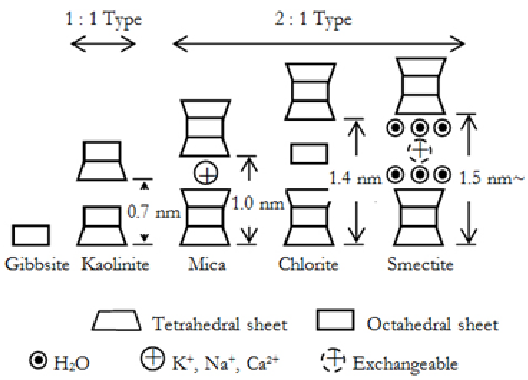

FIGURE 11: Phyllosilicates.

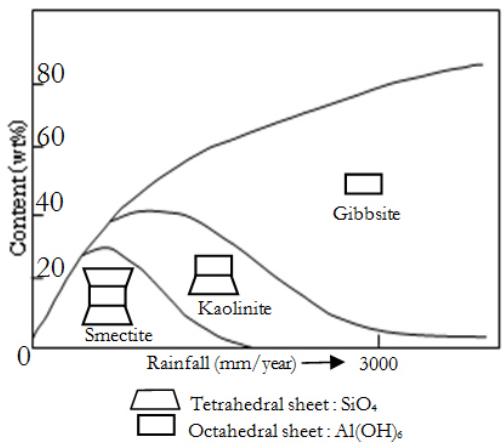

FIGURE 12: Relationships between rainfall and products in weathering [6].