

ASR AND DEF IN CONCRETE FOUNDATIONS IN THAILAND

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Abstract

Deleterious Alkali Silica Reaction (ASR) and Delayed Ettringite Formation (DEF) occur in concrete foundations from a major highway structure located in Thailand. ASR is caused by reaction from slow reactive sericite rock, quartzite and granite with and without cataclastic texture reported by the authors in a separate paper. SEM/EDX analyses from the same concretes presented in this paper give information on the appearance of reaction products and chemical composition compared with Norwegian reaction products and internationally. In the concretes DEF and ASR were observed. Examination of the sequential appearance of DEF and ASR shows that DEF appears first and is succeeded by ASR. It is suggested that DEF might have activated slow reactive aggregates to be alkali reactive and hereby “triggered” ASR. This because Thai cements have a very low alkali content and slow reactive aggregates normally require high alkali content to be alkali reactive and react in the concrete.

Keywords: Concrete, Alkali Silica Reaction (ASR), Delayed Ettringite Formation (DEF), Petrography, Scanning Electron Microscopy/Energy Dispersive X-ray Spectrometry (SEM/ EDX)

1 INTRODUCTION

The study of cracking in concrete foundations from a major about 50 km long infrastructure in the central part of Thailand (near Bangkok) confirms the first case of Alkali Silica Reaction (ASR) in Thailand. Short time after the construction period (1998) cracks were observed in the concrete foundations and repaired with epoxy. Later inspections revealed that repaired cracks still are expanding and new cracks formed. An initial condition assessment in 2005-reported extensive map cracking in about 20% of the surveyed foundations and that damage varied from none to severe [1]. A field inspection by the authors in 2013 revealed beginning map cracking and long vertical up to 0.5 mm wide cracks in some of the pillars in the box girder structure.

This investigation is part of an extensive research program where 10 concrete foundations have been cored [1, 2]. Petrographic analyses and micro structural analyses from two foundations have been presented in a separate paper by the authors [4] and confirm that deleterious ASR has damaged and cracked the concrete. ASR is caused by reaction from slow reactive aggregate as quartzite, sericite rock and granite with and without cataclastic texture. The signs of reaction are morphologically and similar to the ones observed by reaction from slow reactive aggregates reacted in Norway and elsewhere. An important observation from the petrographic analyses was simultaneous occurrence of DEF and ASR in the concretes. Study on other foundations performed by other research group also observed simultaneous delayed ettringite formation (DEF) and ASR. It was concluded that DEF and ASR are the two main causes of cracks in the foundations [3]. Simulation test of semi-adiabatic temperature rise in mass concrete showed temperature over 70°C suggesting the condition for DEF was present in the concrete [3].

In this paper SEM/EDX analyses of reaction products (alkali silica gel and cryptocrystalline reaction products) from reacted sericite rock, quartzite and granite are presented and compared with Norwegian reaction products. Petrographic examination of the sequential occurrence of DEF and ASR in thin sections is presented too. The paper discusses the possibility that high initial temperature (DEF) might have “triggered” slow reactive aggregates to react in the concretes because published chemical analyses of Thai cements have low alkali content with eq. Na₂O varying from 0.20 to 0.48 [4]. At present time when information on the cements not is available one have to presume that local Thai low alkali cements have been used for concreting and therefore not susceptible for ASR of slow reactive aggregates [8]. In literature some few published papers suggest that high initial temperature can “activate” marginally and negligible reactive aggregates to react expansive [6].

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2 TEST MATERIALS AND METHODS

2.1 Test material

Two concrete cores: “Sample 30-XA” (Ø 75 mm and length 100 mm) and “sample 30-XB” (Ø 75 mm x 205 mm) taken from two different mass concrete foundations showing intense cracking in 2008/2009. The authors have presented micro structural analyses of the concretes and petrographic analyses of reacted aggregates from the same cores in a separate paper [4].

2.2 Methods

Micro structural analyses by use of polished fluorescence impregnated slabs (PS) and thin sections (TS) were examined under stereomicroscope and polarizing microscope mounted with UV- filters. Polished thin sections from each sample were examined by petrographic microscope in addition to Scanning Electron Microscopy combined with quantitative X-ray energy dispersive Spectrometry (SEM/EDX). Polish thin sections (PTS), concrete fragments and air void filling have been examined by use of a Scanning Electron Microscope LEO 1450 VP mounted with an Oxford Instrument model 7366 EDS. The samples were coated with carbon. Most EDX analyses have been carried out on polished thin sections (few also from air void and fragments). To avoid “migration” of sodium an acceleration voltage on 10 KV and use of “area analyses” was used. The aim with the EDX analyses is to confirm the presence of alkali silica reaction products not to give an accurate chemical composition of the products. Chemical compositions should be interpreted as “semi quantitative” because H₂O and CO₂ not are included and results are “normalized” to 100 % of detected elements. However, “relative” values of detected element are accurate enough to be compared with other published analyses e.g. the Norwegian as done in the paper. Before SEM/EDX analyses the two polished thin sections were examined by polarizing microscope and target areas were marked up.

3 RESULTS

3.1 Microstructural analysis (thin section)

Signs of reaction were observed in coarse crushed aggregates of sericite rock, quartzite and granite with cataclastic texture. Two types of ASR reaction products occur, namely crypto crystalline reaction products (brownish in thin section and “salt and pepper” texture in polarizing light) in reacted aggregates and amorphous gel (sometimes laminated and recrystallized) in peripheral micro cracks in the contact zone cement paste- aggregate (some inter granular), and fewer in micro cracks in the cement paste. In some sericite rock gel filled micro cracks are observed near the contact zone to the cement paste. In reacted aggregates cryptocrystalline reaction products in cracks are succeeded by amorphous gel in the contact zone to the cement paste as normally observed in slow reactive aggregates.

Significant amount of fibre, needles and fan formed agglomerates of ettringite is precipitated in micro cracks in the cement paste and more or less filling air voids. Peripheral micro cracks surrounding coarser aggregates are more or less filled with ettringite. Ettringite is mostly oriented perpendicular to the length of cracks or radiating from a “center” located at the edges of cracks and air voids. In larger cracks and air voids ettringite consist of inter grown fibrous agglomerates given a more “massive” appearance. Length of ettringite crystals are max 0.1 mm. Figure 1 shows the appearances of cracks and ettringite in PS and TS.

Micro structural examination of the sequential appearance of DEF (peripheral micro cracks) and ASR (reaction products) shows that peripheral micro cracks are developed before ASR because 1) alkali gel have “flowed” out from reacted aggregates into existing peripheral cracks and 2) alkali gel filled cracks in the cement paste cross-cut ettringite filled cracks. Figure 2 show the sequence of DEF and ASR in thin sections.

3.2 SEM and EDX Analyses

Reaction products

The composition of gel and cryptocrystalline reaction products in reacted sericite rock, quartzite and granite is given in Table 1 to 4. Table 5 gives the composition of curettages from an air void and Table 6 gel in the interface sericite rock and cement paste. Table 7 gives the composition of the cement paste (survey). Note that the chemical composition, given as oxides, have been “normalised” to 100 % of detected elements and without water (H₂O). This because gel is hygroscopic and able to take up varying amounts of water during the sampling preparation and loose water during the vacuum drying for SEM/EDX. Cryptocrystalline reaction products consist of plate formed crystals mostly arranged as globulare–and rosette formed agglomerates. Cryptocrystalline reaction products also occur in the centre of gel filled inter granular crack in some reacted sericite rock near the contact zone to the cement paste suggesting crystallization from gel phase (precursor gel) [5]. Figure 3 and 4 show ASR reaction products in SEM/EDX and Figure 5 show a plot of Thai reaction products compared with Norwegian reaction products.

Cement paste

Area analyses (0.3 mm x 0, 2 mm) in cement paste without signs of “deterioration” by EDX are shown in Table 7. Note that sodium is not detected and potassium average is 0.38%. Sulphur is not detected.

4 SUMMARY AND DISCUSSION

4.1 Structural damage and cracking

Damage and cracking in the massive bridge foundations were observed rather short time after construction. Local concrete practice without additional cooling of the concrete, a warm and humid climate and the massive concrete structure suggest possibility of high internal temperature in the concrete and DEF. Micro structural analyses show occurrence of ASR and peripheral micro cracks surrounding aggregates (gab grading) suggesting occurrence of DEF which can occur in concretes with temperature higher than 60-70°C. Peripheral cracks are more significant in sample 30-XA and less or absent in sample 30-XB. The mesh like cracking pattern observed in foundations might be caused by DEF or ASR or a combination of both mechanisms. The “large” and “long” up to 9 mm wide cracks observed in the foundations is likely caused by temperature variations in the foundations. Temperature modelling on foundations from same superstructure suggests the internal temperature to be higher than 70°C whereas DEF might be possible [3].

4.2 Cement

The Thai cements have low alkali content with eq. Na_2O varying from 0.20 to 0.48 [4]. At present time when information on the cements not is available one have to presume that local Thai low alkali cements have been used for concreting and therefore not susceptible for ASR of slow reactive aggregates [8]. The “survey” EDX analyses in Table 7 also suggest use of low alkali cement in the concrete. According to literature, low alkali cement should not be susceptible causing ASR for slow reactive aggregates [8].

Several of the Thai cements contain total SO_3 higher than 2.5% and $\text{SO}_3/\text{Al}_2\text{O}_3$ higher than 0.5 and might therefore be sensible for DEF [7]. The “survey” EDX analyses in Table 7 do not detect sulphur. It is possible sulphur originally occurring in the cement paste has re-precipitated due to DEF and is now located in cracks and air voids forming ettringite.

4.3 ASR reaction products

Cryptocrystalline reaction products occur in distinct amounts in reacted sericite rock and quartzite. Amorphous gel occurs mostly in cracks in the interface aggregate-cement paste and less in the cement paste. In sericite rock amorphous gel also occur in inter-granular cracks near and along the interface to the cement paste. Cryptocrystalline reaction products occur in reacted granite-gneiss but amorphous gel only occurs insignificantly at the interface granite-cement paste.

Reaction products from these concrete foundations are of same morphological type as reported in international literature from “slow reactive aggregates”, namely cryptocrystalline reaction products composed by plate formed crystals assembled in rosette- and globular formed agglomerates and amorphous gel [5]. Cryptocrystalline reaction products in cracks in reacted aggregates are succeeded by amorphous gel at the interface aggregate-cement paste as normally observed in slow reactive aggregates. In some sericite rocks cryptocrystalline reaction products occur in the centre of gel filled crack (near the interface to the cement paste) suggesting crystallization from the alkali gel. In literature it is hypothesised that cryptocrystalline reaction products observed in reacted slow reactive aggregates are re-crystallized gel (“precursor gel”) [5, 9] which looks to be the case here too. The composition of reaction products obtained by EDX analyses has been “normalised” to 100% because gel is hygroscopic and might take up varying amounts of water depending on the humidity in the concrete and preparation process. With high water content, the gel will transform into a sol and becomes liquid as seen in some humid concretes e.g. on cylinder faces of concretes cores with high content of gel in the concrete. In concrete, liquid gel (sol) sometimes can be observed as darker damp appearance and thin white precipitations on surfaces and by use of Uranyl Acetate test. In literature, the water content often is included in the compositions of gel but as mentioned the water content in gels will varies depending on the humidity of the concrete and procedures of the sample preparation. Moreover, sample preparation with water might leach certain elements and vacuum drying will influence the water content in the gel [10]. Therefore, absolute element composition of gel is uncertain and should be interpreted with care.

The chemical composition of Thai reaction products (normalized) is more or less the same as reported by international literature, but here large variations in compositions have been reported [5, 9, 11]. Compared to reaction products from Norwegian structures Thai reaction products are more siliceous and contain less alkalis and calcium as shown in Figure 5. Thai reaction products in reacted aggregates have not been in contact with the cement paste and therefore not enriched in calcium. On the other hand, reaction products from an air void and fragment (Table 4 and 5) have been in contact with the cement paste, and

contain a high amount of Calcium (not plotted in Figure 5). EDX analyses of reaction products from sericite rock, quartzite and granite (only 2 analyses) show that the potassium content in cryptocrystalline reaction products in sericite rock generally contain more Potassium compared to reaction products from quartzite and granite. This suggest that sericite rock (sericite contain potassium) might have contributed with other elements than silicium (here potassium) to the reaction products.

4.4 Ettringite and DEF

Peripheral micro cracks around aggregates (gap grading) and high content of secondary ettringite in micro cracks and air voids suggest internal sulphate attack due to delayed ettringite formation (DEF). Peripheral cracks and secondary ettringite are significant in sample 30-XA and less significant in sample 30-XB suggesting variation in type of damages between the foundations. Peripheral cracks are probably the most significant and important observation on the occurrence of DEF in hardened concrete. DEF has been reported to cause expansion and cracking in steam cured concretes (e.g. railways sleepers) and massive concrete structures where the internal temperature exceeds 70°C and exposure under humid conditions [12]. During the hydration process and high internal temperature ettringite is thermodynamically unstable and will decompose to mono sulphate releasing sulphur to the pore solution. Later under reduced temperature and humid environment sulphur will react and form secondary ettringite (delayed) imposing internal stress [7]. Two hypotheses about the expansive mechanism involved in the expansion have been published [13, 14, 15]. The first hypothesis suggests that late nucleation and growth of ettringite in cracks and in the transition zone between aggregate and cement paste cause sufficient crystallisation pressure to expand the concrete [16, 6]. The second hypothesis suggests that expansive pressure is developed within the cement paste resulting in paste expansion causing micro cracks (peripheral cracks) to occur at the interface between aggregate and cement paste. Secondary ettringite precipitated in newly formed cracks will not cause expansion [17, 18]. Observations in thin sections of investigated concretes show fibrous ettringite and fan formed agglomerates of ettringite oriented perpendicular to the length of cracks or radiating from a “center” at the edge of cracks and air voids. This support the hypothesis that ettringite is precipitated into empty spaces (cracks and air voids) without causing expansion (secondary ettringite).

Secondary ettringite precipitated in air voids and micro cracks occur often in undamaged concrete structures exposed in humid environments. Ettringite is here not related to either DEF or ASR but developed from re-crystallisation of dispersed phases in the cement paste due to high humidity in the concrete [5]. Secondary ettringite is therefore an important indicator for high moisture content in the concrete.

4.5 DEF and ASR

Simultaneous occurrences of DEF and ASR have been reported from laboratory tests and field structures but the expansive mechanism is often controversial and not well understood according to the literature. It is debated if DEF or ASR is the expansive mechanism and which mechanism was first [18]. Some authors claims that ASR is prerequisite and DEF only plays a contributory role in the overall expansion and DEF only can occur when the concrete contain potentially alkali reactive aggregates [19, 20]. The Finnish railway sleepers [12] which was one of the first published cases of DEF has been re-examined by optical microscopy and it is concluded the damages is caused by ASR, not DEF [21].

In sample 30-XA micro structural examination of the sequential appearance of DEF and ASR shows that peripheral micro cracks were developed before ASR because alkali gel have “flowed” out from reacted aggregates into existing peripheral cracks and alkali gel filled cracks in the cement paste cross-cut ettringite filled cracks. It is here likely that expansion first was caused by DEF and later succeeded by ASR. In sample 30-XB peripheral cracks are less significant and it is more uncertain DEF occurs in the concrete even the concrete contains significant amounts of secondary ettringite. Cracking and expansion are here caused by deleterious ASR. A previous petrographic examination on the same concrete foundations concluded also that the overall expanding was due to ASR and not DEF [2].

4.6 Can ASR be activated by DEF?

ASR caused by reaction from slow reactive aggregates is documented in both concrete samples. Normally in colder and temperate climate slow reactive aggregates first show visible cracking on concrete surfaces after about 20 years or more. In the Thai concrete foundations significant cracking appeared few years after concreting and deleterious ASR was documented by petrographic analysis 10 years after [1]. It cannot be excluded that a relatively high temperature in the foundations due to the warm and humid climate at the location has accelerated ASR to be faster compared to a colder temperate climate. However, the use of low alkali cement in the Thai concretes should have prevented ASR to occur. This because ASR by slow expanding aggregates as the ones used in the Thai concretes only is susceptible for ASR with use of high alkali cement [8]. The question can be asked if high initial temperature and DEF during concreting can

“activate” aggregates to be alkali reactive which under “normal” conditions will be innocuous. In literature it has been proposed that high initial temperature (steam curing) can “activate” marginally and negligible reactive aggregates to react expansive [6]. Laboratory test have also shown that aggregates obtain increased expansion in “DEF tests” suggesting that aggregates plays an important role in the expansion mechanism [22, 23, 24]. However, the subject is still debated and the mechanism “controversial” and not “agreed”. Generally, research is based on laboratory testing but recently focus is given on the problem in real concrete structures [24]. The analyses on the Thai concretes from real structures suggest that slow expanding aggregates can be activated to be alkali reactive due to a high initial temperature over 60-70°C.

5 CONCLUSION

Reaction products are morphologically and chemically similar to reaction products from slow reactive aggregates published in literature, but more siliceous. Reaction products from sericite rock have higher content of potassium compared to reaction products in quartzite and granite, which suggest sericite rock might contributes with potassium to ASR. Sequential analysis shows that DEF occur first and succeeds by ASR in sample 30-XA. ASR is the deleterious mechanism and DEF uncertain in sample 30-XB. Because of a presumed low alkali content in Thai cements it is suggested that slow reactive Thai aggregates have been activated to be alkali reactive due to a high initial temperature over 60-70°C. The investigation reveals that different crushed coarse reactive aggregates and damage mechanisms occur in the two investigated concrete foundations.

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TABLE 1: Composition of ASR gel in aggregates (samples 30-XA and 30-XB)

Aggregate/Comp.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
sericite rock	1.66	-	2.28	74.58	-	4.38	7.97	7.85	98.72
sericite rock	1.38	0.47	2.18	74.51	-	4.98	7.6	8.34	99.47
Average sericite	1.52	0.47	2.23	74.55	-	4.68	7.79	8.10	99.10
<i>St. dev</i>	0.20	0.00	0.07	0.05		0.42	0.26	0.35	0.53
quartzite	-	0.51	0.97	91.3	-	0.46	6.76	-	100
quartzite	-	0.51	0.91	92.17	-	0.52	5.89	-	100
quartzite	-	2.06	2.18	90.35	-	0.75	4.66	-	100
quartzite	-	-	1.24	98.76	-	-	5.5	-	100
quartzite	0.35	0.34	0.75	93.08	-	0.92	4.56	-	100
quartzite	-	0.38	0.75	93.32	-	0.66	4.89	-	100
quartzite	-	2.43	5.67	78.14	-	0.45	13.31	-	100
quartzite	-	-	0.95	93.58	-	1	4.47	-	100
quartzite	-	-	0.68	95.85	-	0.52	2.95	-	100
quartzite	-	-	-	96.59	-	0.5	2.9	-	100
Average quartzite	0.06	0.62	1.41	92.31	-	0.58	5.59	-	100.00
<i>St. dev.</i>	0.11	0.88	1.59	5.59		0.28	2.96		0.00

TABLE 2: Composition of cryptocrystalline reaction product in aggregates (30-XA and 30-XB)

Aggregate/Comp.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
Sericite rock	0.81	-	2.95	78.16	-	7.84	9.51	-	99.26
Sericite rock	0.8	-	3.37	78.65	-	7.26	9.45	-	99.53
Sericite rock	0.68	-	3.81	74.91	-	7.23	9.2	3.38	99.21
Sericite rock	0.54	-	4.17	74.92	-	7.51	8.94	3.05	99.13
Sericite rock	0.5	-	2.49	79.04	-	6.51	10.56	0.68	99.77
Sericite rock	-	-	2.47	78.71	-	6.63	10.92	0.71	99.45
Average sericite r.	0.56	-	3.21	77.40	-	7.16	9.76	1.30	99.39
<i>St. dev.</i>	0.30		0.70	1.94		0.51	0.79	1.52	0.24
quartzite	1.58	0.47	10.84	77.06	-	4.06	6	-	100
quartzite	2.36	0.67	1.81	81.64	-	5.78	7.74	-	100
quartzite	-	-	2.49	87.17	-	4.45	5.88	-	100
quartzite	-	-	2.22	84.25	-	5.02	8.52	-	100
quartzite	-	0.57	1.09	85.22	-	2.33	10.44	-	99.64
quartzite	-	-	1.47	81.77	-	6.32	8.8	-	98.35
Average quartzite	1.00	0.21	4.02	81.80		4.54	8.18	-	99.67
<i>St. dev.</i>	1.13	0.30	3.48	3.59		1.25	1.63		0.66
granite	1.44	-	4.69	79.26	-	4.74	9.87	-	100

Aggregate/Comp.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
granite	2.61	-	7.55	77.99	-	3.63	8.22	-	100
Average granite	2.03	-	6.12	78.63	-	4.19	9.05	-	100.00
<i>St. dev.</i>	<i>0.83</i>		<i>2.02</i>	<i>0.90</i>		<i>0.78</i>	<i>1.17</i>		<i>0.00</i>

TABLE 3: Composition of cryptocrystalline reaction products in fragment (sericite rock. 30-XA)

Composition	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
fragment	1.12	-		74.14	-	10.55	13.82	0.37	100
fragment	1.06	-	0.64	74.65	-	10.93	12.41	0.31	100
fragment	0.66	-	1.02	72.86	-	12.17	12.58	0.71	100
fragment	1.18	-	0.8	76.39	-	10.33	10.8	0.51	100
fragment	1.05	0.72	6.55	69.82	-	8.39	12.57	0.92	100
fragment	0.9	0.5	2.13	73.04	-	11.05	11.51	0.88	100
Average sericite rock	1.00	0.20	1.86	73.48		10.57	12.28	0.62	100.00
<i>St. dev.</i>	<i>0.19</i>	<i>0.32</i>	<i>2.40</i>	<i>2.20</i>		<i>1.24</i>	<i>1.03</i>	<i>0.26</i>	<i>0.00</i>

TABLE 4: Composition of gel in fragment (sericite rock) (sample 30-XA)

Composition	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
fragment	1.08	-	2.84	38.08	-	2.27	55.73	-	100
fragment	0.85	-	2.57	45.09	-	2.9	48.59	-	100
Average sericite rock	0.97	-	2.71	41.59	-	2.59	52.16	-	100
<i>St. dev.</i>	<i>0.16</i>		<i>0.19</i>	<i>4.96</i>		<i>0.45</i>	<i>5.05</i>		<i>0.00</i>

TABLE 5: Composition of cryptocrystalline reaction product in air void (sample 30-XA)

Composition	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
Air void	1.08	-	-	61.72	-	5.67	31.52	-	100
Air void	1.06	-	-	61.83	-	5.62	31.49	-	100
Air void	2.4	-	-	39.92	-	3.69	53.99	-	100
Average	1.51	-	-	54.49	-	4.99	39.00	-	100
<i>St. dev.</i>	<i>0.77</i>			<i>12.62</i>		<i>1.13</i>	<i>12.98</i>		<i>0.00</i>

TABLE 6: Composition of ASR gel in the interface to sericite rock (sample 30-XA)

Composition	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
interface to sericite	-	-	1.91	93.4	-	-	4.69	-	100
interface to sericite	-	1.33	1.96	91.98	-	-	4.74	-	100
interface to sericite	-	1.21	1.81	92.1	-	-	4.89	-	100
interface to sericite	-	-	2.1	92.4	-	-	5.5	-	100
interface to sericite	-	-	3.39	92.14	-	-	4.47	-	100
interface to sericite	-	1.25	3.12	91.15	-	-	4.49	-	100
interface to sericite	-	1.11	2.64	90.79	-	0.63	4.83	-	100
interface to sericite	-	1.03	2.81	90.99	-	0.79	4.38	-	100
Average to serite		0.74	2.47	91.87-		0.18	4.75-		100
<i>St. dev.</i>		<i>0.62</i>	<i>0.60</i>	<i>0.86</i>		<i>0.33</i>	<i>0.35</i>		<i>0</i>

TABLE 7: Composition of cement paste (sample 30-XB)

Location	NaO	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Total
Cement paste	-	5.47	9.47	59.2	-	0.62	19.26	5.59	99.6
Cement paste	-	5.76	8.7	62.42	-	-	18.31	4.47	99.66
Cement paste	-	5.7	8.89	61.46	-	0.53	18.34	4.47	99.38
Average	-	5.64	9.02	61.03	-	0.38	18.64	4.84	99.55
<i>St. dev.</i>		<i>0.15</i>	<i>0.40</i>	<i>1.65</i>		<i>0.34</i>	<i>0.54</i>	<i>0.65</i>	<i>0.15</i>

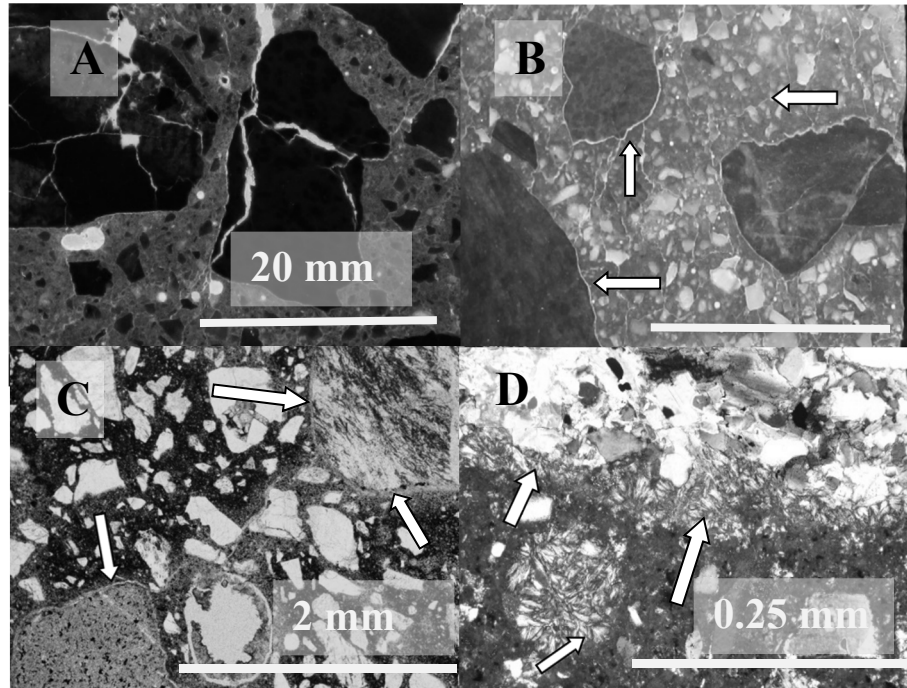


FIGURE 1: A: Cracks in aggregate (quartzite and granite) and cement paste (30-XB, fluorescence light PS). B: PS ordinary light. peripheral cracks (arrows) filled with ettringite (30-XA). C: thin section ordinary light. Ettringite in air void and in peripheral cracks on sericite aggregates (arrows). D: polarized light. Ettringite in air void and in peripheral cracks on granite aggregates (arrows) (30-XB).

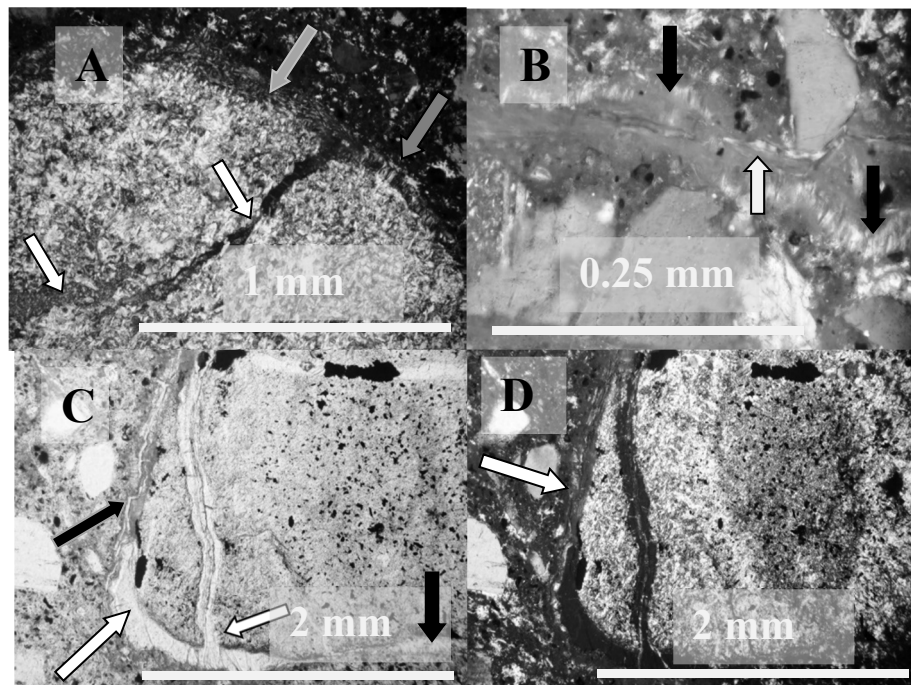


FIGURE 2: (Sample 30-XA) Sequence of DEF and ASR in thin sections: A: ordinary light: cryptocrystalline reaction product and alkali gel in reacted sericite rock (arrows) and peripheral cracks with ettringite (filled arrow). B: ordinary light: gel filled crack (arrow) in cement paste crosscutting crack with ettringite (filled arrows). C: ordinary light: alkali gel in reacted sericite rock and in peripheral crack (arrows) and ettringite in same peripheral crack (filled arrow). D: same as C in polarized light. Note amorphous gel (black) and ettringite in peripheral crack (arrow).

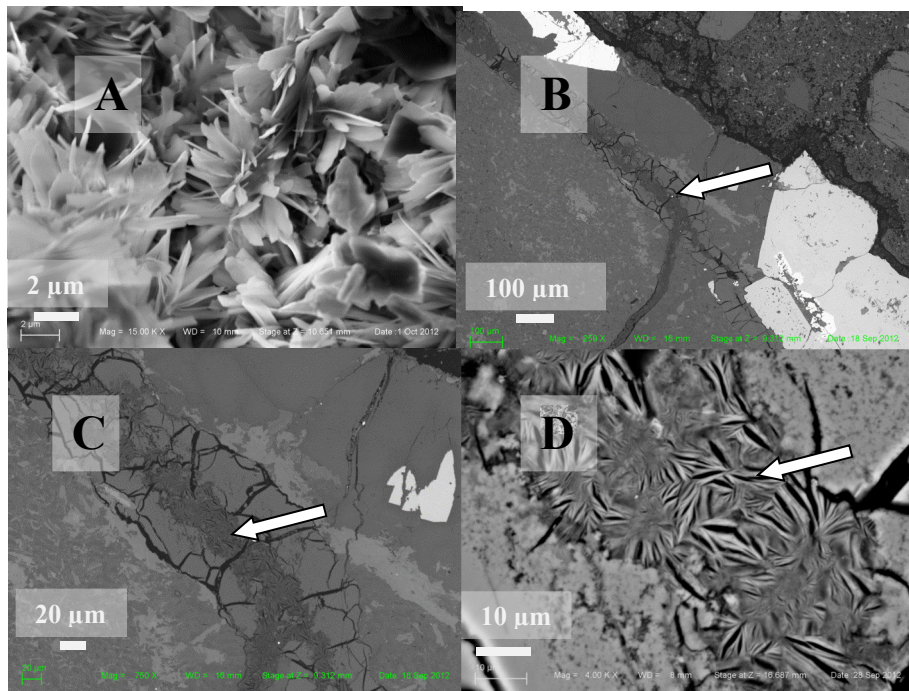


FIGURE 3: (Sample 30-XA) A: Rosettes of plate formed reaction products from fragment (secondary electron mode). B: Gel and cryptocrystalline reaction product in reacted sericite rock near the contact to the cement paste (arrow). C: Detail showing cryptocrystalline reaction product in the center of a crack with gel (arrow). D: Detail with higher magnification. Note globular agglomerates of cryptocrystalline reaction products (arrow). B, C and D in backscatter mode.

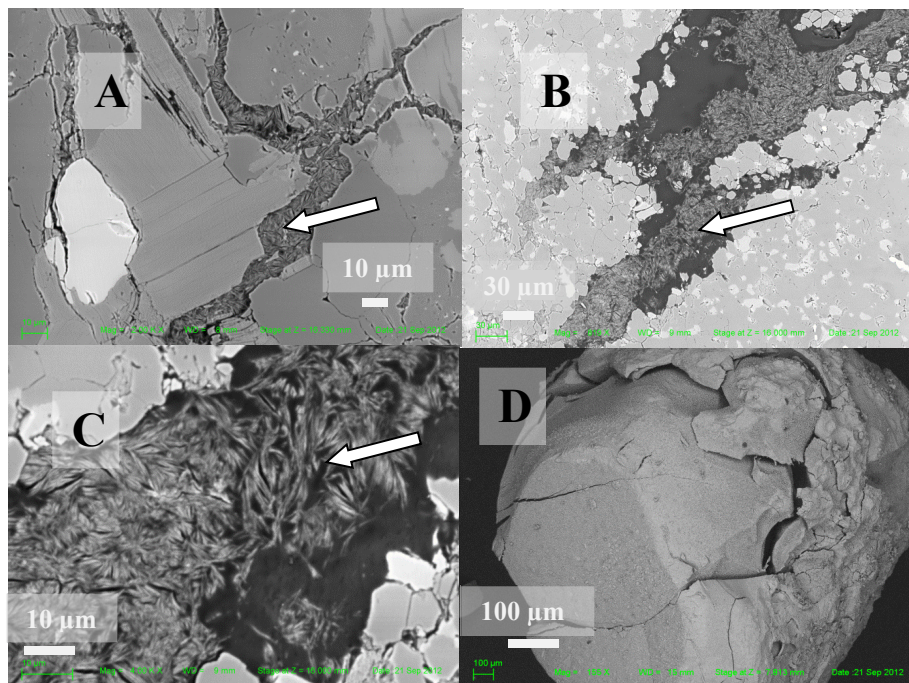


FIGURE 4: (Sample 30-XB) A: Cryptocrystalline reaction products in reacted granite (arrow). B: cryptocrystalline reaction products in reacted quartzite (arrow). C: globular cryptocrystalline reaction products in reacted quartzite (arrow) D: (sample 30-XA): Curettage of reaction products from air void.

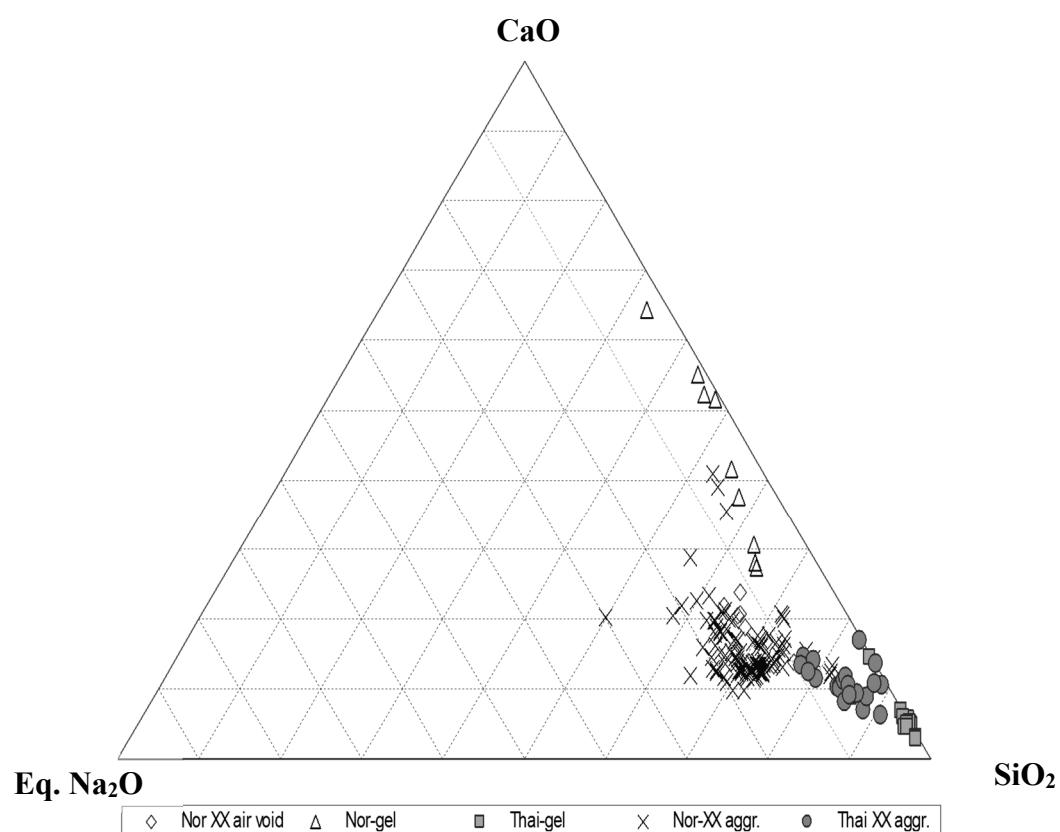


FIGURE 5: Composition of reaction products from Norwegian structures (Nor) and from mass concrete foundations in Thailand (Thai). Cryptocrystalline reaction products are marked XX and gel “gel”.