DIAGNOSIS OF ALKALI SILICA REACTION

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Abstract

The paper presents the authors many years' experiences diagnosing Alkali Silica Reaction (ASR) in concrete structures. Correct diagnosis of ASR from field investigation to laboratory testing is mandatory for correct diagnosis. Very important is the "investigators" qualification and experiences on ASR and use of correct test methods.

Micro structural analyses on fluorescence impregnated polished slabs and thin sections is probably the laboratory method, which gives most correct information on ASR and degree of damages. SEM/EDX gives additional information on reaction products and elemental distribution.

The paper gives information on "signs of ASR" in concrete structures and by laboratory methods, important for correct diagnosis. For assessing the degree of damage it is recommended to do quantification of cracks in the concretes, e.g. by the Norwegian method described in the paper. Thin section analyses of a feldspar rock (rhomb porphyry) from Norway and a sericite rock from Thailand, are shown to be alkali reactive and presented in the paper. These rock types are not formerly reported to be potentially alkali reactive in international literature.

Keywords: Concrete, Alkali Silica Reaction (ASR), Field-and Laboratory Testing, Microscopy, SEM/ EDX

1 INTRODUCTION

Correct diagnosis of the deterioration processes in the concrete structures is essential and decisive for assessment of "future" service life of the structure and eventually type of remedial measures to be planned. Diagnosis and appraisal of concrete structures affected by ASR often involve complex damages caused by a combination of more than one deterioration process such as ASR in combination with frost and/or sulphate attack. A reliable analysis to identify and determine the extent of the damage and to make prognosis of its effect on the structure therefore requires clear and thorough understanding of the mechanisms and the processes of damage. Like many other causes of damage in concrete, diagnosis and appraisal of ASR and other type of damage in concrete structures rely to a large extent on the judgement and the level of expertise of the personnel involved and very important the use of correct and suitable analyse methods valid for the existing structure and deterioration processes. First step to establish a correct diagnosis of the problem(s) should be based on several different inventory stages and analyses as shown in the Table 1.

2 UNDERSTAND THE ASR MECHANISM

Alkali Silica Reaction is a complex chemical-physical reaction between alkalis and alkali reactive aggregates in the concrete. The reaction forms a swelling gel (the chemical reaction), and following uptake of water, the gel exerts a pressure (the physical process) which can crack the concrete. For slow reactive aggregates research suggest that the expansive pressure first is caused by internal expansion of reacted aggregates due to crystallization pressure of reaction products between minerals/grains and then expansion of gel [1]. The reaction may lead to local volume expansion, cracking, loss of strength, and in extreme cases, to the complete "destruction" of the concrete.

Three major contemporary conditions have to be met before ASR can occur in concrete. Traditionally these conditions are designated to be; 1) reactive aggregates in sufficient amount, 2) adequate available alkalis and 3) water. If one of these major conditions are not obtained ASR cannot occur in concrete. Other parameters which influence or determine the occurrence and extent of ASR are temperature and time. High temperature is known to increase chemical reactions and influence the rate of ASR but because ASR is not only a chemical reaction, high temperature in the long run not always is the decisive parameter on the expansion rate of concrete [2]. For slow reactive aggregates low temperature and long time will often give a more damaging effect on the structure than for fast reactive aggregates. For a chemical-physical process such as ASR, time plays a determining role before ASR effects concretes and becomes visible. ASR has recently been reclassified to consist of very fast reactive, fast reactive and slow reactive AAR and a revised lists of alkali reactive constituents and aggregates on a worldwide basis is published [3]. Alkali Carbonate Reaction is today questioned to exist and might be ASR [4].

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3 STRUCTURES

Before a field inspection is carried out all information's and background material about the structure and the problems and history of damage should be analysed. Visual inspection of the structure is the method to give an overview of the problem. Important signs of ASR are map-cracking, longitudinal cracking, pop-outs and movement of structural elements caused by volume expansion and deformation of concrete members indicating that deleterious ASR is present, see Figure 1. Reduction or closing of expansion joints between structural elements indicates the occurrence of expanding ASR. It is important to know that other processes e.g. drying shrinkage, sulphate attack, can cause map cracking and even freeze thaw processes. Sometimes, exudation of ASR gel (which is water-soluble) can be observed on the surface of the concrete not exposed to water.

It is important to know that cracking due to ASR will be influenced by the reinforcement. Therefore, longitudinal cracks parallel with the principal reinforcement often can be observed on beams, plates and columns. ASR can extend steel reinforcement with consequence of reduced carrying capacity. In some cases, ASR occur in concretes without any sign of map cracking, expansions or deformation and can only be identified by laboratory examinations.

Registration of cracks and crack type(s), pop-outs, surface discoloration along cracks, efflorescence and precipitations, measurement of crack widths and sign of expansions, should always be carried out together with photo documentation and a written record. In cases gel has been precipitated gel can be verified by use of uranyl acetate testing.

3.1 Surface mapping of cracks

Registration and measurements of cracks due to ASR is probably the most important measure for assessing ASR damage in structures. Two principles for crack measurements are given in the following which can be used for survey investigation or assessment of individual structures.

Survey investigation

In both Norway and Switzerland survey investigation was important to get an overview of the ASR problem. It was important to use a field investigation system which is "objective", and where subjective assessments are limited. Furthermore, the system had to be efficient, fast and reliable. Fast because a high number of measurements increases the statistical reliability of investigated structures. The field investigation system used in both countries was developed in Norway and hereafter called the "Norwegian system" [1]. The most important measure is measurement of max. crack width caused by ASR in all structural elements; as well as an estimate of the extent of cracks (a subjective measure). Survey investigations according to the Norwegian field investigation system were carried out in Norway 1990-1996 [5] and Switzerland 2002-2006 [6], [7]. In Norway 689 structures randomly distributed in the whole Norway were investigated and the data processed into a database and classified according to the Norwegian classification system. Because of the high amount of structures it was performed several types of statistical analyses e.g. prediction of the future rate of crack expansions in Norwegian structures damaged by ASR [5] [12] see Figure 2. In Switzerland 450 structures were investigated in a similar way. The field investigations only indicate that ASR might have caused the damages in structures. Micro structural analysis should always be carried out to document the real causes of damage as done in numerous structures in both Norway and Switzerland. Experiences show that the interpretation of the typical damage patterns (map cracking) is usually correct according to ASR. The Norwegian system can and has also been used for assessment for ASR on individual structures.

Assessment on individual structures, surface cracking

Institutions of Structural Engineers (ISE) suggest crack summation for initial appraisal of ASR damage in structures [8]. A rough indication of the expansion in the structure is by measuring the widths of all cracks crossed by at least 5 straight lines with minimum length 1 meter and equal distance at least 250 mm. The lines should be perpendicular to the principal crack orientation on the most severe damaged concrete element. The expansion can be assumed to be equal the sum of the widths of the cracks divided by the length of the lines drawn on the concrete expresses as mm/m

A slightly different method compared with the ISE method is the French LCPC method [9], [10]. In Switzerland the crack index after the French LCPC method has been carried out on 103 structures and the expansion rate calculated [12]. The LCPC method has only been used on very few structures in Norway.

The crack development in a structural element is usually not homogeneous and influenced by different factors [11]. The crack measurements give not necessarily the real expansion rate of a structural element. The results are valid only if crack measurements are realised on the most exposed and cracked areas of the concrete surface. This kind of interpretation of the survey data represents only a general approach, giving some indications for a first rough evaluation of the significance of the damages. It cannot replace detailed measurements on a given structure.

3.2 Taking cores

To obtain information on ASR it is necessary to drill out cores from the structure and investigate the concrete under the microscope (micro structural analysis). A strategy for coring should be established depending on the size of the structure, the extent of damage and the client's requirement and economy. Cores should be taken in areas where cracking suspected caused by ASR occur e.g. map cracking, longitudinal cracks or surface exudations. It is recommended to drill out a minimum of two cores from each structure or structural element. The cores should be about Ø 100 mm diameter and longer than 100 mm (preferentially 200-300 mm). This because signs of ASR in many structures not is visible near the surface and for assessment of coarse aggregate particles and the cracks in the concrete [1]. Appropriate precautions should be taken during core sampling and subsequent sample preparation to ensure that evidence of ASR is retained.

4 LABORATORY INVESTIGATION – MICRO STRUCTURAL ANALYSIS

4.1 Introduction

It is strongly recommended to use microscopically techniques e.g. micro structural analyses for diagnosis of ASR. Micro structural analysis is visual examinations of cores, polished half cores (sawn along the length axes) and thin-sections (0.03 mm thin slice of concrete mounted on a 3 cm x 5 cm glass plate) [1]. It is advantageous to impregnate the concrete with epoxy containing fluorescent dye (e.g. Hudson Yellow) to highlight the micro cracks and porosity. For the examination of polished half cores (PS), a low power stereo microscope can be used. Examination with fluorescent light can be done using an UV-lamp. Thin sections (TS) shall be examined by use of a petrographic microscope mounted with polarizing filters and eventually UV- filter. Experienced personnel with petrographic experience and knowledge of ASR shall always carry out micro structural analyses.

Scanning Electron Microscopy (SEM) eventually mounted with an EDX analyser, WDX analyser or a Micro Probe Micro Analyser (EPMA) can further supply micro structural analysis. By these techniques, the composition and nature of reaction products can be verified together with other micro structural changes of the concrete. It is very important not to use scanning electron microscope investigation without other microscope techniques because of limitations of these techniques and that the investigation area only is few millimetres to few micro-meters which not necessarily are representative for the concrete in the structure. It should be noted that the occurrence of alkali-silica gel confirms the existence of ASR in the concrete; it does not necessarily mean that the reaction causes or has caused any damage to the concrete. This can be evaluated by studying the crack pattern in core materials from the structure as described in the following clauses. Unless involved with the site investigation and the selection of core drilling locations, a petrographer should be careful not to reach unqualified conclusions from the laboratory study of concrete.

4.2 Signs of ASR in cores

A first hand visual investigation of the core material gives valuable information on ASR. In case cores have been taken in cracks, cracks width and depth of cracks can be measured. On the concrete surface exudations and cracks is important. On the cylinder face cracks in aggregates and cement paste, dark rims on light coloured aggregates, damp appearance (and white precipitations) and white reaction products in air voids suggest ASR as well as white reaction rims in aggregates on broken faces [1], see Figure 3. In addition other features characteristic of the concrete should be registered e.g. carbonation, reinforce steel (if present), rust, aggregate type-size and other signs of damages if any.

4.3 Signs of ASR in polished half cores

Examination on polished half cores will give important information on ASR and reacted aggregates, which are cracking in aggregates, micro cracks in the cement paste and reaction products in cracks and air voids, see Figure 3. Examination on fluorescence-impregnated slabs in UV-light do it possible visually to observe micro cracks down to one micrometre and is a very important method for crack assessment. Micro cracks in aggregates is the first sign of ASR and in case cracks runs into the cement paste, the reaction is deleterious [1]. However, identification of reacted aggregates and reaction signs are more precise in thin sections.

4.4 Signs of ASR in thin section

Thin sections is probably the inventory methods, which give most information on ASR. The placement of thin section(s) should be in the remaining half core used for PS in areas showing signs of ASR e.g. cracked aggregates, micro cracks from aggregates running into the cement paste and occurrence of reaction products. Often more than one thin section are necessary to identify ASR, especially in case none or few signs of ASR can be identified. Thin sections should not be located in the concrete surface unless the surface is part of the investigation. This because signs of ASR often first occur deeper in the concrete often more than 100 mm from the surface. Important signs of ASR are micro cracks in aggregates, dissolutions areas in aggregates, cryptocrystalline reaction products in reacted aggregates (brownish in thin section and salt and pepper texture in polarised light) and amorphous gel in the interface to the cement paste and in the cement paste and air voids [1]. In case micro cracks from aggregates due to ASR runs into the cement paste, with or without reaction products, the reaction can be classified as deleterious [1], see Figure 4. Amorphous gel (sometimes laminated) occurring in micro cracks in the cement past and air voids are only indicative of ASR.

4.5 Reaction products in SEM/EDX

Scanning Electron Microscopy combined with quantitative X-ray Energy Dispersive Spectrometry (SEM/EDX) is an important method to obtain information on the morphological appearances and chemical composition of reaction products. Analyses are mostly carried out on vacuum dried carbon coated polish thin sections (PTS), concrete fragments or air void filling with use of backscatter techniques or secondary electron mode. To avoid "migration" of sodium a low acceleration voltage, low probe current and use of "area analyses" is recommended. Polished thin sections should first be examined by use of polarizing microscope and target areas marked up before SEM/EDX examination.

As mentioned, there exist to main types of reaction products, namely:

1) cryptocrystalline reaction products of plate formed crystals often in form of globular and rosette formed agglomerates occurring mostly in aggregates and in the centre of larger air voids and

2) none crystalline gel occurring mostly in the cement past and air voids [1], but exceptions has been reported, see Figure 5.

Cryptocrystalline reaction products are formed from gel (precursor gel) as suggested by some researcher [1], [3], as seen in Figure 5B. Gel imbibe moisture in varying amounts and might turn into a liquid phase called sol with high moisture content in the concrete. By vacuum drying for EDX analyses the gel will lose water but still contain about 10-20 % water. Absolute values of gel composition is therefore very uncertain and results should be normalised without water. SEM/EDX is also an important method for element mapping and analyses of the cement paste and aggregates.

4.6 Identifying reactive aggregates

The "signs of reaction" in aggregates indicate that the aggregates has reacted in the concrete. Signs are gel exudation, internal cracking, dissolution of constituents, reaction rims and cracks from aggregates running out in the cement paste with and without gel. Very important is the observation of cryptocrystalline reaction products in reacted aggregates and cracks from aggregates running out in the cement paste. In slow reactive aggregates it can be observed that cryptocrystalline reaction products transform into amorphous gel at the interface. Figure 4 A, B and C show typical signs of ASR reaction in a feldspar rocks (rhomb porphyry) from Norway suggesting feldspar to be alkali reactive. In thin sections the rock consist of fine-grained matrix with feldspar crystals and feldspar phenocryst up to 5 mm. Figure 4 D show typical signs of ASR in a sericite rock (or sericitic rock) from Thailand [13]. Both rock types are not formerly reported to be alkali reactive in literature [3]. Visual examination in cores, polished slabs and thin sections is the methods to identify reacted aggregates but thin section examination is probably the most accurate methods to observe ASR and to identify and classify aggregate types.

4.7 Simultaneously ASR and DEF

In some cases ASR occur simultaneous with DEF. Signs of DEF is difficult to identify correctly in concrete. However, the occurrence of peripheral cracks around aggregates suggest DEF. Ettringite is often abundant in cracks and air voids, but not always. In literature, it is discussed if ettringite causes the expansion or only is secondary precipitation. In many cases it cannot be decided which reaction (ASR or DEF) causes the expansion of the concrete or came first. However, in case gel has flowed out in existing peripheral cracks it can be presumed ASR succeeds DEF [14], see Figure 4D.

4.8 Assessment of damage

For assessment of damages in the concrete the crack pattern can be studied under the microscope on polished slabs of cores taken from the structures under investigation. To make a relationship between observations from the laboratory investigation and field investigation cores should be taken in areas where surface mapping has been carried out. Two methods for assessment of damages rate in cores are given in the following.

Damage rate index (DRI)

Damage in cores can be registered by examining polished cores under the microscope. A method called "damage rate index method" (DRI) is used around the world [15], [16]. DRI method register defects by use of a binocular microscope (16 x magnification) in a minimum area on 180 cm^2). Defects are coarse cracks, coarse particles with cracks and gel, de-bonded coarse particles, reaction zones, cracks in the cement paste, cracks and gels in the cement paste, air voids with gel and coarse particles with "wide" cracks. Each parameter are multiplied with a factor, normalised to 100 cm^2 and summarized.

Norwegian crack counting method

A simpler and faster method than the DRI method was developed during the first national alkali project in Norway [1]. This method uses fluorescence impregnated polished cores examined under UV-light where cracks and porosities are very visible, e.g. cracks as small as few micrometers can be observed without use of microscope. Thin section analysis for assessing possible ASR is recommended to be carried out first. Before the test, aggregate particles with cross sections > 4 mm visible on the plane section have to be counted and the area of the plane section in cm^2 to be measured. Three parameters examined under UV-light shall be registered and counted: 1) aggregates (with cross sections > 4 mm) with internal cracks, 2) aggregates (with cross sections > 4 mm) where cracks run into the cement paste (significant for ASR) and 3) number of cracks in the cement paste. Parameters for aggregates shall then be normalised to percent of aggregates with cross section > 4 mm and cracks in the cement paste to cracks/cm^2. Gel shall be registered too. Examples on use of the Norwegian crack counting method is given in Figure 6.

By conduction, the DRI method on concretes from various portions of investigated structure the variable extent of ASR damage is better characterized. The method has with success been used on several structures and has given important quantified information on the current condition of concretes affected by ASR [17] [18]. The DRI - method is rather time consuming and inaccurate due to the use of "undefined factors" and the Norwegain crack counting methods is preferred to be used [19].

4.9 Other test methods

ASR influences the mechanical parameters of concrete and sometimes significantly in case high expansions occur in the concrete or ASR is in an advanced stage. Compressive strength can be reduced up to 25% and tensile strength even more. The stiffness of the concrete (elastic modulus) is influenced significantly and can be reduced up to 50% depending on the expansions in the concrete [20].

Ultrasonic pulse velocity (UPV) technique can be used to assess the quality of the concrete damaged by ASR. The UPV depends on the presence of open cracks and absence of gel in cracks. Cracking caused by ASR will therefore reduce the UPV compared with uncracked concrete [21]. Impact echo test is another method for detecting cracks in ASR damaged concrete [21].

Rest expansion test on cores is a method which has been used for prediction of future expansion of the concrete. The method has widely been used in UK. However, lack of information on the correlation between core testing and expansion of the structure the core expansion result will be of limited value. The method is therefore not recommended for assessing future expanding due to ASR [22].

Important for ASR is determination of alkali content in the concrete. However, at present time reliable test methods for determination of the "available" alkali content in the concrete or from the cement do not exist.

5 LONG TIME MONITORING

For assessment of future damages and remaining service life on structures damaged by ASR two monitoring methods are recommended to be carried out over time, namely expansion/crack measurements and RH. Expansion and/or crack measurement measure the effect of deleterious ASR on the structure and gives information on the future damages. For assessment of ASR it is important to know that the concrete expand and cracks are "alive" and how much the increment will be by time. If cracks not expand or the concrete not expand it is possible ASR in one way or another has turned to be innocuous (dormant) but only few examples on that has been published internationally. However, only long time measurements over many years should be used for such assessment. Measurement of relative humidity (RH) in different locations and depths in the structure gives information on the variations of ASR in the concrete structure. Higher RH will over time give more damages to the concrete relative to lower RH. RH is not always uniform through the concrete and should therefore be measured in different places and depths to clarify the variables. Long time measurements of cracks/expansions and relative humidity are recommended methods for assessment of remaining service life, future damage and effects of rehabilitation on structures damaged by ASR. Long time measurements on ASR damaged structures in-situ are today only carried out on rather few structures seen in a worldwide perspective e.g. the Norwegian structures [23], [24], [25], [26]. Repeated measurements (over several years) of cracks width and surface cracking will also give an indication on the expansion rate over time.

6 CONCLUSION

Correct diagnosis of the damage process in concrete structures is essential for the assessment of present and future damages and appraisal of remedial measures. For structures damaged by ASR no easy method exists to obtain the correct diagnosis. Field inspection, crack registration and cores drilled out for micro structural analyses should always be carried out as a minimum. In some cases depending on the structure and the structural problem other supplementary tests as e.g. mechanical tests, Ultrasonic Pulse Velocity (UPV) technique or Impact Echo Test will improve the understanding of the problem.

Micro structural analysis is the only method to give the correct answer on ASR, reactive aggregates and damages caused by ASR. A feldspar rock (rhomb porphyry) from Norway and a sericite rock from Thailand, not formerly reported to be potentially alkali reactive in international literature, is presented to be alkali reactive in the paper. Micro structural analysis will also diagnose other deterioration processes e.g. sulphate attack, freeze-thaw and rate of damages in the concrete and much more. An experienced petrographer with knowledge of ASR should carry out the analysis. Micro structural analysis of concrete also named concrete petrography or concrete microscopy is described in several international publications and proceedings.

Long-time measurements of concrete/cracks expansion together with measurements of relative humidity in several locations will give an answer on the variations of present and future damages in the structure. Like many other causes of damage in concrete, diagnosis and appraisal of ASR and other type of damage in concrete structures rely to a large extent on the judgement and the level of expertise of the personnel involved and very important the use of correct and suitable analyse methods valid for the existing structure and deterioration process. It is the owner of the structures that have to take the decisions on which investigations and remedial measures to be carried out and to assess the risk for failure of the structure.

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TABLE 1: Inventory stages and analyses for assessment of ASR.

Stage	Investigation	Information and examples of type of testing
0	Survey Investigation	To obtain information on ASR on a regional or national scale
1	Inventory of existing records	Background information and history of damage
2	Field inspection of structure	Visual inspection, crack types, overview of the problem Measurement of max. crack width by Norwegian the system Measurement of cracks by ISE- or LCPT method Other tests when necessary Photo documentation and written record
3	Coring of samples	Use sufficient number of cores and core sizes Cores taken in most damaged areas and "less" damaged areas
4	Laboratory investigations	Very important to use relevant methods as: micro structural analysis: (visual examination of cores, optical microscopy on polished core slabs and thin sections (*fluorescence impregnated*) Crack counting, DRI or Norwegian method Electron microscopy when necessary Other tests? e.g. mechanical tests: (*compressive and tensile strength)*
5	Assessment of field and laboratory results	Results from field inspection and laboratory to give a correct diagnosis of the problem and variation on ASR intensity in the structure. Assessment of other or simultaneously damage processer
6	Monitoring program	Monitoring of cracks, expansions and relative humidity over long time for assessment of future damage
7	Assessment of service life and safety	Based on long time measurement and damage history

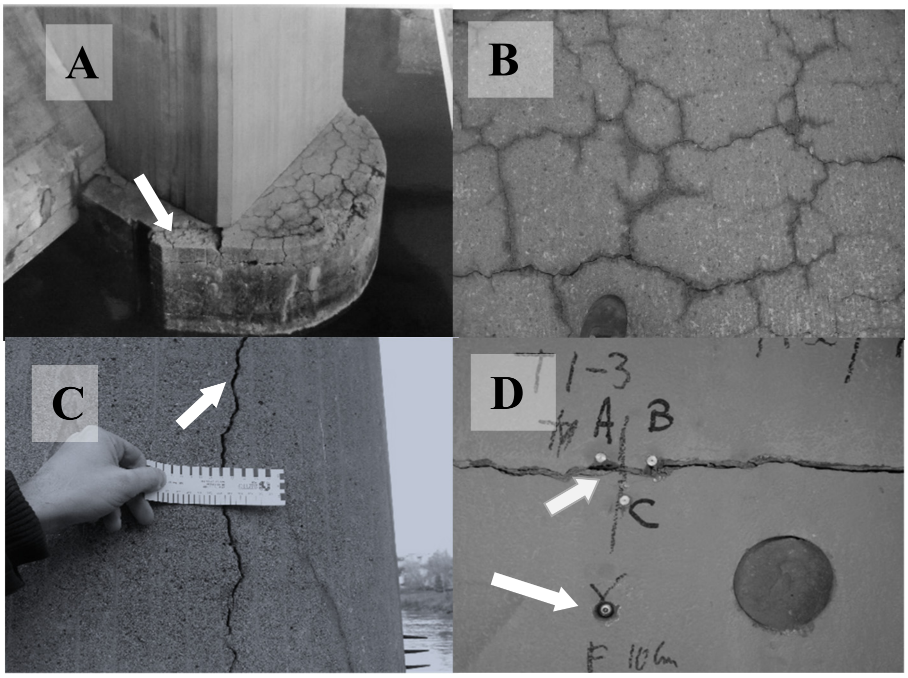

FIGURE 1: Norwegian structures. A: hydropower dam foundation heavily damaged by ASR. Note concrete fragments have broken of (arrow). B: map cracking in airfield pavement. C: longitudinal crack in bridge column (arrow) and crack width gauge. D: crack in a hydro power plant wall due to ASR mounted for tree point's measurement (upper arrow) and relative humidity 5 cm and 40 cm in the concrete (lower arrow) and the hole from core taking.

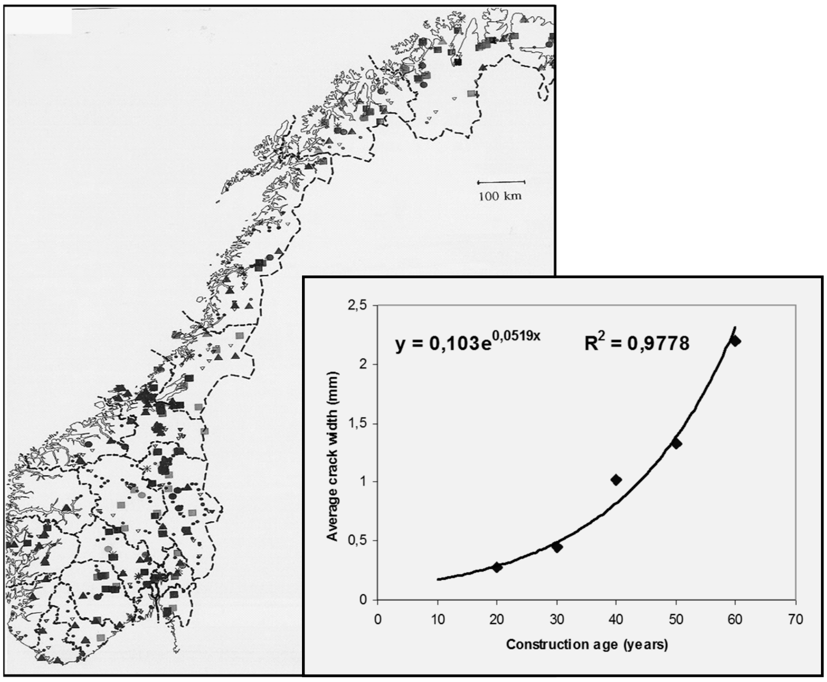

FIGURE 2: Geographical distribution of structures with signs of AAR in Norway (left). Grey points correspond to more detailed investigated structures by micro structural analysis. Right graph is average maximum crack width versus construction age in decades showing an exponential curve and equation of best fit (right) [12].

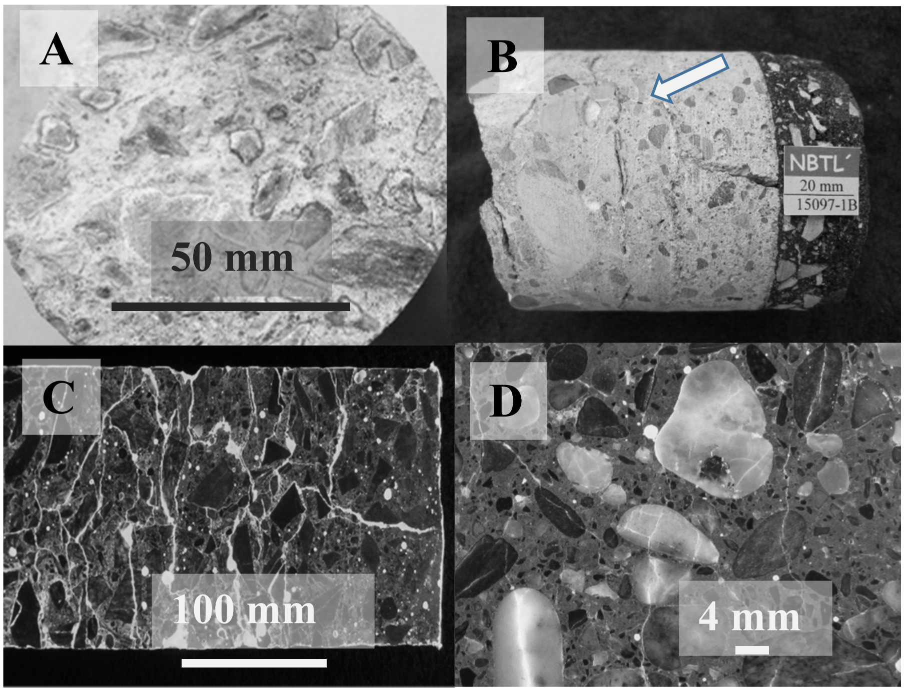

FIGURE 3: Norwegian structures. A: white reaction rims in aggregates on a broken face of a concrete. B: concrete core from a bridge pavement heavily cracked by ASR. Note that the bitumen cover has not prevented ASR. Arrow shows crack in a reacted aggregate. C: high intensity of surface parallel cracks in a bridge pavement (in fluorescence light). D: cracks in aggregates, cracks from aggregates running out in the cement paste and cracks in the cement paste (in fluorescence light).

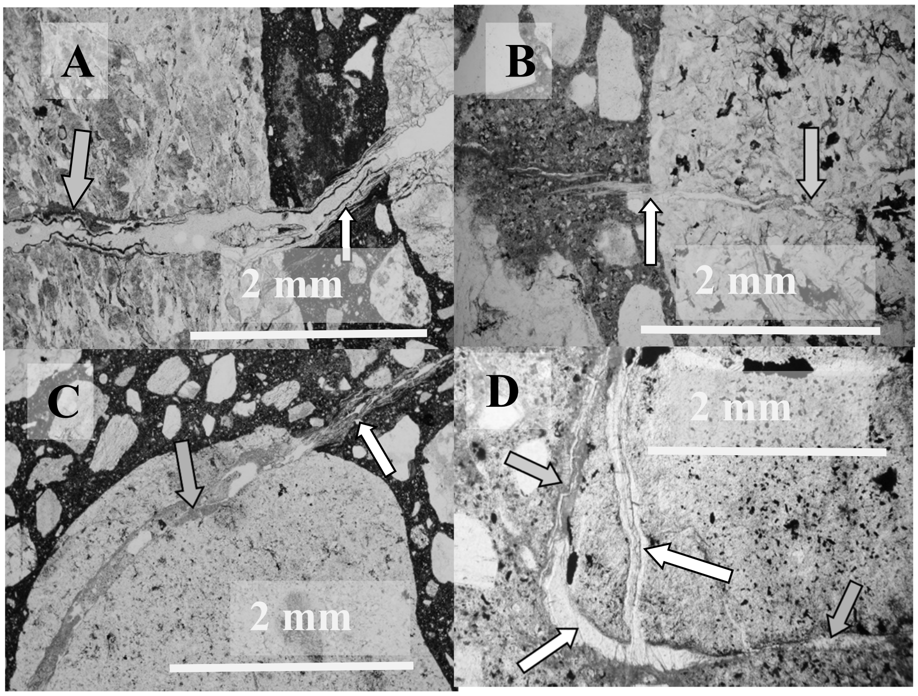

FIGURE 4: (ordinary light). A: connecting crack with gel (arrow) and cryptocrystalline reaction products (filled arrow) in a feldspar rock (left) and cataclasite (right) from Norway. B: cracks with cryptocrystalline reaction products in feldspar rock (filled arrow) running into the cement paste with gel (arrow), from Norway. C: particle with cryptocrystalline reaction products in feldspar rock (filled arrow) running into the cement paste with gel (arrow) from Norway. D: gel (arrow) from a sericite rock filling peripheral crack with ettringite (filled arrow) from Thailand.

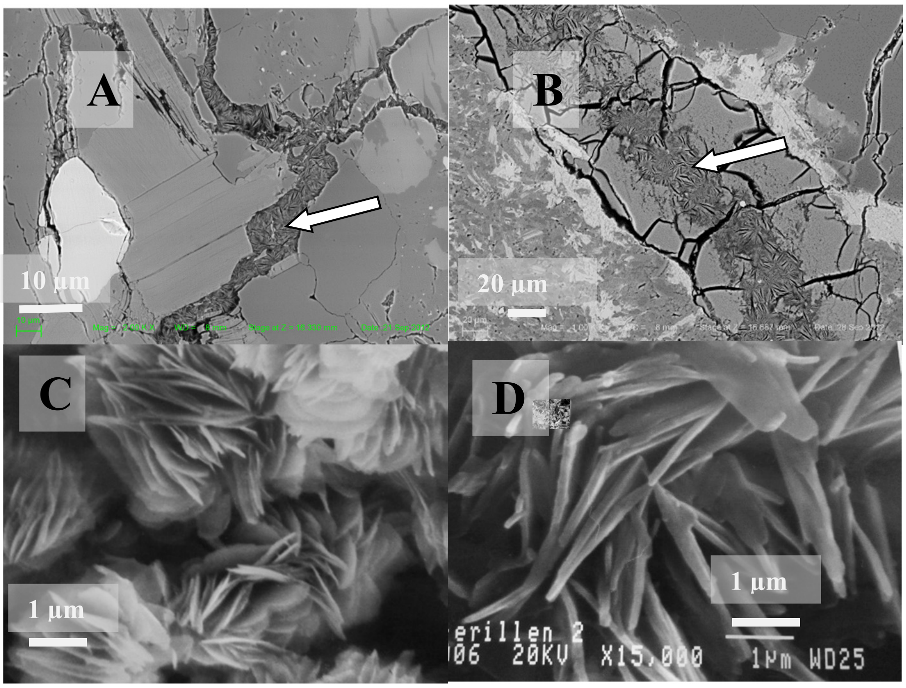

FIGURE 5: A: Cryptocrystalline reaction products in reacted granite (arrow), Thailand. B: Gel and newly formed cryptocrystalline reaction product (arrow) in reacted sericite rock, Thailand. C: globular cryptocrystalline reaction product, Norway. D: plate formed cryptocrystalline reaction product, Norway. A and B in back scatter mode, C and D in secondary electron mode.

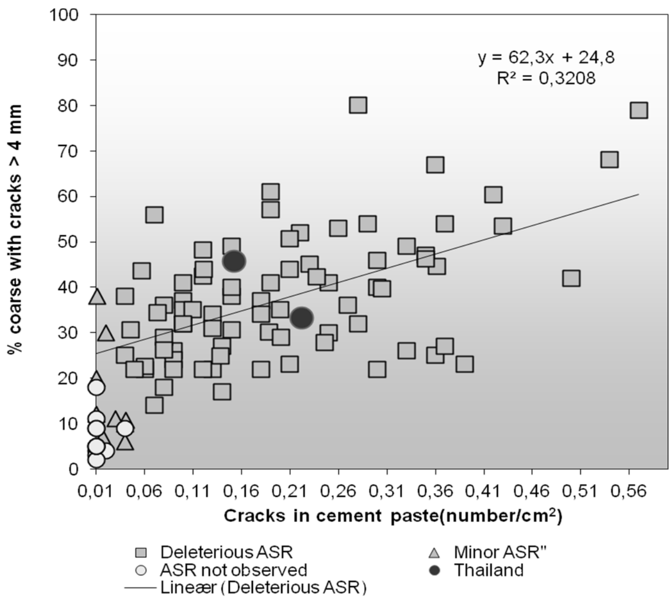

FIGURE 6: Distribution of cracks in coarse aggregates versus cracks in cement paste by the Norwegian method. Note that Thai samples are distributes in the same "cluster" as Norwegian structures with deleterious ASR.