

Diagnosis of concrete structures distress due to alkali-aggregate reaction

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Abstract. Damage and defects observed in concrete elements, such as a network of microcracks, popouts and efflorescence can be caused by a variety of deleterious processes. The causes can include mechanical (overloading), physical (freeze-thaw cycle) or chemical exposure (sulphate corrosion, alkali-aggregate reaction). This paper analyses distress due to alkali-silica reaction, detected in selected concrete structures. The analysed concrete elements exhibited cracking, exudations and surface popouts. Identification of the presence of hydrated sodium-potassium-calcium silicate gel can be considered the primary symptom suggestive of an alkali-silica reaction attack. Other damage-causing mechanisms can occur simultaneously.

Key words: alkali-aggregate-reaction, diagnosis, concrete structure.

1. Introduction

Some of the minerals present in aggregate may react with sodium and potassium hydroxides from the concrete pore solution. Alkali-aggregate reaction (AAR) occurs either as alkali-silica reaction (ASR) or alkali-carbonate reaction (ACR). Due to more common occurrence of aggregates containing reactive silica minerals, alkali-silica reaction is more often the cause of serious deterioration of concrete structures.

Alkali-silica reactivity was recognized as a potential source of distress in concrete in the 1940s. Although reactive aggregates exist in many countries, ASR distress in concrete structures may remain undiagnosed. There are a number of reasons for this. Certain silica minerals present in aggregates do not produce deleterious expansion. Concrete dry in service prevents ASR as does the use of various types of pozzolan or blast-furnace slag and low alkali content in concrete.

Stone or gravel and sand make up matrix of cement paste. The cement paste has interconnected pores through which pore water can migrate. The pore water is the solution of mostly sodium and potassium hydroxides with a low content of calcium ions. ASR is a two-step process. The reaction of Na and K hydroxides with reactive silica produces alkali-silica gel. The gel absorbs water from the surrounding cement paste, swells and induces pressure and expansion causing the cracking of aggregate particles and surrounding paste [1].

The objective of this study is an analysis of ASR-induced deterioration of selected concrete structures.

2. Factors affecting ASR

The following three conditions have to be met for ASR to occur:

- aggregate contains reactive forms of silica;

- pore solution has high content of sodium and potassium ions;
- sufficient moisture is present in concrete.

2.1. Reactive silica forms in aggregate. Aggregate reactivity is a function of types and varieties of aggregate constituents (Fig. 1). Crystalline silica minerals are stable (non-reactive) whereas amorphous forms are mainly reactive. Among crystalline varieties of silica, microcrystalline or strained quartz and its varieties of low density, porous rocks like tridymite and cristobalite, can be highly reactive. Figure 2 shows an example of mineral composition of gavel aggregate containing reactive components determined petrographically [2].

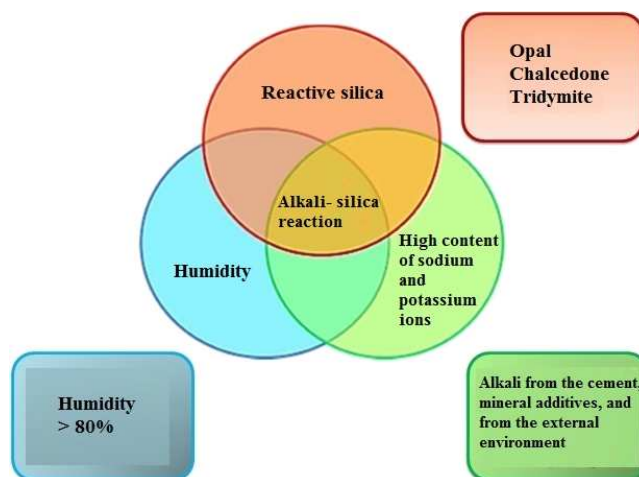


Fig. 1. Factors affecting ASR

The microscopic analysis of aggregate thin cuts under an optical microscope with light transmission helped identify: glauconitic quartz sandstone with clay-carbonate binder,

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organodetrictic limestone filled with micrite and sparite, metamorphous quartz – pyroxene shale with opal as a binder, and feldspar-biotite granite. Microcracks allowing migration of liquid inside the particle was observed in the majority of the rock particles investigated. Three constituent materials may be responsible for the alkali-reactivity of gravel aggregate: strained quartz in feldspar-biotite granite (Fig. 2a), opal in glauconitic quartz sandstone (Fig. 2b) and chalcedony dispersed in organodetrictic limestone (Fig. 2c).

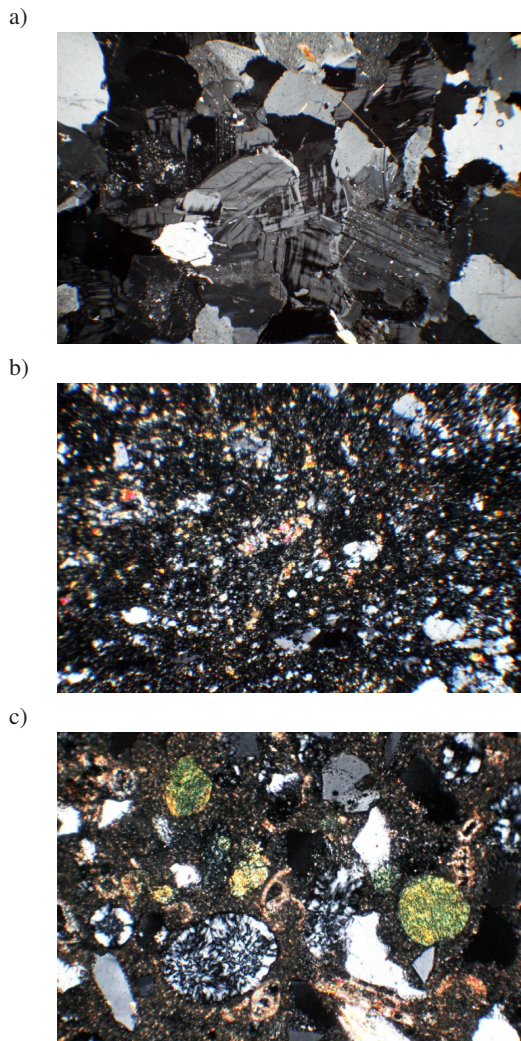


Fig. 2. a) Strained quartz in feldspar-biotite granite (120x), b) opal in glauconitic quartz sandstone (120x), c) chalcedony dispersed in limestone (120x)

Aggregates containing constituents in amounts higher than those given below are identified as potentially reactive [3]:

- opal – above 0.5% by mass;
- chert and chalcedony – above 3.0%;
- tridymite and cristobalite – above 1.0%;
- strained or microcrystalline quartz – above 5.0% (as found in granites, granite gneisses, greywackes, sedimentary rocks, phyllites, siltstones, natural sands and gravels);
- natural volcanic glass – above 3.0%.

2.2. Alkali content in pore solution. Sodium and potassium ions in the pore solution come mainly from cement minerals but also from pozzolanic additives, aggregates and chemical admixtures. Deicing salts are the external source of alkalis. The use of low sodium and potassium cement is not sufficient to protect a concrete structure against ASR with aggregate containing highly reactive minerals. The alkali silicate gel as a reaction product can form even at lower alkali content in high-reactivity aggregate (e.g. when aggregate contains opal). When sodium and potassium hydroxides concentration is high, the most stable varieties of silica can become susceptible to ASR [4]. Strong silica bonds in less reactive aggregates are broken to form the gel reaction product. This explains why the aggregates considered to be non-reactive may occasionally produce ASR products. Also, alternating cycles of wetting and drying may cause local increase in alkali content. Evaporation of moisture from the concrete surface may lead to high alkali (sodium + potassium) concentrations.

ASR occurrence potential increases with high concentration of sodium and potassium ions in the pore solution. Allowable limits for alkali content in concrete (expressed as equivalent of Na_2O_e in certain European countries and in Canada range from 1.8 kg/m^3 to 3 kg/m^3 , depending on aggregate reactivity, size of concrete elements and environment [5]. Total alkali content of concrete includes the alkalis entered into the concrete with all the constituents. However, only the alkalis from cement or binding materials are commonly taken into account because alkali content from the remaining components is typically very low.

In many countries, allowable limits of alkali content range from 1.8 to 3.0 kg/m^3 in concrete in which the reaction can occur. However, as shown in Fig. 3, total alkali content in concrete can exceed the recommended level of 3 kg/m^3 at increased amount of cement or higher alkali content in the cement.

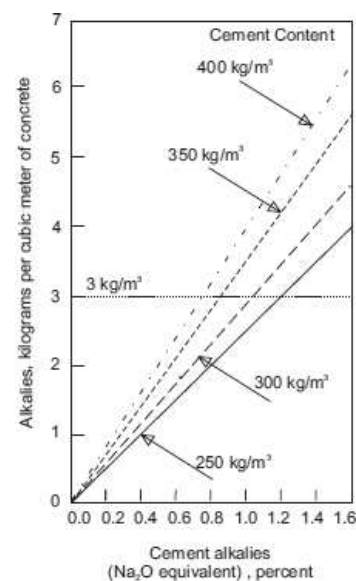


Fig. 3. Total alkali content of concrete for various alkali levels in cement and cement contents

Cement with equivalent Na_2O content of 0.60% or less is specified in [6] as low-alkali cement. However, concrete made with low-alkali cement and extremely reactive aggregate is still susceptible to deleterious ASR if moisture movement concentrates the alkalis in one location [7], if alkalis enter with mineral and chemical materials and admixtures, from aggregate [8] or mixing water, or when total alkali content of concrete is high due to high cement content.

Expansion due to ASR may be increased by external alkalis, especially when the concrete is cracked or is highly permeable [8]. External sources of alkalis include deicing salts, seawater, groundwater and industrial processes water. Sodium chloride deicing salt solutions or seawater can provide unlimited amounts of alkali. Ways to reduce the ingress of external alkalis and potential ASR expansion include lowering concrete permeability through the use of mineral additives in cement and low w/c ratio.

2.3. The role of moisture. Moisture present in concrete elements facilitates migration of sodium and potassium ions to reaction sites, and the resulting alkali silicate gel absorbs moisture, leading to expansion. That is why deleterious ASR does not occur in concrete dry in service. Research has indicated that expansive ASR product can be observed in concrete having a relative humidity above 80% [10]. Well-cured concrete years in service can have a relative humidity of 80% or higher just at or beneath its surface even in dry conditions. Alkali migration occurring with alternate wetting and drying can increase alkali concentration near the drying zone, inducing destructive reaction [7]. Limiting permeability through a lower w/c ratio, the use of mineral additives, and other means can reduce the movement of moisture and alkalis in concrete. Concrete structure service under low moisture conditions is one of the factors that limit ASR-induced damage.

Structures in service at a higher temperature (warmer climate regions) are more susceptible to ASR than those operating at lower temperatures (colder climate) because the speed of reaction increases with the increase in temperature [11]. The effect of temperature on the ultimate expansion depends on the aggregate type but most reactive aggregates causes higher expansion at higher temperatures.

3. Analysis of damage in selected concrete structures

The procedure for diagnosing ASR and assessing its impact on a structure includes the following steps: site inspection and observation, sampling, laboratory testing, evaluation and risk assessment of future reaction [12]. Visual observation and description of the structure is the first element of the procedure. The photograph in Fig. 4 shows a section of a flyover pier severely affected by ASR. The presence of ASR is typically indicated by map (random pattern) cracking, and in advanced cases, gel exuding onto the surface of concrete elements (see Fig. 4b) and discolouration.

Expansive ASR starts with the formation of gel in a reactive aggregate particle or in the surrounding paste. As the

gel absorbs water, it exerts a relatively uniform pressure up to 10 MPa or more in all directions [13]. This pressure exceeds the tensile strength of structural concretes, which is generally around 10% of compressive strength. The concrete cracks in a star pattern. The cracks-stars join with others and form a pattern resembling a map.



Fig. 4. a) Flyover pier with ASR symptoms, b) gel exuding on the surface of concrete

Because ASR is slow, the deterioration and risk of structural failure is low. Several deterioration mechanisms such as

alternate freeze-thaw cycles, deicing, or entrance of sulphatic ions occurring at the same time can contribute to concrete deterioration. Products of ASR that deposit on the surface of concrete elements usually carbonate and the study of their microstructure reveals mainly calcium carbonate and silica, and the amorphous phase reinforced with sodium and potassium (see Fig. 5).

The material from exudations revealed an amorphous phase with potassium, indicative of ASR (Fig. 5b). The amorphous phase is accompanied by the crystalline phase (Fig. 5c) identified as calcium carbonate - calcite. Cracking of slabs and pavements from expansive ASR begins near free edges and joints where moisture is abundant [14]. The cracks are usually perpendicular to transverse settlement joints and parallel to free edges along the road. These cracks form a map pattern are parallel to the steel bars in reinforced pavements.

The crack development model in Fig. 6, developed for road pavements [14] can be used for describing this process in other structures. In the first stage, moisture is lost at the top surface of the slab and a slight drying shrinkage occurs together with very fine cracking on the concrete surface. No ASR products or concrete expansion are observed in this stage.

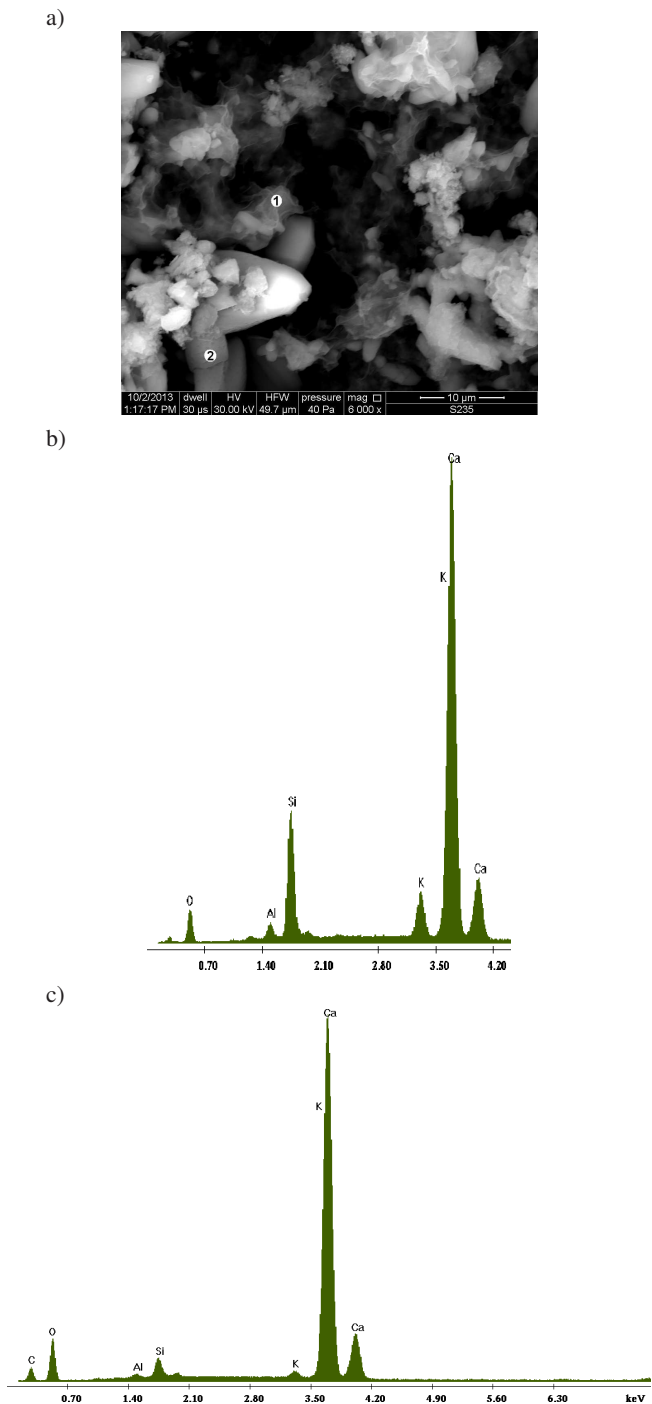


Fig. 5. a) Microstructure of the exudation on the surface of concrete made with reactive aggregate (SEM), b) elemental composition of amorphous phase “1”, c) elemental composition of crystalline phase “2”

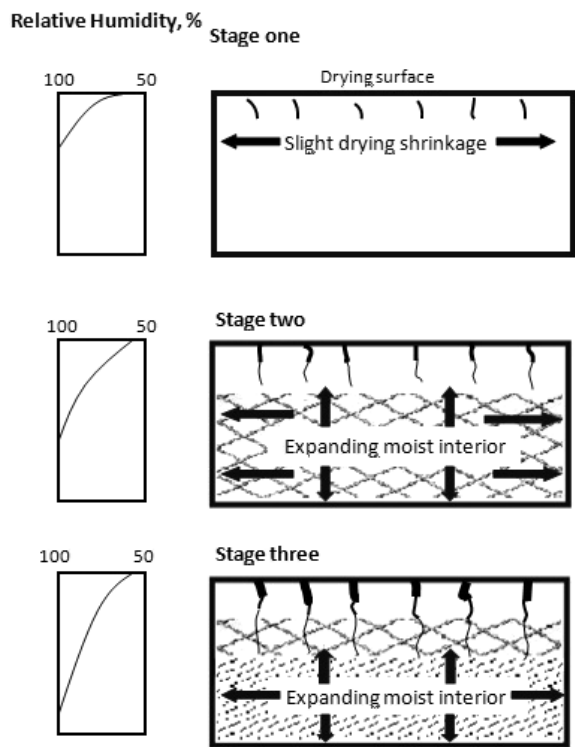


Fig. 6. Model for ASR-induced cracking in concrete pavement after Ref.14

The second stage may begin a month after concrete placement or many years later. The onset of this stage is indicated by gel formation and swelling. Acceleration of ASR progress depends on reactivity of aggregate and alkali content in pore solution.

A gel forms in cracks inside aggregate particles or on their surface. Initially the forming gel may contribute to volume reduction, but as the gel absorbs water, it swells and exerts pressure on the surrounding concrete. This results in the formation of cracks on the concrete surface. Further progress of ASR makes the cracks widen, allowing moisture access to the concrete interior, which contributes to additional gel formation and swelling. During this phase, gel exuding from the widened cracks can be observed on the concrete surface.

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In the third stage, drying the concrete slows the reaction near its surface. The reaction continues in the moist interior of the concrete, contributing to formation and swelling of gel exerting pressure on the concrete surface and widening the surface cracks. The reaction continues until the silica is depleted and until the alkali ion concentration is sufficiently reduced. The formation and expansion of gel stop with moisture loss. The process, represented by a three-step model, can be temporarily or permanently interrupted, for instance, during dry periods. However, if conditions conducive of ASR reappear, the reaction will resume. Most cracks are observed in structures in which the concrete has a constantly renewable supply of moisture, for instance, from the ground to retaining walls, pavement slabs or by capillary action in columns [14].

On retaining wall surface, cracks are mainly oriented parallelly and form cracking maps. The region along the cracks extending from a few to more than ten millimetres from the crack ranges in colour from white to brown-grey (see Fig. 7).

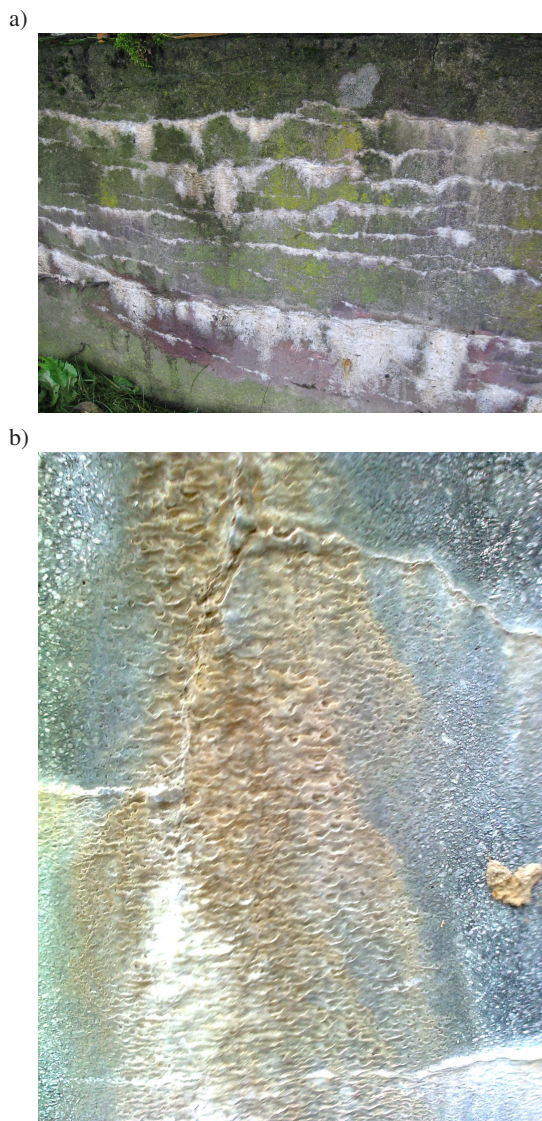


Fig. 7. a) Retaining wall with advanced ASR, b) surface deposits of gel and calcium carbonate

Surface deposits of gel or calcium carbonate occurring along the cracking form exudations ranging in colour from white to rusty-grey. The material exuding from the crack is white, yellowish or colourless fluid and is waxy, rubbery or as a result of drying and carbonation, hard. Its presence is not indicative of ASR as other mechanisms (e.g. frost action) or transmission of water can cause exudations.

Analysis of phase composition of surface deposits occurring along the cracks is helpful to determine processes responsible for deterioration of concrete structure in service.

Fragments breaking out of the concrete surface are another sign of ASR. Pop outs are holes from 25 to 50 mm in size and may be caused by aggregate particles of varying size (see Fig. 8). Pop outs due to expansive ASR result from increased stresses produced by the gel underneath the concrete surface. The presence of the gel at the pop out location is an indication of ASR.

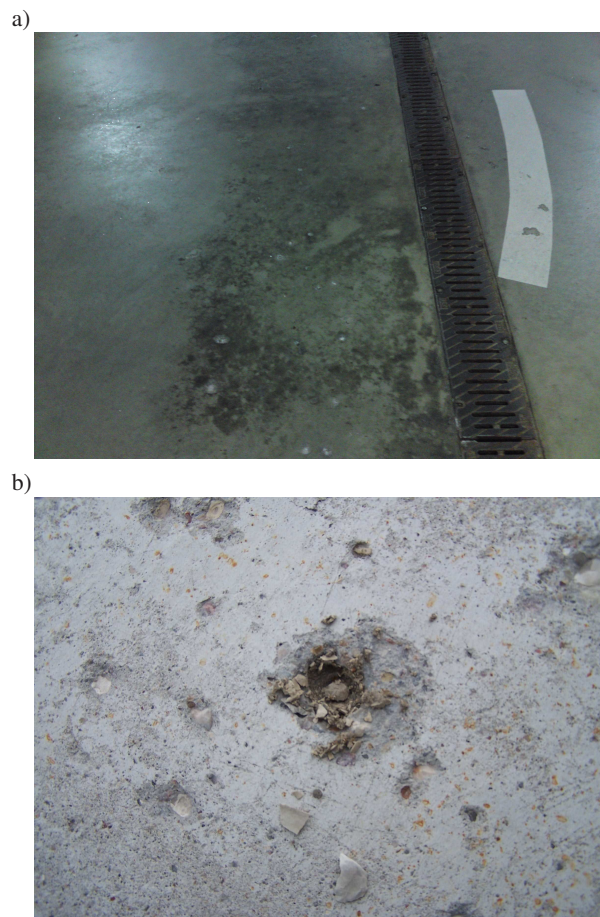


Fig. 8. a) Pop outs near the drain channel, b) crushed aggregate particles with gel in the bottom part of the pit

Pop outs resulting from the reaction were observed on the concrete floor of a underground garage (see Fig. 8). On slabs with poor insulation, placed on wet soils, the humidity increases due to capillary action and may induce the reaction of alkalis with reactive particles of aggregate. Examination of the aggregate from the bottom part of the pit showed the presence of the sodium-potassium-calcium silicate gel, which

explained the cause of the pop outs. Pop outs on the concrete surface are undesirable mainly for aesthetic reasons, as they do not affect the serviceability or durability of concrete. Freezing and thawing of porous, water saturated particles of aggregate can also cause pop outs near or on the surface of concrete, which was not the case in the slabs investigated.

4. Methods for identification of ASR-induced damage

ASR causes concrete deterioration if the signs of damage such as microcracks and separation of aggregate from the paste can be attributed to ASR gel formation. In concrete distress diagnosis, identification of ASR gel is the main sign confirming the presence of the reaction. Other causes of damage cannot be precluded. Expansive reaction can occur in aggregate particles that are recognizable as reactive or potentially reactive and are at least partially replaced by gel (see Fig. 9). Coarse aggregates susceptible to ASR usually exhibit internal fracturing and cracks extending into the surrounding concrete matrix. If only fine aggregate is reactive, the cracks can form in the matrix of the paste without affecting the structure of coarse aggregate particles.

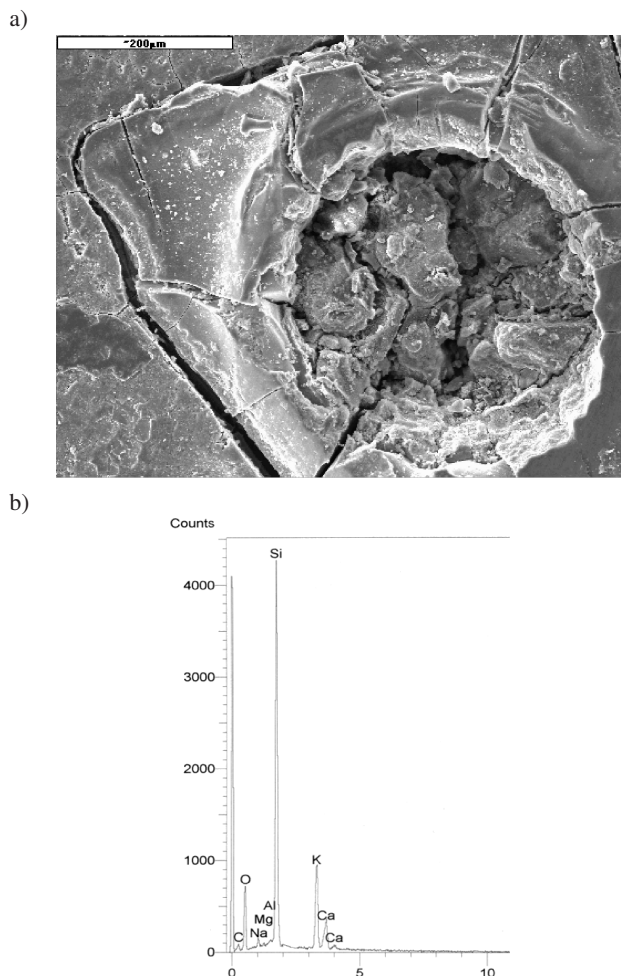


Fig. 9. a). Alkaline-calcium gel surrounding cracked particles of aggregate (SEM x 200), b) Gel composition

Gel can be found in cracks, voids and in the regions surrounding the edges of aggregate particles. A network of internal cracks connecting reactive particles of aggregate indicates clearly that ASR is an underlying cause of cracking (see Fig. 10).

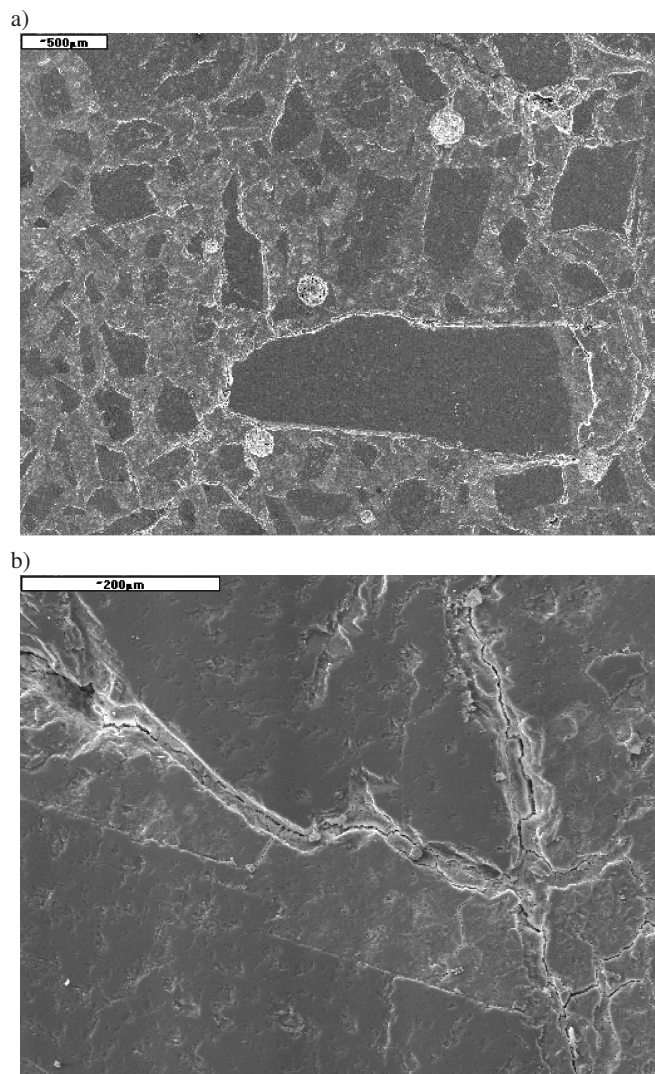


Fig. 10. Gel formed on the particle of aggregate moves along the cracks to voids

The most positive method to detect ASR products is a petrographic examination [15] by optical and scanning electron microscopy with X-ray analysis of the microregion. Microscopic observation of the concrete samples help determine the presence and distribution of reactive aggregate particles and the gel. The gel is represented as a darkened area in the aggregate particle or along its edges. Petrographic methods when used to study concrete can confirm the presence of the reaction products and indicate whether ASR is the primary cause of deterioration.

5. Conclusions

The analysis of damage due to the alkali-silica reaction in selected concrete structures indicated that a description of the

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reaction symptoms is the first element of diagnosis. The main characteristic sign of the reaction are randomly spaced cracks and, in advanced cases, alkali silica gel present on the concrete surface. The arrangement of the cracks is dependent on the type of concrete structure elements. In reinforced members, the cracks are usually parallel to the reinforcement bars. In sidewalk slabs or road pavements, the cracks initiate close to free edges and joints with increased moisture access.

The progress of the reaction and its consequences are strongly influenced by temperature and moisture conditions. The cycles of alternate freezing and thawing enhance gel migration and swelling, which results in further cracking. The description of the deteriorated retaining wall has been presented to illustrate this case.

Another characteristic indicator of the alkali-silica reaction are loose fragments of concrete, as shown on the concrete slabs in the underground parking lot. The pop outs are caused by the swelling of the reaction products gel at the locations of reactive aggregate grains. Some of the fractured aggregate particles can be found in the cavities on the concrete surface.

The need to perform laboratory tests in order to identify the alkali silica gel is a separate problem in the diagnosis of deterioration due to alkali silica reaction. Scanning electron microscope – energy dispersive spectroscopy (SEM-EDS) is essential for proper detection of alkali-silica reaction products in concrete. SEM observations are performed on specimens collected from the cracked surface. At the initial stage of alkali-silica reaction, rims of gel present around the particles of aggregate are found, or in polymineral aggregated, the particles are cracked internally. The network of internal cracks from the aggregate particles through the cement paste indicates an advanced level of the reaction. SEM-EDS is a proper tool for identification of both the reaction products and the degree of reaction advancement. Petrographic analysis including optical microscopy with light transmission allows identifying (on reactive aggregate particles sections) the type of the ingredients responsible for the reaction.

The issues concerning predictions of further progress and consequences of the reaction as well as methods for the pre-

vention of its impacts at the stage of concrete mix design and in the existing structures built with reactive aggregate will be reported in separate articles.

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