

ALKALI-SILICA REACTION IN THE NETHERLANDS

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ABSTRACT

In The Netherlands, the number of concrete structures showing damage caused by ASR has increased from 3 to about 35 over the last 5 years. In general, the concrete of these structures is composed of ordinary portland cement and local river-dredged gravel and sand. The reactive constituent is porous chert, which is present in the coarse aggregate in varying amounts (1-6% by mass). Secondary ettringite formation often accompanies the ASR.

Damage due to ASR has been found in two concrete structures, in which blast furnace slag cement with a low slag content of about 40% by mass, was used.

A recommendation has recently been published describing a procedure, which should be followed in designing concrete mixes, to prevent the occurrence of harmful ASR in concrete. A procedure with respect to the structural assessment of concrete structures affected by ASR is currently in preparation.

Keywords: alkali-silica reaction, blast furnace slag cement, ettringite, microscopy, recommendations

INTRODUCTION

The first case of deterioration as a result of ASR in a Dutch concrete structure was published in 1991 (Heijnen & Van der Vliet 1991; Heijnen 1992). Since then, about 35 cases of deterioration caused by ASR have been found in The Netherlands. Most structures affected by ASR are more than 30 years old. This suggests that the rate of ASR in Dutch concrete structures is relatively slow. Reasons for this slow reaction rate are to be found in the nature of the reactive components (coarse porous chert grains) of the aggregates, the relatively low content of potentially reactive aggregate particles, the generally low cement content of Dutch concrete and the generally low alkali content of Dutch portland cement.

Since the number of structures suffering from ASR is increasing, substantial effort is directed towards specifications and guidance for avoidance of damage due to ASR, as well as for evaluation of the structural consequences.

STRUCTURES AFFECTED

General

The structures that have been found or suspected to be affected by ASR include mostly viaducts, bridges and locks. The age of the structures involved is variable, but in general ranges from about 30 to 60 years. The damage is usually manifested

in the form of map-cracking with the cracks sometimes filled with ASR-gel in combination with ettringite or other leached cement products.

Cement used

The cement used in all but two of the structures that have been diagnosed to be affected by ASR is ordinary portland cement. PFM (Polarising and Fluorescence Microscopy) analysis shows the grains of nearly all such cements to be coarse, with an estimated modal grain size of about $50\ \mu\text{m}$. To date, there has not been any case of concrete structure affected by ASR in which blast furnace slag cement (bfsc), containing more than 65% slag (by mass, as cement replacement) or composite cements of fly ash containing more than 25% fly ash (by mass, as cement replacement) was used.

In the two cases, namely a lock and an in-situ cast foundation block of a power pylon, blast furnace slag cement with a low slag content of 35-40% and 40-50% respectively was used (Fig. 1). In both cases also, most of the residual slag particles in the cement paste were found to be coarse-grained with an estimated modal grain size of about $100\ \mu\text{m}$; a significant number of the grains was found to fall in the $150\text{-}200\ \mu\text{m}$ size range. The majority of the coarser grains ($>100\ \mu\text{m}$) appeared not to have reacted at all. Reaction rims around such particles were clearly absent - they appeared virtually inert.

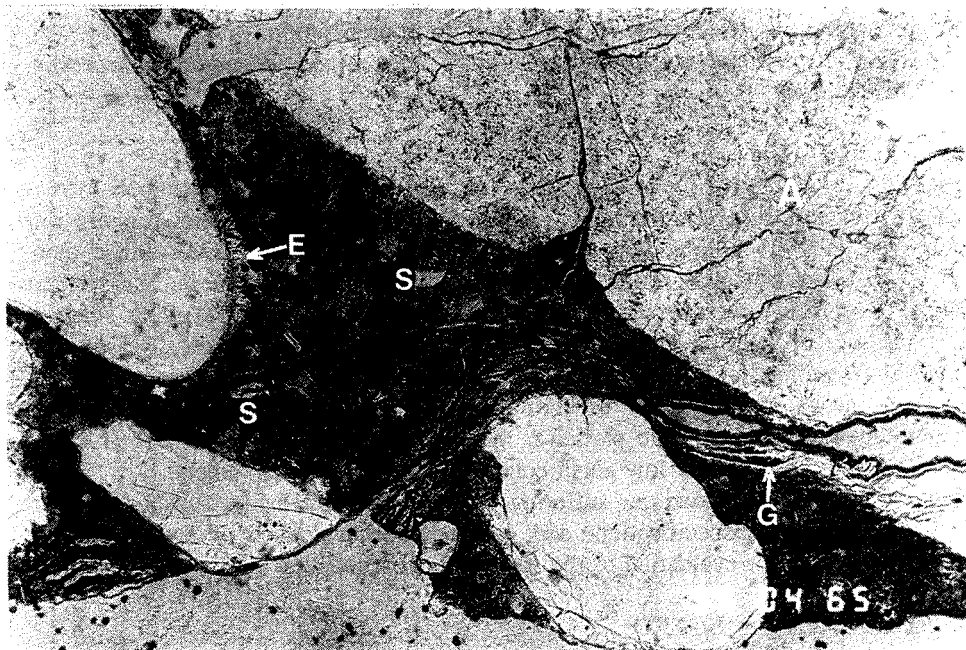


Fig. 1: Thin section micrograph showing alkali-silica gel streaming outward from a sericitic sandstone coarse aggregate particle through cracks into the adjoining cement paste. The concrete was prepared with portland blast furnace slag cement with about 40% by mass of slag. A = aggregate; S = slag particles; G = ASR-gel; E = ettringite. (plane polarised light; micrograph is $1.4\ \text{mm} \times 0.9\ \text{mm}$)

The extent of damage in the concrete, as diagnosed from the PFM analysis was in both cases found to be moderate to severe.

Blast furnace slag cements and composite cements of fly ash currently produced in The Netherlands contain more than 50% slag or more than 25% fly ash (by mass, as cement replacement) respectively. The modal size of the slag particles, determined from PFM analysis is 25-40 μm , with only a small percentage falling above the 100 μm size range. The alkali content (Na_2O -eq.) of Dutch cements varies between 0.6 and 0.8 % by mass. The modal size range of ordinary portland cement and composite cement containing fly ash currently produced in The Netherlands is 15-30 μm .

Concrete characteristics

The mixing of the concrete constituents and especially, the cement is very often found to be poor or at least not optimum, resulting in an inhomogeneous concrete. The packing and distribution of the aggregate particles in the cement paste is not the same throughout the concrete; very often there are zones rich in aggregate but low in cement content. This, however, does not apply to all concretes with an inhomogeneous microstructure. There have been a number of cases in which petrographic analysis of concrete specimens with inhomogeneous microstructure and suspected to be affected by ASR have shown no apparent signs of attack by ASR.

Cement paste characteristics

The cement paste is nearly always inhomogeneous; zones rich in water but poor in cement (zones with high water-cement ratios (w/c) are very often interconnected with each other from the surface of the concrete into the deeper parts) alternating with zones with low water-cement ratios are very common in nearly all the samples that have been examined. The water-cement ratios, determined with the aid of fluorescent microscopy vary considerably within a thin section specimen and in the concrete core as a whole. Typical values range between 0.40 and 0.70.

Degree of cement hydration

The degree of hydration of the cement (which is estimated from the amount of residual, unhydrated or partially hydrated C_3S and C_2S grains in the cement paste) is, in general, high. The occurrence of large clumps of coarse, virtually unhydrated C_3S and C_2S grains (signifying poor mixing of the cement) is quite common in most of the specimens. The modal grain size of the portland cement particles, estimated from the residual unhydrated cement and from reaction rims around the partially hydrated grains is about 50 μm . A considerable portion of the grains of such cements is usually found to fall within the 50-100 μm size range.

Amount of calcium hydroxide

The amount of calcium hydroxide, $\text{Ca}(\text{OH})_2$ found in thin section specimens is very often considerably high. In some specimens, they occur as large crystals even at the paste-aggregate interface of particles that have already reacted indicating high levels

of alkalinity of the pore fluid in the cement paste. Such high levels of alkalis are likely to originate from the cement used or in the case of bridges and viaducts, from a combination of the cement and de-icing salts. PFM and SEM analyses of specimens of concrete suffering from ASR very often do show a depletion of $\text{Ca}(\text{OH})_2$ in the cement paste, especially at the paste-aggregate interfacial zones of the reacted particles (Regourd-Moranville 1989). In such cases, $\text{Ca}(\text{OH})_2$ is believed to go into solution to buffer the alkalinity of the pore fluid after the alkali-silica reaction has taken place. The presence of large crystals of $\text{Ca}(\text{OH})_2$ in the specimens indicates that the pore fluid of such concretes is still rich in alkalis and may have adequate potential for further reactivity under the appropriate conditions. $\text{Ca}(\text{OH})_2$ in such cases does not seem to have contributed to the alkalinity of the pore fluid in the cement paste.

Alkali-silica gel

Manifestations of alkali-silica reaction usually includes the following:

- a. cracked or fractured particles of chert, quartzite or sandstone, with the cracks occasionally filled with ASR-gel and radiating into the surrounding cement paste;
- b. occurrence of reaction rims at the periphery of some of the affected aggregate particles;
- c. simultaneous occurrence of fine, needle-like crystals of ettringite and ASR-gel in pores and cracks in the cement paste.

In thin section specimens, the ASR-gel is found to occur in one or more of the following locations in the concrete: confined to cracks within the reacted aggregate particle, filling cracks in the reacted aggregate and penetrating or streaming outward from the reacted aggregate through cracks into the adjoining cement paste or occurring solely or together with secondary ettringite in pores and cracks in the cement paste. The alkali-reactive particle or constituent in all cases examined so far, is one or more of the following: porous chert, sericitic quartzite, sericitic sandstone, quartzite containing microcrystalline quartz or chalcedony.

Simultaneous occurrence of fine needle-like and massive ettringite

In all cases, fine needle-like crystals of ettringite are found to occur simultaneously with ASR-gel in cracks and pores in the cement paste. This type of ettringite formation has not been observed in cracks within aggregate particles as yet.

The formation of massive ettringite from sulphate attack has been found to occur simultaneously with ASR in a few cases. The ettringite in such cases consists of compact crystals completely filling pores and large cracks ($> 25 \mu\text{m}$ in width) at the interface of both coarse and fine aggregate particles (Fig. 2). In some cases, there is a complete 'enveloping' of the aggregate particles by the massive ettringite. Such cases are very often associated with intense microcracking and all the micro-cracks apparently radiating from the ettringite-filled cracks into the adjoining cement paste. The individual crystals of such compact ettringite are not easily distinguishable even at higher magnifications of 200x and 400x with the PFM. The occurrence of fine needle-like ettringite is not associated with deformation of the cement paste.

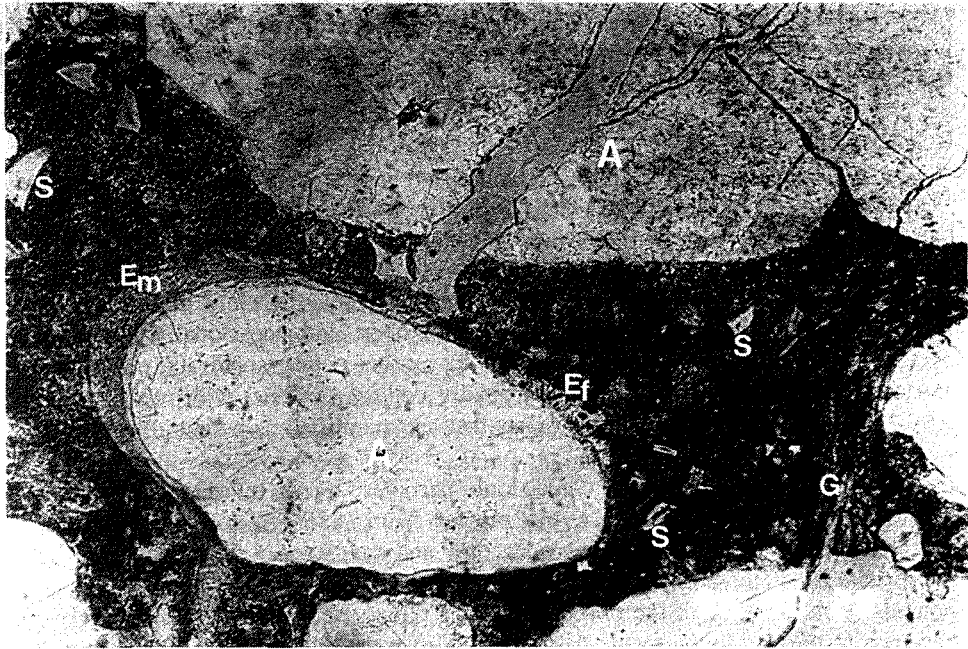


Fig. 2: Thin section micrograph showing alkali-silica gel streaming outward from a sericitic sandstone coarse aggregate particle through cracks into the adjoining cement paste. The concrete was prepared with portland blast furnace slag cement with about 40% by mass of slag. A = aggregate; S = slag particles; G = ASR-gel; Em = massive ettringite; Ef = fine needle-like ettringite. (plane polarised light; micrograph is 1.4 mm x 0.9 mm)

Zones of preferential occurrence of ASR and massive ettringite

In all cases studied so far, the occurrence of the ASR and the formation of massive ettringite seem to be confined to the zones in the cement paste with high water-cement ratios. Such observations are easily made with aid of fluorescent microscopy. In the zones with lower water-cement ratios, the integrity of the cement paste and the concrete is very much preserved. Pores and cracks in such zones are very often empty or contain only crystals of $\text{Ca}(\text{OH})_2$.

CONCRETE AGGREGATES

General

Traditionally, the main aggregates used for production of concrete in The Netherlands have been river gravel and sand which are dredged from the rivers Maas and Rhine. The gravel is composed predominantly of particles of quartzite and sandstone and with small amounts of chalcedony, porous and non-porous chert. The sand is rich in quartz, but contains subordinate amounts of porous and non-porous chert, quartzites, sandstones, limestone, glauconite, feldspars and opaque minerals.

Most of the quartzites and sandstone particles are rich in mica and sericite. Crushed rocks such as limestones, granites, quartzites as well as sea-dredged sands and gravels are also used for concrete but in smaller amounts compared to river aggregates.

Reactive aggregates

Until recently, it was believed that only the porous chert and the chalcedonic particles, found mostly in the coarse aggregate fraction are potentially reactive. This assertion was made in 1992 after an inventory study of the structures that had been affected by ASR at that time. It appeared from investigations at that time that in all the ASR-affected structures only porous chert and occasionally chalcedonic particles were reactive. As such, to date, in routine petrographic analysis of river and sea-dredged aggregates (as part of quality control analysis) with regard to their ASR-reactivity, these are the constituents that are quantified as potentially reactive.

In addition to porous chert and chalcedonic particles, recent investigations with the aid of PFM on cores of concrete removed from ASR-affected structures have revealed that, constituents such as quartzites and sandstones, especially those rich in sericite and those containing micro- and cryptocrystalline quartz are also potentially reactive. Like the porous chert, all the reacted particles found so far are confined to the coarse aggregate fraction and are from river-source aggregates only.

Implications for quality control analysis of aggregates

In The Netherlands, CUR Recommendation 38 (CUR 1994) provides guidelines, for specifications and procedures for evaluating aggregates with regard to ASR. In that recommendation, concrete aggregates are distinguished on the basis of the mineralogical composition in relation to ASR into the following three categories:

- a. aggregates with such a low amount of reactive components that no harmful ASR can occur, indicated as 'under critical'
- b. aggregates with such a high amount of reactive components that no harmful ASR can occur, indicated as 'above critical'
- c. aggregates with an amount of reactive components that harmful ASR can occur, indicated as 'critical'.

One of the means specified by the above recommendation for evaluating the potential reactivity of concrete aggregates is the mineralogical composition obtained from petrographic analysis. At TNO Building and Construction Research, the petrographic analysis is performed on routine basis with the aid of PFM in combination with point-counting analysis of the various fractions in the aggregate sample (sand, gravel or crushed rock).

For chert particles, a combination of the polarising and fluorescent microscopy is crucial in establishing which of the particles are potentially reactive in the aggregate samples submitted for investigation. By means of polarising microscopy, the various mineral constituents (including the porous and non-porous chert) are identified. The porosity of the chert particles are subsequently established with the

aid of fluorescent microscopy. By means of point-counting, the porous chert and chalcedonic particles are then quantified in the various fractions examined and eventually the material as a whole. The material is then classified into one of the three groups above on the basis of the amount of reactive constituents in the sample examined.

The recent revelations made about the potential reactivity of quartzites and sandstones in the coarse fraction of the river aggregates call for re-examination of the present guidelines and criteria for evaluating the potential reactivity of river- and possibly sea-dredged aggregates. There may be the need to develop procedures to re-evaluate the sericitic quartzite and sandstone particles in the light of their potential reactivity with regard to ASR so that they could be adequately classified as potentially reactive or not. In order to be able to achieve this, the following set of questions may have to be carefully examined and possibly answered:

- are all sericitic quartzite and sandstone particles in the river-dredged aggregates potentially reactive or are these reactive aggregates associated to only one source or mining location?
- should sericitic quartzite and sandstone particles in sea-dredged aggregates be considered potentially reactive?
- do they occur in significant amounts in river aggregates to warrant extra examination?
- what should be the criteria for defining the critical limits?

In addition to the above questions, one other issue about the sericitic quartzite and sandstone particles that needs to be resolved is the type and nature of the constituent in the particles that is potentially reactive or causes the alkali-silica reaction. At the moment, the reactive constituent involved is strongly suspected to be opal or its constituents occurring possibly together with the sericitic components in the joint or fracture planes of the particles. Because of its amorphous character and the fact that it occurs in small amounts, it is hardly identifiable in thin sections with the aid of optical microscopy. In order to remedy this shortcoming in the PFM analysis of aggregates, extension of the microscopic analysis with the gel-pat test is under consideration.

MEASURES TO PREVENT DAMAGE DUE TO ASR

In The Netherlands, the susceptibility of aggregates to ASR is considered to be of relatively minor importance, because the concrete mix design and cement type can be chosen in such a way, that the risk of harmful ASR is negligible (CUR 1994).

For the following cements, it can be assumed that a harmful ASR will not occur:

- * portland blast furnace slag cement with more than 65% (by mass) slag and an alkali content less than 2.0% (by mass)
- * portland blast furnace slag cement with more than 50% (by mass) slag and an alkali content less than 1.1% (by mass)
- * portland fly ash cement with more than 25% (by mass) fly ash and an alkali content less than 1.1% (by mass)

More than 70% of all concrete in The Netherlands is produced with the cements mentioned above.

STRUCTURAL ASSESSMENT

The number of concrete structures suffering from ASR now is larger than was expected originally. So now it has been decided to establish a Dutch guidance for the structural assessment of concrete structures with damage due to ASR. The basis of this guidance will be formed by existing knowledge and information as present in the Dutch Concrete Codes and the ISE-guidance (Institution of Structural Engineers 1992). From pilot structural assessments, it will be verified whether this knowledge and information is sufficient. At this moment it is already clear that there are questions to be answered with respect to:

- the internal forces in a static independent structure; the magnitude of the internal forces depends also on the deformations of the structure and as a consequence also on the swelling of the concrete structure
- the buckling behaviour of columns; due to non-uniform swelling of the concrete the eccentricities of axial forces can increase dramatically
- the residual service life; for ordinary concrete structures the insight in service life is for a large part based on experience, for structures with damage due to ASR this insight is very restricted and must be improved.

The Dutch guidance for the structural assessment which is currently in preparation is scheduled to be ready and available by the beginning of 1998.

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