Diagnosis of Alkali-Aggregate Reaction in Concrete

DIAGNOSIS OF THE CAUSE OF CRACKING IN FOUR STRUCTURES IN WHICH ASR IS OCCURRING

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ABSTRACT

Four examples are considered of the diagnosis of the primary cause of visual cracking in concrete within which alkali-silica reaction has occurred: a dam, a reinforced beam, a prestressed beam and a wing wall. In the first, it is shown that frost attack is the likely primary cause of the visual cracking, in the second, alkali-silica reaction, in the third, thermal shock and in the fourth, 'delayed ettringite formation'.

Keywords: Alkali-silica reaction, delayed ettringite formation, frost attack, thermal shock.

INTRODUCTION

Often when alkali-silica reaction occurs, concrete has sufficient strength to resist the deleterious effects of the reaction, either because the available 'alkali' content is too low or because the reactive silica content is low or well above the pessimum. Gel-filled fine cracks, and aggregate particles which have cracked as a result of ASR can therefore be found in sound concretes, in concretes which exhibit visual cracking due to ASR, and in concretes which exhibit cracking due to other causes. As a consequence, the identification of ASR in a petrographic examination of a single representative thin section of a suspect concrete does not enable a judgement to be made that ASR is the primary cause of any visual cracking (Diagnosis Working party, 1992). To establish that ASR is likely to be the cause of the visual cracking it is necessary firstly, to rule out other causes of such cracking, secondly, to establish that expansion has occurred, thirdly, to establish by thin section examination that there is considerable evidence of alkali-silica reactivity within the concrete and fourthly, to establish that the internal crack distribution is characteristic of that induced by ASR (Diagnosis Working Party, 1992). Fig. 1 shows the characteristic internal crack pattern induced by the reaction. This crack pattern has been observed both in laboratory concretes and field concretes adversely affected by ASR. When abnormal expansion is induced by ASR, a network of fine cracks connecting cracked aggregate particles is formed in the heart of the concrete. The cracks are frequently filled or partially filled with gel, and in some cases, also partially filled with ettringite. In the exposed surface region of the concrete the reaction is of lower intensity and consequently, the exposed surface layers of the concrete restrain the expansion of the heart concrete resulting in a tensile stress in the surface layers and, if the intensity of the reaction is sufficient, macro-cracks are induced at right angles to the exposed surface of the concrete member. If some of the cracks in a section of a suspect concrete are filled with gel and the internal crack distribution is typical of that induced by ASR, then ASR is likely to be a major cause of the deterioration (Diagnosis Working Party, 1992).

Four examples are considered of the diagnosis of the primary cause of visual cracking in concretes in which ASR has occurred: a dam, a reinforced beam, a prestressed beam and a wing wall. In the first, it is shown that frost attack is the likely primary cause of the visual cracking, in the second, alkali-silica reaction, in the third, thermal shock and in the fourth, 'delayed ettringite formation'.

A DAM

In 1989 BCA was asked to investigate the cause of cracking in a 40- to 50-year old dam in the South of Scotland. In 1976 it had been concluded that the cracking in most of the exposed parts of the dam may have resulted from an alkali-aggregate reaction. The aggregate employed was a greywacke. The dam has a concrete core wall with rock fill either side. The surface of the exposed part of the concrete core wall exhibited cracking broadly of two types: firstly cracks up to 10 mm in width, probably associated with a number of the construction joints and sometimes intermediate between visible construction joints, and secondly, random cracking of varying levels of intensity orientated primarily in the horizontal direction. Tapping the concrete in areas of random cracking indicated that internal cracks were present parallel and close to the surface of the concrete. Such cracking is characteristic of that induced by freeze-thaw attack.

Test programme

If both ASR and frost had contributed to the visual cracking in the exposed parts of the core wall then characteristic cracking due to ASR would be expected in concrete below the rock fill level. As a consequence, pits were dug to a depth of 2 m either side of the core wall to enable examinations to be made of parts of the wall unaffected by freeze-thaw attack. No visual ASR-type cracking was observed, the concrete exposed in the pits being uncracked apart from one fine crack associated with a construction joint.

Fig. 1 Internal crack pattern which can be caused by ASR: reactive silica content in the coarser end of the sand fraction.

Table 1: Summary of observations made on dam and test results

Observation or test	Comment	Is the observation of test result compatible with :	
		ASR cracking?	Freeze-thaw cracking?
Cracking above rock fill level	Some spalling, cracks parallel to exposed face of wall.	no	yes
Cracking below rock fill level	Concrete in good condition, very limited cracking	no	yes
Condition of cores above rock fill level.	Cracks parallel to surface, decreasing in intensity as the distance from surface increases.	no	yes
Condition of core below rock fill level	No visible cracking.	no	yes
ASR gel on surface of cores	Few air pockets filled or partially filled with gel.	unlikely	-
Crack distribution under UV light (section from above rock fill level). Core depth ≤ 360 mm	Inter-connected system of random cracks in 'heart' of concrete. Also cracks roughly parallel to exposed surface. Expansion has occurred.	no	yes
Crack distribution under UV light (section from below rock fill level)	Cracking of significantly lower intensity than in concrete above rock fill level. Fine cracks not interconnected. Expansion has not occurred.	no	yes
Thin section examination (concrete from above rock fill level).	Concentration of ASR gel low compared to concretes which are known to have cracked due to ASR. A number of air pockets and cracks lined with gel (approximately 1/5th)	unlikely	yes
Thin section examination (concrete from below rock fill level).	Concentration of ASR gel low. A number of air pockets and cracks lined with gel (approximately 1/5th).	unlikely	yes
Expansion of core sections maintained moist.	Small expansion, 0.01-0.06%	possibly	-
Expansion of core sections in a caustic solution.	Further ASR gel formation, small contraction.	no	-
Shrinkage of core sections, 20°C, 65% RH	High shrinkage for sections taken from above and below rock fill level, 0.07 to 0.10 %.	possibly	possibly
Freeze-thaw resistance (section from above rock fill level), prism size 95x95x311 mm. ASTM C666 (Procedure A).	Low freeze-thaw resistance.	possibly	yes

Six cores were taken from the upstream face of the dam, including one taken 1.5 to 2 m below the top of the rock fill level. The following tests were carried out on sections of the cores: Internal crack distribution on sections impregnated with a resin containing a fluorescent dye and ground to achieve a flat surface. Examination of thin sections using a petrological microscope under plane and polarised illumination. Expansion of core sections maintained moist at 20 °C and immersed in a 1-M sodium hydroxide solution. Shrinkage tests. Freeze-thaw tests.

Summary of main observations and test results

The field and test observations are summarized in Table 1. Photographs of the internal crack distribution in a core taken from above the rock fill and in a section of core taken from below the rock fill level, are shown in Figs. 2 and 3 respectively. In the final two columns of Table 1, the question is considered as to whether or not the observations or test results are compatible with alkali-silica reaction or freeze-thaw attack being the mechanism which has led to the general deterioration of the concrete core wall above the rock fill level. It is concluded that the deterioration of the concrete in the exposed part of the core wall is due primarily to freeze-thaw attack and that ASR is unlikely to be a secondary cause of deterioration.

A REINFORCED BEAM

In the late 1970's it was concluded that a number of concrete structures in the South West of the UK had cracked as a consequence of ASR. The fine aggregate employed was a washed sea-dredged sand and the coarse aggregate a low-porosity limestone or granite. The cement used had an alkali content, at the time the concretes were cast, of between 1.05 and 1.4% by mass. In the 70's the judgement was made that ASR was the cause of deterioration because gel and cracked aggregate particles were observed in thin section. It is now known that such observations are not sufficient conditions for concluding that ASR is the cause of the visual cracking (Diagnosis Working Party, 1988 and 1992).

Table 2 summarizes the field and test observations made on more recent sections taken from one of the beams, where in the 70's the judgement had been made that ASR was the cause of the visual cracking. In the final column, a judgement is made as to whether or not each observation is compatible with ASR being the cause of the visual cracking. It is concluded that ASR is probably the cause of the visual cracking.

A PRESTRESSED BEAM

In 1974 four T-shaped prestressed beams manufactured in the North of England were rejected by a UK County Council on the grounds that the steel cover was inadequate. These beams had been cast in March 1974, subject to a steam cure for 16 hours prior to stressing and then at an age of about 24 hours stored in the Precaster's yard. The materials used in the beams were a RHPC with an alkali content of about 0.9% by mass, a siliceous limestone coarse aggregate and a natural sand. The cement content was in the range 450 to 500 kg/m^3.

An inspection of beams in the mid 1980's showed fine longitudinal cracking in the web and fine cracking in the lower flange. In 1989 tests were carried out by BCA to establish the possible cause of the visual cracking in the beams. Four 74 mm diameter cores were taken through the full width of the web of one of the T-shaped prestressed beams. Cores 1, 3 and 4 were 148 mm in length and core 2, which was taken through the shear region of the beam, was 245 mm in length. A visual examination of the cores indicated that they were of high quality and apart from core 2, no gel or white deposit was visible in the air pockets on the core surfaces. Two of the exposed air pockets on core 2 were partially filled with gel. From these observations it may be concluded that the intensity of the ASR reaction was low.

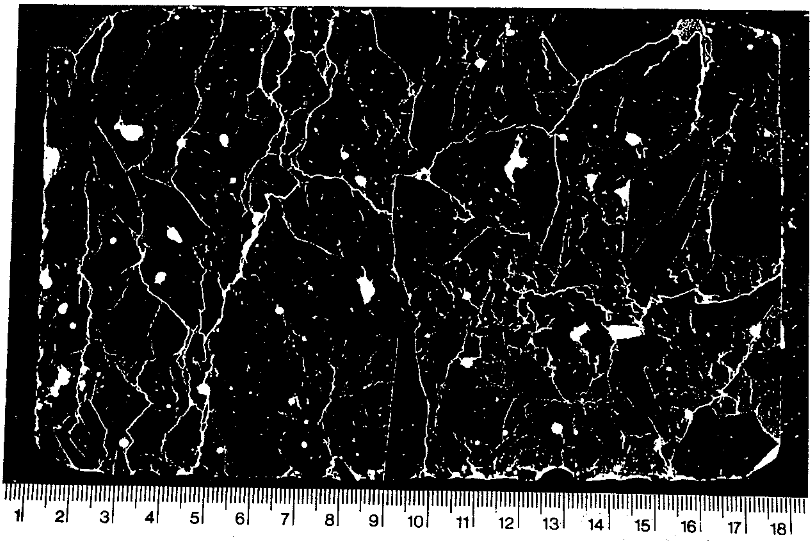

Fig. 2 Crack distribution in section taken from above rock fill level.

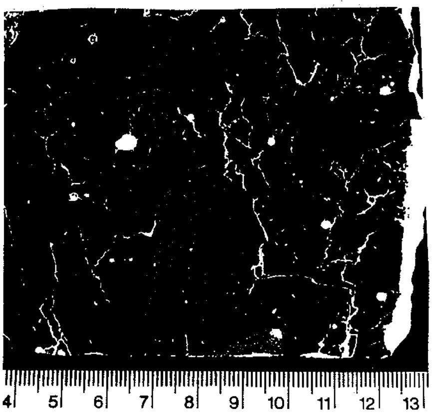

Fig. 3 Crack distribution in section taken from below rock fill level.

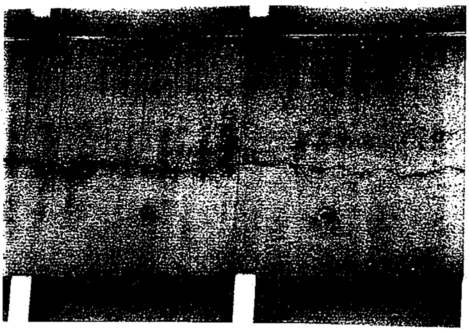

Fig. 4 Section of the exposed beam.

Table 2: Summary of observations. Reinforced beam

Observation	Comment	Is the observation compatible with ASR being the possible cause of the cracking?
Visual cracking (see Fig. 4)	Cracking characteristic of that induced by excessive shrinkage or expansion.	Yes
Age to cracking	< 5 to 6 years	Yes (Hobbs, 1994 and 1996)
Core examination	Macro-crack depth 15 to 45 mm, some gel filled air pockets, some cracked coarse sand particles.	Yes
Internal crack distribution (Fig. 5)	System of fine cracks interconnecting cracked aggregate particles in the coarser end of the sand fraction. Macro-cracks present but fine cracks absent in surface region (Fig. 6)	Yes (Diagnosis Working Party, 1992)
Thin section examination for gel	Isotropic gel, gel filled fine cracks, gel saturated paste.	Yes (Diagnosis Working Party, 1992)
Cement content	~ 470 kg/m^3	Yes (Hobbs, 1996)
Estimated original alkali content	4.9-6.6 kg/m^3	Yes (Hobbs, 1996)

Fig. 5 Section of affected core. Depth 40-57 mm (mm scale).

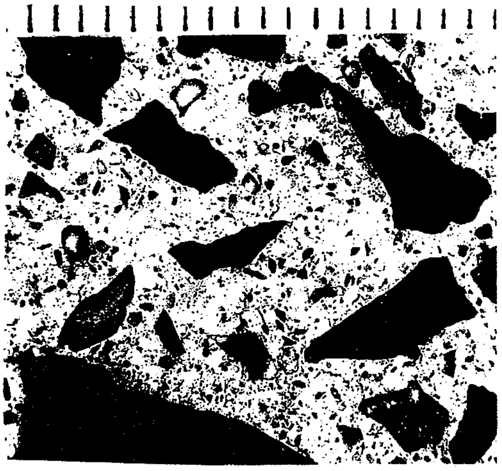

Fig. 6 Section of affected core. Depth 22-40 mm (mm scale).

Thin section examination

The petrographic examination of two thin sections, approximately 74 x 65 mm, prepared from a resin-impregnated section of core 2 showed the following: 1. Extensive fine-cracking with crack widths up to 40 μm but generally in the range 10-30 μm. 2. Fine cracks in the coarse aggregate and the cement matrix. These cracks skirted round the fine aggregate. 3. A proportion of fine cracks partially filled with ASR gel: the gel was present both within some limestone particles and the cement matrix. 4. Several voids, up to 400 μm in size, filled with ASR gel and several larger voids up to 3 mm in size rimmed with ASR gel. 5. Gel-saturated cement matrix close to some of the fine cracks which were partially filled with ASR gel. 6. An absence of reaction sites associated with the fine aggregate. 7. Small amounts of silica within some of the limestone particles in the form of small coarse-grained quartz crystals and lens-shaped inclusions of micro-crystalline quartz. 8. No evidence of reaction or cracking appeared to be associated with the visible silica present within the limestone particles. 9. No ettringite banding around aggregate particles. 10. Some secondary infilling of fine cracks by ettringite as single or groups of needle and tabular crystals.

From the thin section examination it was concluded, firstly, that the limestone coarse aggregate was the most probable source of reactive silica and secondly, assuming the sections examined were representative of the concrete, that ASR had probably not been of sufficient intensity to induce abnormal expansion and visual cracking.

Fine crack distribution

The fine cracking distribution visible under ultra-violet light in a full-width web section taken from core 2 and impregnated with a resin containing an ultra-violet sensitive dye is shown in Fig. 7. An examination of this figure shows that the fine cracks are uniformly distributed over each section. Little evidence of fine cracking is apparent within the limestone particles. Microscopic measurements showed that the width of the fine cracks was generally in the range 10 - 30 μm and that the 'macro-crack' crack visible on the surface of the web was approximately 50 μm in width.

A comparison of the fine crack widths in regions where it was suspected that ASR had occurred, with regions in which it was suspected that ASR had not occurred, showed no material difference. A comparison of Fig. 7 with Fig. 1 shows that the fine cracking in the web is untypical of that induced by ASR. The fine cracking has the appearance of being induced by a physical process, the limestone particles either expanding by more than the mortar matrix or alternatively contracting less than the mortar matrix. Such differential movement would induce tangential tensile stresses around the limestone particles and could, if the differential movement was of sufficient magnitude, induce the fine crack pattern shown in Fig. 7.

Limestone aggregate particles generally have a lower coefficient of thermal expansion than either cement paste or siliceous sand (Browne, 1972) and since the prestressed beam was steam cured shortly after casting, it is concluded that the fine cracks were probably induced by differential thermal contraction. Because of the uniformity of the fine crack distribution, it is also concluded that ASR had no material effect upon fine crack width or their distribution.

Conclusions

The following conclusions relate to the web of the particular steam-cured prestressed concrete beam from which cores were taken for examination:

1. ASR is neither a primary nor secondary cause of the fine cracking within the web or of the fine longitudinal cracking which is visible on the surface of the web.
2. The most probable cause of the longitudinal cracking on the exposed surface of the web is early age differential thermal contraction.

A WING WALL

In 1991 BCA carried out tests to investigate the cause of cracking in a section of a reinforced wing wall of a bridge in the South West of the UK . The cracked section was cast in the summer upon an uncracked section, probably cast 48 hours earlier.The cracks were first noted in 1985 when the bridge was about 11 years of age. The coarse aggregate was a limestone and the fine aggregate a natural sand. The cement content was about 480 kg/m^3 and since the wing wall was about 500 mm thick, it is probable that the early peak temperature within the concrete exceeded 80°C.

Three 94 mm diameter cores were taken from the wing wall to enable thin section and internal crack distribution examinations to be made. No evidence of ASR was observed on the surface of the cores, however, a white deposit could be seen lining some of the air voids.

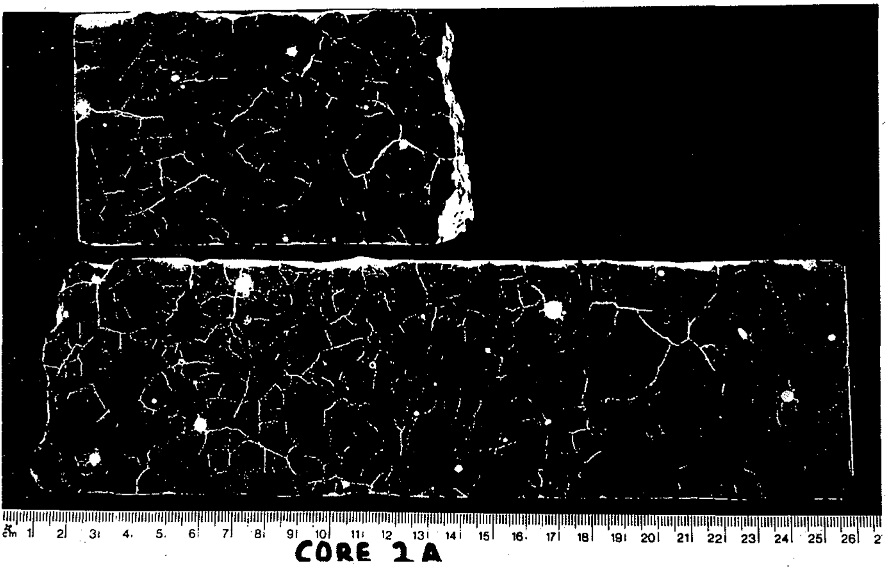

Fig. 7 Fine crack distribution in full width web section.

Thin section examinations

The petrographic examination of thin sections taken at a depth of about 400 mm from each of the cores showed the following:

- A high ferrite-phase Portland cement
- Fine cracking around the periphery of coarse aggregate particles and fine aggregate particles of up to 50 µm and 15 µm in width respectively (Fig. 8). These fine cracks were infilled, or partially infilled, with densely packed ettringite. Approximately 90 % of the coarse aggregate particles had periphery ettringite bands. Less than 50 % of the sand particles had periphery ettringite bands.
- The voids were rimmed with ettringite.
- Fine cracks were present running through the cement paste and skirting the sand particles.

In one thin section (Core 3), the following was also observed:

- A major macro-crack system, up to 100 µm in width, extending through the section and skirting the aggregate particles. It was judged that these cracks were induced by restraint to plastic settlement.
- One particle of cracked chert with associated gel (Fig. 9).

Fine crack distribution

An examination of the internal crack distribution in sections impregnated with a UV-sensitive dye showed the following:

Fig. 8 Ettringite band around limestone particle. Core 3. Magnification 280.

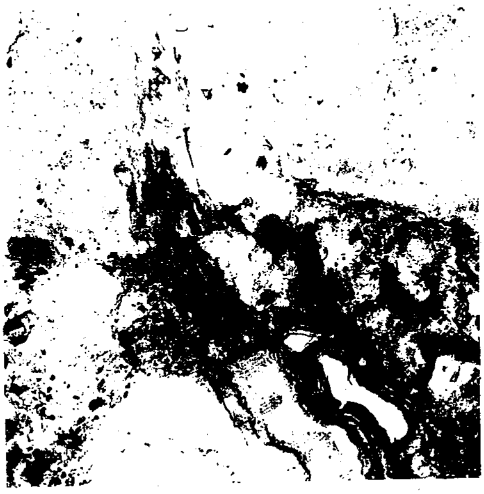

Fig. 9 Reacting chert particle showing cracking and ASR gel. Core 3. Magnification 210.

Cores 1 and 2: Discontinuous fine cracks together with some cracked coarse aggregate particles.

Core 3: A macro-crack at right angles to exposed surface of depth 73 mm, together with macro- and fine cracking inclined to the vertical axis. It is considered that this cracking was induced by restraint to plastic settlement.

Conclusions

In the following conclusions, it has been assumed that the sections examined were representative of the concrete in the wing wall:

1. The intensity of alkali-silica reaction is very low and would not have had an adverse effect upon the concrete in the wing wall.
2. The concrete in the wing wall has expanded as a consequence of 'delayed ettringite formation'.
3. The visual cracking in the wing wall is due to non-uniform expansion induced by 'delayed ettringite formation' (Hobbs, 1994).
4. It is estimated that the expansion induced by 'delayed ettringite formation' may be as high as 0.8 %.

ACKNOWLEDGEMENTS

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