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AN ENGINEERS PERSPECTIVE ON U.K. EXPERIENCE WITH ALKALI–AGGREGATE REACTION

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1. ABSTRACT

This paper reviews the developments of studies on AAR in the UK where the reaction has been found since the 1970's to be developing in a substantial number of buildings, bridges and water retaining structures. UK developments in specification to minimise the risk of ASR are presented in the context of their impact on construction practice. The evolution of research on materials, for diagnosis for structural assessment and to quantify the physical severity of the reaction, is discussed. Gaps in our knowledge which necessitate research are identified.

2. INTRODUCTION

The reaction of aggregate with alkali from cement in concrete was first identified in 1940 in a bridge structure in the USA. Alerted by this, UK studies started at BRS in the 1950's [1] to consider and evaluate the risks of a wide range of land aggregate sources with the then available cements. However, the cautions about checking new materials in these research reports were not carried through into BRE Digest 126 [2] which stated that AAR wasn't a UK problem. In 1971 Val de la Mare Dam in Jersey was found to have AAR [3], but that island was nearer France than the UK and the aggregate was unusual, so the mainland UK remained off guard.

It was in the South West of England that the first cases on the UK mainland of Alkali–Silica Reaction (ASR), were diagnosed in 1975. These were CEGB Transformer Station foundations and Charles Cross Car Park [4]. Since then a wide range of UK structures have been found to be suffering from Alkali Aggregate Reaction. There is a cluster of structures in the South West, others in the Trent Valley and isolated cases throughout the UK including one in Northern Ireland, an area which was thought to be immune until the Autumn of 1988!

In the South West (S.W.) Charles Cross Car Park and many of the other major structures with the reaction were built in the late 60's or early 70's using Plymstock Cement. At that time it had a high alkali content of over 1.2% sodium oxide equivalent (Na_2Oeq), giving alkali levels of over 6kg/m^3 in some cases where high cement contents (400–500 kg/m^3) were used. High alkali mixes have not caused problems where the aggregates are free of reactive proportions of silica. The main form of reactive aggregate in the S.W. has been found to be chert contained in a sea dredged material, used as fine aggregate. When mixed with either limestone or granite coarse aggregate, which are free of reactive silica, this gives a 'pessimum' proportion of reactive silica, with about 5% chert. This combination of aggregates with the old high alkali Plymstock cement has caused some of the most severe damage from AAR. Core expansions can exceed 2.5mm/m and cracking is often over 1mm wide. A number of the structures with this mix, which are being monitored, show the movement of cracks from the ASR continuing after nearly 20 years. Annual rates of crack width growth of over 0.1mm/year are not uncommon.

Studies on other structures in the S.W. have shown that a range of other aggregate types have produced AAR to damage the concrete. These include both aggregates containing cherts and quartzite giving Alkali Silica Reaction (ASR) and aggregates containing greywackes and argillites which produce an Alkali Silicate Reaction. Alkali Carbonate Reaction, the other variety of AAR, is still not thought to be a problem in the UK.

Similar problems are arising in the Midlands, Trent Valley, aggregates but with somewhat lower cement alkali levels. Structural damage and expansions are generally less severe and develop slowly. Trent Valley Aggregates are an all in one alluvial material with cherts and slower reacting quartzites.

The development of damage from AAR raised a range of questions for the owners of structures. They have put these to the engineering profession and, to the construction industry including cement and aggregate suppliers as follows:–

1. How are you going to prevent the reaction in new construction?
2. How do I know if my structure is free from the reaction?
3. If the structure has the reaction, does it reduce its safety or serviceability?
4. How much extra maintenance expenditure will be required?

The publication of the reports in 1987 and 1988, by the Concrete Society Hawkins Committee [5], Building Research Establishment [6] the Cement & Concrete Association/British Cement Association Palmer Working Party [7] and the Institution of Structural Engineers Doran Committee [8] provide balanced professional views on the current state of the art on these questions. However, the preparation of the documents and their application in industry have highlighted gaps in our knowledge and the need for further research.

3. MINIMISING THE RISK FOR NEW CONSTRUCTION

The Concrete Society Committee, chaired by Michael Hawkins of Devon County Council, on 'Alkali Silica Reaction – Minimising the Risk of Damage to Concrete' has made a major contribution to developing the understanding of ASR in the UK profession through conferences and publishing guidance. The original 1983 guidance [9], which was developed from BRE advice in 1982 [10], was based on consideration of the three essential components needed for alkali silica reaction.

i) The amount of alkali available
ii) The amount of reactive silica in the aggregates
iii) The availability of moisture

The view was taken that the majority of concrete structures have a proportion of their elements sufficiently damp for there to be a risk of the reaction, therefore control must normally be based on either limiting alkali levels or the selection of the aggregates. The majority of UK aggregate sources contain some minerals of potentially reactive types. The difficulties of evaluating UK aggregates to ensure freedom from reactive proportions of silica were such that the main emphasis was put on limiting the alkalis. Two approaches were adopted 0.6% and $3kg/m^3$. The first was based on the old American procedure of specifying cements with an alkali content guaranteed below 0.6%; however this cannot be achieved in the UK with OPC, although SRPC cement is supplied with guaranteed low alkalis. The other was the $3kg/m^3$ rule limiting the amount of alkali in the mix. The use of pfa and slag was put forward as a method of diluting alkali levels.

In 1985 a draft revision [11] to the original document was produced bringing in some new research results and including draft specification clauses. The 1983 Hawkins report had mainly considered the alkalis from the cement and discounted alkali contribution from pfa, slag, admixtures, or aggregates when used in the mix. In 1985 the scientific view had moved on and the water soluble alkalis from pfa and slag and alkali from sodium in NaCl in aggregates as well as alkalis from admixtures and water had to be considered. Following a period of discussion and public comment this 1985 draft was developed into what has been referred to as "Hawkins 3" which was published by the Concrete Society in November 1987 [5]. However, publication did not stop the controversy. The opinion of the cement makers [12] is that a higher proportion of the alkalis in pfa and slag might become available in the mix, but research data is uncertain. The Hawkins Committee recommendations have not been revised, but fuller research co-ordinated by Dr Nixon at BRE has been initiated to provide data. Those making concrete may well be inclined to maintain their legal position by following the cement manufacturers recommendations when using OPC with slag or pfa.

The BRE updated their recommendations on AAR as BRE Digest 330 in March 1988 [6]. This provides an excellent and balanced explanation of the reaction and its potential consequences. It acknowledges the cement makers view and, in the absence of clear scientific evidence, suggests that their pfa ($^1/6$ total alkali) and slag ($^1/2$ acid soluble alkali) recommendations should be followed. The other difference between the 1985 Hawkins document and the 1987 version is that the definition of the $3kg/m^3$ has been revised and slightly relaxed. However this tends to be balanced by the tighter quality control now applied to the variability of alkalis in UK cements.

The Department of Transport (DTp) [13], which has pioneered UK specification against ASR, adopts slightly more rigorous rules. Hawkins 1987 bases alkali limits of cements on the monthly average alkali content, while the DTp uses the average plus 2 standard deviations. Hawkins puts a qualified 5% limit on cherts, but DTp uses a 2% limit. Many cases of ASR have chert proportions in the mix of the order of 5%. However, in considering the difference between the DTp approach and Hawkins it must be remembered that bridge structures are particularly liable to AAR because of the damp conditions and risk of salt ingress. They fall into the category classified as 'more vulnerable construction' in clause 4.3 of Hawkins, which may require extra precautions.

The title of Hawkins clearly states "Alkali–silica Reaction – Minimising the Risk of Damage to Concrete". The structures where serious damage has occurred generally have substantially higher levels of alkali than the $3kg/m^3$ limit so it will substantially reduce and minimise occurrences of AAR damage. One cannot be sure that it will eliminate AAR. It does not consider alkali–silicate or alkali carbonate reaction nor are rules available for aggregates containing opal for which lower alkali limits are necessary; fortunately opal is rare in UK aggregate sources. The alkali levels of UK produced cements are now substantially lower than they were in the early 70's. For example Plymstock which was over 1.2% is now typically of 0.8% alkali content. Thus it is not difficult to achieve the limits of alkalis set out in the Hawkins document, provided that water/cement ratios are kept down to achieve the strength required. The somewhat lower cement contents appropriate to minimising the risk of AAR have beneficial effects in reducing shrinkage and excess thermal effects. Similarly the introduction of pfa or slag into mixes to assist in the control of AAR can (provided they are well cured for a sufficient period) give benefits from the less permeable microstructure of the concrete.

British Standards are being developed for concrete prism expansion tests and to cover guidance on petrographical examination of aggregates. This will in time enable more emphasis to be put on selecting non–reactive aggregates, as a means of controlling AAR, as is the practice in USA, Canada and Japan. The high proportion of aggregate sources containing flints, chert and quartzites makes the non–reactive aggregate option difficult in the UK, but it is used on some major structures where the scale and importance of works justify the detailed petrographic inspection and testing.

While AAR control is now recognised as an important part of concrete specification the three main priorities in ensuring durable concrete are the avoidance of:

i) Inadequate cover.
ii) Low grade concrete, poorly compacted and cured leading to premature spalling from carbonation triggered corrosion.
iii) Chloride induced corrosion.

4. DIAGNOSIS OF AAR

The well publicised cases of AAR have to a degree produced a hypochondria and a demand for diagnostic checks for AAR. A wide range of methodologies have been suggested. The Palmer Committee (the C & CA/BCA Working Party, chaired by Dennis Palmer) has recently produced "The Diagnosis of Alkali Silica Reaction" [7]. This sets out the range of tests available for diagnosis from which a cost effective and appropriate set can be selected by the Engineer for a particular structure. Normally AAR checks are only desirable if:–

a) the structure is showing unusual cracking. The checking of the possible causes of cracking should follow the approach in the Institution of Structural Engineers 'Appraisal of Existing Structures' [14] and Concrete Society, TR22 'Non-structural Cracks in Concrete' [15]. ASR should be considered as only one of many possible contributory causes of cracking.

b) the structure is known to have mix characteristics which are similar to those in other cases of AAR.

The Palmer Committee document enables the Chartered Engineer checking the structure to commission appropriate tests from experienced materials laboratories. If AAR is present in the structure on the basis of these diagnostic tests, its structural significance should be considered on the basis of the Institution of Structural Engineers Doran report on Structural Effects of ASR [8].

5. THE STRUCTURAL EFFECTS OF ASR

In December 1988 the Institution of Structural Engineers published 'Structural Effects of Alkali-silica Reaction, Interim Technical Guidance on Appraisal of Existing Structures' [8] and it is summarised by David Doran and John Moore [16] at this Conference. A study tour [17] of research centres and structures in Japan greatly assisted in the evolution of the report.

In our experience the majority of cases where petrography indicates AAR can be categorised as having little structural significance, either because the magnitude of expansion from the reaction is small or the structure is robustly detailed with good reserves of strength to make it insensitive to the effects of the reaction. Remedial works are required only in those parts of the structure with:

i) the most severely expansive material and/or
ii) highly stressed elements and/or
iii) in damp conditions and/or
iv) lacking well anchored 3-D reinforcement.

However, any above ground structure with the potential for expansive AAR can benefit from a degree of cladding and improved drainage to help dry it.

The Institution of Structural Engineers Report [8] is an interim document and provides a reasonable basis for assessing those structures which are well detailed and in which the degree of cracking from expansion to date and potential for further expansion is small. For the structures where there is a more substantial problem, specialist investigation is recommended. A number of new techniques are being evolved both in the investigation of particular structures and in research on laboratory concretes now underway at BRE, The University of Birmingham, Plymouth Polytechnic, BCA etc..

Mott, Hay & Anderson, Special Services Division working with the local offices of the Mott MacDonald Group, have carried out detailed studies on over 100 structures with AAR in the UK and overseas. Cases include bridges, dams, water retaining structures, a multi-storey car park and multi-storey commercial and public buildings. The specialist techniques developed have been set out in a series of papers which are referenced in [18]. Expansion tests are discussed in the Palmer Report and form the basis of the Institution of Structural Engineers grading. Our tests for expansion cover temperatures from 38°C to 5°C with and without restraint, freeze/thaw and site exposure. The interpretation includes consideration of the variability of expansion in concrete and its relationship to weight change from moisture uptake. Coring and sampling techniques are particularly important, if sufficient representative samples are to be obtained without damage to the structure. Surface grinding of local areas of concrete, so that aggregate types can be determined at low cost with little damage to the structure, has greatly simplified the checking of the materials in structures.

We have been developing a stiffness damage test to provide a quantitive measure of the degree of microcracking damage to the structure of the concrete. This is linked to strength testing for the compressive and tensile strengths of concrete which is combined with expansion data in finite element analysis of effects to compare with large scale tests. We have also evolved techniques of measurement of insitu relative humidity in concrete to evaluate its effect on the rate at which cracking from the reaction develops. Tests are in progress to evaluate the effects of coatings and exposure conditions on the rate of expansion and changes in moisture uptake of concrete samples.

Using these techniques the majority of the structures we have assessed have been classified in the mild range for which management can be based on:–

i) Improvements to waterproofing.
ii) More frequent monitoring of the structure.
iii) Additional protection to prevent secondary deterioration due to corrosion and frost action.

Other structures have needed a degree of strengthening of weakened sensitive details. In some instances this has been made necessary by low reserves of strength inherent in the original design or standard of construction. Structures with AAR often have a number of other peculiarities (eg. increased loading, thermal cracking, badly placed steel etc) which need to be dealt with in the overall structural management. This is one reason why the work should be handled on an engineering basis with material science support rather than purely as a materials and testing study.

6. RESEARCH

From the perspective of Practising Engineers the following are of the highest priorities for the UK research on Alkali–Silica Reaction. We would hope that co–operation and exchange of information with our colleagues around the world will help these endeavours:

a) Specification.

i) The better fundamental understanding of the sources of alkali in concrete over the 100 year timescale at normal temperatures and environments from cement pozzolans, aggregates and sodium chloride, including the effects of migration of alkali within the concrete.
ii) Improved assessment and classification of source mineral deposits for aggregates using petrography, concrete prism expansion tests and chemical testing to categorise clearly non–reactive materials and the long term safe limits of alkali appropriate to the UK types of silica, silicate and carbonate reactive minerals.

b) Management of existing structures.

For the existing stock of structures with alkali–silica reaction the long term priorities are as follows:

i) A better knowledge of the rate of development and timescale of the reaction in large members subject to low fluctuating temperatures and limited water supply. These conditions apply to actual structures, and are distinct from the artificial conditions in the majority of research.
ii) Improving techniques of monitoring the behaviour of structures in the field.
iii) Prediction of the rate of deterioration from primary alkali–aggregate reaction with secondary deterioration from frost action and corrosion initiation down cracks, especially in structures subjected to de–icing salts and in marine conditions.
iv) Determining changes to the strength and ductility of structural elements with the more sensitive types of detail identified in the DABI paper [19] and commonly found in 1960's and 1970's UK concrete structures with the reaction. This includes establishing the sensitivity of structural behaviour to the load and restraint applied while the reaction is developing.
v) Further developing the quantification of physical changes in AAR affected concrete in a way which can be input into finite element analysis for comparison with structural testing.

7. CONCLUSION

We now know how to minimise, but not eliminate, the risk of alkali silica reaction in new structures on the basis set out by the Hawkins Committee and the DTp. Techniques of diagnosis are available and can be used in a balanced and cost effective way to identify structures which may be at risk of damage from AAR. In the small proportion of structures which have significant AAR, detailed overall assessment of the behaviour of the structure in terms of material and structural behaviour can be carried out. This provides a basis for maintaining the function of a wide range of structures at a reasonable cost consistent with minimising disruption. However there is still a need for further research to provide the most cost effective approaches to specification and management of structures.

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