SPECIFICATION FOR MAJOR PROJECTS

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The effectiveness of current specifications and laboratory testing procedures in preventing AAR in major projects have been reviewed relative to construction contract requirements and to data from AAR damaged structures. Priorities have been identified for the developments required to reduce the risks of AAR damage in the future.

INTRODUCTION

Standards and test methods for specifications to reduce the risk of alkali aggregate reaction have been evolving since the 1940's. Most of these have been tailored to particular local conditions of aggregate or cement supply. It has become apparent that many are unreliable when used generally. The increase in published knowledge has not prevented AAR developing in countries where it was previously unrecognised [eg UK in the 1970s (1) (2), France in the 1980s and Holland in the 1990s] and recurring where it has been an acknowledged problem [eg North America and Denmark]

It is therefore necessary to critically reassess how developments in specification, testing and research on Alkali Aggregate Reaction meet the needs of the purchasers of concrete structures and the construction industry that supplies them The last decade has seen substantial improvements in National Standards and Guidance Notes (3) (4) to reduce the general risk of AAR in construction. However, in some important respects, they are not sufficient for economic, simple and reliable application to meet the contractual obligations of the Construction Industry. In particular there are substantial uncertainties in the specification for sensitive long life major structures such as dams, bridges, nuclear installations, hazardous waste disposal sites and prestige buildings. The growing international trade in aggregates, cementitious materials and precast concrete elements both increases the risks and makes the conflicting national recommendations on AAR a problem for industry.

We have had to evolve suitable AAR specification clauses for major Mott MacDonald Group bridge, tunnel and water management projects in Europe, Africa, Far East and North America. These requirements have been developed from national standards and research, into specifications to suit the local materials, the environment and contract requirements. We have

also applied the results from our detailed studies and remedial work (1) (5) on over 100 structures with AAR damage. This paper aims to highlight the construction industry's priorities for AAR research for the next decade so that reliable specification can be more readily achieved.

THE LABORATORY PERSPECTIVE

The understanding of Alkali Aggregate Reaction in the laboratory has largely come for the ASTM C227 mortar bar expansion test and its derivatives and from microscopic analysis of aggregate minerals and their reaction products. This has developed our understanding of the range of reactivity of siliceous minerals in strong alkali solutions, from inert unstrained alpha quartz to rapidly reacting amorphous opals. The behaviour of rapidly reacting minerals (opals, fused silica, etc) is easily identified by mortar bar or chemical tests, and they have had a disproportionate emphasis in research. Remaining uncertainties with these minerals relate to the upper and lower bound proportions at which the long term expansion will produce damage at different levels of effective alkali, especially with pfa and slag.

The risks of expansion induced damage over the long term at intermediate alkali levels with many commercially available construction aggregates containing some potentially reactive minerals has yet to be reliably quantified. The slower reacting minerals are more difficult to classify as the traditional mortar bar tests and concrete prism tests do not pick up the full potential expansion in a one or two year test, and so may erroneously classify an aggregate as innocuous.

The necessary yardsticks for the calibration of the acceptance criteria for chemical tests or expansion tests against field performance are not yet available. A substantial amount of reported research calibrates new tests against the discredited ASTM C227 test, which does not inspire confidence in the innovation. Bérubé (6) has recently suggested a limit of equivalence with low alkali cement [ie 0.1 mm/m at 1 year] for the CSA concrete prism test, compared to the 1.0 mm/m of traditional mortar bar tests. Perhaps the criteria should relate to the time when the expansion has ceased rather than an arbitrary time limit.

We know that reducing alkali levels reduces the risks. It is less clear whether there is a cut off or a progressive reduction in the rate of reaction with lower total alkalis. We do not know for field conditions if "3 kg/m³" is reliable. Some analyses of AAR damaged structures show levels close to or less than 3 kg/m³ of alkali. This suggests that we should be cautious with some aggregate types, particularly in vulnerable structures like dams and foundations.

The emerging evidence shows that silica fume, once hailed as a panacea, acts only to delay the damage not to prevent it. This should make us careful in our evaluation of the reliability of rapid testing particularly with pfa and slag which delay any reaction as well as influencing effective alkali levels.

The prime questions for laboratory research to tackle in the next decade are:

1.   What level of expansion is damaging in the field ?
2.   How do short term accelerated expansion tests at higher temperatures and humidities or immersed in hot alkali solution relate to field expansion over 60 to 250 years?

3. How does the size range distribution of aggregate particles in tests and in the field relate to the rate and ultimate magnitude of expansion?
4. How can we obtain sufficient data on the alkali and mineral compositions in damaged and undamaged parts of structures with AAR, and adjacent undamaged structures with similar concrete composition, to calibrate the laboratory chemical or expansion tests?
5. What are the threshold alkali concentrations for long term damaging reaction for different mineral forms of silica and for mixtures of them, as found in the field?
6. How can these alkali concentrations be related to 'effective' alkali contents of cementitious materials, aggregates and admixtures in specifications?
7. How can we distinguish between the delaying effects of pfa, slag and silica fume on expansion and their long term effect in suppressing damage?

THE REQUIREMENTS OF THE CONSTRUCTION CONTRACT.

The designer's brief from the client and the specification to the contractor are legal documents with substantial financial implications for all parties both during construction and if problems arise later. Too onerous and restrictive a specification can cause both delay in approving concrete mixes and additional cost for the transport of cementitious materials and/or aggregates from a distance.

In the U.K. the reasonable good practice is set out in the Concrete Society TR30 "ASR-Minimising the risk of damage to concrete"(3). This document has substantially reduced the risks of recurrences of Alkali Silica Reaction in U.K. construction. It is primarily intended for reasonably well reinforced concrete building structures with a 60 year nominal design life. It gives warnings about a number of uncertain hazards which it does not cover eg foreign materials, alkali carbonate reaction and 'silicate' reaction, alkali contribution from aggregates, alkali migration, etc. It is at variance with cement makers and BRE advice on effective alkali levels from pfa and slags, but the Concrete Society is promoting research to clarify this issue. It is in the nature of construction industry that one is not infrequently faced with these cases where reasonable good practice just says 'Beware'.

The generally used alkali control option in TR30 is based on a nominal 3 kg/m^3 alkali limit from all source, which in practice can permit alkali levels of up to a little over 3.5 kg/m^3. While this limit has certainly reduced risks there are some structures where the mineral types, the potential for alkali migration, the sensitivity of structure and/or its long design life make more rigorous limits on alkali or the non reactive aggregate option more appropriate.

Aggregate Evaluation. Many UK construction contracts contain a catch all "no deleterious materials" requirements and so the detailed specification must cover the carbonate and 'silicate' reactions, which are not covered in the Concrete Society TR30, as well as the limits of pyrites, shrinkable aggregates, porous frost sensitive aggregates etc.. The dropping of the "no deleterious material" provision in British Standard for aggregates just means it has to be covered explicitly in the contract specification. We await the Euro Codes with interest!

It is important for the composition of commercial aggregate supplies to be regularly audited by a qualified petrographer to assess the source deposits and the processing as well as the regular run of production samples. The vague description of rock types on a two year old one small bag sample, which is hopefully offered as proof of 'non reactive' aggregate,

on the morning of the first pour, can never be acceptable. This 'one old bag ' procedure is international, we have had it from US contactors on a multi-billion dollar project in New England as well as in the UK. The 'rudimentary consideration of aggregate composition' (TR30 para 6.3.1) is only contractually reliable where it concludes that an alkali limit will be the basis for the control of AAR. Even then, to meet the TR30 limitations, the report on aggregates must also confirm that there is no opal and that the rocks are not of the types associated with carbonate or 'silicate' reactions.

For major contracts where aggregate supply may be critical there is a strong case for potential aggregate sources being checked for the client prior to contract, with the details being made available to tenderers. Other aggregates could only be approved on the basis of similarly rigorous evaluation. This unlikely to be possible during the timescale of a normal contract unless the supply has been subject to regular petrographic audits.

We have found some practical difficulties in using the 'rocks and minerals unlikely to be reactive' table in TR30. Although it is applicable only to UK rock types, virtually every rock type listed is associated with alkali aggregate reaction in some other part of the world. We prefer to base the evaluation of aggregates on specialist petrographic examination of the source deposits to establish the range of mineral types. This should take into account bedding in sedimentary deposits, variations within alluvial deposits and intrusions into rocks which may produce local alterations. The identification of potentially deleterious minerals extends beyond AAR checks to cover sulphates, shrinkable aggregates, etc. Tests methods are then tailored to the mineral types found to determine their reactive characteristics and then, using simpler rapid test methods, to monitor for changes in the run of production.

Once the basic mineralogy of the rock source has been established a decision can be taken to classify it as:
a) Consistently and reliably dimensionally stable in service conditions.
b) Mostly stable and non-reactive but selective extraction or blending will be necessary with specific tests to monitor its characteristics and reject uncertain material.
c) Potentially reactive and expansive unless alkali levels are controlled to a defined limit.
d) Unsuitable for concrete.

In this categorisation it must be positively established that aggregates will be stable and non-reactive. It is not sufficient for major projects to rely on vague views based on past performance of possibly similar cement and aggregate source or on uncertain rapid test data.

Special Structures   Many clients for major structures [eg Storebaelt Tunnel] specify 100 year design lives. For the containment of nuclear and hazardous wastes a longer period of absolute security is required. Dam structures are particularly wet, prone to the migration and concentration of alkali, and are sensitive to very small expansions which can open fissures between successive pours of concrete and which may distort flood control gates, turbines, etc. While an expansion of 1.0 mm/m may only cause marginal damage in a well reinforced structure, expansions of less than 0.5 mm/m can cause serious operational and serviceability difficulties and significantly reduce overall safety margins in dams.

No general specification requirements can be written to cover the range of criteria appropriate to different types of special structures, so their specifications must be individually tailored to the use, structure sensitivity and the local environment.

THE CHARACTERISTICS OF AAR DAMAGE IN THE FIELD.

The following points are based on our evaluation of the field performance of many different types of structures with AAR damage ranging from the trivial to the severe.

Expansion Rates. Expansions of only 0.6 mm/m developed in the steady dampness of a dam over 30 years have caused major damage to an arch dam. This represents only 0.02 mm/m/year expansion rate compared to the 1.0 mm/m/year for ASTM compliance.

In appraising over 100 UK structures (7) with slight to serious AAR damage we have found that crack summation, in areas of low stress which are lightly restrained by reinforcement, gives estimated total expansions after 20 years (typically 1970 build, monitored 1985 to 1990) of 0.6 to 6.0 mm/m, that is 0.03 mm/m/year to 0.3 mm/m/year. Detailed monitoring indicates that crack growth over the last 5 years (1985-90) on average showed a linear growth rate similar to that which developed the cracks over the first 15 years. This type of field expansion rate data needs to be related to the reactive mix composition to provide a basis for calibrating laboratory expansion tests with real structures as discussed above. The effect of temperature needs more consideration as some evidence (5) suggests that expansions can be greater, but slower, at normal structure temperatures than at elevated laboratory test temperatures.

Structure Type. The structural effects of AAR are very sensitive to the stress states in the structure and to the restraint provided to expansion and cracking by the reinforcement. The Institution of Structural Engineers revised report 'The Structural Effects of ASR' (8) now puts more emphasis on this when appraising the effects of AAR damage. Reinforcement cannot fully control AAR damage because serviceability problems will still arise, so this cannot provide a basis for relaxing standards for concrete mixes. However the particular sensitivity of concrete members where the reinforcement is light or does not provide a full well anchored 3D cage may make tighter controls appropriate. Takeing the three reinforcement categories, shown in Figure 1, based on the IStructE report, limits of 1.0 mm/m for Class 1, 0.6 mm/m for Class 2, and 0.3 mm/m for Class 3, might be appropriate for the acceptable maximum expansion during the planned service life.

Movement Sensitivity Structures are normally designed to resist or accommodate movements due to overall and differential temperature effects, including early thermal stresses. This will normally permit small movements due to overall AAR expansion to be accommodated without difficulty. However, where steel machinery, eg large turbines and power generating equipment, is fixed to a block of concrete with AAR it will try to resist the expansion. The consequent forces on the equipment may distort or fracture it. Dam structures are particularly sensitive to this as the accumulation of a relatively small expansion over the large scale of the structure can disrupt the operation of flood gates or create cracking which disrupts the key between the dam structure and the bed rock. If these features are part of the overall design of a major structure then the limits of acceptable expansion may have to be more tightly restricted than those suggested above.

Secondary Deterioration.   There are many examples of the adverse interaction of AAR with frost damage, corrosion etc.. Salted highway structures and marine structures are particularly at risk because, while the sodium aggravates the AAR, the chloride initiates and accelerates reinforcement corrosion. There is a case for more rigorous control of aggregate types and initial alkali levels in these circumstances. Cladding panels on buildings and parapets and soffits   on bridges, where spalling of concrete from the interaction of AAR, frost and/or corrosion can create a public hazard, may also merit extra precautions.

Severe Environments. The Concrete Society TR30 (3) draws attention, in para 7.1 and 7.3, to the need to consider alkali migration and concentration, but it makes no recommendations. These effects can be a particularly important in slabs and blocks in wet ground with surfaces exposed to drying (9), retaining walls and basements, tunnel structures and in chemical works. Where the ground treatment, the cementitious grout and/or the ground water contain sodium or potassium the normal problem of migration of the alkali in the concrete from wet to dry areas becomes aggravated by the supply of additional alkali. In some cases design detailing for drainage and the provision of waterproofing can prevent the concentration process. In other cases, particularly tunnels in saline ground water, rigorous control of aggregates to ensure they are not reactive at high alkali levels, is the only reliable approach.

Good Track Record.   The "we have never had a problem here" approach to specification persists as an excuse for not following a straightforward specification, such as TR30, to minimise the risk of ASR. Almost every case of AAR in the UK used materials which had no previous record of problems at the time of construction. The increase in the transport of aggregates and cementitious materials is substantially increasing risks of AAR, unless rigorous specification is used.   Previous records of use must be thoroughly checked by detailed analysis of a range of old structures before they can be considered relevant to the approval of materials for major structures. This may be more expensive and less reliable than checking current materials at source.

Variability.   Concrete on site, ie 'Realcrete', is substantially more variable than 'Labcrete'. In preparing concrete prisms for testing for expansion every effort is made to achieve uniformity of water/cement ratio, cement content, aggregate grading and composition. On site a large variability is inherent in the mixing of materials and substantial segregation normally occurs during the actual casting process. Comparisons of the expansion of cores removed from the same pour of structures show a high degree of variability both between cores and within cores in:

   a) the petrographic evaluation of the degree of microcracking, the estimated cement content and water cement ratio and in the proportions of reactive minerals within the aggregate.

   b) The expansion of adjacent 50 mm lengths of cores on expansion tests will typically range from 0.5 mm/m to 2.5 mm/m on a core with a 1.5 mm/m average expansion. It is clear that the internal stresses generated by this variability of expansion are a major factor in causing internal micro cracking and loss of tensile strength and stiffness.

   The examination of the variation of the chert content and the monitoring of movements in large specimens cut from structures during remedial work illustrates the same phenomena on a larger scale.

It is a general feature of large structures with AAR, all built with the same sources of aggregate and cement, with the same nominal mix throughout and with the same level of exposure to wet conditions [eg comparing above ground columns with above ground columns, buried foundations with buried foundations etc] that half the pours of concrete will show no damage after 20 years while the damage in other similar pours ranges from slight to severe cracking.

In relating laboratory concrete prism tests to site conditions the magnitude of site variability must be quantified and allowed for with a sufficient factor of safety. Thus if the average chert content is 5% in an aggregate supply it is likely to vary to between 2 and 10% within pours of concrete. The 10% chert material which is close to its pessimum will be the prime cause of damage even though it may only occupy 5% of the total volume of concrete.

Similarly the alkali content which creates reaction relates to the concentration in grams in a 100 mm sided cube [g/l] rather than kilograms in a cubic metre. In a laboratory prism 5 kg/m^3 may be required to create significant damage. In a structure the 10% of material at 5 g/l within a pour with an average 3.5 kg/m^3 may well cause unacceptable damage. It is only by the rigorous and detailed post-mortem analysis of concrete structures with AAR damage and of nominally similar concretes that are undamaged that we will be able to establish the factor of safety needed between laboratory results and field performance. Relating mortar bar results to "Realcrete" is probably too speculative to justify the effort.

CONCLUSIONS.

The contract specification for a specific structure requires aggregates for concrete to be rigorously classified as: 'Unsuitable', 'Suitable below a defined safe alkali level,' or 'Suitable at any alkali level'. The criteria for this need to be based on the environment, structural form and design life of the structure.

The procedures for defining safe alkali levels need much more research. Much of this must be based on more extensive and rigorous analysis of structures in the field.

Unless aggregate producers have already carried out comprehensive geological and petrographic evaluation and testing of the source deposits and established the variability of the material produced, they should not be considered for major projects.

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CLASS 1   CLASS 2   CLASS 3
Hooked or Welded   Conventional   No Through Ties   Light Steel or
                                        No Links or   Mass Concrete
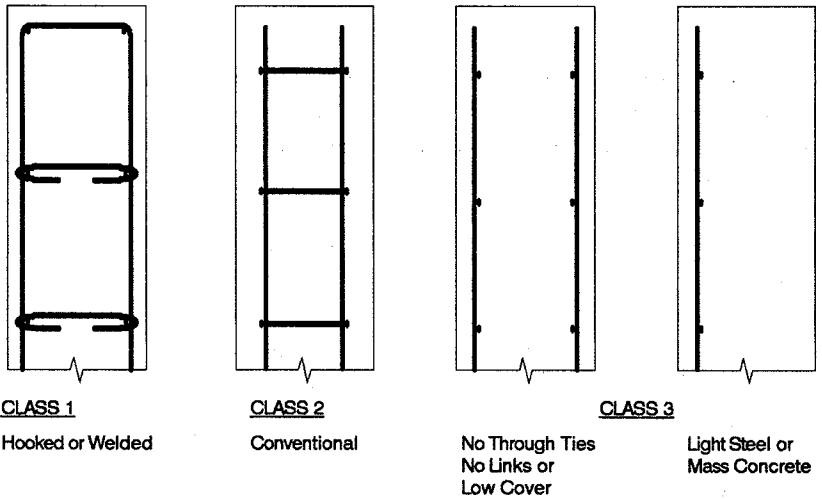   Low Cover

Figure 1: Detailing Classes For Walls & Slabs