Structural effects of alkali-silica reaction.
Technical guidance on the appraisal of existing structures.

Addendum, April 2010

1. Introduction.

1.1 Alkali Aggregate Reaction (AAR) was first recognised in structures in the UK in about 1980. At that time there was very little information worldwide on the effects of AAR on structural behaviour, on the time scale over which AAR damage developed, or on the practical management of cracked structures.

1.2 Testing and monitoring of a wide range of UK structures, combined with research and experience from around the world, provided the information for the 1988 edition of the Institution of Structural Engineers ‘Structural effects of alkali-silica reaction. Technical guidance on the appraisal of existing structures’. This was further developed and refined in 1992 [1] and launched at the 1992 ICAAR conference [2]. It has provided a practical basis for the appraisal of a wide range of structures [3] and its principles have been adopted in other countries [4]. However there have been some important developments internationally since 1992.

1.3 The ‘Hawkins’ rules [5], introduced and developed in the 1980s and updated by BRE [6], recommended limiting the alkali content in concrete in the UK. This has achieved the objective of minimising the risk of AAR in new construction. So there have been relatively few new UK structures with AAR, none of which are classified as ‘severe’. RILEM is developing AAR-7-1 International Specification for Minimising Risk of AAR [7] which confirms and supplements earlier UK recommendations. It is linked to improved tests and petrographic interpretation for assessing aggregates.

1.4 UK research activity on AAR has diminished, but continuing monitoring and management of older structure has yielded some further valuable information [8]. A wide range of reactive minerals in aggregate can give rise to damaging alkali aggregate reaction and this, rather than ‘alkali-silica reaction’, has become the preferred general term.

2. International Developments.

2.1 The number of cases of AAR worldwide continues to increase and more structures have needed major remedial work or replacement. There are now 47 countries where AAR has been reported, up from 35 in 1992 [9]. However RILEM, which is drawing up an atlas of known reactive rock types, has found that many owners and countries are reluctant to publicise cases. The indications are that few, if any, countries are free from AAR. The growing international trade in cementitious materials and aggregates is increasing risks.

2.2 A number of countries, e.g. France and the Netherlands, which had considered themselves free from AAR in the 1980s, have found damage from AAR in bridges, dams, roads and buildings. They have initiated major research programmes yielding valuable new information from laboratory programmes and testing and monitoring damaged structures. Other countries, e.g. Canada and Japan, have maintained their active research programmes which are progressively improving our understanding.

2.3 Many of these developments have been published, but scattered in the specialist literature. However the ICAAR conferences [2 and 10 - 13], held every three or four years, have brought together papers on research and case studies of materials and engineering practice from around the world.

2.4 Increasingly AAR research is carried out in international cooperative research programmes. RILEM has become the focus for this international cooperation and maintains links with the ICOLD committee working on the particular problems that are developing worldwide from AAR in dams.
2.5 RILEM Technical Committee TC 191-ARP Alkali-Reactivity & Prevention: Assessment, Specification and Diagnosis is actively developing improved guidance, drawing on the full range international research and practical experience of structures. It has published recommendations 6-1 Diagnosis [14] which supersedes the UK procedures recommended in 1992. This is linked to improved test methods, some of which have been validated, while others are still being developed and evaluated in international inter-laboratory trials. It recommends that, from the start of an investigation, there should be close links between the materials science team inspecting and testing for diagnosis and structural engineers carrying out appraisal [15].

2.6 The drafting of RILEM TC 191-ARP 6-2 Guide on Appraisal and Management of Structures [16] is progressing, with publication hopefully in about 2013. It will be linked to a guide setting out the developments in the modelling the structural behaviour of concrete elements and overall behaviour of structures with AAR. These modelling studies are being calibrated against the long term laboratory testing of concrete beams in controlled conditions and the observed behaviour of structures suffering AAR damage.

3. Significant developments

3.1 The overall philosophy and principles set out in the 1992 IStructE report have gained wide acceptance around the world. It, with material from similar national recommendations, is the framework which RILEM is using to develop its guidance on Appraisal and Management. The RILEM recommendations will include some changes in emphasis, the most important of which are summarised below. More detailed information on developments can be found from ICAAR proceedings.

3.2 Over-reaction to Traces of AAR.

3.2.1 There have been some UK cases where a petrographic examination of cores has identified signs of AAR, but there is little cracking attributable to AAR in the structure. If properly assessed these would be classified in Table 5 ‘Structural severity rating’ as ‘n – negligible’. In some instances demolition has been recommended to the owners before the structure has been assessed for ‘structural severity’ following IStructE recommendations.

3.2.2 It needs to be stressed that 95% of structures with signs of AAR from cracking and confirmed by petrography, need no action other than improved protection and drainage and inspection in accordance with Table 7. Isolated particles in many UK concretes will show signs of AAR under the microscope. This should not be judged without site inspection followed, if appropriate, by full structural assessment.

3.3 Monitoring Cracking and Expansion.

3.3.1 A major uncertainty when the IStructE recommendations were being drafted was the duration of crack development and damage in structures. There were suggestions that it exhausted itself after about 10 years.

3.3.2 Monitoring of structures in the UK [17] and internationally, has now shown that, once cracking is established, generally after about 5 years, cracks will grow at a broadly linear rate as further expansion occurs in the mass. There are few reported instances of the damage development slowing up or stopping, even after over 50 years, unless measures have been taken to reduce the moisture in the damaged elements. The rigorous long term monitoring (16 to 18 years) of expansions of cast blocks with OPC, as part of BRE AAR exposure site programme [18], has confirmed this linear expansion with time with no sign of it slowing up.

3.3.3 This clear evidence that AAR damage and cracking does not stop makes it essential that structures diagnosed in the 1980s and 1990s have a full specialist re-inspection and reappraisal.
3.3.4 In the UK monitoring has mostly been carried out using groups of Demec gauge lengths in 'Triples' across and parallel (to give seasonal thermal and moisture movement correction) to cracks in representative areas. The crack movements reflect internal expansions. Trends often take 2 or 3 years to become clear and need to be based on groups of cracks.

3.3.5 Improvements in instrumentation are making it easier to monitor overall expansions. In France, LCPC [19] have used this on several structures. The influence of restraint in each direction on expansion needs to be considered. Compressive stress from normal structural behaviour and prestress, (and that developed by the restraint of expansion by reinforcement), must be considered in planning and interpreting this data. Monitoring of overall movements and differential movements at joints has been of particular value in dams. Relatively small expansions can cause problems, but are measurable over the height or length of a dam.

3.3.6 In almost all structures there is a trend of steady growth of expansion and cracking with time unless the moisture state is changed. Drying can slow the reaction, but a later increase in moisture in the concrete will accelerate damage. The breakdown of waterproofing onto AAR concrete can trigger rapid damage development. This needs to be considered when inspecting and maintaining waterproofing on bridge decks and flat roofs. These are often slabs with few shear stirrups (i.e. with only 2-D restraint), so they are vulnerable to delamination and loss of shear strength. On bridge decks the interaction of corrosion, frost damage and AAR with wheel loading can initiate serious and rapid deterioration. This needs to be highlighted when drawing up inspection and maintenance procedures.

3.4 Inspection frequencies

3.4.1 Inspection frequencies in Table 7 can be relaxed for severity ratings C ‘moderate’ and D ‘mild’, once trends for that structure have been established and moisture conditions are stable. This is because long term monitoring in most instances show that crack width growth is slow and linear with time, so a 0.3mm crack on a 20 year old structure will need another 20 years to reach 0.6mm width.

3.5 Containment of Expansions by Reinforcement

3.5.1 The effectiveness of containment by well anchored reinforcement in 3 dimensions, Class 1 in Section 8, has been confirmed in many shear and flexural tests. However for Class 3 details where there is no through thickness reinforcement there is now more evidence of delamination and loss of anchorage developing with ‘Severe’ AAR. Some Dutch bridges of this type [20] have been demolished and sections tested. This has shown a significant loss of shear strength. This is of greater concern in structures designed to old shear design and detailing rules which have low safety factors when assessed to current standards.

3.5.2 The Section 8.1 of the 1992 guide with Figures 14 and 15 merits further development to cover a wider range of sensitive details. For example laps at the bottom of cantilever retaining walls are particularly vulnerable to delamination. Loads on them increase from passive pressures developed as the wall curves pressing back against the soil, due to expansion of the outer compression face relative to that of the tension face, where reinforcement limits expansion.

3.6 Steel fracture.

3.6.1 In Japan over 40 bridges [21] have developed problems on crossheads and foundations, where reinforcing steel of a type which becomes brittle on bends, has been used. The forces from AAR expansions have fractured the bend reducing anchorage and containment against delamination. This has necessitated substantial remedial works. This seems to be a particular metallurgical problem with Japanese reinforcement.
3.7  Expansion to date.

3.7.1  Estimates of the ‘expansion to date’ and ‘potential for further expansion’ in different structural elements are essential for assessment of structures with AAR. The crack summation procedures for estimating expansion to date work well in directions where there is little restraint from structural stress, reinforcement or prestress. Further research data to help in making adjustments for the effects of compressive or tensile stress state are now available. It is also necessary to adjust for other causes of cracking.

3.7.2  There were indications when the 1992 edition was prepared that the substantial fall in Young’s modulus (E) of concrete and the development of hysteresis found in testing cores using the low stress range Stiffness Damage Test (SDT) [22] gave a useful measure of the degree of microcracking from AAR in the sample.

3.7.3  This has now been confirmed internationally in a number of research programmes and there is a good correlation with petrographic evaluation. The changes in E and hysteresis have now been calibrated to estimate the ‘expansion to date’ in the sample. It is of particular value in evaluating the condition of bridge decks where internal damage occurs through the depth but visible cracking is suppressed by heavy reinforcement. Similarly in foundations, the damage can be evaluated by coring down rather than full excavation. As the SDT has a low stress range (0.5 to 5.5MPa) it does not alter the sample. Therefore, the SDT can be used to evaluate ‘expansion to date’ on all cores prior to strength, expansion or analytical tests.

3.8  Expansion testing of cores.

3.8.1  Expansion testing of cores provides a basis for estimating the ‘potential for further expansion’. Difficulties have arisen with many of the procedures for testing expansion of cores from structures and with testing cast samples. Many of the methods are summarised in Tables A1(a) and (b) in the 1992 guide, but variants have been developed over the years.

3.8.2  Inter-laboratory trials have highlighted problems arising from leaching of alkali from the sample, variation in moisture conditions and the difficulties of accelerating test procedures at higher temperature without distorting the results. This is highlighted by comparison of accelerated tests on prisms at BRE [18] which typically expanded 3.5mm/m and stabilised while the corresponding large block exposed externally developed very severe cracking from 15mm/m expansion still continuing after 16 years.

3.8.3  The very high variability of the reaction and expansion within cores and between cores, due to the variations in composition, adds to the difficulties of interpretation. Because of this variability, which is the root cause of AAR cracking from differences in expansion, it is necessary to use large batches of samples to obtain the average behaviour and to quantify the variability of expansions. Tests over a few months on two or three samples will almost always give misleading results.

3.8.4  The laboratory ambient, 20 to 25°C, Type a) capillary water supply test, with moisture weight changes monitored, is simple and reliable for gauging potential further expansion, but it is slow. It accelerates by a factor of about 10 relative to the site expansions. Normally it is used over a period of at least 2 years in parallel with monitoring of cracks and/or overall expansion on the structure.

3.8.5  RILEM is collating results from a range of expansion test procedures in ongoing inter-laboratory trials and will be publishing the results and, in due course, it will make recommendations.

3.9  Modelling

3.9.1  In initial assessment, finite element modelling is not yet appropriate. Once severe AAR with structural sensitivity is established, the growing research literature on modelling can be used to guide detailed appraisals of critical parts. RILEM is developing guidance.
3.10 Interaction of AAR Cracking and Microcracking with Frost and Corrosion.

3.10.1 AAR interacts with other deterioration processes. The developing cracking and microcracking opens up the structure making it more vulnerable to water and Chloride ingress and frost damage. The water and Na from salts aggravates the AAR.

3.11 Delayed Ettringite Formation (DEF).

3.11.1 DEF is an expansive reaction in the cement phase of concrete and can cause long term development of cracking similar to that from AAR. This can occur when early age temperatures over 70°C give rise to monosulphates, which in time convert to larger ettringite crystals. Petrography will clearly differentiate DEF from AAR. Sometimes DEF and AAR interact and LCPC in France are studying this on structures and in the laboratory.

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