IMPROVING GUIDANCE FOR ENGINEERING ASSESSMENT AND MANAGEMENT OF STRUCTURES WITH AAR

Jonathan G M Wood*

Structural Studies & Design Ltd, Northbridge House,
CHIDDINGFOLD, Surrey GU8 4UU UK

Abstract

25 years experience of over 100 structures and reviews of international research on the management of bridges, buildings and dams, are compared to the 1992 IStructE guidance on the 'Structural Effects of ASR'.

The IStructE principles have been validated by experience, but there are now significant refinements. These, with international developments, are contributing to RILEM's Guidance on Diagnosis, Assessment and Modelling of AAR.

An engineer's approach for testing for prognosis, assessment and modelling of the response of structures is given. This question driven methodology establishes the variability of expansion in structures, influenced by mix, restraint and moisture availability and establishes potential expansion from realistic expansion tests.

Variable expansions develop macro-cracking and micro-cracking and anisotropic changes in stiffness and tensile strength due to restraint. This needs to be considered in modelling AAR. Variability in moisture controls the rates of development of damage and can be used to limit damage.

Keywords: structural assessment, expansion testing, variability, cracking, restraint

1. INTRODUCTION

Most of the proceedings of the twelve ICAAR are filled with detailed chemical and mineralogical studies and tests on small samples in extreme accelerated test conditions. It is only since the 6th ICAAR in Copenhagen in 1982 that engineers, charged with assessment and management of structures, have been reporting on the difficulties of determining the structural effects of AAR at full scale as it develops over decades. In doing so, they have challenged the research community to provide quantitative data on the physical effects of AAR expansions resulting from the underlying reaction of alkalis with silica. Some progress is being made.

Damaging Alkali Aggregate Reaction (AAR) was first diagnosed in the UK in 1975 and concerns about its effects on the safety of major bridges, buildings and dams led to the initiation of a structural engineering programme of investigation and testing of structures. This work was linked to material science studies and research programmes on AAR in the UK and international links were established with similar programmes around the world.

With over 100 structures to asses, with widely varying severity of AAR cracking, it was essential to identify those structures where real safety risks were developing, as distinct from those where AAR damage was not significant. This led to a method of determining the 'Structural Severity Rating' for structural elements and structures. This in house Mott MacDonald methodology was evolved into the IStructE Report 'Structural effects of AAR' [1] 1988 and then revised in 1992 before the London ICAAR. It sets out the principles for identifying where severe structural damage from AAR may develop. However detailed appraisal requires engineers to develop specific assessment and analytical procedures for the particular structural form, by working from first principles and the published research literature to develop a model for the effects of AAR. The principles underlying the IStructE report and details of the associated test methodologies have been reported [2, 3] and are in a series of papers to ICAAR since the 1980s.

Only a small selection of examples of the over one thousand water supply expansion tests and stiffness damage tests and other comprehensive testing covered by Mott MacDonald investigations have been published in the research literature. The full results are in confidential reports to clients. Many of these were made available to those drafting the IStructE guidance. With this quantity and quality of data the importance of the variability of AAR behaviour in structures

* Correspondence to: jonathan@ss-design.demon.co.uk

became apparent. This must be considered in relation to the number of samples required to give a statistical confidence that the results are representative. When modelling the variability of expansion which disrupts both the micro-structure and the concrete members of a structure must be considered.

Early identification of risk

The main advantage of the IStructE approach is the early identification of the 'Structural Severity Rating' of those elements in structures at risk from AAR, so that the structural and materials investigations and remedial work can be focused on them. The identification of elements with 'Severe' or 'Very Severe' ratings is usually sufficient to convince owners that full materials investigation and structural assessment are necessary and need to be funded. In the UK this approach has enabled the majority of structures with some signs of AAR to be classified as 'Mild' or 'Moderate', so that no action, other than improved water shedding and routine inspection, is appropriate. There have been some of instances in the UK of unnecessary premature demolition of structures with slight AAR cracking when the IStructE approach has not been followed.

Severe damage from AAR, assessed in accordance with IStructE guidance, has been a major factor in decisions to completely rebuild a range of structures with a combination of structurally sensitive details and severe AAR (free expansions >1mm/m). These include Charles Cross Car Park, the 400 bed RD&E Hospital Exeter, a substantial office building and parts of or all of several bridges including the 400m long twin Marsh Mills Viaducts.

This paper reviews lessons from more recent experience of testing, monitoring and assessing a range of structures and the progress that has been made on the research priorities identified in the IStructE report. It is hoped that this will contribute, with similar approaches from other countries [4, 5, 6], to the forthcoming RILEM TC191-ARP Guidance on Appraisal and Modelling of AAR damaged structures linked to a RILEM Report on Diagnosis of AAR.

2. STRUCTURAL PERSPECTIVE ON INITIAL INSPECTION AND SAMPLING

There are fundamental differences between the questions that need to be addressed in structural testing in relation to AAR and those considered in the voluminous literature on AAR testing related to fundamental materials research and specification requirements. The engineer has to follow a question driven approach which follows from and is constrained by the owner's requirements and budget. It is necessarily based on samples from the structure in which the reaction has already developed to a greater or lesser extent.

The structural engineer's questions start with the state of a structure in the field. This usually has quite severe cracking before those responsible for its management receive reports from inspectors that there is something odd with the structure. At that stage AAR is but one of a range of possibly interacting causes.

Cracking from well developed AAR in accessible lightly reinforced elements can be distinctive. But in most real structures there are likely to be a range of other structural and non-structural cracks [7] combined with AAR cracking which will be orientated by stress and constraint. This complex interaction of crack types makes visual diagnosis on site unreliable, particularly in the early stages. For example high cement contents, which increase the risk of AAR, also increase risks of differential thermal and shrinkage cracking. Figure 1 shows the relative magnitude of thermal and shrinkage strains compared to the IStructE AAR expansion classes.

So the wider question to the petrographer needs to be *"What are the characteristics of the concrete and how might these have contributed to cracking?"* This must be considered when site sampling is carried out.

Sometimes one or two cores are sent to a petrographer with the question *"Is there AAR in the sample?"*. Enthusiastic to find a rarity, the petrographer may identify two or three reactive particles and a little gel and report to the owner that "*There is AAR*". In one instance the owner then argued that this slight evidence justified demolishing a Heritage listed well reinforced concrete tower structure where cracking was almost imperceptible. There are similar cases of the unnecessary demolition of robust bridges with slight cracking.

The question should be *"Is it significant AAR?",* which requires a quantitative answer which depends on:

- The current and potential severity of reaction and expansion
- The sensitivity of the structural details to expansions.

This can only be answered by a partnership of engineer and materials specialists evaluating site cracking and tests on a statistically significant set of samples reflecting the variability found on the structure, relative to the reinforcement configuration.

It was to quantify the significance of AAR that the IStructE approach to determining the 'Structural Severity Rating' was evolved. The 'Structural Severity Rating' of structural elements is based on determining:

1. The extent to which the reinforcement and stresses in the structure limit expansion and control the development of structural cracking.
2. The potential consequences of failure.
3. The level of stresses and factor of safety in the part to provide a reserve of strength for deterioration.
4. The magnitude of expansion to date and the potential for further expansion.
5. The availability of moisture to develop the reaction and the extent to which this can be controlled.

The structurally sensitive areas and the likely influence of reinforcement on expansions, cracking and failure modes should be assessed by an engineer before he accompanies a materials specialist to site. This initial assessment can be made from inspection of the detailing on the reinforcement drawings. A more rigorous evaluation can follow after the site inspection.

The understanding of the reinforcement configuration and the flow of forces in the structure is essential for understanding and interpreting the crack patterns. It enables the inspection and any sampling to be focussed on the important elements of a structure. It is also essential for avoiding coring damage in highly stressed areas or to reinforcement, which can be more damaging than AAR.

The engineer may well be able to form a preliminary view on site of the 'structural severity ratings' of the parts of the structure. Where cracking is slight and all reinforcement provides well anchored 3-D constraint to expansions, it will be classified as 'Mild', so a limited materials investigation will be appropriate, provided the structure will be monitored. Where some parts are in the 'Severe' or 'Very Severe' categories, because of the severity of cracking and/or the lack of containing reinforcement, an initial set of core samples for testing should be taken. Planning will need to be started for more comprehensive sampling and for initiating quantitative monitoring of cracks and overall movements.

It is essential during this first inspection to note the availability of moisture to the structural elements and how this relates to crack development. It will also be important to record other forms of cracking and deterioration features due to salt ingress, corrosion and frost which can interact with AAR and may need parallel investigations. It should not be forgotten that the wettest concrete is usually in buried elements which may be only lightly and partially reinforced. In UK experience this is where the most severe AAR damage has been found. These may need full excavation later, if AAR is evident in the superstructure.

Crack summation

Crack width summation, as mm/m, of cracks crossing grids of lines normal to the cracking, provides a preliminary estimate of expansion to date. This needs to be refined by eliminating the contribution to crack widths from other structural and non-structural phenomena and the reduction in crack widths in directions normal to reinforcement and compressive stress. The stress fields and cracking need to be considered in three dimensions. This can be difficult in structures with heavy top and bottom reinforcement, but cracking of the edge may give warning of deeper AAR problems. Clarifying and developing the crack summation methodology in the IStructE guidance and drawing on French experience with their procedures, is one of the improvements to be incorporated in RILEM guidance.

An initial small set of core samples can be taken from two or three badly cracked, but accessible suspect areas, but away from high stressed details. These must be taken without cutting reinforcement, so75mm diameter cores are best for reinforced structures. When results of preliminary tests on this material are available a larger scale coring programme will be appropriate where the structure has elements in the 'Severe" or "Very Severe" range. This coring programme needs to fully reflect the range of mixes in the structure, the observed severity of cracking and the availability of moisture over the service life to date

Cases studies, following this approach, are reported for the 1904 Hennebique Tuckton Bridge[8] and Montrose Bridge[9] both of which had a range of other problems.

3. TESTING: WHAT CAN THE CORES TELL US?

The testing of core samples needs to be conducted using methodologies which answer specific questions about the current and potential future behaviour of the structure. Owners will fund this utilitarian testing, but not 'research'. By careful selection for specific tests, analytical, petrographic, expansion and strength testing can be carried out on material from the same core.

Stiffness Damage Test (SDT)

Low stress range 0.5 to 5.5MPa Stiffness Damage Test [10, 11] developed by Crouch with the Mott MacDonald team and Bristol University gives a very sensitive measure of microcracking in the sample, without damaging the material to affect other tests. Higher stress ranges used by others can be damaging. It measures the development of hysteresis (as DI the damage index) as well as the reduction of Stiffness Ec, see Figure 2. DI is the more sensitive indicator of microcracking at higher expansions. USPV measurements give an indication of microcracking, but have a low sensitivity and wide scatter.

As Crouch noted in his original paper, when cores are taken from concrete subject to compression in one axis the stiffness becomes anisotropic with high stiffness remaining in the direction where compression restricts micro-crack growth and reduced stiffness in the less restrained directions. This anisotropy needs careful treatment when modelling AAR in structures.

Normally coring is from a free surface in a direction of low constraint and for this the empirical relationship of reduced stiffness Ec against expansion to date can be used as shown in Figure 3. This is a complementary technique to the crack summation. SDT is of particular value in checking microcracking when coring down into foundations which cannot be easily inspected and for checking the internal condition of flat slab bridge decks where stresses and reinforcement make crack summation uncertain. However petrographic checks to establish the cause of the microcracking are needed before it can be attributed to AAR.

Stiffness is a fundamental property required when modelling AAR and the SDT data sets provide an insight and a basis for the development of constitutive equations. Most importantly SDT has demonstrated the variability of properties and expansions in three dimensions throughout the mass of concrete.

Using SDT to quantify microcracking and sort samples by severity prior to further tests, facilitates the correlation of results from the range of tests which may be required. The results of all tests can be related to the degree of microcracking measured as Ec and DI.

Petrography

Petrography is an essential test, not only to identify AAR or other deleterious phenomenon, but also to report on the overall mix composition which may help clarify thermal and shrinkage cracking characteristics. However the small volume of material examined in petrography and the high inherent variability of concrete and the reaction create problems in judging the severity of AAR damage. Published petrographic damage rating systems are highly specific to local aggregate types. It is usually sample variability, rather than petrographer variability, that contributes to conflicting interpretations. Once petrography has identified the causes of microcracking, it is of less value for quantifying the severity compared to SDT and crack summation on the structure.

The Exe bridges, where variation in mixes in different lightly reinforced pours gives a complete range of cracking and expansions up to over 4mm/m, have been used with other structures, to compare petrography, crack summation, SDT, expansion testing and variation in alkali concentration. This work with BRE was summarised at the 10th ICAAR Melbourne [12]. Samples selected by careful site inspection for the earliest stages of surface cracking showed a drop in Ec stiffness in STD at expansions of 0.3 to 0.6mm/m, before petrography clearly detected the signs of reaction. Petrography only started to detect AAR when expansions were in the range 0.6 to 1.0mm/m and it become unambiguous when the expansion in the sample was over 1mm/m, calibrated by surface cracking. However chance variability of sampling can show localised AAR in petrography at negligible levels of expansion.

Petrographic examination has been essential in understanding the orientation of microcracking and cracking that result from restraint. This has been done on cores and on diamond cut surfaces of large samples taken during demolition of structures with AAR. It has identified the development of a layer of 'sub-parallel' cracking in the plane of and adjacent to upper and lower reinforcement mats in foundations and flat slabs. In severe cases this leads to delamination and a significant loss of shear strength. These delaminations must be modelled explicitly as discontinuities in modelling idealisations.

Strength tests

The IStructE report gives a simplified relationship between strength loss and expansion based on the limited data available at the time. Recent data confirms the general trends, but is of better quality, particularly on tensile strength loss. However when the variability encountered in normal site concrete is combined with the variability arising from AAR differential expansions it will be appreciated that substantial sets of cores and tests are required to establish the mean and characteristic values of strength.

Compressive strength on conventional short specimens does not show much strength loss from AAR, due to platen friction holding the sample together, so this test is inappropriate with AAR. Uni-axial compression tests, most simply by using cores with a length/diameter of >2.5, show that compressive strength is reduced as microcracking develops with expansion. It must be remembered that under variable restraint anisotropy develops with orientated microcracking. Compressive strength will be reduced where microcracking and delamination layers develop parallel to the direction of compression. This needs to be considered in both the orientation of core and test samples and in the modelling of ultimate behaviour. As as-built compressive strengths are, in UK experience, usually well above the design value specified (due to high cement contents which trigger AAR), reductions in compressive strength are seldom significant.

The tensile strength of concrete falls rapidly as microcracking develops from AAR. As with compressive strength, the orientation of microcracking develops anisotropy, with microcracking growth greatest where concrete is in tension. The tensile strength of concrete is not explicitly considered in normal design, as detailing requirements normally require tensile forces to be carried by reinforcement. Where tensile strength is important, as in shear behaviour, code strength formulae are expressed in terms of compressive strength, assuming the normal ~10:1 ratio of compressive to tensile strength. As AAR develops, this ratio changes with the substantial fall in tensile strength. So one of the consequences of AAR is that tensile strength needs to be explicitly considered particularly for shear and bond behaviour and around prestressing anchorages, as normal code simplifications are not valid. Bond behaviour is further complicated by the increase in bond stress as reinforcement tries to restrain expansion.

Testing for tensile strength with normal concrete is very sensitive to preparation of samples and the method of test. With AAR it is even more sensitive. Indirect methods like the splitting test cannot be related to tensile failure stress and strain. Uni-axial tensile strength can provide data of the minimum strength of the test length, if preparation and end conditions are well controlled. However with site cored material there is always sensitivity to damage from coring. An approach which reduced these problems and yielded good results was the Torsion Test developed at Cardiff University [13]. The core is twisted to induce tension and compression, as in a shear stress field, and tensile strength, strain to failure and tensile stiffness can be obtained. These provide important inputs for modelling.

The programme of research [14] initiated by TNO and RWS following the discovery of AAR in bridges in Noord-Brabant (southern Netherlands) led to a much better understanding of tensile strength and the significant reduction in overall shear strength that arises when concrete, rather than full shear links, is relied on to carry shear tensions in slabs and beams.

4. EXPANSION TESTING AND MONITORING

For the management of structures it is important to know.

- *What is the potential for further expansion? --How quickly will the expansion develop?*
- *When will it stop?*
- *How will temperature and moisture availability influence expansion?*
- *How does alkali migration influence expansion?*
- *How will reinforcement or stresses restrain expansion?*

We now know that the answers to many of these questions are specific to the environment, the type of aggregate and the mix, so one must trust the structure not the literature. Unless there is a change in the water availability to the structure, the rate of AAR damage and crack growth, once cracking has initiated, is steady and roughly liner with time. So a ten year old structure in a consistent environment, it is likely to have doubled crack widths and expansion after a further ten years. As structural severity rating is dominated by the effectiveness of reinforcement containment and strength reserves, the structural vulnerability may not change significantly over these 10 years, so there is no need to rush expansion tests.

Monitoring the actual structure and extrapolating crack growth and overall expansions is the most reliable approach to predicting very long term damage trends and for planning the management of the structure. Long term monitoring of the structure for expansions, joint movements and/or crack width growth will over two or three years (so seasonal wetting and drying and thermal effects can be differentiated from AAR trends) show the overall trends of damage development in the structure.

For an earlier indication of possible trends or where access to some parts of the structure is difficult, expansion tests are very valuable. Expansion tests should be related to the conditions in the structure. Importantly they can relate expansion trends to the measured uptake of water so that the sensitivity to moisture availability in the structure can be judged.

There are many indications in the literature and from the behaviour of structures in the field that AAR expansions are a two stage process related to the availability of moisture with less moisture required for the attack of alkali on silica than for the full swelling of the resultant gel. There are many other complicating factors like gel viscosity, the influence of calcium in replacing Na or K in the gel and the competition for moisture from cement hydration etc, etc. which are not further discussed here.

In a structure the concrete with AAR will have developed some partially hydrated gel and will usually be only partially saturated with moisture. It may also be restrained by the stress state. There may have been alkali migration and surface leaching changing its susceptibility. When removed from the structure by coring it will adjust to its changing environment.

The first response of a core to the availability of water is a recovery of shrinkage strains which have arisen either in the structure or because the core has dried between coring and the start of test. Rigorous procedures for coring, wrapping the core and preparation reduce this, but it is essential to differentiate swelling which can be 0.15 to 0.3mm/m from the expansions due to AAR. This requires monitoring water uptake by weighing throughout the test and using multiple 50mm gauge lengths to differentiate uniform swelling from the very variable AAR expansions.

Over the first 2 months or so the partially hydrated gel will swell to produce an initial phase of expansion which is followed by a very much longer slow expansion, as further silica is attacked by alkali. It is essential to maintain expansion tests in parallel with site monitoring for years, see Figure 4.

The initial expansion test programmes we had carried out in the 1980s were at 38°C and '100%RH' using large numbers of cores at various laboratories. It became clear that serious anomalies in the results were due to wide differences in the 'humidity' achieved, alkali leaching to halt expansion and gauge wear and bad practice in taking readings. The expansion test regimes in the UK 'Diagnosis' recommendations [15] were found to be inadequate, as confirmed by their inter laboratory trials. This led to the development by Mott MacDonald, in cooperation with a number of laboratories, of the 'Water Supply Expansion Test' [16] with built in double checks. This typically uses a 250 long 70mm diameter core with 3 lines of three 50mm Demec gauge lengths, as shown in Figure 5, to measure the variability of expansions and from them the average expansion.

Testing is carried out at 'Lab Ambient' temperature, typically 18 to 22°C, to avoid expensive ovens. This provides a slight acceleration relative to conditions for most UK structures. The simplicity of the test environment makes it economic to store large batches of samples for testing over years. It also eliminated the cycle of drying and wetting as cores are removed from 38°C to be measured at 20°C. The slight variations in temperature are of little significance compared to the overall variability inherent in the tested material.

The important innovation was the replacement of complicated wrapping and humidity controlled storage with storage in individual sloped cylindrical containers, where the concrete acts as the wick to draw the water up into the sample. The amount of water added can be controlled by adding known amounts of water and monitoring both the weight of the core and the weight of surplus unabsorbed water in the base of the container. For the standard test 10gms water per kg of core is added and topped up to 10g/kg surplus water whenever the core lengths and weight is measured. This ensures the concrete is well saturated and that there is little reduction in the alkalinity of the sample. In practice this has been found to give greater moisture uptake than 'vacuum saturation' or any of the "100%" RH techniques. This ample availability of moisture is the prime means of accelerating expansions relative to most site conditions. For comparison parallel batches of cores were exposed in sheltered and ponded site environments for major structures.

The use of a steel plate with matching Demec gauge lengths and weight which is read with the cores, ensures that gauge wear and damage are detected and provides a means of temperature correction for the slight variations. This has been found essential for checking the long term reliability of testing and identify the flaws in procedures at laboratories when personnel change.

This type of built in double checking is essential both for long term lab tests and site measurements of crack movements. Over 10 years wear and damage to gauges and changes to personnel are inevitable. Electronic gauges tend to be expensive and unreliable in the long term in the damp conditions of test. Excel spread sheets enable the mass of data on 9 gauge lengths on large batches of cores to be analysed without difficulty. Statistical analysis can then be carried out to determine within core and between core variability and relate it to recorded moisture uptake and composition. Tests are normally run for years in parallel with the site monitoring of crack growth trends for example [17].

Early in our testing programmes we found that expansion of similar cores from one pour of concrete was very variable due to differences in cement content and aggregate concentration within that pour. The differences between pours of the same nominal mix were even greater [18]. Many of our reactive concretes had chert in the 2 to 4mm fraction, as the main reactive aggregate which has a pessimum of about 10%, so fluctuations about this pessimum may have contributed to the variability.

5. EFFECTIVE CONSTRAINT

The very simple IStructE three category examples of reinforcement containment need to be developed into more comprehensive guidance, particularly for shear and for laps and anchorage of reinforcement.

When concrete is contained by a well anchored 3 dimensional reinforcement cage, the early stages of expansion tend to 'prestress' the concrete. This has little effect on flexural strength and can enhance shear strength, as the compression reduces the tensile shear stress. The rigorous test programmes by Larive [19] at LCPC and others [20] and elsewhere have provided a quantity and quality of data to enhance our understanding of the 3-D effects of constraint on the concrete and the forces that can be generated by AAR expansion. Data from these need to be used when considering the crack summation estimates for restrained conditions relative to free expansion to date.

With higher expansions the restraint forces generated in the reinforcement need explicit consideration. Typically 4MPa in the concrete will restrain further expansion in the direction of compression. This can arise from the vertical axial compression in a column or from restraint from reinforcement. However if the yield force (steel area x yield stress) is insufficient to restraint further expansion, the reinforcing steel will yield and stretch once the expansion exceeds the yield strain of the steel (2.25mm/m for HYS). So for AAR giving large expansions progressive ductile yielding will occur where the steel area is less than 0.85% of section for high yield steel (HYS 460MPa) or less than 1.6% of section for Mild Steel (250MPa). This can be accepted as long as the end anchorage and any lap connections can contain it. Data from comparisons of modelling with site structures and laboratory test beams will be needed to properly clarify this behaviour.

In refining the IStructE approach to the adequacy of reinforcement containment explicit checks on the anchorages and laps will be required for the containment forces generated by AAR. Nomura [21] and Torii (personal communication) have found many cases of reinforcement fracturing at anchorage bends with steel lacking sufficient ductility. There also need to be explicit checks that delamination fractures do not develop between the expanding mass of concrete and near surface reinforcement of the type found when sectioning UK structures with severe AAR. Studies by the Dutch [14] have provided more information on the serious reductions in the shear strength of bridges where shear reinforcement is inadequate or absent. This risk was not emphasised in the IStructE guidance.

6. MODELLING

Modelling provides the essential link between the behaviour we can evaluate in small scale tests of samples, experimental beams and sections from structures and the prediction of structural behaviour on full scale structures. However as modelling is developed it must be calibrated against measurements on real structures. This is an objective for the important new RILEM group on Modelling AAR.

Major challenges for modelling are correctly incorporating:

- The high variability of expansions at the micro and the macro scales.
- The rate functions for expansions as a function of temperature and moisture availability
- The modifying effects of the tri-axial stress state.
- Interaction of AAR with other chemical and physical deterioration processes.

The major challenges for research in understanding and predicting AAR are:

- The time scale of the reaction and expansions in the field and the influence of varying temperatures and moisture availability on it.
- Quantifying the inherent variability of the reaction and expansion.
- The influence of structural stresses and restraint from reinforcement on tri-axial expansions and development of orientated microcracking
- Development of anisotropy of tensile strength, strain limit and stiffness with expansion and restraint.
- Ultimate limit state failures from AAR including shear failures and reinforcement bond/anchorage failure.

These need to be quantified in a form so that constitutive equations for modelling both local behaviour within concrete elements and the overall behaviour can be formulated to meet the needs of appraisal.

7. LESSONS FOR DESIGN AND SPECIFICATION

Sometimes it is necessary to design structures where there will be a residual risk of AAR, because of the lack of economically available aggregate or cementitious materials. The potential for damage can be reduced by appropriate design for expansion. This needs to be based on lessons from the management of structures which have been damaged by AAR. The designer should consider how differential expansions might damage the structure and/or adjacent facilities. FE modelling is a powerful tool for this.

The designs can be made more resilient against AAR by incorporating:

- Appropriate joints to separate parts of the structure and allow for additional movements.
- Design so that water is effectively shed from the superstructure.
- Ensuring that 3-D reinforcement configurations are provided and that shear is fully carried by links in both slabs and beams.
- Ensuring that ductile grades of reinforcement are used with hooks for anchorage and avoid reliance on simple laps in reinforcement.
- Provision for monitoring of movement, joints etc with robust reference points.

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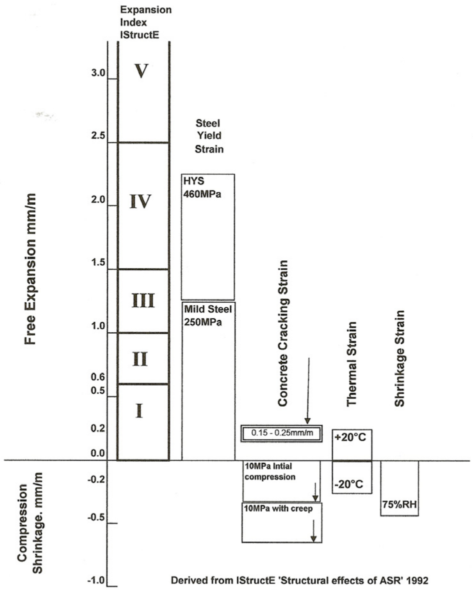

Figure 1 The relative magnitude of thermal and shrinkage strains compared to the IStructE AAR expansion classes

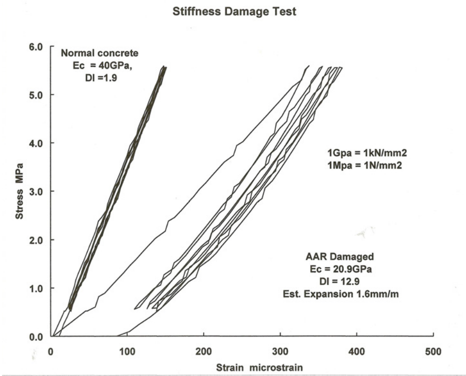

Figure 2. SDT cyclical loading to 5.5MPa on normal and AAR damaged concrete cores.

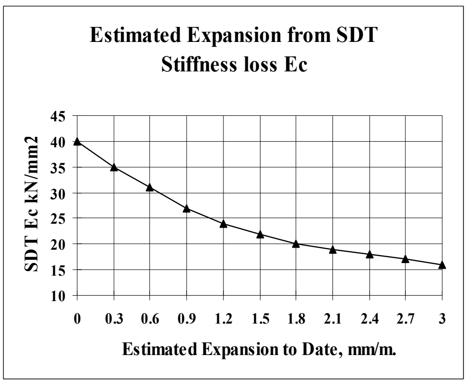

Figure 3. Stiffness Ec against AAR expansion to date

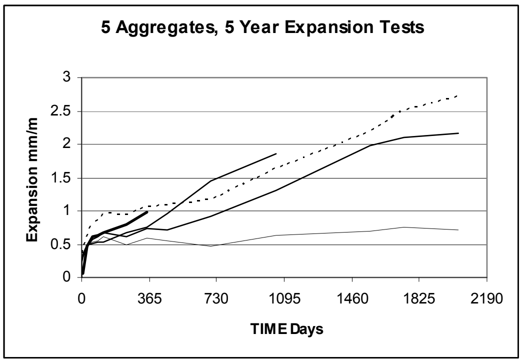

Figure 4a. Long term 20°C Water supply expansion tests. Typical trends for 5 distinct aggregates.

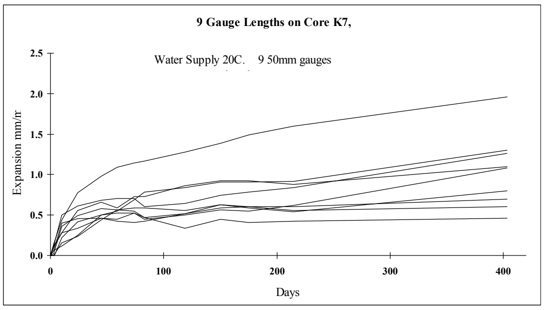

Figure 4b. Long term 20°C Water supply expansion tests. Variability of expansion on Nine 50mm gauge lengths on one core.

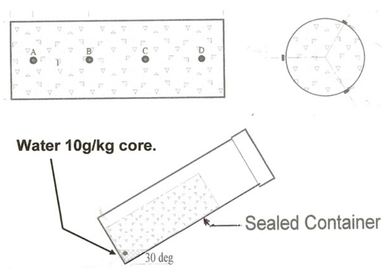

Figure 5, Water supply expansion test to relate expansion to measured water uptake without alkali leaching. Typically uses a 250 long 70mm diameter core with 3 lines of three 50mm Demec gauge lengths to measure the variability of expansions.