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Assessment and Rehabilitation of AAR-affected Structures

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Abstract

The overall thrust of this paper is to show that an integrated material and structural design strategy needs to be adopted to develop techniques that are meaningful and effective for the identification, evaluation and rehabilitation of concrete elements and concrete structures affected and damaged by AAR. It is shown that exposure to environmental and climatic changes is the major factor influencing the rate of expansion and total expansion of concrete in real structures. AAR is also closely and intimately involved with testing and test methodologies so that material and structural rectification requires a global approach involving diagnostic methods, tests to establish the potential of future expansion, selective sealing of cracks and protection from environmental attack, structural evaluation using non-destructive test techniques and structural strengthening. © 1997 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

The diagnosis, assessment and rectification of concrete structures affected by alkali aggregate reaction (AAR) are complex, difficult and time-consuming. In many respects, this is analogous to the treatment of human beings suffering from complicated diseases, but there are major differences, as no doubt, one would expect. To identify, evaluate and counteract the effects of AAR, as well as the prescription of remedial measures, like the problems of health, require a clear and thorough understanding of the enemy, the resources and friends it can muster in initiating and continuing the reactivity, and the ways and means of how it operates and attacks an apparently normal concrete structure. We need to know and recognize the visible and invisible aftermaths arising from the affliction, and particularly, realize the implications of the internal debilitations and enervations that follow once the existence of the disease has been confirmed. Above all, we need to be quite clear about the rationality, validity and meaning of the methodology of the tests and the ensuing results, that need to be carried out in order to identify or remedy the illness, and especially their limitations and implications. Without this confident, convincing and unambiguous picture, it is very likely that not only will the diagnosis be faulty, but also, the remedial measures, as a *sine qua non*, will also not be fully effective or be only short-term.

One of the major problems facing those involved in identifying and evaluating the presence and effects of AAR is the many stages where confusions, contradictions and uncertainties face and challenge the assessment. AAR is closely and intimately involved with testing, and test results depend entirely on test methodologies. Blind testing can be misleading and, following accepted test methodologies, can still lead to misinterpretation of data. The difficulties of testing aggregates or cement–aggregate combinations for AAR should thus not be underestimated. Further, many tests are sensitive to test procedures and small variations in them, and there is always an element of subjectivity in carrying out the tests and interpreting the results. All these demand extreme care and sound engineering judgement not only in choosing assessment techniques but also in appraising and evaluating the test results associated with AAR.

The thrust of this paper is therefore to show that an integrated material and structural design strategy needs to be adopted to develop techniques that are meaningful and effective for the identification, evaluation and retrofitting/rehabilitating structures that are affected by AAR. Because of the large number of complex interactive and interdependent parameters involved in the initiation and continuation of the reactivity, each structure may, at the end of the day, have to be treated and assessed individually and independently, although the basic engineering requirements for the reactivity remain the same, and structures built using a particular reactive rock mineral in a region may exhibit broadly similar characteristics and pattern of development of damage. In such cases, and in general, developing damage indices to classify the severity of attack and rate of damage in the different components of a structure can be very helpful in identifying the degree and type of rectification required, just as in the case of a fire damaged building.

AAR — THE PHENOMENON

Experience from many countries tells us that AAR is an unusual and still a largely unpredictable phenomenon. The factors involved are too many, very interdependent and highly interactive. Simplistic models, assessment/testing techniques or treatment methods belie the complex nature of the reactivity, but the problem is not intractable.[1,2]

Like many other concrete deterioration processes, AAR is primarily a time-dependent phenomenon, and invariably occurs during the service life of a structure, often after several years or even decades of good and satisfactory performance. The reaction can therefore occur at a very early age if all the ingredients necessary for the initiation of the reaction coalesce at that time. However, the reactivity can lie dormant for many years or continue at an unidentifiable and insignificant expansion lèvel only to be triggered off dramatically by some simple changes in local microclimatic conditions or inadequacies/weaknesses of some other structural or construction component (like the sealing membrane in a bridge deck) unconnected with AAR. However, unlike most other deterioration processes, because the damage effects arising from AAR are expansive forces, and since they are superimposed on members already stressed and cracked, there will always be additional stresses induced in both the concrete and steel embedded in the structure.

There is also the further complication that AAR itself, because of the nature of the damage that it creates, can provide the means for other deterioration mechanisms to develop, operate and co-exist, just as environmental and load-induced cracking processes other than AAR, may provide just the favourable conditions necessary for the initiation of a dormant AAR. External agents, climatic changes, environment conditions and local microclimates can all thus have as much a devastating influence on an AAR-affected structure as the basic ingredients of the reaction itself.

AAR is thus a very complex deterioration process to recognize, identify and monitor. What is important is that engineers should not allow themselves to be overwhelmed or blinded by either field occurrences or confusing laboratory findings at microstructural and engineering levels. It is serviceability, stability and structural integrity rather than ultimate strength that are most at risk in structures affected by AAR. Because of the complexity of the problem, there is probably no single solution or unique method that will obviate deleterious effects of AAR all the time in all situations.

DIAGNOSIS OF AAR

Age of structure

Perhaps the first step in the assessment and rectification of an AAR-affected structure is to establish the age of the structure concerned. The age can often give some idea and clue as to the rock type involved in the reactions. This is particularly true of rock types associated with the slow, late expanding type of reaction. In a survey of AAR-affected structures in New Brunswick, for example, it was found that some 8–10 years were required for such aggregates to manifest the visual effects of the reactivity, whereas upwards of 20–30 years were required for the reaction to fully develop and become severe.[3] In the same review, some 75% of the pre-1955 structures showed signs of reaction, whereas only about 35% of those built between 1955 and 1975 showed some evidence of AAR.

Satisfactory field performance is always a good guide to the nature and quality of the aggregates in a region, and comparison with structures of similar age exposed to a variety of exposure conditions can be a strong aid in evaluating the nature and effects of AAR.

Identification of reactive aggregates

Petrographic analysis is a very useful tool for the identification of deleteriously reactive aggregates. Such examination enables us to characterize the various constituents, and to identify, determine and assess potentially alkali-reactive types present in a particular set of aggregates. The great advantage of petrographic analysis of cores taken from structures as well as laboratory test prisms is that it can show silica gel formation, cracking of aggregates and of the paste matrix, reaction rims and formation of crystalline silicates, and these can all later be closely related to expansion tests when they become available.

It should, however, be borne in mind that it is not always possible for petrographic studies to distinguish reactive aggregates from non-reactive ones from within the same suite of rocks, although there might be, and often will be, strong evidence of AAR in the field in structures made with these aggregates, and of reactions associated with a particular reactive mineral.

There is strong evidence that petrographic analysis can sometimes create considerable confusions and contradictions. For example, petrographic examination of cores taken from structures with and without signs of AAR deterioration have both shown to contain high proportions of potentially reactive rock types.[3] However, whilst petrographic studies classified rock types such as quartzites, silicic volcanics, granites, gabbros and pure limestones as non-reactive, most of them showed increased expansion with increased alkali in the concrete mixture. Even when a particular rock type is identified as the type of aggregate most often associated with deterioration of concrete structures in a region, the geology of the rock can impart varying degrees of reactivity to that aggregate. Greywackes, for example, found in the New Brunswick area have been found to range from non-reactive through moderately reactive to very highly reactive.[3]

With alkali silica reaction (ASR), experience has shown that the forms and reactivity potential of silica are complex and difficult to identify and determine. Silica minerals can occur in a wide range of polymorphic forms, many of which are unstable at atmospheric temperatures. Further, the structure and texture of siliceous components have a complex influence on the rate and extent of reactivity.[4] Apart from the amount of order in a crystal structure, temperature can also be a major accelerator of the reactivity as shown later.[5]

All these studies confirm that it is neither right nor appropriate, when dealing with problems such as AAR, to place total reliance on petrographic studies alone for the identification of deleteriously reactive aggregates. It is clear that petrographic studies should always be combined with other laboratory tests that alone will enable the detection of all types of alkali reactive aggregate. When AAR is involved, XRD analysis of the sample and a control mix of known reactivity is capable of indicating the complex array of minerals produced by AAR and substantiate visual examination of the material.

THE WAY FORWARD

The most difficult and apparently intractable task facing assessment and evaluation of AAR is the determination of the potential for further expansion of the concrete in an AAR-affected structure. Here lies the crux of the problem. What test or tests should one adopt? Should one adopt a well-known standard test, or should one use an accelerated test? What do the test results mean, and how do they relate, and more importantly, how would they relate, to the future performance of the structure?

Further, what is the role of the environment to which the concrete structure is exposed? Do the laboratory test data bear any relationship to the vagaries of climatic conditions to which a concrete structure will be exposed during its life? How do we separate or identify the influence of the environment from an accelerated laboratory test result? Or, how do we superimpose the effect of environment on the results of a laboratory test?

We need to answer these questions before we can identify a laboratory and/or field test — accelerated or not — that can be adopted to evaluate the status of an AAR-affected structure. There is no doubt that the most realistic and accurate way to assess the potential for future expansion of AAR-affected structure is to monitor movements and deformation *in situ*. However, *in-situ* monitoring is time-consuming, costly and needs to be carried out over a sufficiently long period of time to obtain a consensus result of the effects of thermal and climatic variations to which the actual structure is exposed. Laboratory tests on concrete cores thus become expedient — they are less costly, and expansion results can be obtained in a relatively short period of time, particularly if one adopts an accelerated test. However, we need to be absolutely clear as to the limitations of the laboratory tests and their results, and indeed of the parameters that the laboratory test is supposed to evaluate.

Traditionally, we believe that for AAR to occur and cause damage, three essential conditions need to be satisfied:

(1) a critical amount of reactive mineral phases in the aggregate particles,
(2) sufficient alkali in the pore solutions, and
(3) sufficient humidity.

However, experience now tells us that this concept ignores a vital component of AAR in the field, namely, the environment. In a real structure, AAR and related expansion and damage will continue as long as the above three conditions are met. The reactive mineral phase and the source and amount of alkali already present in the concrete structure obviously cannot be changed or controlled. Therefore, the critical factor that will control the development of AAR and related deterioration in a real structure has to be the availability of moisture, from whatever source it may be.

Moisture movement inside a concrete member depends on the complex interactions of initial moisture content, concrete quality and the external environment.[6–9] Here again, the major factor is obviously the external environment. We seem not to fully appreciate or comprehend the role and cumulative effect of the environment and indeed underestimate its influence. The variation of relative humidity inside concrete follows climatic conditions, and field tests show that even severe drying conditions induce only near-surface reduction in RH.[1,2,8] The size of a concrete member can then be critical to the occurrence of severity of AAR. Thin members such as parapet walls, walkways, spillway piers and pavements may thus show moisture conditions favourable to ARR within 50–200 mm from the exposed surface, whereas more massive concrete members may be drier in this surface zone. More importantly, many concrete elements, and particularly mass concrete, may retain sufficient residual mix water, even in arid conditions, sufficient to initiate and sustain alkali–aggregate reactivity. Climatic conditions can thus play a critical, and perhaps superficially inexplicable, role in creating seasonal and cyclic AAR activities in exposed concretes.

In real structures, therefore, for a given set of reactive aggregates present in the concrete, the development of AAR and the related expansion and damage will be the result of complex effects of the combination of the amount of internal and external alkali available for reactivity, and exposure conditions such as temperature, humidity, wetting/drying, and freezing/thawing. This complicated combination of alkali, reactive mineral and environment can lead to unexpected and unpredictable expansions and damage as is amply confirmed by both field data and laboratory tests. In the review of structural damage of AAR-affected structures in the New Brunswick area, for example, greywacke was identified as the type of aggregate most often associated with AAR deterioration. Greywackes themselves can exhibit a range of reactivity, depending on the amount of clay minerals present, from non-reactive to moderately reactive to very highly reactive. In evaluating damage, there appeared to be a definite correlation between the extent and severity of damage and geographic location.[3] In other words, there is a clear and distinct inter-relationship between AAR and the environment.

Both field and laboratory test data emphasize the crucial role and function of environment in the phenomenon of AAR.[2,10] These results show that both rate of expansion and the total expansion are highly dependent on the environment and exposure mode (i.e. water availability) in that environment. The choice of the test methodology is thus absolutely critical to the whole process of structural assessment and rectification of AAR-affected structures.

TESTING FOR EXPANSION POTENTIAL

There are thus three requirements to be satisfied from any test programme adopted for the evaluation of the potential for further expansion of the concrete in an AAR-affected structure.

(1) A knowledge of the residual ultimate total expansion of the concrete in the structure, and
(2) lA knowledge of the residual ultimate total expansion of the concrete in the structure, and
(3) Availability of test data in a relatively short time.

In the light of the discussion above, the two test methods suggested here are:

(a) Accelerated laboratory expansion tests on concrete cores extracted from the AAR-affected structure, fully immersed in a 4% sodium chloride solution at 38°C.
(b) Field expansion tests on concrete cores extracted from the structure and exposed to the same environmental/climatic conditions as the structure.

Implication of field expansion tests

The field tests on the structure and extracted cores will necessarily be slow, but will give a very good idea as to the rate of expansion that can be expected in the structure over a period of time, since the cores are tested under the same environmental/climatic exposure conditions as the structure. The field test needs to be carried out for a sufficiently long period to give the assessor a feel for the effects of variations in the external environmental conditions (such as temperature, humidity and presence of chlorides) on the rate of expansion.

Implications of the accelerated laboratory tests

The choice of the test conditions for the accelerated laboratory test, i.e. the temperature and humidity of the test as well as the solution in which the test is to be carried out, is crucial and requires a clear understanding of the influences and implications of all three parameters individually and in combination. Expansion tests in IN NaOH are basically very unrealistic and unrepresentative in relation to what happens to concrete structures. In life, it is a chloride environment to which concrete is exposed and not a NaOH environment (e.g. marine exposure, deicing salts, ground water, etc.). From a materials engineering point of view, the use of IN NaOH solution has many other unwelcome disadvantages. The availability of a relatively unlimited supply of alkali in the test totally overwhelms, and makes completely irrelevant, the effects of the alkali content of the cement. Further, the test also becomes irrelevant for the evaluation of cement–aggregate combinations, which is a prime necessity in assessing residual expansions in real structures. The NaOH solution may thus be appropriate for aggregate screening but appears to be unsuitable and improper for structural evaluation, and is far too severe for many normal situations.

Temperature/humidity interactions

The choice of the temperature of the test is also absolutely significant. What we need to adopt is as sufficiently low a temperature as practicable that will give us a reasonably realistic result in a relatively short time. From practical and cost points of view, a realistic quick result at a lower temperature than at a higher temperature is to be recommended and adopted.

The other important point to note is that the effects of temperature, humidity and external alkali are interactive and interdependent.[8,11–15] In general, the higher the temperature, usually the greater are the reaction and expansion rates due to AAR. The smaller the amount of expansion, and the slower the reactivity of the aggregate, the higheris the critical ambient humidity level usually required for deleterious expansion; however, the higher the temperature of the test, the lower is the level of humidity required. The confusing interactions of temperature, humidity and reactivity of the aggregate can be readily appreciated. It seems logical that what we need is as sufficiently low a temperature as practicable that will give us a reasonably realistic result in a relatively short time. At the moment, accelerated expansion tests at 80°C, 60°C and 38°C have been reported, recommended and some accepted, but there are few test data available for us to evaluate relationships and interactions between expansions at these temperatures and those at ambient temperatures.

Accelerated tests at 38°C, 4% NaCl

The author therefore recommends a test at 38°C in a 4% NaCl solution which is much more relevant and appropriate to concrete structures. The 4% represents a meaningful average between the different intensities of marine exposure and the amount of deicing salts used in practice. From an extensive study of AAR at these conditions, some typical test data are shown here in support of these arguments.[2] The tests were carried out on $75 \times 75 \times 300$ mm concrete prisms with a cement content of 350 kg/m^3 and a total concrete alkalinity of 3.89 kg/m^3 sodium oxide equivalent. Two types of reactive aggregates were used — a carefully selected and tested moderately reactive synthetic aggregate, namely fused silica, and typical natural reactive aggregates. Only data related to fused silica reactive aggregate are reported here. The test specimens were exposed to a wide range of environments and water availability exposure modes. Tables 1–3 and Figs 1–3 summarize some of the results. These data show that both the rate of expansion and the total expansion are highly dependent on the temperature of the tests and presence of external alkalies, and in a given environment, on the mode of exposure, i.e. availability of moisture.

These results confirm that an elevated temperature clearly enhances the chemical

Table 1. ASR percentage expansion under ambient/outdoor conditions

Age (days)	*Exposure period (days)*	*Ambient*			*Outdoor*	
		0% FS	*5% FS*	*15% FS*	*5% FS*	*15% FS*
28	0	−0.039	0.001	−0.014	0.002	−0.013
91	63	−0.018	0.020	0.008	−0.009	0.117
175	147	−0.090	−0.058	−0.017	0.042	0.010
371	343	−0.103	−0.034	0.002	0.075	0.222

Table 2. Influence of environment on ASR expansion

Age (days) (days)	*Exposure period*	*Expansion (%)*			
		20°CW	*38°CW*	*20°C NaCl*	*38°C NaCl*
28	0	−0.011	−0.004	−0.008	−0.012
91	63	0.173	0.575	0.215	0.680
175	147	0.242	0.589	0.276	0.973
371	343	0.258	0.618	0.282	1.498

Table 3. Effect of environment and exposure mode on ASR expansion

Environment	*Percentage expansion after 343 days*			
	Exposure mode			
	Full immersion	*Half immersion*	*7 days W/D*	*3 days W/D*
20°C water	0.258	0.234	0.303	0.311
20°C NaCl	0.282	0.358	0.451	0.477
38°C water	0.618	0.436	0.704	0.880
38°C NaCl	1.498	1.785	1.392	1.396

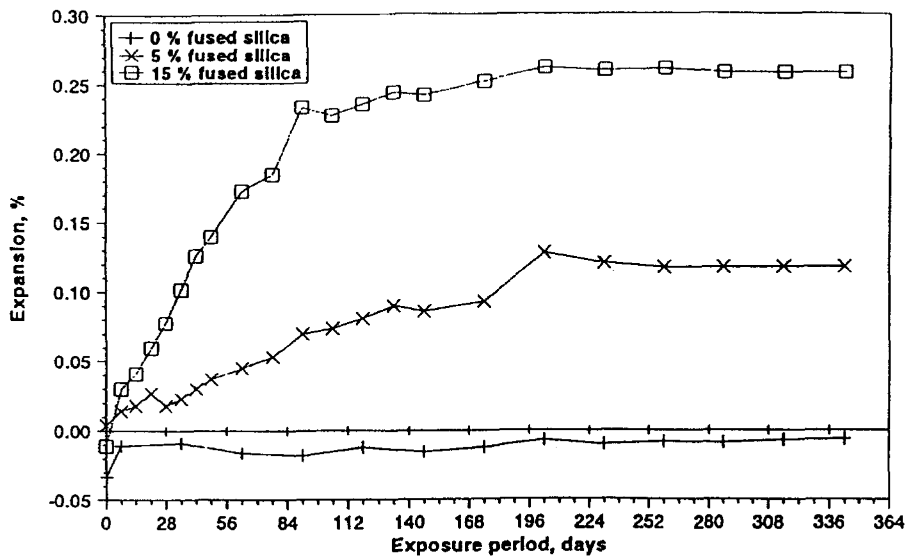

Fig. 1. Expansion of 75 × 75 × 300 mm concrete prisms exposed to 20°C water, full immersion.

reactivity whether external alkalies are present or not. In a wet environment without chlorides, expansion at 38°C is about two to three times that at 20°C, whereas in a humid chloride environment, the expansion at 38°C can be three to five times that at 20°C, depending on the mode of exposure (Fig. 2). Thus, a higher temperature accelerates the rate of expansion more than the presence of external alkalies. Further, in a given environment, the exposure condition and water availability (i.e. wetting/drying) can also have a significant influence, as shown in Fig. 3. In such cases, the length of exposure in the field, and the duration of monitoring in laboratory tests can be a major factor. However, at testing conditions of 38°C and 4% NaCl solution, the differences due to the mode of exposure are much less, as shown in Table 3. Thus, an accelerated laboratory test at 38°C in 4% sodium chloride solution appears to be more relevant and realistic for structural evaluation of AAR-affected structures.

These data emphasize the need for the engineer involved in structural assessment and rectification of AAR-affected structures to be fully aware of the implications of the test

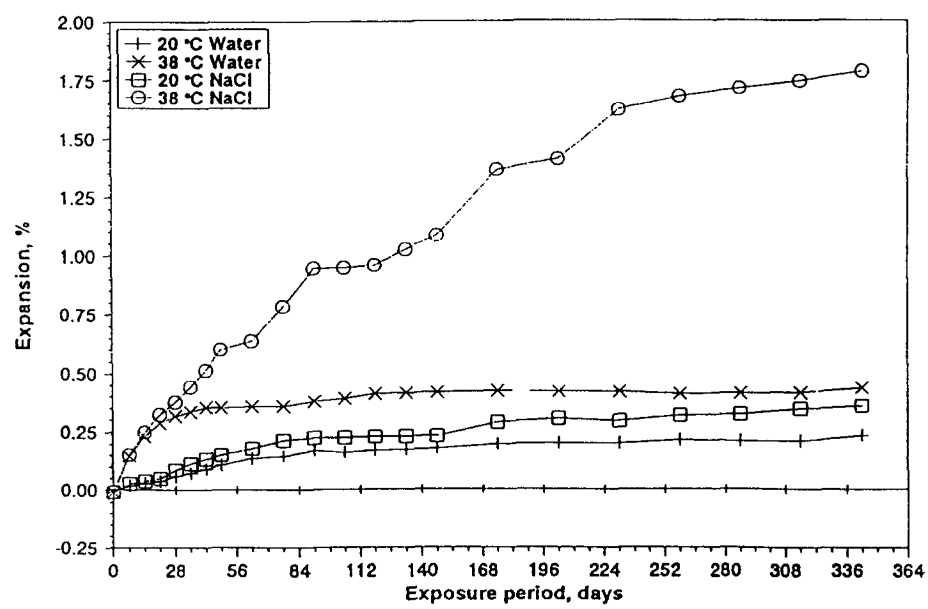

Fig. 2. Influence of external alkalies on ASR expansion: 75 × 75 × 300 mm concrete prisms, 15% fused silica, half immersion.

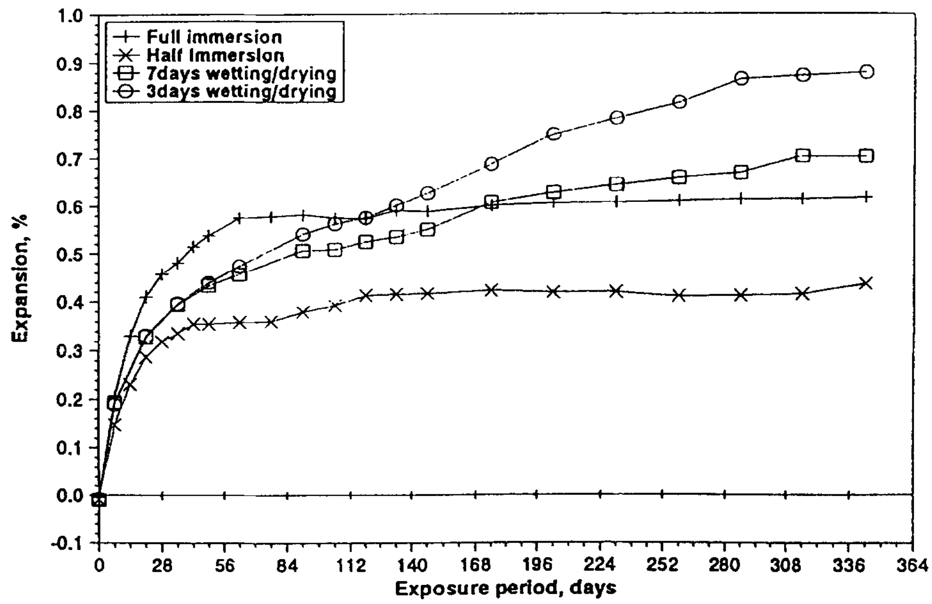

Fig. 3. Influence of water availability on ASR expansion, 75 × 75 × 300 mm prisms, 15% fused silica, 38°C water.

methodology adopted in evaluating the potential for further expansion.

STRUCTURAL EVALUATION

Surface cracking

Apart from the external signs of unsightly stains and exudations through cracks, the immediate and most direct visible external evidence of AAR is surface cracking. The tensile strain capacity of concrete is only of the order of 150–200 μs (microstrains) and seldom exceeds 300–500 μs. Expansive strains of 0.04–0.05% and beyond will therefore produce cracking.

Surface cracks on AAR-affected structures are, however, not a true measure of the effects of AAR. Random and irregular cracking is an inevitable consequence of the chemical reactivity if no stiff element such as reinforcing steel is present to control this cracking.[1,16,17] In practice, the irregular pattern on large exposed surfaces is greatly influenced and modified by the presence of drying shrinkage from wetting/drying cycles, by internal freezing and thawing and restrained cracking due to moisture and thermal gradients.[1,8,17,18] Surface cracking is thus a visible external characteristic but unreliable for quantitative evaluation of structural deterioration.

Freezing and thawing, in particular, can seriously distort the intensity and location of cracking, and can consequently affect damage ratings unless care is taken to separate areas of a structure that are vulnerable to freezing and thawing. Analysis of crack patterns and cumulative additions of crack widths over a period of time can thus be very misleading, and cannot be accepted as 'simple and cost-effective method of determining the magnitude of AAR damage to a structure' as suggested in the literature.[19] Nor should measured crack widths be used for estimating 'expansion to date' as suggested elsewhere. Surface cracking cannot thus represent a quantitative measure of either expansion or degree of internal damage.

As with drying shrinkage, the presence of steel reinforcement also controls AAR cracking. Detailing, or rather, bad, incorrect, and inadequate detailing can therefore have a predominant influence on cracking. Cracking due to AAR in real structures can thus be highly complex, very variable and unpredictive. It is very much dependent on the amount of expansion, care and efficiency of reinforcement detailing, nature of the structure and the stress distribution in the structure.[1,16–18]

Higher temperature, a NaCl environment and wetting/drying modes all enhance the distribution and intensity of cracking. Although internal microcracking occurs at tensile strains of 150–500 μs, external visible cracking occurs only at about 1300–1400 μs. Thus, considerable loss in serviceability may occur before cracking due to AAR becomes apparent. Surface cracking measurements in deteriorating structures are thus fundamentally an inaccurate basis for evaluating expansion and structural damage.

Evaluation of structural damage

The two major properties influenced by AAR are flexural strength and elastic modulus, both of which affect the overall structural integrity of any concrete and particularly of any load-bearing element. However, these losses in engineering properties do not occur at the same rate or in proportion to expansion, and since, for a given reactive aggregate and alkali content in concrete, environment influences expansion most, environmental effects also mostly control the loss in engineering properties in an AAR-affected concrete element and structure.

The importance here is not so much the loss, *per se*, of the engineering properties of the concrete but the effects of the expansive reaction on material stability, steel stresses, the structural stiffness of the affected member and the overall flexural rigidity (EI) of the structure as a whole. In a load-bearing member with constantly changing microstructural characteristics, then, the properties related to dynamic testing, i.e. dynamic modulus, are more relevant than static modulus or static stiffness damage. It has been reported[19] that expansions in a structure can be estimated on the basis of crack summation and using the change in stiffness in the cores measured using the Stiffness Damage Test. Estimating structural expansions based on crack summation can be extremely misleading and unreliable, and Ec values based on such relationships should be treated with great caution.

Non-destructive testing

In field evaluation of AAR-affected structures, the best and most useful information is obtained through non-destructive testing of not only the structure itself, but also laboratory and field exposed cores extracted from the structure. Non-destructive test methods (NDT) have been widely used to evaluate existing structures, to detect imperfections, weaknesses and deterioration, and in post-mortem examination of structural distress. The use of pulse velocity and dynamic modulus techniques is particularly ideal to monitor the initiation and progress of concrete deterioration. Resonance frequency methods have, for example, been used to monitor the influence of various factors related to AAR involving opaline sandstone-factors such as bulk density, grain size of reactive aggregate, relative humidity and curing conditions.[20] Resonant frequency methods have also been successfully used to evaluate the effectiveness of mineral admixtures to counteract expansive strains and of remedial measures such as surface impregnation.[20]

The ability and sensitivity of the pulse velocity and dynamic modulus test techniques to monitor and evaluate damage due to AAR are summarised in Tables 4–6. These data confirm positively that both pulse velocity and dynamic modulus are highly sensitive to changes in the internal structure of the concrete arising from material damage due to AAR. They also show that both these properties register measurable losses at a very early age even before any significant expansion has occurred, i.e. long before any change in physical properties or visible cracking occurs. These data again emphasize that there is no unique relationship between expansion and loss in pulse velocity or dynamic modulus. Since losses in engineering properties do not occur at the same rate or in proportion to expansion, unique relationships between

Table 4. Effects of AAR expansion on pulse velocity and dynamic modulus

Test	*Mix*	*Age (days)*							
		1	*2*	*3*	*7*	*10*	*28*	*100*	*365*
1. Expansion (%)	(a) Control	0.0	0.0	0.0	0.0	0.001	0.003	0.017	0.021
	(b) 4.5% opal	0.0	0.0	0.004	0.071	0.097	0.316	0.883	1.644
	(c) 15% fused silica	0.0	0.0	0.0	0.0	0.005	0.023	0.259	0.623
2. Ultra-sonic pulse velocity (km/s)	(a) Control	4.28	4.48	4.36	4.60	4.64	4.67	4.71	4.78
	(b) 4.5% opal	4.12	4.27	4.32	4.02	3.70	3.48	3.29	2.70
	(c) 15% fused silica	—	4.45	—	4.57	4.59	4.61	3.80	3.64
3. Dynamic modulus of elasticity (GPa)	(a) Control	35.6	38.1	38.8	41.0	41.1	42.5	44.2	45.4
	(b) 4.5% opal	33.9	36.3	37.5	32.7	23.7	20.8	19.6	10.4
	(c) 15% fused silica	—	37.0	—	39.5	40.2	40.8	24.0	18.9

Table 5. Percentage loss in pulse velocity of AAR affected concrete

Age (days)	*4.5% opal*		*15% fused silica*	
	Expansion (%)	*Loss (%)*	*Expansion (%)*	*Loss (%)*
2	0.0	1.1	0.0	<1.0
7	0.071	9.5	0.0	<1.0
10	0.097	17.0	0.005	1.0
28	0.316	23.0	0.023	1.3
100	0.883	30.1	0.259	19.3
204	1.442	44.0	0.615	32.0
300	1.618	48.9	0.625	25.3
365	1.644	43.5	0.623	23.8

expansion and pulse velocity or dynamic modulus cannot be expected.

The data in Tables 4–6 also show that NDT test methods can be used for highly reactive as well as slowly reactive aggregates. For a highly and rapidly reactive aggregate such as opal, the losses in engineering properties are very rapid, sudden and high, whereas for a moderately reactive aggregate such as fused silica, these losses occur more slowly and at a slower rate. These data also highlight that losses in dynamic modulus are much higher than those in pulse velocity, emphasizing that the effects of AAR on stiffness are more critical than the effects on microcracking.

The data in Tables 4–6, and other test data not reproduced here, also confirm that pulse velocity measurements can detect the formation of first crack, and that they are sensitive enough to pick up small reductions and changes in pulse velocity due to AAR deterioration, even when such losses occur at different rates of expansions or at different ages. These results also manifest that dynamic modulus is more sensitive to changes in the damage to concrete due to AAR than pulse velocity, but the latter is much more amenable to field testing, and is adequately sensitive for monitoring deterioration of real structures.

Whilst the pulse velocity is highly sensitive to internal deterioration and to environmental conditions that induce such deterioration, a common and mistaken assumption made often is that such measurements can be used directly, without special calibration, to assess the strength or changes in the strength of concrete in a deteriorating structure. Pulse velocity–strength relationships are exponential, and isolated or spot measurements, or random measurements in a deteriorating structure of high residual strength (which is often met with in real AAR-affected structures, and which therefore leads to high levels of measured pulse velocity) may therefore appear to be meaningless, insensitive or confusing to assess the extent and ongoing changes in deterioration. This probably arises from our lack of understanding of the true role and implications of NDT. It should never be overlooked that deterioration due to AAR is a time-dependent phenomenon, and that its effects on structural damage can be satisfactorily assessed only if realistic and meaningful information is available over a period of time. Non-destructive tests alone can offer a

Table 6. Percentage loss in dynamic modulus of AAR affected concrete

Age (days)	*4.5% opal*		*15% fused silica*	
	Expansion (%)	*Loss (%)*	*Expansion (%)*	*Loss (%)*
2	0.0	4.6	0.0	2.7
7	0.071	20.3	0.0	3.8
10	0.097	42.3	0.005	2.3
28	0.316	51.1	0.023	4.0
100	0.883	55.8	0.259	45.7
204	1.442	74.7	0.615	68.0
300	1.618	81.9	0.625	59.8
365	1.644	77.1	0.623	58.4

cost-effective and reliable method of continuous monitoring and accumulating such data reflecting the varying internal and external effects occurring at different rates and different ages. If used with engineering judgement, and other tests where appropriate, pulse velocity and dynamic modulus measurements can provide engineers excellent data for evaluating structural deterioration due to AAR.

STRUCTURAL RECTIFICATION

Crack sealing

Since cracks are the most direct and visible external evidence of AAR, the first and probably the most obvious solution in the rectification process may appear to be to seal the cracks with an injected epoxy resin. Cracking is a form of stress release, but extensive cracking will obviously affect adversely the stability of the material and integrity of the structure. Whilst sealing wide cracks will be beneficial in preventing ingress of external contaminants, it may also block the pathways for the gel to flow and fill, and consequently increase the internal pressure from the gel and enhance new crack formation. In any case, epoxies can fill surface cracks for only about 25–30-mm depth of typically wide cracks of about 0.2 mm, and cannot penetrate smaller crack widths; also, they are invariably brittle and possess little crack-bridging ability. There have been several cases of epoxy repairs opening up, new cracks forming and widening of other cracks arising from rigid epoxide resin injection repairs. Crack injection and crack sealing should therefore be adopted only after careful evaluation of its implication on future reactivity and expansion.

Environment, the fourth member of the triad gang

In the light of the earlier discussions, we now have to recognise that there are four critical conditions related to AAR that are essential for the continuation and progress of material and structural distress in field structures. To the three well-known requirements, namely,

(1) presence of reactive minerals,
(2) presence of sufficient alkalies, and
(3) presence of sufficient moisture,

we need to add a fourth,

(4) environment/exposure conditions.

As pointed out earlier with many moderately reactive and slow, late reactive aggregates, the rigours and vagaries of seasonal climatic exposure conditions are the main cause of the continuation and acceleration of the reactivity (see Tables 1–3, for example).

Protection from the environment

Many laboratory tests and field studies[6,8,9] show that in almost all concrete mixes used in practice, there is nearly always enough residual mixing water to initiate AAR. However, invariably in all cases, the availability of internal residual mixing water is not sufficient to create ongoing damaging widening of cracks and loss of engineering properties. External sources of moisture are thus required to continue and accelerate the deterioration process. There is now enough field evidence to confirm that seasonal exposure and climatic variations enable most concrete structures to maintain internal relative humidities sufficiently high to sustain expansive alkali–aggregate reactivity. Thus, most of the concrete in highways and dams in desert areas, and bridge decks and columns in dry climates can maintain sufficient internal dampness to sustain expansive reactions on and off. Similarly, massive concrete members indoors in controlled environments can also retain adequate humidity for a long time. Equally, moderately elevated temperatures can also be effective in drying concrete sufficiently to reduce substantially or even stop the rate of reactivity for some period of time. Thus, for many structures, it is the external environment that is the primary cause of continuing damaging expansive reactivity. Therefore, protection from external environment and control of ingress of water and water-borne contamination is the first step in the rectification process of any concrete element suspected of AAR.

Penetrants, sealants and coatings

Protective coatings offer a very positive and reliable solution for the long term protection of concrete structures from the surrounding environment and ongoing AAR.[1] However, experience world-wide on the use of such coatings, sealants, penetrants, impregnants, and membranes has not always been favourable, partly because of the high variability of coatings of similar generic types in their diffusion characteristics and resistance to external aggressive agents, partly because of their lack of long-term durability, and above all, because of our lack of understanding of the basic engineering requirements needed for them to perform satisfactorily in realistic environments.

The use of a wide range of sealants, penetrants, membranes and coatings has been reported in the literature, but only a few salient aspects of their performance characteristics are discussed here. Silane impregnation has been widely used, and existing data show that under laboratory conditions, alkyl alkoxy silanes prevent the ingress of water and chloride ions, but they have no effect on pore size distribution nor do they improve the carbonation resistance of the concrete. However, field trials of alkyl (isobutyl)-trialkoxy-silane (silane) show that penetration is minimal, ranging from less than 0.5 mm to 2.0 mm, and that silane is a water repellent and not a waterproofing agent or pore blocker. In many instances, the reported penetration of impregnation is no more than 1 mm; at these limited depths of penetration, the effectiveness of the impregnant will be rapidly eliminated by environmental degradation. It should also be recognised that standing water will penetrate silane as will rain driven by strong winds.

A highly flexible surface coating, however, can prevent the intrusion of moisture and chlorides into concrete.[21] Such a coating can also act as an effective surface crack sealing compound as well as control the expansive strains due to AAR.[22]

Flexible polymer cement mortar (PCM) coatings consisting of a polyacrylic latex, portland cement and some admixtures have also been found to have the ability to inhibit AAR, and have been used to repair damaged structures.[23] Shrouding of concrete with ventilated cladding has been found to be effective in laboratory studies in controlling AAR, but there is little quantitative information on their performance characteristics in real structures or their long term effectiveness.

STRUCTURAL STRENGTHENING

Structural retrofitting and strengthening of deteriorating structures require a clear understanding not only of the structural behaviour of load-bearing elements undergoing AAR,[1,10] but also of the structural design aspects and reinforcement detailing of the various elements. The most direct approach to restore loss of strength of AAR-affected members is to apply external restraint through strapping and tensioning or prestressing the strapped plates to provide adequate containment of the expansive forces. Both strength and stiffness can also be restored to original design values through 'Plate Bonding Technology'.[24]

Hydraulic structures

Hydraulic structures such as dams and generating stations that provide their service life in environments of high humidity and highly variable exposure conditions pose particularly difficult problems of structural rectification not only because of their massive nature but also because of the wide range of installations associated with such structures such as intakes, sluiceways, spillways, shafts and gates. Further, the vast exposed surfaces invariably ensure that concrete in the various parts of such structures is affected differently by AAR and shows a wide range of damage, whereas the damage due to AAR itself is often intermixed with the effects of wetting/drying cycles, freezing and thawing cycles as well as moisture and thermal gradients. It is impossible within the space available here to develop any meaningful discussion of these problems, and reference only can be made to specialist literature on this topic.[13,25–28]

CONCLUDING REMARKS AND RECOMMENDATIONS

The diagnosis, assessment and rectification of concrete structures affected by AAR is a complex, difficult and time-consuming process. A major problem facing those involved in identifying and evaluating material and structural damage is the many stages where confusions, contradictions and uncertainties challenge the assessment. Inevitably, assessment of AAR damage is closely and intimately involved with testing, and test results depend entirely on test methodologies. Environment, or most precisely, the changes in climatic and exposure conditions, is probably the most critical factor influencing and modifying accepted concepts of behaviour of AAR-affected concrete. Because of the many complex interactive and interdependent parameters involved in controlling the rate of expansion and total expansion, each structure may have to be assessed and treated individually and independently, while appreciating the known commonalities of the damage process and similar patterns of behaviour exhibited by affected structures.

This paper advocates an integrated material and structural design strategy for the assessment and retrofitting of concrete elements and structures undergoing and/or damaged by AAR. The following approach is recommended.

(1) Diagnosis
  (a) Age of structure
  (b) Petrographic analysis+XRD where necessary
(2) Expansion Potential Assessment
  (a) Accelerated laboratory tests of extracted cores at 38°C in 4% NaCl solution
  (b) Field tests of extracted cores under ambient environment
(3) Protection from Environment
  (a) Selective crack sealing
  (b) Barrier/surface coating to stop or control ingress of moisture, and hence, AAR
(4) Structural Evaluation
  (a) Continuous NDT monitoring of structure and cores for evaluation of material damage and structural integrity
(5) Structural Strengthening
  (a) Application of external structural restraint; prestressing
  (b) Plate bonding technology.

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