The Structural Effects of Alkali-Aggregate Reaction on Reinforced Concrete

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ABSTRACT

The structural assessment of the effects of Alkali Aggregate Reaction (AAR) requires the reaction to be quantified in terms of expansive strain, stiffness and the forces generated when restrained. The control of AAR requires the measurement of RH in structures and the determination of the effects of RH on expansion. This paper sets out the results of tests to quantify these effects.

1. INTRODUCTION

The development of strategies for the cost effective management of structures suffering from AAR (Wood et al 1986) has required a quantitative knowledge of the changes in strength, dimensions and stiffness of the concrete. Because of the dearth of published data (Wood et al 1983) we set out to determine, for the particular varieties of AAR in the UK, these properties, so that a basis for predicting the effects of AAR on the serviceability and strength of reinforced concrete structures, could be developed. While we have made substantial progress, a great deal more testing and fundamental research will be required before the bond and shear behaviour of reinforced concrete structures can be predicted with confidence. In parallel with the determination of the physical effects we have studied the rate at which they develop and the potential for control. Some of the results of this work to date are set out below.

2. FREE STRAINS

For normal concrete design it can be assumed that the stress in the concrete is proportional to strain, but with some small allowance for shrinkage and creep effects (see Table 1). With AAR in the UK free strains (i.e. of unstressed cores) of up to 10mm/m can occur so the normal linear elastic assumptions are invalidated. Tests by many workers (Nixon et al 1985) have shown a reduction in stiffness of Concrete (Youngs Modulus) with AAR and we are collecting further data. The compressive and tensile strain limits are also being investigated as part of the overall determination of load strain characteristics. Embrittlement can be more dangerous structurally than strength loss.

TABLE 1. COMPARISON OF TYPICAL MATERIAL STRAINS

Example of Material Strain	Strain mm/m
Drying Shrinkage to 90% RH of concrete	0.1
Temperature Differential 20°C	0.24
Limiting Tensile Strain of Concrete	0.1 to 0.2
Creep of Pretensioned Concrete @ 13N/mm^2	0.64
Steel Yield Strain - Grade 250	1.25
- Grade 460	2.30
Ultimate Compressive Strain of Concrete	3.5
Latent Free Expansions with AAR	
(a) 38°C & 100% RH @ 3 mths - 53 cores	0.19 to 2.16
(b) 20°C & 100% RH @ 7 mths - 4 cores	0.65 to 4.40
(c) 13°C & 100% RH @ 7 mths - 2 cores	4.55 to 5.40
(d) Outdoor exposure @ 20 mths - 110 cores	0 to 12.0

3. CORE TESTS

Starting from the traditional 100% R.H. 38°C average expansion test for AAR we have evolved a more detailed test procedure for cores. It is based on measuring the strains in mm/m, longitudinal USPV and weight changes in cores subject to a range of environments, some cores with coatings and some with restraint. For diagnosis, cores are taken from a representative range of pours of concrete on each structure being examined. Typically, 2 cores from uncracked areas, 2 cores from slightly cracked areas and 2 cores from severely cracked areas are taken. For more detailed long term comparative expansion tests, groups of up to 50 cores have been taken from single pours of concrete. We are now standardising on a 70mm diameter core (75mm hole) which is cut into sections, 50mm for outer chemical analysis, 20mm petrographic record disk, 180mm expansion test section, 20mm petrographic disk, 50mm inner chemical analysis. Larger cores increase the risk of damage to the reinforcement during cutting and give little advantage in testing. Demec gauge reference studs are fitted in the core in three equally spaced rows of three 50mm lengths. These enable the variability of the expansions, as well as the average to be determined. Figure 1 gives a typical range of variability of expansion measured on one core. Figure 2 shows the range of average expansions from one nominally constant concrete mix. It is the variability of these expansions that produces the AAR damage which will be more severe the larger the concrete member.

Despite the substantial variability of expansions, we have found it possible to broadly classify the potential damaging effect of the latent expansion from AAR in a mix by using the upper quartile value of the 38°C 100% relative humidity expansions from at least 4 cores. This scale which runs from A+ down to E is shown in Figure 3. The strain limits adopted (Wood 1985) are related to those which are structurally tolerable. Thus expansions of level D/E would be of no greater order than the normal temperature, moisture and creep effects in a reinforced concrete structure.

4. RESTRAINED EXPANSION

The majority of structures suffering from Alkali Aggregate Reaction contain steel reinforcement which will attempt to resist the expansions. To determine the degree to which the steel could reduce the strains and forces generated by the expansion we have conducted expansion tests in parallel to the free expansion tests using cores restrained between two steel end plates with the stresses in the steel and concrete monitored. Areas of steel of up to 8%, corresponding to steel areas in particular structures, have been used for this series of tests. Figure 3 shows how with 0.9% steel a core can produce sufficient force to yield the steel. The forces generated by the expansion are sufficient to substantially increase the bond and anchorage stresses in reinforced concrete members. The data from these tests is being fed into structural analyses for comparison with reinforced concrete elements where an anchorage/ delamination failure has developed between the reinforcement and the reactive concrete.

5. THE EFFECT OF ENVIRONMENT ON EXPANSION

The economic benefit of reducing the rate of deterioration of structures with AAR is very great. We have liaised closely with Queen Mary College in tackling this problem (Jones et al 1986). Our own robust approach to assessing the effect of temperature and humidity on expansion has been based on exposing cores in 100% relative humidity conditions in the laboratory at 38°C, 20°C and 13°C and leaving samples exposed on site with differing degrees of shelter and coatings.

Although we have asked commercial laboratories to carry out tests above salt solutions to give intermediate humidities, it is clear from the weight uptake characteristics that they did not achieve consistent humidities. The monitoring of weights during expansion tests has shown that substantial expansions can take place with weight uptakes of less than 2g/kg, but typically with 5-10g/kg. Very wide fluctuations arise in commercial laboratory conditions due to variations in the actual humidities in "100% RH" containers. We now base our standard free expansion tests using a closed but pressure vented container in which the core sits in 10 g/kg of water. We hope that this will enable much better comparative assessments to be made of expansivity as it will eliminate the scatter due to poor humidity control in commercial laboratories.

A regrettable conclusion of our tests is that expansion tests done without weight uptake monitoring cannot be relied upon where there is any doubt on the quality of humidity control. The effects of temperature in our tests are shown in Figure 4. This shows the magnitude of expansion being greater by a factor of about 4 at 13°C compared to the standard 38°C. Testing at 38°C effectively kills the reaction with SW aggregates. Trent aggregates are less temperature sensitive. As 13°C is a mean outdoor structure temperature in the UK the implications of this on the potential magnitude of damage are large. Our testing is now largely carried out at 20°C, 13°C and 5°C, or at site ambient temperatures.

6. SITE EXPOSURE EXPANSIONS

In parallel with the laboratory testing we have exposed on site 110 cores of three mix types. One mix is non-reactive, another is South West sea dredged fine aggregate with reactive chert in the 2-8mm range with limestone and the third has Trent Valley aggregate with reactive chert and some other minerals in the full size range. The expansions of the South West material are typically two to four times those of Trent Valley material and in this paper we have concentrated on the former.

To determine the relative expansions under the range of environments encountered in structures, we exposed the cores, a) in troughs which can fill and empty with water during periods of high or low rainfall b) on open racks exposed to the full sun and rain, and c) under a simple three-sided roofed shelter exposed to the North so that little rain or sun strikes the samples. Some of the cores were left uncoated, others were treated with chlorinated rubber, liquid plastics, silane, silicones and methylmethacrylate.

After a period of 500 days in Plymouth one of the warmer but damper corners of England, the expansion patterns are as follows:-

a) In the troughs, where in wet weather water accumulates around the coated core, the expansions have exceeded 10mm per metre. Many of the cores are starting to fragment and disintegrate and the coatings are generally in poor condition.

b) On the racks exposed to rain, expansions of between 1 and 2mm/m have occured in most of the exposed cores. There is no significant difference between the coated and uncoated cores. Many of the coatings are starting to deteriorate.

c) In the shelter, uncoated and coated cores generally show a very small expansion or a small contraction of the order of plus/minus 0.2mm/m.

These exposed cores are monitored for weight changes and internal relative humidity changes using the wooden plug technique. This is giving us a much clearer idea of the effect of changing humidity conditions on expansion than the laboratory tests. The relative humidities measured in the cores are in the 95-100% range in the troughs, 90-95% range in the open exposure and from 80-90% relative humidity in the shelter. Substantial seasonal fluctuations occur in cores in all three environments.

Our current view, is that none of the surface coatings or treatments shows a sufficient positive benefit or reliability for recommendation for use generally on structures with AAR in the UK climate. However, ventilated cladding shows a clear positive benefit and can be of value on structures where the long term durability does not hinge on the deterioration below ground level. Similarly, ventilated cladding will not help in bridge decks where the greatest risk comes from a breakdown of the deck waterproofing.

7. CONCLUSIONS

The results of over 1,000 core tests on over 100 structures are now being collated. The separate series of tests described above have linked samples enabling their results to be cross correlated. These laboratory and site expansion tests are also being compared with the crack growth rates, relative humidities and overall movements of the structures from which the cores were removed. Some of the structures are subjected to annual proof loading tests to determine the effect of a large cycle of load on displacements, stiffnesses and crack movements during test, compared with comparable movements from the reaction in the intervening year. Similar comparisons will be made with the mixes and structures in the BRE and University research programmes which are starting in the UK on the structural effects of Alkali Aggregate Reaction, particularly on bond, anchorage and shear failure. The data from the core tests also provide the stiffness and strain characteristics for incorporation in developing finite element methods of predicting the serviceability and strength effects of the reaction upon structures.

The compass of this paper only permits a sketchy outline of the data, testing and development work we have carried out to cost effective structural management systems for structures with AAR. The full reports will be published elsewhere.

It has become clear from our work that the physical effects of AAR are highly sensitive to the type and size range of the reactive aggregate particle and that the characteristics of AAR cannot be generalised.
It is hoped that similar techniques to those we have applied to UK aggregates can be applied by others to other varieties of AAR, so that we can develop a system of classifying the physical effects of the reaction. This will require future research to give these physical effects at least as much attention as the chemical and petrographic phenomena.

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REFERENCES

1. Wood J G M, Johnson R A, Norris P. 1986 Management Strategies for Buildings and Bridges subject to Degradation from AAR. 7th Int Conf on AAR. Ottawa.

2. Wood J G M and Wickens P J. 1983 Structural Effects of AAR in Reinforced Concrete and Consideration of Remedial Action. Alkali in Concrete 6th Int Conf. Copenhagen.

3. Nixon P J and Bollinghaus R. 1985 The Effect of AAR on the Tensile and Compressive Strength of Concrete. Durability of Building Materials 2. Amsterdam

4. Wood J G M. November 1985. Engineering Assessment of Structures with Alkali Silica Reaction. Concrete Society Conf. London.

5. Jones T N and Poole A.B. 1986. ASR in Several UK Concretes. 7th Int Conf on AAR. Ottawa.

Figure 1

Variation in expansion of core testing at 38°C and 100% R.H.

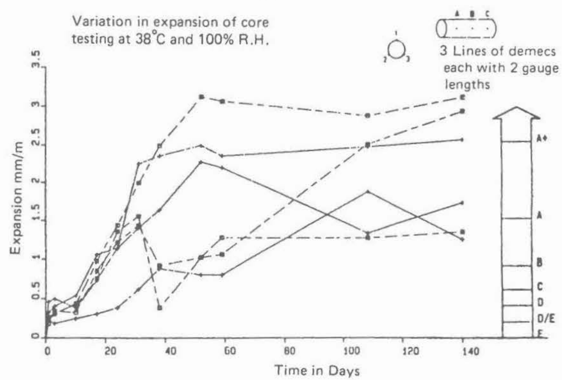


Figure 2

Variation in overall mean expansion of all gauge lengths of 7 cores from deck slab testing at 38°C and 100% R.H.

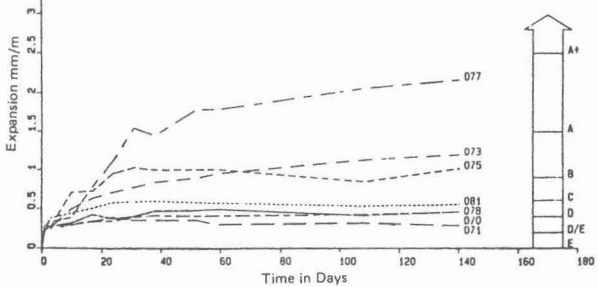
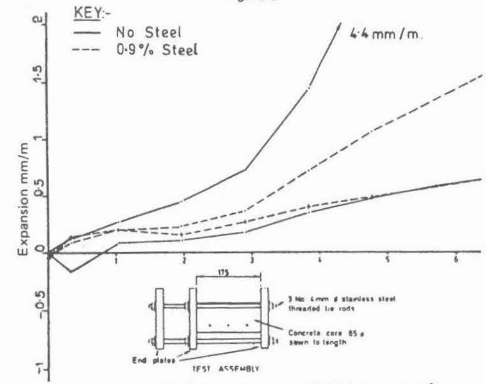


Figure 3



Restrained expansion at 100% R.H. and 20°C

Figure 4

Core expansion at 100% R.H. and different temperatures

SW Aggregate