RELATING ASR STRUCTURAL DAMAGE TO CONCRETE COMPOSITION AND ENVIRONMENT

J G M Wood,
Structural Studies and Design Ltd, Northbridge House,
Chiddingfold, Surrey, GU8 4UU, UK. Fax (+44) 1428- 685902

P J Nixon,
Building Research Establishment, Garston,
Watford, WD2 7JR, UK. Fax (+44) 1923- 664010

P Livesey
Castle Cement Ltd, Clitheroe
Lancashire BB7 4QF UK Fax (+44) 1200- 29668

ABSTRACT

Over 100 core samples have been taken for analysis from nine bridges and a river wall in South West England. The structures all showed some ASR type cracking and most had already been subject to detailed diagnosis, monitoring and test programmes for 10 years. On each structure samples were taken in matched sets of nominally identical mix composition, from identical structural members in similar environments. These sets cover concrete pours ranging from uncracked through to severely cracked. The emphasis was on pours with cracking from slight to moderate expansion and the most extreme cracking was deliberately avoided. The degree of cracking and ASR damage has been assessed using procedures and tests from the IStructE 1992 Report 'Structural Effects of ASR'. For some structures insitu RH has been measured and expansion tests have been undertaken to determine potential for further damage. The cores are being analysed for alkali contents and petrographically so that the relationship of mix characteristics to field damage can be evaluated.
Keywords: Structural ASR Damage, Petrography, Diagnosis, Alkali Analysis.

INTRODUCTION

This paper sets out the general approach and methodology being developed in a study by SS&D and BRE to relate the severity of structural effects in a range of structures with ASR to the nature and variability of the composition of samples of the concrete. Some initial trends are indicated here and the further results will be published in due course. It is hoped that this study will help bridge the gap between the procedures and data used in structural analysis and those used in diagnosis, petrography and laboratory studies on ASR.

The knowledge of the composition of concrete in structures with ASR damage in the field potentially provides the best basis for developing and calibrating specifications for minimising the risk of damage from ASR (Hawkins 1995). However the difficulties of reliably relating the analysis of core samples to the original mix composition and in quantifying the current and future ASR damage have deterred studies in this field. Compared to the massive literature on accelerated short term tests on mortar bars and concrete prism testing, there is little data on the field composition related to damage and most of that is based on relatively few samples.

Nixon et al. 1987 carried out a detailed study of alkali variation on ASR cracked foundations. Since then a number of limited studies of alkali contents and variability in structures have been carried out by the authors and others (eg Livesey et al. 1996), which have further developed the procedures. It was considered that the methods of assessing damage in structures set out in the "Structural Effects of ASR" (IStructE 1992) and the developments in detailed petrographic diagnosis and analysis of concrete, including those in "Diagnosis of ASR" (Palmer 1992), provided the basis for a more comprehensive programme to evaluate the composition of concretes which are suffering ASR damage in the UK. However it was appreciated that it would be necessary to develop and refine procedures as data came available.

The South West of England has many cases of ASR damage (Wood 1992). In a few structural elements this has caused serious structural damage, but in most it has just produced some unsightly cracking without structurally detrimental damage. Since the early 1980s Mott MacDonald, and more recently Structural Studies & Design, have carried out detailed structural assessments (Wood & Johnson 1993) on about 50 structures with ASR in the South West of England. Agreement was reached with the owners of 10 of these structures for the coring for samples for detailed analysis by BRE. Relevant data from the owners testing and structural assessment programmes is being made available to BRE to complement their data.

SELECTION OF STRUCTURES AND CORE SETS

The primary objective of the sampling programme was to obtain matched sets of 6 to 10 cores from very similar structural elements, which showed a range of ASR cracking damage, ie from no apparent cracking up to moderate damage (1mm/m). With a few exceptions, pours of concrete showing severe cracking (> 2mm/m) were avoided, so that the compositional data would be concentrated on samples at the interface between 'ASR with no significant damage' and 'ASR with just significant damage', which is of most interest for calibrating specification requirements.

Table 1 Summary of coring for all structures

Ref	Structure	Town	Owner	Built	Cores Taken	IStructE AAR Class	Aggregate Type
1	Exe Bridge, Upstream.	Exeter	Devon CC	1968 - 70	14	B - D	R
2	Exe Bridge, Downstream.	Exeter	Devon CC	1970 - 72	5	C - D	R
3	Marsh Mills Viaduct	Plymouth	DTp	c1970	32	A - n	S(G) & S(L)
4	Plympton Hill	Plymouth	DTp	c1970	12	C - D	S(G) & S(L)
5	Voss Farm Column	Plymouth	DTp	c1970	3	A	S(L)
7	Burbarrow Bridge	Nr Bristol	Avon/ DTp	1966 - 67	8	A - D	T
8	Tiverton River Walls	Tiverton	NRA	c 1970	12	A - D	U
10	Countess Wear Flood	Exeter	Devon CC	1966	11	D	R
13	New Grindle Brook	Clyst St Mary	Devon CC	1967	15	C - D	R
14	Kempstown	South Molton	Devon CC	1976	6	B	U

About 30 structures were considered, before selecting 10 where there was easy access to suitable matched sets. Table 1 shows the main details of the selected structures including the range of 'Structural Element Severity Ratings' for the cored elements determined from the IStructE 1992 procedures. In each structure, sets of elements were selected which had been cast in successive pours of concrete and which showed a range of severities of damage. For example, Plympton Hill Bridge has 2 rows of 6 columns with cracking damage apparent in the outermost columns which are slightly more exposed to weather. Six of these columns were cored for analysis. A similar set was taken on the columns of Marsh Mills Viaduct Fig. 1 and from the severely damaged column from the adjacent Voss Farm Bridge, which was retained after demolition. On other structures the sets of cores have been taken into retaining walls and bridge abutments. As far as possible coring locations were selected so that the risk of alkali migration leading to concentration and/or leaching was minimised.

The 10 structures cover four distinct aggregate types, as shown in Table 2 below. Most of them had cement from Plymstock cement works, which is known to have had high alkali, up to 1.2% Na_2O equiv. in the early 1970s, but this has since been reduced. All the structures had been petrographically diagnosed as having ASR as a major factor in the development of cracking, or were of a similar mix to cases which had been diagnosed. Confirmatory diagnosis is included in the test programme.

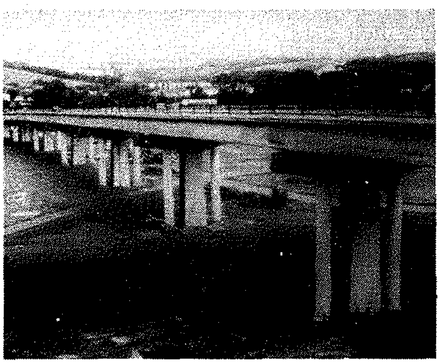

Figure 1. Marsh Mills Viaduct

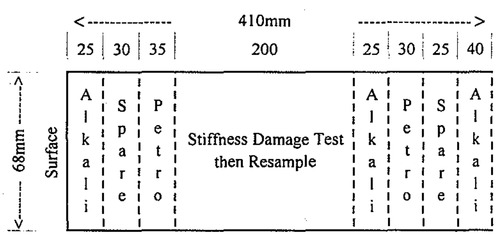

Figure 2. Typical Initial Core Subdivision

CORING AND CORE SUBDIVISION

The coring was carried out to a standard procedure using wet diamond coring with a 75mm barrel to give a 68mm diameter core. The use of larger cores increases the risk of cutting reinforcement, which can both damage the structure and make the cores less suitable for structural testing. Core locations were selected off the line of reinforcement and at least 100mm from a surface crack to ensure, as far as possible, that intact cores were obtained. In most cases cores of 400mm to 600mm length were obtained to provide sufficient material so that sets of tests could be carried out on one core to facilitate direct comparisons between the results. The coring was carefully supervised and logged with cores cleaned, dried, cling film wrapped and then packed for delivery to BRE. Checks have confirmed that wet coring does not lead to significant alkali loss.

After initial inspection and recording at BRE, the cores were dry cut into ~25mm slices, or 200mm lengths for Stiffness Damage Testing, prior to further tests. A typical initial subdivision is shown in Fig. 2. As the data from the initial testing becomes available further selections for sample subdivision and testing are made.

SITE MEASUREMENTS OF DAMAGE AND HUMIDITY

To quantify the degree of damage from ASR, crack summation has been used to estimate 'expansion to date' following the IStructE procedures. At each coring location the width and spacing of cracks were recorded. However these cracks result from the combined effects of ASR expansion, thermal, shrinkage and structural strains, in typically $1m^3$ of concrete, in the vicinity of the core. These estimates of 'expansion to date' were made on a simple basis ignoring the effects of stress and restraint. For more detailed analysis, where stress or restraint levels are significant, their influence in reducing or increasing the crack intensity is being considered. In most cases, sampling was carried out in areas of low stress and low restraint so that the simple estimate of expansion would be valid.

There are many causes of differential strains which develop in concrete as it is cast, matures and dries. Differential thermal strains and shrinkage strains between the surface and core of the material are the 2 main phenomena. These typically induce strains of 0.2 - 0.4mm/m, which is close to the tensile strain capacity of concrete (0.3 -0.4mm/m) at which cracking initiates. This is shown on IStructE 1992 Fig. 13. As ASR effects are superimposed on these normal residual strains, the initial cracking, with ASR expansions of up to 0.6mm/m, arises mainly from the interaction of ASR with thermal and shrinkage effects. In setting limits to ASR expansion in specifications it will be important to distinguish between ASR expansions which, by themselves, will induce cracking and the lower level of ASR expansion which will unacceptably accentuate the cracking from early thermal and shrinkage effects.

The timescale of crack development with UK aggregates is still uncertain. From records of monitoring crack widths on many structures since the mid 1980s there is clear evidence of a progressive increase in crack widths with time, as shown for structural members cored for BRE on Marsh Mills Viaduct in Fig. 3.

The long term equilibrium relative humidity in the concrete at a depth of 75 - 100mm has been recorded adjacent to the core location on many of the structures. A wooden dowel is sealed into a 16mm diameter hole and allowed to equilibrate over a period of months. The moisture content of the dowel is used to determine the equilibrium relative humidity RH. The results show significant variations in RH typically between a 23% dowel mc (ie 94%RH) and 50% dowel mc (ie 100% RH) within a bridge abutment. This moisture variability is clearly a factor in the rate at which the potential expansions and cracking develop in different parts of the structure.

STRUCTURAL TESTS

As most of the 10 structures have already been subject to detailed structural testing programmes the additional testing for this study has been concentrated on the expansion testing of some cores and the Stiffness Damage Testing of most cores.

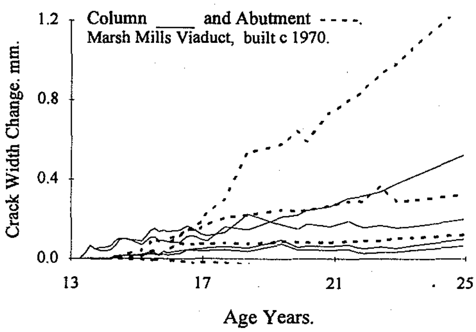

Figure 3. Long term crack movements.

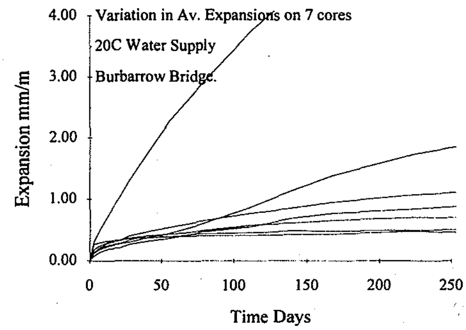

Figure 4. Expansion test results.

Expansion testing, at 20°C in water supply conditions, has been carried out on some of the 200mm core lengths after Stiffness Damage Testing. This test shows if the ASR has stabilised or if it may in time, and with sufficient moisture availability, develop more severe cracking. Fig. 4 shows a typical example of the high variability of average expansions for seven cores from Burbarrow Bridge. There is a similar variability in expansion along the length of each core. Expansion tests over 5 or more years are needed to indicate the long term potential for further expansion. Data on these and other structures shows a good relationship between expansion tests and site monitoring of movements and crack growth. In comparisons between mix composition and ASR damage to structures, the potential for further expansion and cracking must be considered.

The development of ASR microcracking produces a marked reduction in the stiffness of concrete and the development of hysteresis (Wood et al. 1989). This provides a sensitive indication of 'expansion to date' for the material being analysed. 200mm lengths were tested at Sheffield University using the Stiffness Damage Test (SDT) to measure the Young's Modulus (Ec) and the hysteresis (DI). Fig. 5 shows the estimated relationship between Ec and expansion to date which is being refined and re-calibrated using data from this study and laboratory studies (Jones 1994). Fig. 6 shows the range of expansions to date estimated from the SDT Ec for the full set of samples and shows how the material covers the range from normal concrete to 'expansions to date' of over 2mm/m.

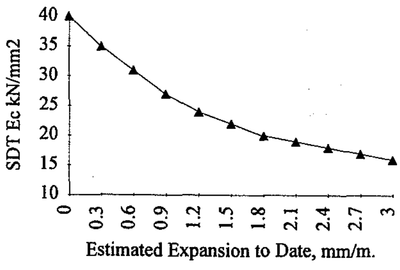

Figure 5. Estimated Expansion from SDT.

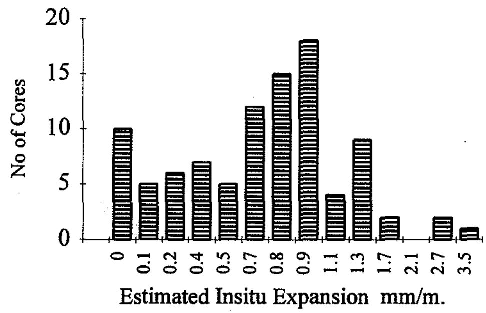

Figure 6. Range of Estimated Expansions.

ALKALI ANALYSIS

The 25mm concrete slices were crushed, dried and ground according to the British Standard method (BS1881 Pt. 124 1988). Acid soluble and water soluble extracts were analysed for sodium and potassium oxides. The extraction procedure can extract alkalis from aggregates which would not be 'effective' in ASR. Blank determinations are necessary to separate these from the 'effective' alkalis, predominantly from cement, considered in specification (Hawkins 1995). In the case of aggregate types R and S (Table 1) aggregate alkalis have been shown to be insignificant. In the case of other aggregate types further analyses are required.

An example of the analytical data obtained is shown in Fig 7 for samples from Kempstown bridge abutments. This shows considerable scatter in the alkali contents of individual 25mm slices and there are differences between the surface and heart concrete alkalis. The depth of surface effects due to weathering and contamination must be determined. These will depend on the quality and integrity of the concrete and the exposure conditions. In estimating the original mix alkali content only the analyses from the interior should be taken into account.

With a sufficient number and distribution of slices the original mean alkali content can be determined together with variations between cores, between pours and between different elements in the structure. The mean alkali content of cores from different locations can indicate whether there are significant differences in the concrete composition due to cement content or alkali variation. This can be a valuable guide for the interpretation of different degrees of deterioration within the same structure.

The size of the 25mm x 68mm diameter slices was chosen to provide a measure of the local concrete composition. It was recognised that surface effects and the heterogeneity of concrete would need to be considered before relating local composition to that in the structure. In comparing alkali data with tests the scale of sample needs to be considered. Slice alkali data may relate to petrographic measures of local damage. Average expansion and stiffness data on cores may relate to the average core alkali. Alkali values averaged over larger volumes need to be considered for assessing overall structural damage and defining alkali for specification. Further analyses of structures will help to refine the statistics and their significance.

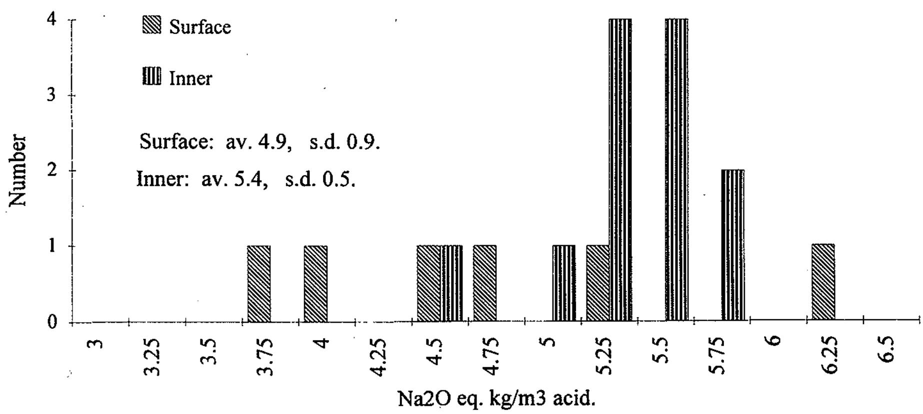

Figure 7. Kempstown. Na_2O Equiv. (Acid). Variation at surface and at depth.

PETROGRAPHIC ANALYSIS

The initial petrographic analyses was carried out to:

- categorise the mix types of various cores, see Table 2.
- identify the potentially reactive rock types and ASR features for diagnosis.
- assess the severity of microcracking in the samples.

The refinement of petrographic examination has enabled ASR damage to be identified in samples, even when it does not have sufficient effect to produce identifiable cracking on the structure. Further data to relate the level of ASR microcracking damage recorded petrographically to the site severity of structural cracking and the Stiffness Damage Test data, is being collated. The initial petrographic analyses are identifying features which merit more detailed study and this is in progress. This includes evaluation of other mix characteristics and deterioration processes which may have interacted with ASR to develop the cracking.

Table 2. Mineralogy of aggregates

Concrete Type R — Structures 1, 2, 10, 13.
Aggregate: Part crushed natural gravel, predominately sandstones with metaquartzite, vein quartz and a little chert.
Reactive Minerals: Mainly Sandstones and some Chert

Concrete Type S — Structures 3, 5, 6,
Coarse Aggregate: Moorcroft limestone in S(L). Hinkston Down granite in S(G).
Fine Aggregate : Cherts with finer quartz grains and some shell.
Reactive Mineral: Chert 3 to 8mm in fine aggregate.

Concrete Type T — Structure 7.
Coarse Aggregate: Carboniferous limestone.
Fine Aggregate : Severn sea dredged with a little chert and shell.
Reactive Minerals: Chert

Concrete Type G — Structures 8, 14,
Coarse Aggregate: Crushed rock mainly greywacke.
Fine Aggregate: Quartz rich with sandstones etc
Reactive Minerals: Greywacke

CONCLUSIONS

The results provide a quantitative record of mix composition relative to the local severity of cracking and structural effects from Alkali Silica Reaction which can help relate laboratory studies to field performance.

This methodology enables surface effects to be differentiated from the inner concrete characteristics to determine to the original concrete composition. It is possible to identify significant differences between pours or between concrete elements. When mix analysis is used in conjunction with measures of expansion, cracking and microcracking severity, insitu RH values and core tests for residual expansion and stiffness, it provides a basis for the assessment of a structure.

The variability found in the analysis of composition, test data on cores and in crack damage to structures highlights the need for comprehensive sampling, so that values of the means and standard deviations can be determined for all tests. There is a significant risk that tests and analyses based on isolated spot samples may give misleading information.

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