Structural Effects

of

Alkali-Aggregate Reaction

A REVIEW OF THE INSTITUTION OF STRUCTURAL ENGINEERS REPORT "STRUCTURAL EFFECTS OF ALKALI-SILICA REACTION (1992)"

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ABSTRACT

The publication of the Institution of Structural Engineers' Report "Structural Effects of Alkali-Silica Reaction" (Doran 1992) coincided with the 9th International Conference on Alkali Aggregate Reaction. Since the publication a three year research programme, undertaken at The University of Birmingham, has been completed. Much of the research carried out related to the "Research Needs" described in the Institution of Structural Engineers' Report. During the research programme over 200 concrete specimens affected by Alkali Silica Reaction (ASR) were tested. The results of these tests are discussed in relation to the Institution of Structural Engineers Report. It is shown that the report overestimates deterioration in relationship to expansion and reasons are given for this. The paper also discusses the relationship between expansion and restraint and methods of predicting expansion are tested. It is shown that a better estimation of expansion can be obtained from crack widths when the crack angle is also considered.
Keywords: Alkali-silica, Concrete properties, Crack widths, Expansion, Restraint.

INTRODUCTION

The Institution of Structural Engineers' (IStructE) Report "Structural Effects of Alkali-Silica Reaction" (Doran 1992) listed areas where it believed additional information was required to aid in the assessment of structures affected by ASR. Experimental work was carried out at The University of Birmingham to investigate: the changes in the characteristics of the concrete as ASR develops and how these changes should be considered in the appraisal of a structure, the phenomena of laboratory scaling and acceleration and their effects on the reaction, and the effects of restraint on expansion. The results of this experimental work are discussed in relation to the relevant chapters of the IStructE Report.

EXPERIMENTAL PROCEDURE

The experimental work involved the testing of Alkali Silica reactive specimens with various sizes, expanded at various rates. The rate of expansion was varied by modification of the conditioning temperature of the water the specimens were stored in. Temperatures of 38, 30, and 20°C, giving approximate expansion rates of 0.1 0.06 and 0.01 mm/m/day. The specimens were reinforced with steel ratios ranging from zero to 2% and expanded under applied stresses ranging from 4 N/mm^2 tension to 7 N/mm^2 compression. The specimens were monitored until their expansion was complete and then tested to failure (Jones 1994). These failure tests were carried out to ascertain the compressive strength, elastic modulus and tensile strength of both specimens and cores removed from the specimens. All the specimens tested were manufactured from a concrete mix with a Na_2O equivalent of 7 kg/m^3, obtained by the addition of sodium and potassium hydroxides, and a Thames Valley reactive aggregate.

RELATIONSHIP BETWEEN EXPANSION AND CONCRETE PROPERTIES

Chapter 4 of the IStructE report discusses the "Physical effects on concrete of ASR expansion". A table is given which relates the properties of Cube compressive strength, Uniaxial compressive strength, Elastic modulus and Tensile strength, as a ratio of their 28 day value, to expansion. This table represented the lower bound to the then available data. The properties of uniaxial compressive strength and elastic modulus are likely to be the most significant for assessment purposes. The values given are discussed in relation to the research described here.

Uniaxial Compressive Strength

Figure 1 presents the crushing strengths of 100 mm x 200 mm long cylinders expanded under different applied stresses to induce different final expansions. On this figure the relationship between uniaxial compressive strength and expansion given by the IStructE report is also plotted along with a new relationship proposed by the Authors later in this paper.

The relationship between uniaxial compressive strength and expansion given by the IStructE report underestimates the compressive strength. This is not surprising given that the relationship was based on a lower bound to a large number of data sources, however, the research described here has highlighted reasons for this underestimation:

- The crushing strength of ASR affected control specimens was found to be more sensitive to length to width ratio than normal concrete. This was found to be due to the restraining effect of the non-reacted surface layer of the ASR control specimens in the direction perpendicular to loading. It was found that a length to width ratio of at least 3 was required to give the true uniaxial strength (Jones 1994) and this agrees with the value stated by Clayton et al (1990).
- The data plotted in the IStructE report included those from cores. These cores did not have the non-reacted skin of the control specimens and would not have experienced the benefit of restraint which it applied. The concrete in a reacted structure will generally be under some degree of restraint perpendicular to the direction of loading in the form of the surrounding concrete, reinforcement or applied loads. It has also been shown (Jones *et al* 1994) that cores deteriorate during the cutting process and continue to deteriorate during the time between cutting and testing. For these reasons the strength found from cores removed from an affected area of a structure will underestimate the true compressive strength of the in situ concrete.

It is suggested that the proposed relationship shown on Figure 1 is adopted when comparing compressive strength to expansion. This relationship uses the same factors as those proposed by the IStructE report; however, these factors are applied to an estimated undeteriorated strength instead of the 28 day strength. In Figure 1 the estimated undeteriorated strength was obtained by extrapolating the data back to the zero expansion line and taking a reasonable lower bound. In reality it could be found by testing unreacted areas of the structure. It should be noted that in all cases the 28 day strength quoted is the actual 28 day strength which in itself may be significantly greater than the value used for design purposes.

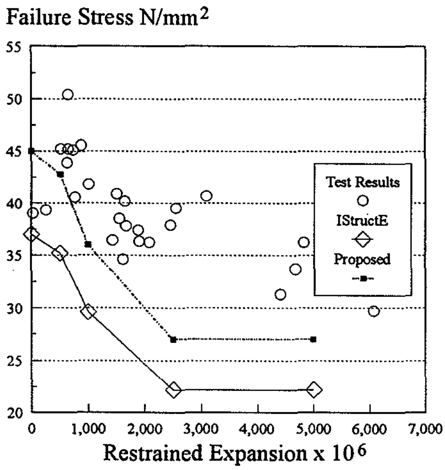

Figure 1 Compressive strength of concrete compared to expansion.

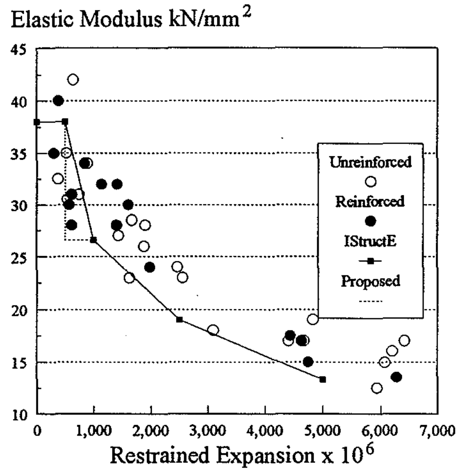

Figure 2 Elastic modulus of concrete compared to expansion.

Elastic Modulus

Figure 2 compares the elastic modulus of the cylinders discussed above, to their restrained expansion. Again the relationship given by the IStructE report is plotted. The correlation between the data and the relationship given is good except at low expansions where the relationship overestimates the elastic modulus of some specimens. It should be noted that there is much scatter in the results at these low expansions. It is unlikely that the expansion estimation of real structures will be accurate to 500 microstrain. Hence, it is proposed that estimated expansions in the range 500 to 1000 microstrain should be rounded up to 1000 microstrain to give the relationship shown in Figure 2. Thus, a member would either be classed as having negligible expansion and zero deterioration, or an expansion of 1000 microstrain or above with an appropriate loss of stiffness.

EFFECTS OF ASR ON CONCRETE STRUCTURES

Chapter 5 of the IStructE report discusses "The effects of ASR on Concrete Structures". Whilst much of the research carried out confirmed the information given in the report this section highlights areas where the research has added to the understanding.

Influence of Restraints

Reinforcement

When ASR affected reinforced concrete expands the reinforcement is placed in tension. This places the concrete in compression which restrains further expansion. The IStructE report calculated the stress developed in the concrete for various specimens with various reinforcement ratios. It was concluded that the stress generated increased with reinforcement ratio and this was confirmed by the testing carried out. The IStructE report also proposed that the stress generated was related to the expansion rate. In the tests described here the stress generated was found to be unrelated to expansion rate (Jones 1994).

In the experimental work reported here the concrete stress generated by the tensioning of reinforcement was found to be highly dependent on the orientation of the reinforcement in relation to the casting direction of the member. Figure 3 presents the upper and lower bounds of the stresses found by other researchers (Hobbs 1988), (Cope *et al* 1993) and (Kobayashi 1986) along with the results found by the Authors for 100 mm x 200 mm long cylinders and 100 mm x 200 mm x 2000 mm beams. It can be seen that the cylinders generally developed stresses close to the upperbound of those found by others, whilst the beams developed stresses towards the lower bound. The cylinders were cast (and reinforced) in the vertical position, whilst the beams were cast in the horizontal position. From this it can be concluded that the stresses developed, by the stressing of reinforcement, in the direction of casting are greater than those generated in the direction perpendicular this.

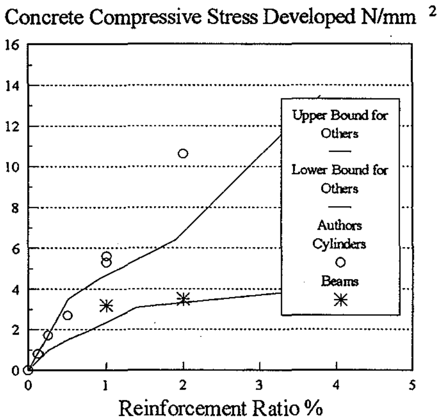

Figure 3 Stress developed in concrete compared to reinforcement ratio

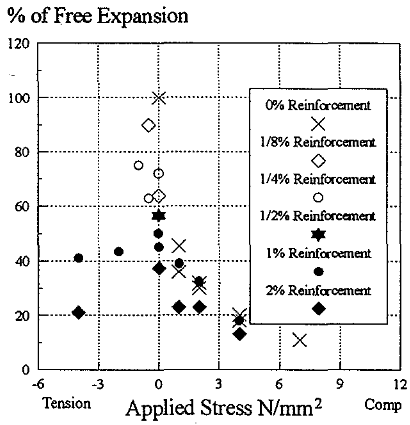

Figure 4 ASR expansion compared to applied stress for specimens with different reinforcement ratios

Applied Stress

Applied compressive stress has been shown to reduce expansion, however, Figure 8 of the IStructE report shows a significant variation in the relationship found by two separate researchers (Clayton *et al* 1990) and (Ng 1991). The research described here showed that this was due to size effects caused by the non-reactive skin. For smaller specimens the non-reactive skin was a greater proportion of the overall cross section than for larger specimen. Thus although the applied stress was calculated on the basis of overall cross section it was in fact restraining only the reactive heart concrete. This caused the actual stress on the reactive core of the smaller specimens to be greater than that on the larger specimens. This in turn caused the smaller specimens to expand less.

Tests were carried out to ascertain the compressive stress required to prevent any expansion. Even under an applied compressive stress of 7 N/mm^2 an expansion of 500 microstrain was recorded and it was estimated that to prevent any expansion a stress of 10 N/mm^2 was required. This compares well with that predicted by theory (Diamond 1989).

Tests were also carried out to ascertain the effects of applied tensile stresses on the expansion of reinforced specimens. It was shown that tensile stress increased the overall expansion of specimens. However, when non-ASR strains such as elastic and creep strains were considered applied tensile stresses did not increase ASR expansion. Indeed for some of the more heavily reinforced specimens the ASR expansion appeared to reduce under increasing applied tensile stress. This was due to some of the expansion potential being used to overcome the initial elastic and creep strain.

Combined

To demonstrate the effects of applied compressive or tensile stresses and reinforcement ratio Figure 4 was drawn. This plots the expansion of the cylinders tested as a percentage of the free (unreinforced under zero applied stress) expansion against applied stress for various reinforcement ratios. The expansion plotted has had the non-ASR strains deducted. This non-ASR strain was taken to be the strain experienced at 50 days, which was before ASR expansion started in the free expansion specimens.

Expansion Perpendicular to Restraint

The IStructE report questioned the effect of applied stress on the ASR expansion perpendicular to the direction of stress. In the tests reported here neither applied stress nor reinforcement ratio had a significant effect on the expansion perpendicular to the direction of stress/reinforcement. This is significant as it implies that when estimating expansion, the effects of stress perpendicular to the direction being considered can be ignored.

Effects on Member Strength

Section 5.3 of the IStructE report describes the effects of ASR on the properties of concrete members. Generally the report recommends that members can be assessed in a similar manner to unaffected members provided that the deteriorated concrete properties are used. The report also recommend that the effects of prestress, due to ASR, can be considered. This was researched further in the tests described here.

Reinforced cylinders, which had expanded due to ASR, were loaded, via their reinforcement, in tension. It was found that the prestress caused by ASR did increase the stiffness of the cylinders. For reinforcement ratios of up to 1/2% the behaviour of the specimens could be predicted by calculating the tension in the reinforcement, considering the surface expansions, and analysing the specimens using normal prestress theory. For the 1% and 2% reinforced specimens normal prestress theory over estimated the benefits. This was indicated by an earlier than predicted cracking load. It was concluded that this was due to the distribution of stresses along the specimens. At certain points along the reinforcement bar the reaction caused yielding and there would have been high compressive stresses in the surrounding concrete. Remote from these areas the concrete was under less stress. Cracking occurred through the concrete sections with the lowest compressive stress.

The 2% reinforced specimens cracked at about 50% of the load predicted by prestress theory and for this reason it is proposed that only 50% of the prestress calculated from surface strains is used in analysis. It was found that applied tensile stresses during the conditioning of the specimens increased this effective prestress. In addition, in a member with more than one bar, there will tend to be an averaging of prestress along the specimen. This will increase the ratio of effective prestress to prestress calculated from surface strains. The behaviour of specimens loaded in tension was not significantly affected by the expansion rate indicating that the prestress did not deteriorate, significantly, with time.

ASSESSMENT OF EXPANSION

From the previous discussion it can be seen that the current expansion is central to the assessment of the current structural properties of an affected structural member. The estimation of expansion is dealt with in section 7.3 of the IStructE report. The IStructE report proposed the use of the summation of crack widths to estimate expansion and this was investigated in the research discussed here. In addition a mathematical expansion model proposed by May *et al* (1991) was extended and compared to the results obtained from the test specimens

Use of Crack Widths

The IStructE report proposed that the crack widths along at least five lines no less than 1m long and 250 mm apart be summed and divided by the total length of all the lines to give an estimation of the expansive strain. It was not possible to have this number and length of line on the cylinders tested and the crack widths were measured along four lines 100 mm long and running along the length of the specimens. The estimated expansions compared with the actual expansions are shown in Figure 5.

The Authors proposed (Jones and Clark 1994) that the expansion demonstrated by the opening of a crack actually occurs perpendicular to the direction of that crack. Therefore the expansion in the direction of a line intersecting the crack at an angle is the width of that crack multiplied by the sine of the angle. The expansion estimated using this method is compared to the measured expansion in Figure 6. It can be seen that the correlation between estimated expansion and measured expansion is better in Figure 6 than Figure 5. However it can also be seen that the gradient of the best fit line increases from approximately 1 in Figure 5 to 1.2 in Figure 6. This is due to the inherent inaccuracies in the measurement of crack widths which have been discussed elsewhere (Jones and Clark 1994). It should also be noted that in both Figures the intercept is at approximately 800 microstrain. This represents the average expansion required before crack widths are measurable. It is proposed that when estimating the ASR expansion of a member, from crack widths, the following relationship be used:

$$Expansion = \frac{1.2 \sum crack\ widths \times \sin crack\ angle}{Length\ of\ reference\ line} + 800\ microstrain$$

It is likely that both the 1.2 and the 800 factor are slightly conservative for real members due to size effects.

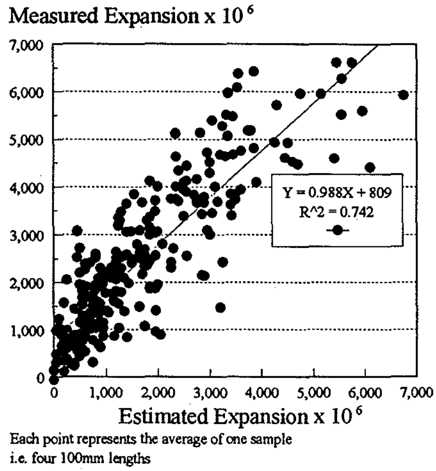

Figure 5 Expansion estimated from the sum of crack widths compared to measured expansion.

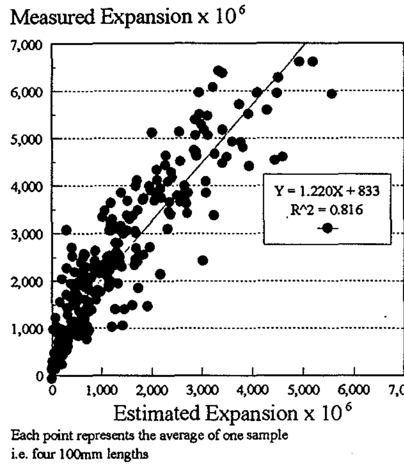

Figure 6 Expansion estimated from the sum of crack width x sine of crack angle compared to measured expansion.

Use of Mathematical Models

A mathematical model for estimating the ASR expansion of reinforced members, proposed by May *et al* (1991), was extended by the Authors (Jones and Clark 1996) to include the effects of an applied conditioning stress. The model required a knowledge of the original Elastic modulus for both the concrete and the reinforcement, the free expansion of the concrete and the stress required to prevent any expansion (critical stress). The model predicted upper and lower bounds to the ASR expansion and showed fair correlation with the experimental results. However the amount of information required to calibrate the model probably restricts its use in the field.

CONCLUSIONS

1. The IStructE report overestimates the deterioration in compressive strength with ASR expansion. However it adequately predicts deterioration in elastic modulus.
2. The effects of restraint in both reducing expansion and developing prestress are far more dependent on the orientation of the restraint, in relation to the casting direction, than expansion rate.
3. The applied stress required to prevent ASR expansion is dependent on specimen size and may be as high as 10 N/mm^2.
4. Applied tensile stresses increase overall expansion but have little effect on ASR expansion.
5. Applied stresses have no significant effect on ASR expansion perpendicular to their direction of application.
6. Prestress is developed in reinforced concrete expanding due to ASR. However this prestress may be only 50% of that calculated from consideration of surface strains.
7. Estimation of ASR expansion from crack widths can be improved by the consideration of the crack angle.

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REFERENCES

Clayton, N., Currie, R. J. and Moss, R. M. 1990, "The Effects of Alkali Silica Reaction on the Strength of Prestressed Concrete Beams". The Structural Engineer, Vol. 68, No. 15, 7 August.

Cope, R. J., May, I. M. and Wen, H. X. 1993, "Structural Performance of Reinforced Concrete Members Affected by Alkali Aggregate Reaction". Project Report 44, Transport Research Laboratory, Crowthorne.

Diamond, S. 1989, "ASR-Another Look at Mechanisms" Proceedings 8th International Conference on Alkali Aggregate Reaction, Kyoto, pp. 83-92.

Doran, D. K. 1992, (Chairman of Task Group) "Structural Effects of Alkali Silica Reaction". The Institution of Structural Engineers, p.45, July.

Hobbs, D. W. 1988, "Alkali Silica Reaction in Concrete". Thomas Telford, London, p.183.

Jones, A. E. K. 1994, "Cracking, Expansion and Strength of Concrete Subjected to Restrained Alkali Silica Reaction". PhD Thesis, The University of Birmingham, UK.

Jones, A. E. K. and Clark, L. A. 1994, "The Practicalities and Theory of Using Crack Width Summation to Estimate ASR Expansion". Proceedings of the Institution of Civil Engineers Structures and Buildings Journal, Vol. 104, May, pp 183-192.

Jones, A. E. K., Clark, L. A. and Amasaki, S. 1994, "The Suitability of Cores in Predicting the Behaviour of Structural Members Suffering from ASR". Magazine of Concrete Research, Vol. 46, No. 167, June.

Jones, A. E. K. and Clark, L. A. 1996, "The Effects of Restraint on ASR Expansion of Reinforced Concrete". Accepted by the Magazine of Concrete Research, to be published early 1996.

Kobayashi, K. 1986, "Load Carrying Behaviours of Concrete Structures and Members Affected by Alkali Aggregate Reactions: Reinforced Concrete Beams". Concrete Journal, Japan Concrete Institute, Vol 24, No. 11, Nov, pp. 70-78.

May, I. M., Wen, H. X. and Cope, R. J. 1991, "An ASR Expansion Model". Interim Report for the Transport and Road Research Laboratory Contract: The Numerical Modelling of ASR Affected Concrete (CON/9971/65). Unpublished.

Ng, K. E. 1991, "Effect of Alkali Silica Reaction on the Punching Shear Capacity of Reinforced Concrete Slabs". PhD Thesis, The University of Birmingham, UK.