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The effects of ASR on the properties of concrete and the implications for assessment

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This paper discusses the nature of damage caused to concrete by alkali silica reaction (ASR). The effect of this damage on the behaviour of structural members is discussed. Recommendations are then made as to the best way of estimating the properties of concrete in actual structural members. It is shown that, generally, much of the damage caused by ASR is offset by secondary effects. It is proposed that members can be analysed in a similar manner to unaffected members with revised concrete properties. However, some additional checks are required. © 1998 Published by Elsevier Science Ltd. All rights reserved

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1. Introduction

Alkali silica reaction (ASR) is the reaction between the hydroxyl ions present in the pore water of concrete and certain forms of silica which are present in some aggregates. The product of this reaction is a highly expandable gel which imbibes water and swells. If sufficient reaction takes place the pressures induced cause micro-cracking and then expansion of the surrounding concrete. The surface of the concrete does not expand to the same extent as the interior of the concrete, because, for example, the surface is subject to leaching of the alkalis required for the reaction. This causes tensile stresses to be created in the surface which can induce surface macro-cracks. The formation and orientation of both micro and macro-cracks are affected by restraint which also reduces expansion.

The ASR micro-cracking affects the properties of the concrete. However, the properties of affected concrete found from control specimens and cores do not necessarily predict the behaviour of actual members. Reasons for these differences in the case of ASR are primarily due to the effects of restraint and are discussed in this paper with reference to the nature of the damage to the concrete and its effect on each of the concrete properties.

The Institution of Structural Engineers[1] has published guidance on the structural effects of ASR in which the effects of ASR on material properties and structural behaviour are considered and recommendations made for structure management. General guidance on the assessment of structures with ASR has been published by The Highways Agency[2], and detailed recommendations have been made by Clark[3] and McLeish[4]. The recommended procedures require the input of information on the properties of the affected concrete and on the response of restrained concrete.

Full reviews of the literature on the structural effects of ASR have been published elsewhere[3,4]. In this paper, unless otherwise stated, the quoted data are those obtained by Jones[5,6], and further details can be found in References 5 and 6, including the test methodology used to obtain the data.

2. Effects on concrete compressive strength

2.1. *Cast specimens*

The apparent deterioration of concrete compressive strength due to ASR is very dependent on the test method used. The cube test is particularly insensitive to ASR, with strengths after significant expansion often being greater than those at 28 days. The cylinder crushing strength is more sensitive to ASR expansion than is the cube test. However, the length to diameter ratio of a specimen required to give the uniaxial strength of ASR concrete is significantly greater than that of non-reactive concrete[5,7]. It is likely that the results from cylinders with height to diameter ratios of 3 and less underestimate the deterioration of the uniaxial strength of concrete with ASR cracking. It is considered that the restraining effect of the less reactive surface layer of a specimen affects the apparent strength. As a result the cube test is relatively insensitive to ASR expansion, whilst the sensitivity of a cylinder is dependent on its height to diameter ratio.

The crushing strengths of 100 × 200 mm long cylinders expanded under different applied stresses to induce different final expansions are plotted against their final expansions in *Figure 1*. The specimens contained a reactive Thames valley fine aggregate, had an equivalent sodium oxide content of 7 kg/m^3, and were conditioned under water at 38°C. The expansions of these specimens in the direction perpendicular to the applied stress were similar in all of the tests and, hence, independent of longitudinal stress and expansion. It can be seen that a reduction in expansion, induced as a result of applied compressive stresses, increased the cylinder crushing strength. The average 28 day strength of these specimens was 37 N/mm^2 and it can be seen that expansions of the order of 1700 microstrain were required before the crushing strength of the specimens dropped below that at 28 days. The estimated strength of a specimen with zero expansion at the same age as the expanded specimens was determined by extrapolating the data in *Figure 1* back to the zero expansion axis. The ratio of each actual strength at a particular expansion to the estimated strength at zero expansion was then calculated. The relationship between these strength ratios and expansion was found to be very similar to the relationship proposed by Doran[1] which was based on a lowerr bound to the then available data. However, Doran expressed strength as a ratio of 28 day strength. For the specimens tested the 28 day strength was significantly less than the estimated strength of a specimen with zero expansion due to continued cement hydration beyond 28 days.

2.2. Cores

Core specimens, from test beams manufactured from the same mix as the cylinders in *Figure 1*, were also tested in compression. It was found that the crushing strengths of reactive core specimens were much less sensitive to height to diameter ratio than those of the cylinders, because cores do not have a non-reactive surface layer and, thus, did not experience restraint from such a layer. Such lack of restraint also resulted in a greater strength reduction for core specimens than for cast cylinders. In some experiments cores were taken from the same specimen, but in directions subjected to different levels of restraint and, hence, different levels of expansion. It was found that the compressive strengths of cores removed from the direction of greatest restraint were generally stronger than those removed from the direction of least restraint. However, the differences were small. Rigden *et al.*[8] carried out similar tests and found that cores removed from the direction of greatest restraint were significantly stronger than those removed from the direction of least restraint. However, it should be noted that the reactive aggregate used by Rigden *et al.* had a free expansion well beyond that experienced in the field.

2.3. Summary of effect on compressive strength

The true uniaxial compressive strength of reactive concrete is related to expansion and deteriorates significantly with an increase in expansion. From the additional data obtained by Jones[5] it is concluded that the relationship, between uniaxial strength and expansion, proposed by Doran[1] provides an adequate lower bound to the true relationship. However, the extreme sensitivity of the strength of reactive concrete to restraint perpendicular to the direction of applied stress means that in most cases it is not suitable to use the concrete uniaxial strength in assessment. It has been shown that the restraining effect of a non-reactive surface layer can increase the apparent compressive strength. Therefore, the strength of concrete confined by links is likely to be much greater than the uniaxial strength. Unfortunately, test data are not available on the strength of reactive concrete under triaxial stress conditions. The compressive strength

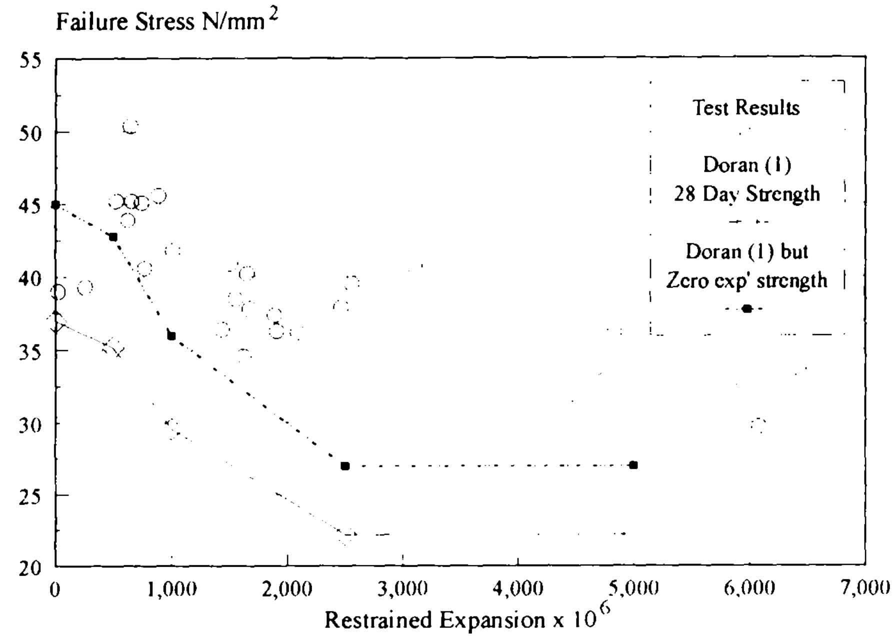

Figure 1 Cylinder crushing strength compared to restrained expansion, specimens conditioned under applied stress

of reactive concrete subjected to restraint differs with direction due to the effects of the restraint on the micro-crack pattern.

3. Effects on Young's modulus

3.1. Cast specimens

Figure 2 relates final expansion to the Young's modulus of the cylinder specimens in *Figure 1* and some additional, similar, reinforced cylinders. All specimens were conditioned under a range of applied compressive stresses to produce different final expansions. The 28 day Young's modulus for these specimens was found to be 38 kN/mm^2 and it can be seen that at expansions over about 500 microstrain the Young's modulus dropped below this value. It is significant that above expansions of 3000 microstrain there is little further reduction in a specimen's Young's modulus. Tests on similar specimens with different conditioning temperatures and hence different expansion rates showed similar results[5]. A similar relationship was found by Cope *et al*[9] who proposed that the Young's modulus of ASR concrete could be calculated from consideration of: the expansion; the Young's modulus of the unreacted concrete; and an estimation of the Young's modulus of the gel. It was assumed that the reduced Young's modulus of the concrete could be represented by a simple model in which intact concrete acted in series with a less stiff material represented by the gel.

The results in *Figure 2* are in general agreement with those proposed by Doran[1] although *Figure 2* shows evidence of a reduction of Young's modulus at an expansion of 500 microstrain. At this strain Doran indicates no reduction of Young's modulus.

Young's modulus tests were also carried out on specimens which had not reached their final expansion. It was found that if the Young's modulus of these specimens were plotted against their expansion at the time of testing the points fell below those in *Figure 2*. However, if the Young's modulus of these specimens were plotted against their estimated final expansion they were more in agreement with those in *Figure 2*.

The Young's modulus of specimens was also compared to the time between release from conditioning restraint and testing. It was found, that generally, the Young's moduli of specimens tested 7 days after removal from restraint were about 10% lower than those of specimens tested within 12 h of release although there was no significant expansion accompanying the drop in Young's modulus.

3.2. Cores

The Young's moduli of cores removed from test beams in directions parallel and perpendicular to the direction of restraint were also compared. It was found that the Young's moduli of cores removed from the direction of restraint were significantly greater than those of cores removed perpendicular to the main restraint. For beams with 2% reinforcement the Young's modulus for cores removed perpendicular to the reinforcement was generally under half of that for cores removed parallel to the direction of restraint.

The ultrasonic pulse velocity (UPV) of cores were recorded before they were cut from their specimens and again directly after cutting. It was found that the UPV of a core removed from the direction of least restraint actually increased after coring. However, the UPV of a core removed from the restrained direction reduced with coring. The differences were small, being of the order of 2%. However, tests reported by Jones *et al*[10], using a highly reactive and very fine aggregate, found that the reduction in pulse velocity of cores removed from a reactive column was 11%.

3.3. Summary of effect on Young's modulus

It is concluded that it is the amount and orientation of the micro-cracking of the concrete that governs the reduction in Young's modulus. Whilst expansion gives an indication of the nature of the micro-cracking it is possible to have micro-cracking without significant expansion and expansion without additional micro-cracking. This explains the following factors:

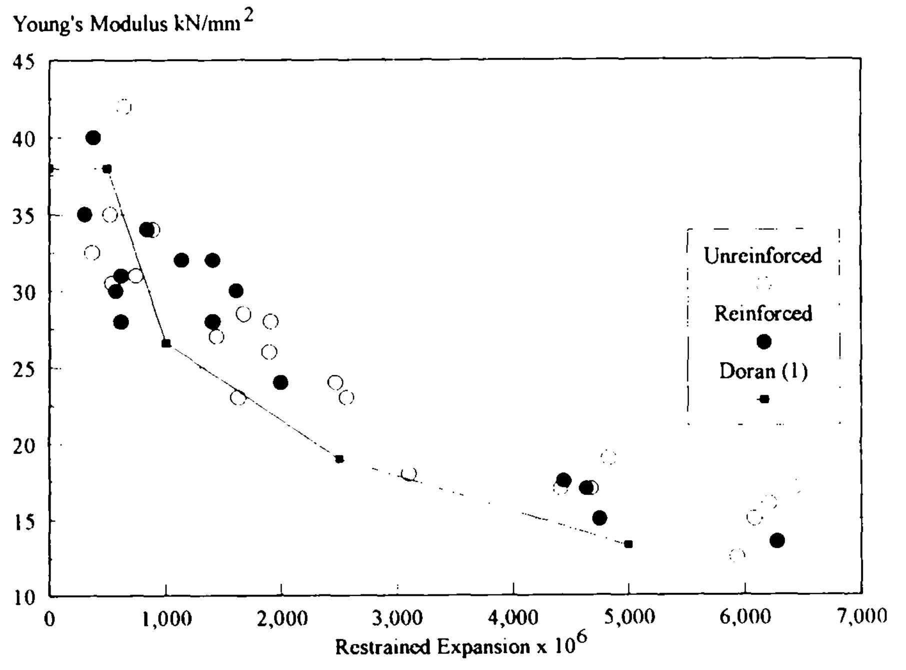

Figure 2 Concrete Young's modulus compared to expansion

(i) For the cylinder specimens tested with final expansions of 3000 microstrain and above the orientation and number of micro-cracks were similar. Differences in the expansion were due to the width of these cracks. Hence the Young's moduli of these cylinders were similar.

(ii) Specimens which had not finished expanding had already formed their micro-crack pattern at the time of testing for Young's modulus. Subsequent expansion by widening of the micro-cracks would have had little effect on the Young's modulus.

(iii) On release from restraint the internal stresses within a specimen change and micro-cracks start propagating. These micro-cracks, being unfilled by gel, are very narrow and cause little overall expansion. Hence, when specimens were released from restraint, micro-cracking began to occur and the Young's modulus started reducing. A similar effect occurred with cores on their removal, with the additional micro-cracking and the drop in Young's modulus being indicated by the drop in UPV.

4. Effects on tensile strength

The apparent effects of ASR on the tensile strength of concrete are dependent on the test method used. Doran[1] quoted the tensile strength of concrete obtained from the cylinder splitting test as 85, 75, 55 and 40%, of 28 day strength, for expansions of 0.05, 0.1, 0.25 and 0.5%, respectively. However, several authors[11,12] have shown that the loss in tensile strength actually occurs before significant expansion occurs. Clayton *et al*[11] and Swamy[12] also used the gas pressure tension test and the modulus of rupture test, respectively, to determine the tensile strength of ASR concrete. It was found that the reduction in tensile strengths found from these two tests were significantly greater than those found from the cylinder splitting strength with the strength found being as low as 20% of the 28 day strength.

The loss in tensile strength is due to the micro-cracking that occurs. This explains why much of the loss occurs before significant expansion is recorded. The cylinder splitting test is less sensitive to the effects of ASR than the other tests for tensile strength, because it causes failure along a predetermined line. As such this test is very sensitive to the position and orientation of surface cracking and it is likely that the non-reactive skin on cylinder samples enhances the tensile strength found. It is likely that due to the nature of ASR deterioration the true long term direct tensile strength of affected concrete is negligible. This was confirmed by Cope *et al*[9] who found that specimens conditioned under tensile load failed, usually at the beginning of expansion, when the applied tensile stress was greater than 0.5 N/mm^2. The effects of the extremely low tensile strenght of ASR affected concrete will be offset by the development of compressive stresses in reinforced members as explained in the next section. It should also be noted that, in practice, for most situations where the tensile strength is used in an assessment, the phenomenon being considered, such as shear or bond splitting, is analogous to the conditions in a cylinder splitting test. Hence, the tensile strength from the latter test is more appropriate to the assessment of a structure and the suggestion that the long term direct tensile strength is negligible is generally not relevant in practice.

5. Development of prestress

In a reinforced concrete member, the reinforcement is placed in tension by the expanding concrete and, in order to maintain equilibrium, compressive stresses are developed in the concrete. Hence, ASR prestresses a reinforced concrete member. In the assessment of members affected by ASR, allowance can be made for the development of the ASR-induced prestress in the concrete.

Reactive specimens with various levels of reinforcement were tested in tension after the completion of ASR expansion. It was concluded that specimens with low reinforcement ratios, where the reinforcement had yielded significantly due to ASR, followed the behaviour predicted by considering them as conventional prestressed members with the prestress calculated from considerations of average surface strains. However, reinforced cylinder specimens similar to those in *Figures 1* and *2*, tested with 1% reinforcement (*Figure 3*) and 2% reinforcement cracked at significantly lower loads than expected. From *Figure 3* it can be seen that the 1% reinforced specimens cracked at about 2/3 of the predicted load even considering the reduction in Young's modulus due to expansion. It was concluded that this was due to the distribution of stresses along the specimen. At certain points along the reinforcement bar the reaction will have caused yielding and there will be high compressive stresses in the concrete. Remote from these areas the concrete will be under less stress. Cracking will occur in the sections with the lowest compressive stresses.

Although it is confirmed that prestress is developed by ASR, for reinforcement ratios over ½% the amount of prestress at a particular section cannot be calculated from considerations of average surface strains due to the variation of strains along the specimen. In the worst case the effective prestress was found to be 50% of that calculated from average surface strains. However, applied tensile stresses, during the conditioning of the specimen, tended to increase this effective prestress[5]. In addition, in a member with more than one reinforcing bar, there will tend to be an averaging of the compressive stresses developed along the specimen and this will also increase the ratio of effective prestress to prestress calculated from surface strains.

6. Estimation of expansion

The properties of ASR concrete have all been shown to be sensitive to expansion. A full discussion of the methods for estimating restrained ASR expansion is beyond the scope of this paper. Jones and Clark[13] investigated the use of crack widths for the estimation of expansion, and proposed the following formula which related crack width and crack angle to give estimations of minimum expansion and maximum expansion:

$$\text{Expansion} = \frac{\beta \sum w \sin\theta}{L} + \epsilon_c$$

where w is crack width, θ is crack angle, and L is the length over which crack widths were measured. β and ϵ_c are constants for which values were given.

However, this work proposed that two different estimations of expansion should be adopted: a relationship which overestimates expansion to predict the detrimental effects of ASR; and a relationship which underestimates

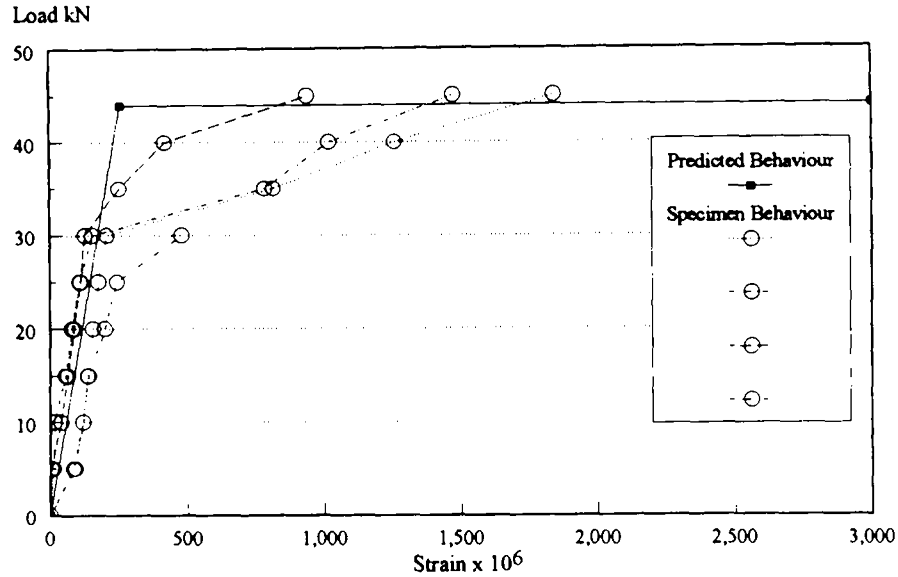

Figure 3 Tensile load characteristics for 1% reinforced specimens after expansion

expansion to predict the beneficial effects of ASR. Subsequently, it has been concluded that this would lead to excessively conservative assessment and it is more appropriate to use a common relationship between crack data and expansion to estimate both the detrimental and beneficial effects of ASR. An assessment of the structure can then be carried out using these estimated effects. However, because of the interaction between detrimental and beneficial effects, an assessing engineer may wish to undertake a sensitivity analysis using a number of different common relationships.

May *et al*[11] proposed a closed form solution to estimate ASR expansion. This solution assumed the following trilinear relationship between expansion and applied compressive stress: tensile stresses did not affect expansion; there was a straight line relationship between applied stress and expansion from zero stress to the stress which stopped any expansion (the critical stress); and compressive stresses in excess of the critical stress also prevented expansion. The solution requires much information, including the unrestrained expansion of the concrete and the stress required to prevent expansion. It is unlikely that this information will exist for real structures, and, therefore, the method is of limited use in practical situations.

It is likely that the crack width method and the method proposed by May could best be used together, with data from crack widths being used to estimate the input values required for the equations proposed by May *et al.* In this way expansions could be estimated in positions where crack width measurements are not practical.

7. Estimation of compressive strength

Compressive strength has been shown to be related to expansion, however, it has also been shown that compressive strength is extremely sensitive to restraint perpendicular to the direction of stress. In the situation where the concrete is confined by links the best estimation of compressive strength is likely to be found using the values proposed by Doran[1] relating compressive strength to expansion. However, the values should be calculated as a percentage of the strength estimated for concrete of the same age as that under consideration, but with zero expansion, rather than the 28 day strength. If the concrete is completely unrestrained, perpendicular to the direction of stress, then the percentage of the 28 day strength should be used.

Even if deterioration of concrete strength is calculated from the strength of a similar concrete with zero expansion rather than 28 day strength it is likely that, in cases where significant restraint perpendicular to the direction of stress is present, the values found for compressive strength will be conservative. Testing of ASR specimens under triaxial stress regimes is required to determine the precise effects of lateral restraint on compressive strength.

8. Estimation of Young's modulus

The Young's modulus of ASR concrete has been shown to be related to expansion. However, there were several other factors that affected Young's modulus and it is proposed that the cause of the reduction is the micro-cracking.

It is proposed that to estimate the actual Young's modulus of concrete within a structure it is necessary to relate expansion to the Young's modulus found from cores. Cores should be removed from the structure preferably from areas with a range of expansions. Before the cores are removed expansion should be estimated both at the position and in the direction of coring. The ultrasonic pulse velocity (UPV) should be recorded just before and just after the cutting of the core. Once the core is removed it should be tested in compression as soon as practical. If this testing is to be more than 24 h after removal then the core should be measured between removal and testing. The Young's modulus found from the cores should then be plotted against their estimated expansion, including the expansion between cutting and testing if this is significant. The expansion in the position and direction in which a value for the Young's modulus is required should then be estimated. From this estimated expansion and the graph relating core Young's modulus to expansion, the Young's modulus in the position required can be found (see *Figure 4*). It is emphasised that *Figure 4* is diagrammatic and intended only to demonstrate the proposed procedure. It is likely that each structure will show a unique relationship.

There are two problems with this method:

(i) There could be an error in the estimated expansions

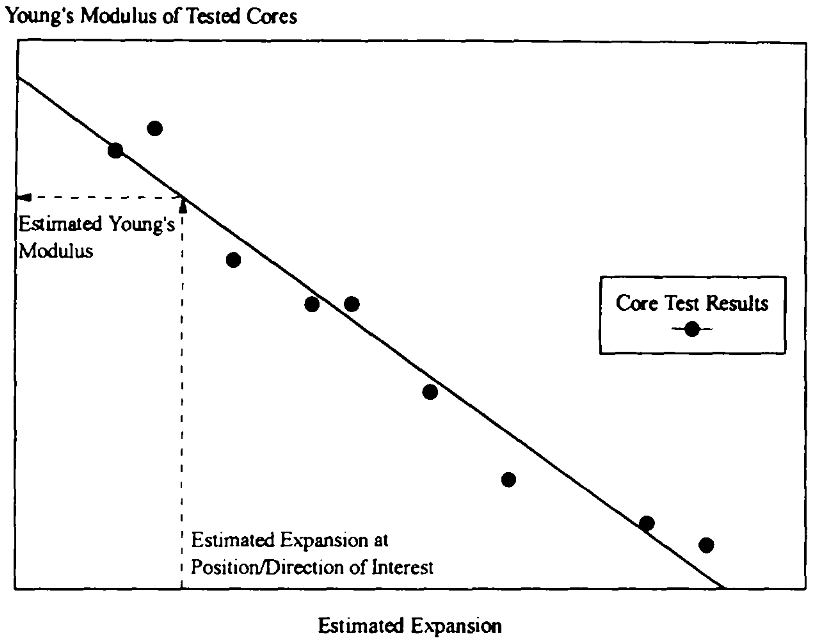

Figure 4 Method for estimating Young's modulus

such as, for example, in the relationship assumed between crack widths and expansion. If the error is constant this is to a certain degree self correcting. For example, if the adopted relationship overestimated expansion then the deterioration at a certain actual expansion level would be underestimated. However, the expansion at the position where knowledge of the Young's modulus is required will also be overestimated and the errors will cancel.

(ii) Young's modulus is related to the micro-cracking of the concrete. In areas where the expansion is progressing slowly there may be significant micro-cracking, but the expansion will be less than that of concrete with similar micro-cracking, but expanding at a quicker rate. The Young's modulus will usually be required in the direction of high restraint, whereas cores will normally be removed from a direction of low restraint. A low expansion in the direction of low restraint will be due to the expansion progressing at a slower rate and the Young's modulus found from a core removed from this position will be lower than that of concrete with the same expansion in a position of high restraint. Thus the above method is conservative.

The above method is inherently conservative as no account is made of the reduction in Young's modulus that occurs with coring. If a significant change in UPV is found before and after coring it may be possible with further research to include an additional factor to allow for this. However, at present, it is not clear how the change in UPV relates to a drop in Young's modulus.

9. Estimation of prestress

9.1. For shear capacity

Clark[3] proposed that any reduction in the shear strength of a beam due to a reduction in the concrete compressive strength could be offset by the prestress developed by the expansion. It was proposed that the shear strength of an expanded beam could best be calculated by considering it as a prestressed beam and including the prestress from ASR. Clark[15] compared this approach to experimental data and found that in general the predicted strength was conservative. However, once expansion reached 1600 microstrain the approach was no longer conservative. It has been shown that the strain distribution along reinforcement bars was not constant, and hence the prestress developed in the concrete was not constant. It is likely that a shear failure would occur through areas of least prestress. Therefore, it is proposed that only a proportion of the prestress causd by ASR is used in the shear calculation. From the results obtained 50% seems reasonable. This value is probably conservative when more than one bar is contributing to the prestress, as a result of the averaging of stress across the member's section increasing the minimum prestress.

9.2. For stiffness

Tests have shown that, prior to cracking, the stiffness of reinforced specimens expanded due to ASR can be predicted by considering the specimens as conventional prestressed members. Thus, any reduction in the stiffness of beams due to the reduction of the concrete Young's modulus can be offset by the increased load required to cause cracking in the tension zone of the beam. Again, allowance should be made for the fact that the prestress developed may be less than that calculated from surface strains.

10. Additional checks required when assessing a reactive member

10.1. Tensile stresses in compressive steel

Columns and beams with significant amounts of compression steel will need additional checks to calculate the contribution of the reinforcement at ultimate load. If significant expansion occurs then the compression reinforcement could be placed in tension. Under subsequent load, the compressive strain developed in the reinforcement will be that predicted by elastic analysis less the ASR expansive strain. If the difference between the yield strain of the concrete and the yield strain of the reinforcement is less than the ASR expansion then the steel will not reach its yield strength before the concrete fails. The expansions at which this occurs have been shown to be 1200 microstrain for high strength bars and 2500 microstrain for mild steel bars[3]. These values were derived assuming that the 'failure' strain of the concrete was 3500 microstrain. However, it has been shown that the Young's modulus is affected by ASR to a greater degree than is compressive strength. This suggests that the 'failure' strain of the concrete will increase as a result of ASR. Thus, it is likely, that the ASR expansion at which the yielding of the reinforcement is prevented is significantly more than the values stated by Clark. If the ASR expansion exceeds that at which compressive yielding of the bars is prevented, then the reduced contribution of the steel will need to be considered along with the reduced concrete strength.

10.2. Interfacial shear stresses

Another effect that needs to be considered when assessing a structure with ASR is the development of interfacial shear stresses between different concrete mixes expanding at different rates[5]. This could become critical when such stresses are combined with stresses due to load, as in the case of beam and slab construction. If, for example, the slab expanded and the beam did not, the slab would be restrained by both the steel within it and the beam to which it was connected. Whilst stresses induced in the slab concrete by stretching of the reinforcement would be self-equilibrating, the stresses induced in the slab concrete due to restraint from the beam would need to be transmitted across the beam–slab interface.

11. Conclusions

(1) The compressive strength of concrete is reduced by ASR, with the reduction increasing with an increase in expansion. However, restraint perpendicular to the direction of loading has a significant effect on the apparent compressive strength. For most cases the strength of ASR concrete can be calculated from the reduction factors given by Doran[1]. However, these factors should be applied to the strength of an equivalent non-reactive concrete of the same age rather than the concrete's 28 day strength.

(2) The Young's modulus of concrete can be significantly reduced by ASR. This reduction is due to the micro-cracks rather than the expansion per se. However, the expansion generally gives an indication of the extent of the micro-cracking and hence the deterioration in Young's modulus. When assessing the Young's modulus of a structural member the results from cores should be compared with the estimated expansion at the position from where the core was removed. Additionally, it should be remembered that coring causes a deterioration in Young's modulus and that this may vary with direction.

(3) The direct tensile strength of concrete is significantly reduced by ASR and may be taken as zero under long term loads. However, in an assessment the cylinder splitting strength is generally a more appropriate indicator of tensile strength.

(4) Prestress is developed by the ASR expansion and this enhances the shear strength and stiffness of beams. The amount of prestress generated, however, may be less than that calculated from surface expansion.

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