8th ICAAR 1989 KYOTO
8th Internationl Conference
on Alkali-Aggregate Reaction

STRUCTURAL IMPLICATIONS OF ALKALI SILICA REACTION

R Narayan Swamy

Material and Structural Integrity Unit,
Dept of Mechanical and Process Engineering,
University of Sheffield, Sheffield, England.

1. INTRODUCTION

Despite almost half a century of research on alkali silica reaction (ASR), there is still considerable lack of understanding on the mechanisms and processes of concrete deterioration due to ASR, its engineering and structural implications, and on the control of ASR in real structures. There is a dearth of information as to how structures under stress behave when subjected to ASR, and how the structural deformations develop with time. This paper attempts to make a contribution to our understanding of how ASR affects the behaviour of typical concrete structural elements.

2. GENERAL CONSIDERATIONS

2.1 Cracking due to ASR

The reaction between alkalies present in cement and certain reactive forms of silica within the aggregate is internal, chemical, and time-dependent, and results in expansive strains due to the ability of the gel to imbibe water, swell and exert pressure which can crack the concrete. In rare circumstances, such expansion can be as much as 2-3%. Because of the expansive nature of the reaction, and because the tensile strain capacity of concrete is only of the order of 150 to 200 μs, and rarely exceeds about 500 μs, the most direct and visible evidence of ASR is external cracking. Such cracking can at times be extensive and deep; in plain concrete elements, such cracks tend to be dramatic, and occur in all directions, whereas in reinforced concrete beams and columns, they tend to appear parallel to the reinforcing steel.

In laboratory tests, when the concrete member is free from external stresses, the cracks can be a few millimetres wide and several millimetres deep. Field examination of many ASR affected structures, on the other hand, shows that cracks due to ASR can be many millimetres wide and very deep - often deep enough to extend beyond the cover of the reinforcing and prestressing steel. Crack widths up to 15mm and crack depths up to 300mm have been observed [1,2]. In general, wider cracks tend to penetrate deeper, and expansive strains of 0.05% to

0.20% are enough to cause extensive cracking if a sufficient amount of reactive aggregate is present and the alkalinity of the concrete is high. Bearing in mind that ASR is time-dependent, that it occurs invariably when the structure is in service, and that all concrete structures under service loads are cracked (although such cracks may never be damaging and sometimes not visible to the naked eye), part of the measured crack widths and crack depths in real structures is obviously due to load induced stresses aggravated by the imposition of expansive concrete strains. Since structures in service are stressed and cracked, expansive strains of even 0.10 to 0.20% superimposed over load induced cracks can lead to structural distortion and displacement, as has been observed in dams, pavements, retaining walls, parapet walls, buildings and bridges.

Visible cracking due to ASR can be further complicated if the aggregates are slowly reactive, since the reaction needs both moisture and a favourable temperature for it to initiate and continue. Thus the interior columns of an exposed bridge, sheltered from direct sunshine and rain, may show no cracking whilst the exterior columns may develop extensive cracking. On the other hand, a structural member, partly sheltered and partly exposed, may show very different crack patterns in the same structure. The effects of bad or inadequate detailing in an ASR-affected structure can also be readily recognised by the irregular cracking observed, for example, at the free ends of structural members or at the corners of abutments. With mildly reactive aggregates, a structure may thus show relatively no cracking except at locations where bad detailing has left the concrete exposed, unable to counteract the expansive strains of ASR. Cracking due to ASR in real structures can thus be highly complex, very variable and unpredictive; it is very much dependent on the amount of expansion, quality and efficiency of detailing, nature of the structure and the stress distribution in the structure.

2.2 Effect on Engineering Properties

The effect of ASR on engineering properties cannot often be generalised since both the rate of expansion and the total expansion depend very much on the reactive aggregate, cement type, cement content and the environment. Tests show that losses in strength and elastic modulus do not all occur at the same rate or in proportion to the expansion[3]. For expansive strains of 0.5 to 1.5%, loss in compressive strength can vary from 40 to 60%, whereas loss in tensile strength can be as high as 65 to 80%. Loss in elastic modulus can also be high from 60 to 80%. Problems can arise with supposedly innocuous or very slowly reactive aggregates such as flint which may show little or no expansion and loss of strength at ambient temperatures and may remain so for a long time. Yet at higher temperatures and other favourable conditions, harmful expansions and considerable loss in strength may occur [3]. Similarly, cores taken from ASR affected structures may sometimes show high residual compressive strengths, particularly if they are taken at an early stage of development of ASR, but tensile strengths will invariably be more sensitive to the expansive strains.

Measurements of strength and elastic modulus on cores taken from various concrete structures containing different reactive aggregates confirm the loss in elastic modulus and tensile strength shown by laboratory tests [1]. Both these losses lead to a reduction in flexural rigidity and stiffness of individual structural elements. Load tests on ASR affected structures, however, tend to show smaller losses in elastic stiffness for the structure as a whole, partly because of load distribution in two directions and other elements contributing to the overall structural stiffness [1,4].

3. STRUCTURAL EFFECTS DUE TO ASR-RC BEAMS

3.1 Expansive Concrete Strains

One of the primary effects of ASR in concrete is the development of expansive strains. Tests show that expansive strains measured in mortar bars instead of on concrete prisms will give unrealistically high magnitudes and rates of strain development for similar conditions of concrete alkalinity, reactive aggregate and environment [5]. Mortar bar tests are therefore not the best methods for quantitative evaluation of the expansive potential of a given aggregate. Concrete prism tests are much more realistic, but even here there may be some size effects and the influence of reinforcement to be considered when assessing expansive strains in structural members from laboratory tests on concrete prisms.

The largest expansive concrete strain in a flexural member will occur at the compressive face remote from the tension steel, and this will be a maximum when the compression face is un-

Table 1. Expansive strains in RC beams

Reactive aggregate	concrete expansion %			steel strain %
	control prism	RC beam		
		compn. face	tension steel level	
Opal	1.665	1.288	0.117	0.234
Fused silica	0.634	0.518	0.085	0.110

restrained by the presence of steel. Table 1 shows how the expansive strains are distributed over the depth of a reinforced concrete beam for two different reactive aggregates; it is also seen that the maximum measured expansive strain in a beam is about 80% of the expansion shown by a concrete control prism of similar characteristics [6]. These data have several important implications for structural members:

(1) concrete expansive strains are irreversible;

(2) there is a strain gradient over the depth of the member, and the maximum gradient occurs when the compression face is unrestrained;
(3) steel reinforcement controls expansive strains;
(4) the differential expansions over the depth of the beam can create a hogging deflection;
(5) such a deflection is analogous to a prestressing effect and can be beneficial from strength considerations;
(6) a correctly detailed beam should not suffer distress in shear, bond or anchorage.

3.2 Steel Strains

The expansive concrete strains create irreversible strains in the tension steel also. Table 1 also shows these strains which correspond to 80% and 40% respectively of the steel yield strength for the two reactive aggregates i.e. stresses of about 450 MPa and 220 MPa are induced in the tension steel for expansive concrete strains of about 1.3% and 0.52% respectively. In real structures, these stresses will be superimposed on load induced stresses. Assuming tensile stresses in steel of about 250 MPa in a concrete structure under service loads, even moderate expansions of 0.1% to 0.2% can substantially increase the steel stress to levels leading to undesirable and irreversible structural deformations.

3.3 Ultimate Flexural Strength

Since the steel stresses due to ASR are superimposed on the stresses due to external loads, a loss in ultimate flexural strength can be expected in reinforced concrete beams. For a highly reactive aggregate with expansions of 1.2 to 1.3%, loss in strength can be as high as 25%; for a moderately reactive aggregate expanding by 0.5 to 0.6%, the loss in strength can be 15 to 20% [6]. In a symmetrically reinforced beam, the benefits of the prestressing effect may not be available, and the loss in strength could be higher. Ductility could also be affected, and ASR could induce an apparent lack of ductility at failure.

4. STRUCTURAL EFFECTS DUE TO ASR- COLUMNS

4.1 Concrete and Steel Strains

Unlike reinforced concrete beams, a reinforced concrete column has longitudinal steel on all four sides and links throughout the height of the column. There is thus much greater restraint on the concrete in a column than in a beam, and this has beneficial effect on concrete strains. Table 2 shows the concrete and steel strains in model columns (95 x 95 x 750mm) for two types of reactive aggregates and a control ASR-free column.

As in reinforced concrete beams, the expansive strains in concrete and steel are irreversible. The more interesting

Table 2. Expansive strains in RC columns

Reactive aggregate	strain-microstrain	
	concrete	steel
Control	61	37
Opal	2407	2335
Fused silica	1559	1470

phenomenon, however, is that the concrete and steel strains are nearly the same - in other words, the bond between concrete and steel remains largely unaffected by ASR and this is a very promising feature which ensures the composite action of the column. This preservation of the steel-concrete bond was observed in other tests and larger sized columns. The steel strains in the beams and columns containing opal reactive aggregate was almost the same. On the other hand the steel strain in the column with fused silica was about 30% higher than that in the beam.

4.2 Ultimate Strength

When tested to destruction at the end of the expansion period, the ASR affected columns gave 10 to 15% lower strength compared to the control unaffected column. Here again, the influence of external loads needs to be superimposed on the strains shown in Table 2, so that real structures, which undergo moderate ASR expansions of 0.1 to 0.2%, can be expected to suffer substantial structural distress and will have serviceability problems.

5. CONTROL OF ASR EFFECTS IN STRUCTURES

Real life structures are very different from laboratory specimens and laboratory tests. Although the major source of alkalies is often the cement or other constituents present at the mixing stage, alkali rich aggregates may also contribute to the alkalinity of the concrete by being leached out [7]. Alkalies from outside sources such as ground water and deicing salts may also penetrate into the concrete, and there is evidence that their effect can be much more damaging than that arising from cement and other sources present at the mixing stage [8]. Thus in real structures there will nearly always be a concentration gradient of alkalies, and alkali salts cannot be assumed to be uniformly distributed throughout the mass of the concrete mix. Further, when alkali salts permeate from an external source or when local drying and evaporation take place at certain parts of the structure, the local concentration of alkali salt may exceed an assumed critical value. This may give rise to alkali silica expansion even though the overall alkali content may be lower than the critical value. And nearly always, such expansion is likely to be non-uniform and non-homogeneous.

It is clear from the data presented in this paper that it is very unlikely that structures will collapse because of ASR. The most significant effect of ASR is on serviceability, and even moderate expansions of 0.2 to 0.3% could create significant structural distress when the effects of ASR are superimposed on the effects of serviceability loads. How can one then design structures to have satisfactory serviceability behaviour and preserve its safety, ductility, stability and integrity, even if, in spite of all precautions, expansions up to 0.5% do occur during the serviceability life of the structure? The data presented in this paper indicate two basic requirements - first, the strength and stiffness of the ASR affected concrete should be restored to its original values; second, the stability and integrity of the structure should be preserved. A dual engineering approach is suggested to achieve this - the use of mineral admixtures in concrete and secondary distribution reinforcement. Typical structural elements designed in this way are shown in Fig.1.

The rationale behind this approach is two fold. Firstly the effects of ASR are influenced by the alkali content in the concrete, the rate of reactivity, the rate of pozzolanic activity and the specific surface of the mineral admixture, the moisture content of the concrete and the method of cement replacement. Further, reduction in pore solution alkalinity, ionic diffusivity and permeability may all be involved as expansion control mechanisms. Second, only reinforcement can be effective in controlling cracking and contributing to structural stability and integrity. Fig.1 in the author's opinion thus shows the way forward.

REFERENCES

[1] Ono, K., Damaged Concrete Structures in Japan due to Alkali Silica Reaction, International Journal of Cement Composites and Lightweight Concrete, 10, 4, 247, 1988.

[2] Palmer, D., Alkali Aggregate Reaction - Recent Occurrences in the British Isles, Proc. 4th Int. Conf. on the Effects of Alkalies in Cement and Concrete, Purdue University, 285, 1978.

[3] Swamy, R.N., and Al-Asali, M.M., Engineering Properties of Concrete Affected by Alkali-Silica Reaction, ACI Materials Journal, 85, 5, 367, 1988.

[4] Blight, G.E., Alexander, M.G., Schutte, W.K., and Ralph, T.K., The Effect of Alkali-Aggregate Reaction on the Strength and Deformation of a Reinforced Concrete Structure, Proc. 6th Int. Conf. on Alkalis in Concrete, Copenhagen, 401, 1983.

[5] Swamy, Narayan R. , and Al-Asali, M.M., Expansion of Concrete due to Alkali-Silica Reaction, ACI Materials Journal, 85, 1, 33, 1988.

[6] Swamy, R.N., and Al-Asali, M.M., Effect of Alkali Silica

Reaction on the Structural Behaviour of RC Beams, To Be Published.

[7] Stark, D., and Bhatty, M.S.Y., Alkali-Silica Reactivity: Effect of Alkali in Aggregate on Expansion, ASTM Publication STP930, 16, 1986.

[8] Swamy, R.N., and Al-Asali, M.M., Alkali-Silica Reaction - Sources of Damage, Highways and Transportation, 35, 12, 24, 1988.

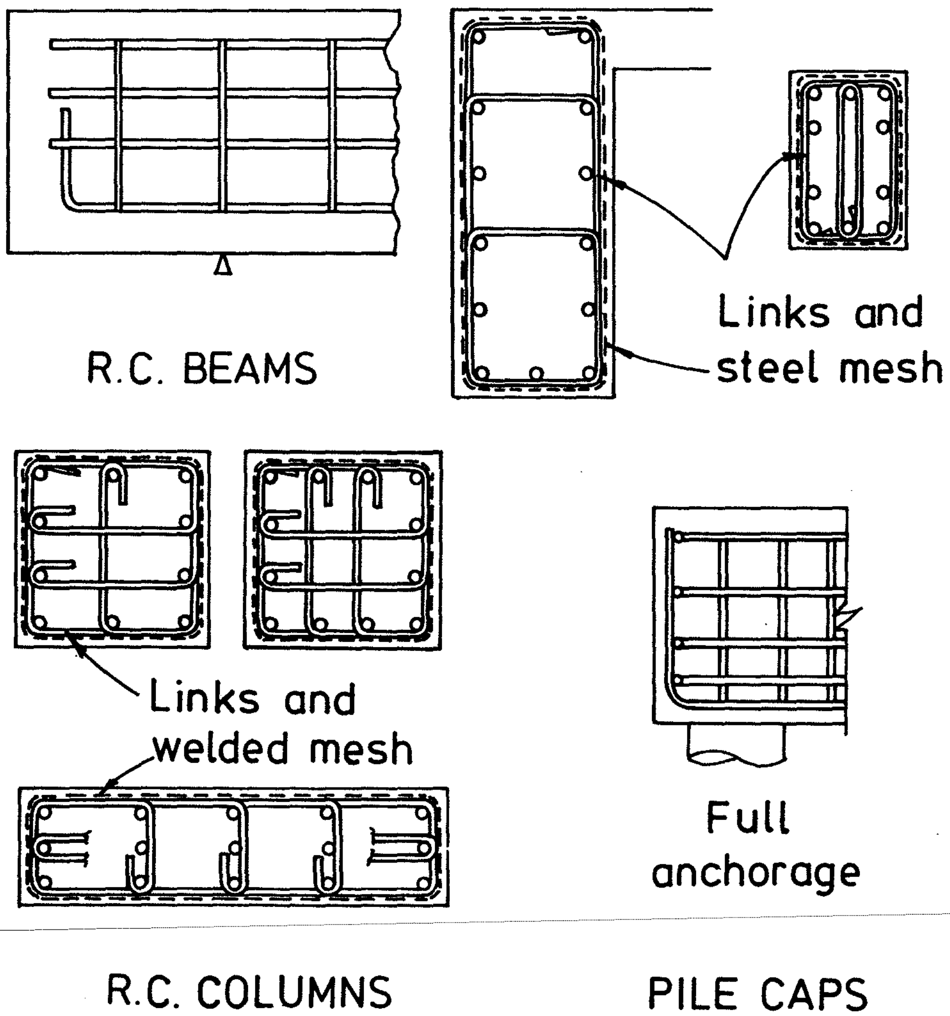

Fig. 1. Reinforcement detailing to control ASR