Repair and Maintenance

of

Structures

Affected By

Alkali-Aggregate Reaction

ENGINEERING PROPERTIES OF REINFORCED CONCRETE DAMAGED BY AAR

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ABSTRACT

Although AAR is a phenomenon that has been known and studied for 40 years, most research has been aimed at investigating the mechanisms of deterioration,identifying materials susceptible to reaction and preventing AAR from occurring in structures still to be built. Relatively little effort has been expended on assessing the effect of AAR in causing deterioration of the strength and deformation properties of concrete. In order to assess the safety margin of structures that have deteriorated and to formulate measures for repairing and strengthening them, an assessment of the likely strength of the deteriorated concrete as well as its elastic and time-dependent deformation properties is required. This review will summarise the effects of AAR on these properties, as well as describing means for assessing the extent of the overall deterioration of full scale structures.
Key words: AAR, reinforced concrete, swelling pressure, strength, elasticity, creep, full-scale testing.

SURFACE EFFECTS OF AAR ON REINFORCED CONCRETE

AAR occurs when the alkali associated with the cement content of a concrete reacts with the concrete aggregate. The reaction is expansive and results in disruption of the concrete. Because of its expansive nature, the disruption of reinforced concrete is restrained by the reinforcing, and patterns of surface cracking reflect the effects of this restraint.

Cracking caused by AAR may vary from continuous cracks aligned parallel to the direction of the major reinforcing in a compressive member to severe omni-directional block cracking of the surface of relatively unstressed areas. Cracks are usually not static, but progressively widen as time proceeds and they penetrate more deeply into the heart of the R.C. member. Figure 1 shows some crack width-time relationships that have been observed on the surface of a R.C. member (Blight et al, 1989). The growth in width of the cracks is influenced by the weather. Close examination of Figure 1 will show that an acceleration of movement occurs in the second half of each year (i.e. each rainy season) and that the rate of expansion slows during May to August (the dry season). This structure was 13 years old at the end of 1978. The numbers in the figure identify each crack.

Increasing crack widths are accompanied by swelling strains on the surface of the concrete. Figure 2 shows a set of surface strains measured on the same R.C. member

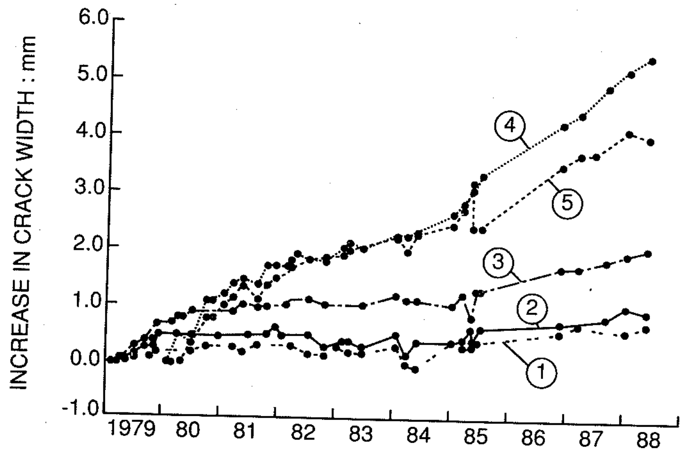

FIGURE 1: Relationship between crack width and time for selected surface cracks in a R. C. member damaged by AAR

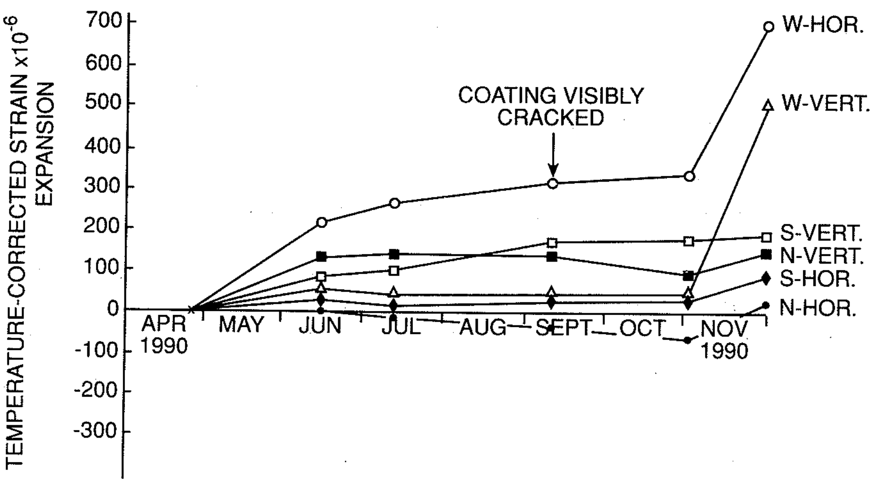

FIGURE 2: Measured expansion of the surface of a 25 year old R. C. member.

(Alexander, et al, 1992) that is the subject of Figure 1. At this stage the concrete was 25 years old. The surface cracks had been sealed and repaired, but the expansion still continued. The measurements were carried but with a 400 mm gauge length Demec gauge and were corrected for temperature by means of thermocouples embedded in the concrete.

SWELLING PRESSURES GENERATED BY AAR

Because the swelling of the concrete is restrained by the reinforcing, swelling pressures are generated within the concrete. Relatively little seems to be known of the magnitude of the swelling pressure developed in concrete by AAR. The earliest measured swelling pressures appear to be due to McGowan and Vivian (1955). Data collected by Hobbs (1988) suggests that swelling pressures of up to 4 MPa are possible, although in one case a swelling pressure of 13.5 MPa was recorded. However, all of these measurements were made in accelerated laboratory tests. Under field conditions where the reaction takes place over decades rather than weeks, relaxation of stress might be expected to reduce swelling pressures to less than the quoted values.

Figure 3 shows the result of swell-under-load tests undertaken on cores from the R.C. member referred to in Figure 2. The tests were made to assess if the concrete still had an appreciable swelling potential after 25 years of exposure to the elements. The constant stress applied to each specimen is indicated next to each curve. It will be seen that free swells of over 450 x 10^{-6} were recorded and that strains of close to 250 x 10^{-6} occurred under a confining stress of 1 MPa although results were very variable.

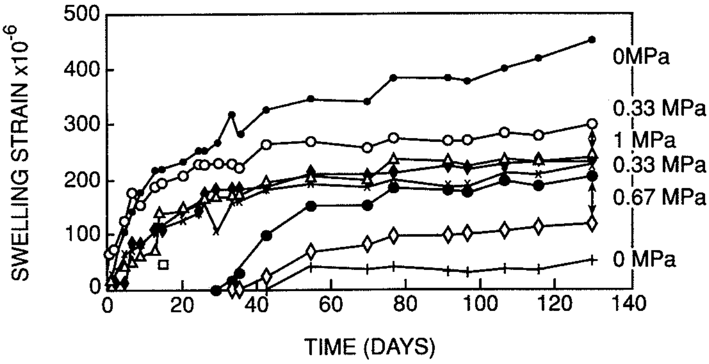

FIGURE 3: Swell-under-load versus time relationships for cores of 25 year old concrete

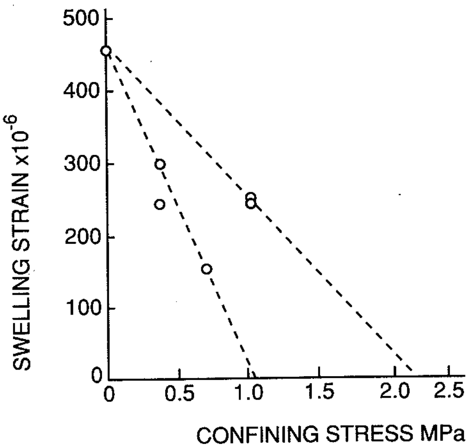

FIGURE 4: Relationships between equilibrium swell strain and confining stress for cores of 25 year old concrete.

Figure 4 shows the approximate equilibrium swell strains plotted against the corresponding confining stresses. Extrapolating the trend lines of swell versus stress to zero swell strain gives an indication that the fully restrained swelling pressure of the concrete specimens (ie. with strain prevented) was in the range of 1 to 2 MPa, even after 25 years of exposure to the elements.

EFFECTS OF AAR ON STRENGTH OF CONCRETE

The swelling pressure generated by AAR, acting against the restraint of the reinforcing ensures that AAR has relatively little effect on the strength of concrete. Even when the prestressing effect is removed by coring the concrete, the strength remains surprisingly high, presumably because of mechanical interlock between the disrupted blocks of concrete. Figure 5 shows the results of a series of compression and splitting tensile strength tests on sets of cores from two series of concrete structures having different concretes but the same design strength of 30 MPa. Although the cores were taken from structures that had apparently been badly affected by AAR, Figure 5 shows that the mean strength for concrete 1 still exceeded the design strength. The mean compressive strength for concrete 2 was still up to specification, although the splitting tensile strength had been reduced.

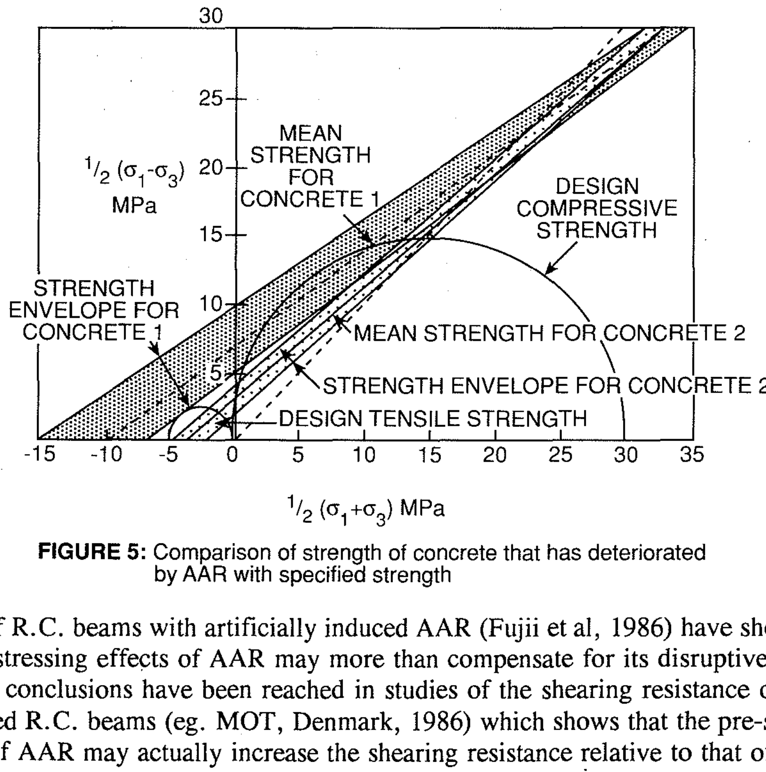

FIGURE 5: Comparison of strength of concrete that has deteriorated by AAR with specified strength

Tests of R.C. beams with artificially induced AAR (Fujii et al, 1986) have shown that the prestressing effects of AAR may more than compensate for its disruptive effects. Similar conclusions have been reached in studies of the shearing resistance of AAR-disrupted R.C. beams (eg. MOT, Denmark, 1986) which shows that the pre-stressing effect of AAR may actually increase the shearing resistance relative to that of similar beams not affected by AAR.

ELASTICITY AND CREEP

Strength effects apart, the disruption caused by AAR does adversely affect the elastic, and also the time dependent creep properties of concrete. This point is illustrated by Figure 6 which compares the instantaneous and creep strains measured on three cores of concrete, all of which were subjected to a stress of 15 MPa, or half the design strength. Core A was of sound concrete showing no signs of AAR attack while cores B and C had deteriorated by AAR. The results show that the elastic deformations of the deteriorated concrete were three and a half times as large as those of sound concrete, while the creep strain was two and a half to four times as large.

There are indications that laboratory tests on cores (from which the prestressing effect of AAR have been released) still represent the effects of AAR on elasticity and creep fairly realistically. For example, Figure 7 shows a field creep curve measured on an R.C. cantilever that had been damaged by AAR and repaired by poststressing. A comparison between laboratory creep curves B and C in Figure 6 with the field creep curves of Figure 7 shows that the elastic moduli of the cores and cantilever were similar (7 and 10 GPa). The one year creep moduli were also very similar (10 and 7 GPa).

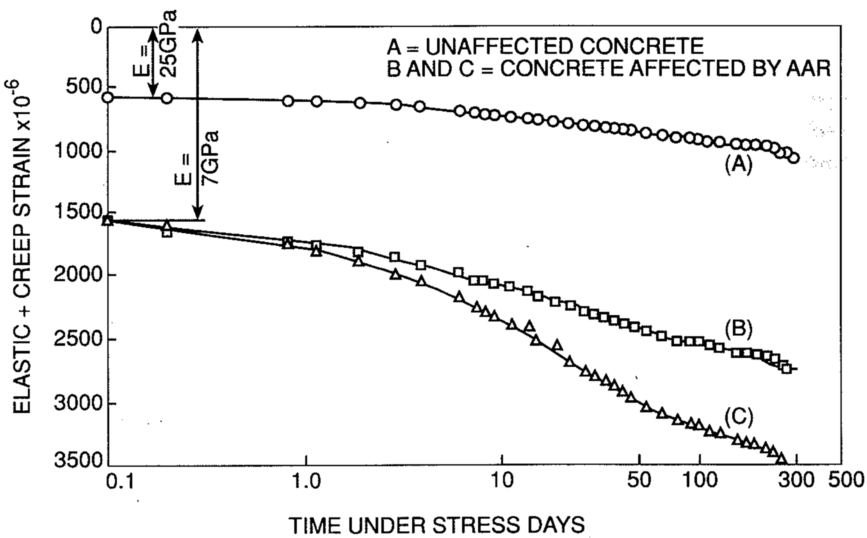

FIGURE 6: Effect of damage by AAR on elastic and creep properties of concrete

STRUCTURAL ASSESSMENT BY OBSERVING IN-SERVICE BEHAVIOUR

Full-scale load testing is the ultimate measure of safety and serviceability of an AAR-deteriorated structure. If the structure behaves predictably and in accordance with the design requirements, and if strains and deformations are predictable and recoverable, there can be little doubt that structural adequacy has been demonstrated. Such testing is, however, extremely expensive. In many cases it may be sufficient to instrument

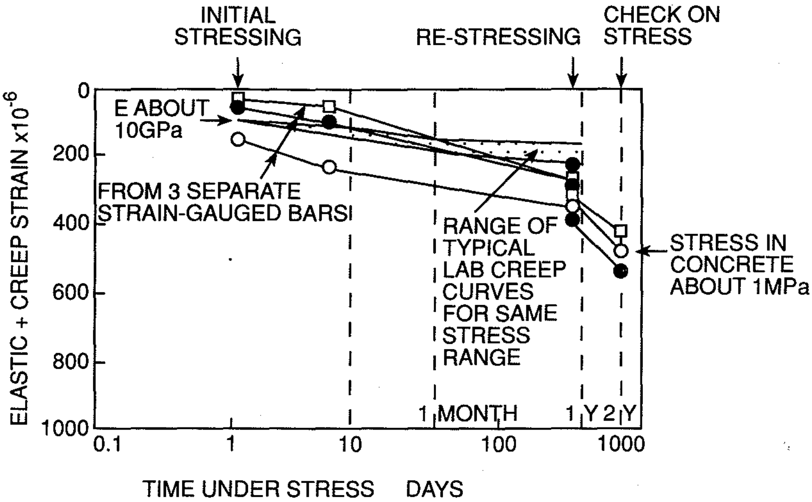

FIGURE 7: Field creep curves measured on a RC cantilever repaired by prestressing

the structure, or part of the structure, and observe its behaviour under service loading.

Figure 8 shows the results of observing the in-service behaviour of a bridge pier that had cracked severely as a result of AAR. Strain gauges affixed to the pier showed that during a normal peak traffic period, the live load stresses amounted to a maximum of only 0.4 MPa. This information, together with reassuringly large core strengths was sufficient to demonstrate that the structure remained adequately strong even in its deteriorated condition. (Note that the stresses are based on a value of elastic modulus of 30 GPa, which according to the data of Figure 6 is probably a conservatively high value for the pier).

FULL-SCALE LOAD TESTING

The literature records two structures damaged by AAR that have been subjected to full-scale load testing. Imai et al (1986) carried out comparative test loadings on four of

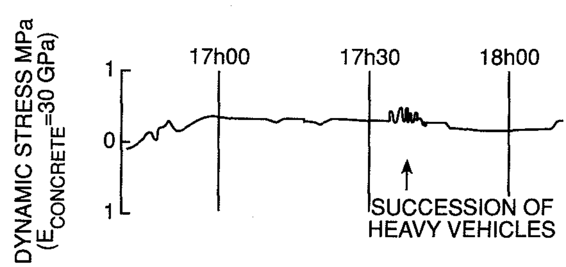

FIGURE 8: Dynamic strains recorded on a pier during an in-service test

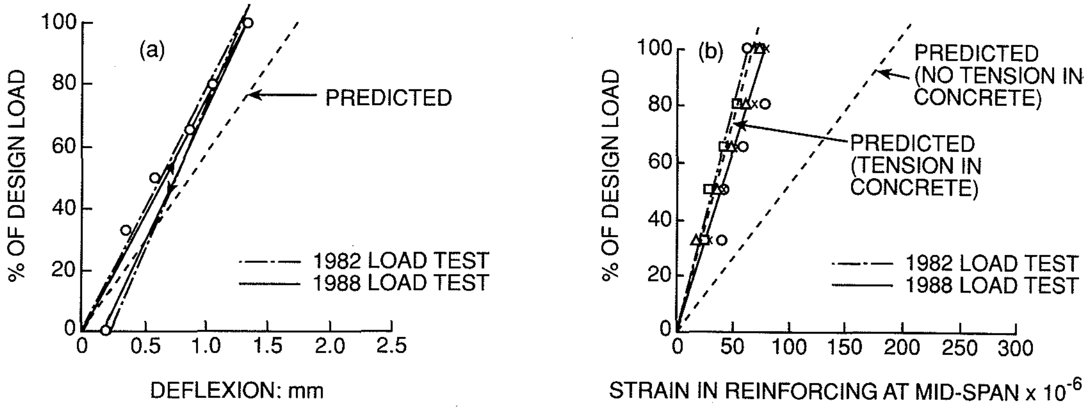

FIGURE 9: Comparison of (a) measured and predicted deflections of upper transverse beam: and (b) strain in reinforcing at midspan of beam during full-scale loading test on RC portal frame.

the columns supporting the double-cantilever overhead structure of the Hanshin expressway in Kobe, Japan. Two of the columns had been affected by AAR and two had not. It was concluded that the stiffness and load carrying capacity of the AAR-affected columns was almost indistinguishable from that of the unaffected columns. (Large parts of this over-head freeway structure were subsequently destroyed by toppling in the 1995 Kobe earthquake.)

Blight et al (1989) carried out two full-scale loading tests, six years apart, on a reinforced concrete portal frame that was showing (apparently) severe deterioration as a result of AAR. Prior to the loading tests an elastic finite element analysis of the frame was made using a reduced value of elastic modulus for the concrete that had been established by means of laboratory measurements on cores taken from the structure. Measured deflections, rotations and strains were then compared with the previously predicted quantities. In every case, close agreement was found between prediction and measurement. Over the short time duration of each of the loading tests , the structure behaved almost completely elastically and deformations were nearly fully recovered on removal of the load. Figure 9 shows the predicted and measured load-deflection curves for midspan of the beam of the asymmetrical portal and the corresponding predicted and measured strains in the midspan tensile reinforcing. The agreement obtained between strains, rotations and displacements predicted by analysis on one hand and observation on the other was surprisingly good, and the results of the two tests made 6 years apart are almost indistinguishable.

CONCLUSIONS

1 Concrete subject to attack by AAR undergoes an expansion that results in unsightly and alarming surface cracking. The cracks usually appear up to a decade after construction and may continue to widen and develop for a further 15 years or more.

2 The restraint provided by the reinforcing in reinforced concrete allows a swelling pressure to develop in the concrete. Swelling pressures of up to 4 MPa appear possible, and even 25 year-old concrete may develop swelling pressures as high as 2 MPa.

3 The restrained swelling acts as a prestress on the concrete which, even though disrupted, retains most of its compressive and shear strength. Even its tensile strength, although reduced, does not disappear.

4 The disruption caused by AAR does, however, reduce the elastic and creep moduli of the concrete.

5 Apart from laboratory tests on cores taken from an affected structure, the safety and structural integrity of the structure can be evaluated by measurements made during service under actual service loads, or by means of full-scale load testing to the design load. Measurements made in this way have shown that AAR has little overall effect on the performance of R.C. structures.

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