USE OF ANALYTICAL METHODS TO ESTIMATE CONCRETE DETERIORATION DUE TO AAR

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ABSTRACT

In a structure affected by alkali-aggregate reaction (AAR), the expansion and deterioration of concrete properties vary, often significantly, throughout the structure. This is due to the sensitivity of the expansion to the restraint. The variation may play an important part on the effect of AAR on structures. The traditional appraisal technique for concrete, in which the concrete is regarded as an 'uniform' material, is not suitable for structures affected by AAR.

In this paper the variation of the expansion and concrete deterioration is demonstrated through numerical analyses. It is shown that a suitable appraisal approach may be the combination of field investigation and numerical analysis taking into account of the special feature of AAR affected concrete.

Keywords: AAR, structural appraisal, deterioration of concrete, finite element method, computer simulation.

INTRODUCTION

Structural appraisal is a difficult task facing engineers who are dealing with concrete structures affected by alkali-aggregate reaction (AAR). The common methods adopted for the appraisal include the testing on cores drilled from the structure and the load testing on the whole structure. In the case of core testing, mechanical properties such as compressive strength and modulus of elasticity of the core are determined and overall capacity of the structure is estimated. However, it has been reported by many researchers that the performance of affected structures observed from load testing differ, often significantly, from the prediction based on the properties of the core using conventional analytical methods.

One example of this discrepancy is the tests on piers of Hanshin Expressway (Imai 1986). In these tests, the Young's modulus of concrete cores from affected piers was about 20% of that of unaffected concrete with a value of only 6.2 kN/mm^2; the deflections, however, measured on both affected and unaffected piers were similar.

The apparent discrepancy between core testing and load testing is normally attributed to the following two reasons: firstly, the modulus of elasticity measured from the cores may not reflect the deformation property of the concrete inside the structure where the concrete is restrained by surrounding concrete; secondly, the stresses induced in the concrete and reinforcement due to AAR expansion stiffen the structure by preventing or reducing tensile cracks in the concrete.

Another reason which may have often been overlooked is the variations of AAR expansion within affected structures. It is known that AAR expansion is sensitive to the stress in concrete; a compressive stress of the order of 4 N/mm^2 can stop the expansion in the direction of the stress completely. Concrete subjected to stronger restraint, for example in the compression zone, expands less than concrete under weaker restraint. Since concrete deterioration is closely associated with the expansion, the properties of concrete, particularly the compressive strength and modulus of elasticity, varies with location within the structure. The variation could be as high as 60% for modulus of elasticity and 10% to 40% for compressive strength. The difference in concrete properties could have noticeable influences on the performance of a structure and must be taken into account when assessing the structure.

The variation of concrete properties renders the traditional analytical methods, in which the stress-strain relationship is considered to be the same for concrete throughout a structure, unsuitable for the analysis of AAR affected concrete, and a new approach must be adopted.

Load testing on a structure can affirm the adequacy of load capacity of the structure under a given load. To assess the adequacy under an impact or accidental load, it is often desirable to have the ultimate load capacity be evaluated so that safety margin of the structure can be estimated. This also calls for an analytical method for concrete with AAR.

In this paper, the structural effects of AAR are discussed quantitatively through numerical analyses using a computer program[1] (Cope 1994, May 1992, Wen 1993a).

THE COMPUTER PROGRAM

General introduction

The computer program uses finite element (FE) approach incorporating an expansion model and taking into account the deterioration of concrete due to AAR expansion. The analysis is generally carried out in three stages:

Stage 1: pre-AAR analysis,
Stage 2: AAR expansion analysis, and
Stage 3: post-AAR analysis.

The first stage comprises a routine non-linear FE analysis for unaffected structure under a given load. This is to simulate the situation when the structure is under its service load before AAR takes place.

The second stage is to simulate the situation when the structure is undergoing AAR expansion.

[1] The program was developed as part of a research project jointly financed by the Science and Engineering Research Council and the Transport Research Laboratory, 1989 - 1993.

The third stage is to simulate the load test on the affected structure. In this stage the affected member is subjected to external load up to failure in order to determine the post-AAR behaviour and the ultimate load capacity of the structure. This stage is a non-linear analysis similar to that for normal concrete but with the deteriorated material properties and induced stresses.

The expansion and material models

In the expansion analysis, the basic variable for expansion is the free expansion, which is defined as the expansion when the concrete is free from any restraint. The maximum value of free expansion needs to be specified for the analysis. The value can either be estimated based on field investigation or, in the case of laboratory experiment, on the free expansion of unrestrained specimen. The restrained expansion, at a given point (quadrature point) in the structure, is a function of the free expansion and stress history at that point. Because the expansion and the induced stresses in concrete interact to each other, an incremental approach must be used. In this approach, the development of AAR is simulated by a large number of small increments of free expansion until a pre-specified level of free expansion is reached.

A constitutive model based on the theory of incremental plasticity is adopted to represent the behaviour of concrete in compression, with associated flow rule and work hardening. The effective stress-equivalent strain curve, which governs the progress of yielding surface, is derived based on the uniaxial stress-strain relationship obtained from cylinders of AAR affected concrete (Wen 1993b).

Concrete deterioration is a function of equivalent expansion.

AAR expansion analysis procedure

The analytical procedure for stage 1 and stage 3 are similar to that for normal reinforced concrete structures. The procedure of the second stage, the analysis of AAR expansion, is outlined below:

i) At the beginning of each step, an incremental free expansion is specified. The restrained expansions at concrete quadrature points are calculated according to the stress and free expansion-restrained expansion relationship.

ii) The analysis is carried out as an initial strain problem with the restrained expansions as the initial strains. An iterative process is employed at this step to eliminate the unbalanced nodal forces and achieve equilibrium.

iii) After equilibrium is achieved, the concrete properties are modified at each quadrature point, according to the total equivalent expansion.

iv) Steps i) to iii) are repeated until the pre-specified free expansion is reached.

ANALYTICAL EXAMPLES

A large number of laboratory tested members have been analysed using the computer program. Analytical results generally agree with the test results. Numerical parametric studies on structural members have also been carried out. Two examples are given below.

Example 1: Beams tested for shear strength in Denmark (Bach 1992)

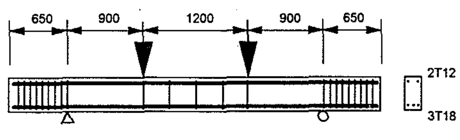

Fig. 1 Details of the beam (Bach 1992).

Fig. 1 shows details of beams tested in Denmark (Bach 1992). The beams, made of both concrete with and without AAR, were designed to investigate the effect of AAR on the shear capacity of beams without shear reinforcement. According to Bach, AAR expansion resulted in a significant increase in shear capacity, from 55 kN to 130 kN, despite substantial drop in compressive strength and elastic modulus of the concrete. Two beams have been analysed, one control beam, A0, and a reactive beam, A12. The maximum expansion of the reactive specimen was about 5 mm/m.

Table 1 Input data for the beam tested by Bach et al.

Concrete:	
Compressive strength	45 N/mm^2
Tensile strength	2.5 N/mm^2
Elastic modulus	40 kN/mm^2
Poisson's ratio	0.2
Fracture energy	0.1 N/m
Ultimate crushing strain	0.0035
Reinforcement:	
Yield stress (main bar)	560 N/mm^2
Yield stress (stirrups)	400 N/mm^2
Elastic modulus	200 kN/mm^2

The finite element mesh for the beams is shown in Fig. 2(A). The input data for the analysis is given in Table 1. Fig. 2(B) shows the deformation profile of the beam when the free expansion reaches 5 mm/m. The deformation shown in Fig. 2(B) is exaggerated by a factor of 5. Fig. 3 compares the load deflection curves from the analysis with those from the tests. It can be seen, from Fig. 3, that the analytical results follow the general trend observed in the tests. Fig. 4 shows concrete principal stress contour and induced stress in the reinforcement when the free expansion is 5 mm/m. Fig. 5 shows the analytical crack pattern of the beams when they failed. These patterns reflect the failure mode shown in the test report (Danish 1986).

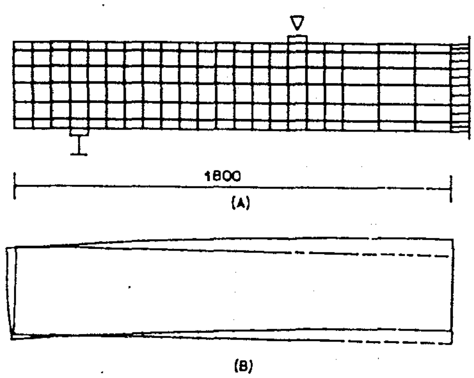

Fig. 2 (A) Finite element mesh. (B) Deformation at free expansion 5 mm/m.

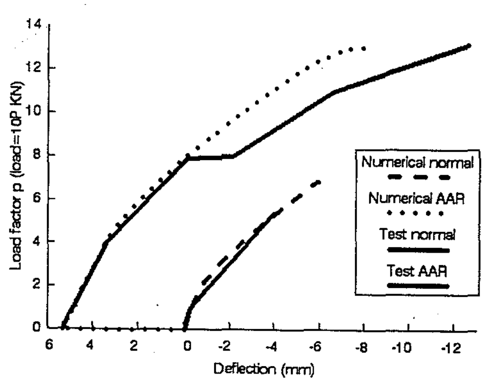

Fig. 3 Numerical and experimental load -deflection curves of the beam by Bach et al.

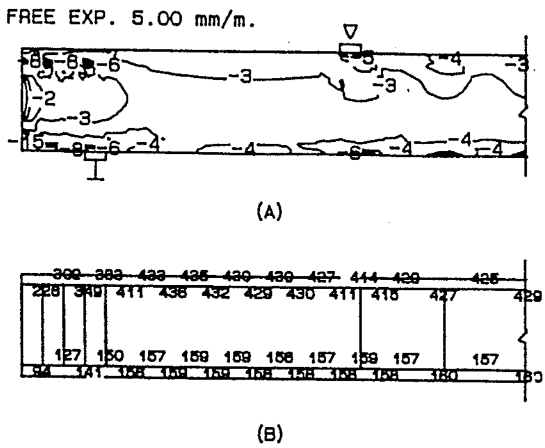

Fig. 4 (A) Concrete principal stress contour, and (B) stress in reinforcement of the beam with AAR when free expansion is 5 mm/m. All stirrups in (B) have yielded, stress = 400 N/mm^2.

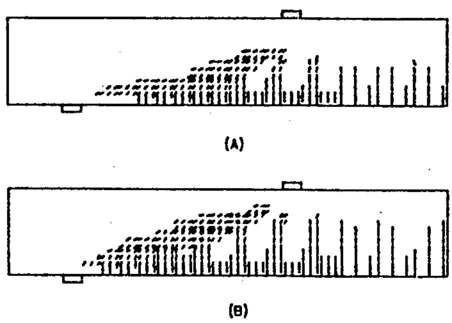

Fig. 5 Predicted crack pattern of (A) beam with AAR and (B) control beam.

The analysis showed that the control beam failed due to the formation of a major shear crack. This crack is initiated near the support at a relatively low load and widens rapidly when approaching failure, Fig. 5(B). The analysis reveals that when the control beam fails, the maximum tensile stress in the longitudinal tension reinforcement is only 270 N/mm^2, less than half of its strength 560 N/mm^2.

For the beam affected by AAR, the compressive stress induced by AAR near the soffit of the beam delayed the initiation of the shear crack and the major shear crack forms at some distance away from the support, Fig. 4(A) and Fig. 5(A). The AAR expansion changes the failure mode from a brittle shear mode to a more flexible bending mode by shifting the major shear crack away from the support. At failure, the steel stress is about 540 N/mm^2 close to 560 N/mm^2, the strength of the steel.

Example 2: A reinforced concrete beam for numerical studies

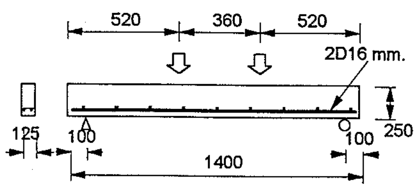

Fig. 6 Details of the beam for numerical studies.

Fig. 6 shows a singly reinforced beam for numerical studies in order to investigate possible influence of various factors such as the load applied during expansion and the level of free expansion. The input data for the analysis are shown in Table 2.

Figs. 7 and 8 show, respectively, the stress patterns of two beams, one being loaded and one without loading during AAR expansion. For the loaded beam, the concentrated load shown in Fig. 6 is 15 kN each, about 30% of the load capacity of the unaffected beam.

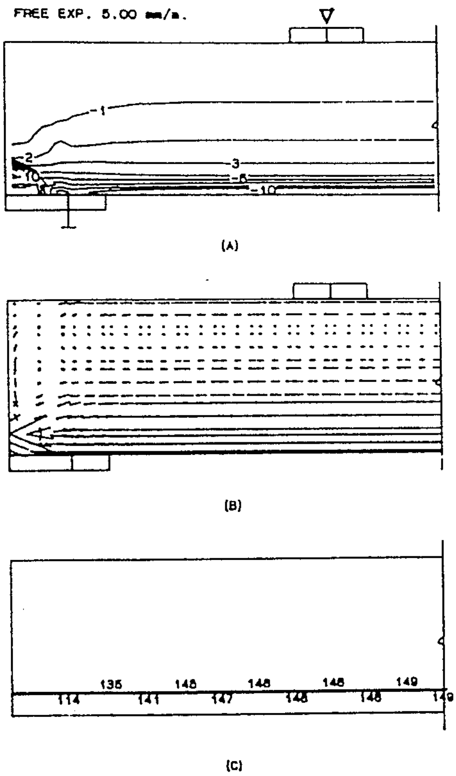

Fig. 7 (A) Concrete principal stress contour, (B) stress vectors and (C) reinforcement stresses of the beam without loading during AAR period.

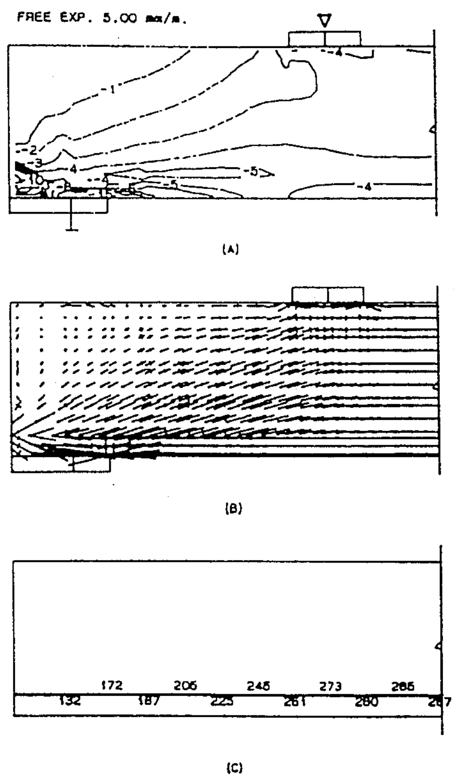

Fig. 8 (A) Concrete principal stress contour, (B) stress vectors and (C) reinforcement stresses of the beam with loading during AAR period.

Table 2 Input data for the beam for parametric studies.

Concrete:	
Compressive strength	45 N/mm^2
Tensile strength	2.5 N/mm^2
Elastic modulus	40 kN/mm^2
Poisson's ratio	0.2
Fracture energy	0.1 N/m
Ultimate crushing strain	0.0035
Reinforcement:	
Yield stress (main bar)	320 N/mm^2
Elastic modulus	210 kN/mm^2

The predicted variation of the initial modulus of elasticity of the affected concrete is illustrated in Fig. 9 for three levels of AAR expansion: 1, 3 and 5 mm/m. The original modulus of the concrete was 40 kN/mm^2. The figures show that the less restrained area suffers greater loss of the initial modulus of elasticity. For instance, when the free expansion is 5 mm/m, the modulus in the tension zone drops to 25 kN/mm^2 , 60% of its original value, whereas the modulus of the concrete in the compression zone drops to 35 kN/mm^2 , 85% of its original value. The unrestrained concrete in the corner suffers the highest loss in the modulus with a value of only 15 kN/mm^2 , 35% of its original value.

It may be noted that the deterioration of the concrete in the tension zone is less than the deterioration in the corner zone when the expansion is higher than 3 mm/m. This is due to the restraint to the expansion from the reinforcement gradually turning the tension zone into a compression zone during AAR expansion. The concrete in the 'tension' zone, under compressive stress, expands less than the concrete in the corner, and has a smaller drop in the initial modulus of elasticity.

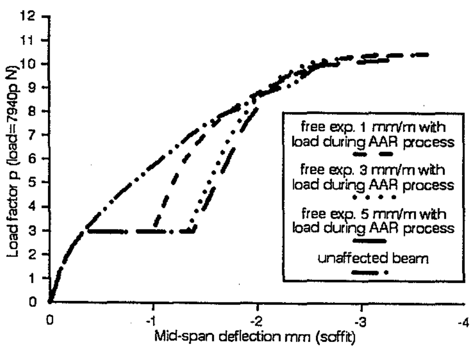

Fig. 10 The load-midspan deflection curve.

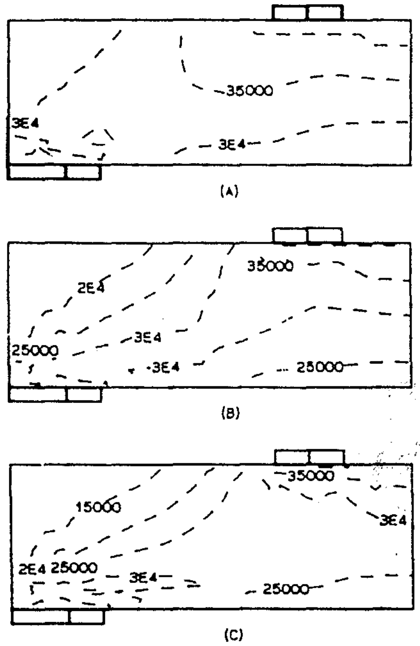

Fig. 9 Contours of the predicted initial modulus of elasticity of the affected concrete when the free expansion are (A) 1 mm/m, (B) 3 mm/m and (C) 5 mm/m.

Fig. 10 shows the load deflection curve. The deflection is measured at the soffit of the beam at the midspan section. The figure shows that the stiffness of the affected beam is higher than that of the unaffected beam when the load applied is in the range between the service load and about 80% of the ultimate load. For the unaffected concrete beam under the given load, concrete in tension zone cracked and the stiffness of the section drops significantly. For AAR beam, on the other hand, with increasing AAR expansion, the cracks in tension zone were closed and compressive stress in the concrete was induced due to the restraint from reinforcement, Fig. 8(A). The compressive stress delayed the initiation of tensile crack when the beam is subjected to further loading. Referring to Fig. 10, it appears that the beam behaves 'elastically' up to about 80% of its ultimate load. This behaviour is in line with the observation in a load test on a highway portal frame in South Africa (Alexander 1992). In that load test, it was found that the frame behaved 'elastically' up to 80% of its design load. It should be mentioned, as illustrated in Fig. 10, that the extent to which the structure behaves 'elastically' depends on the level of expansion.

CONCLUDING REMARKS

The examples presented in this paper demonstrated the capability of the computer program to predict, with reasonable accuracy, the behaviour of AAR affected structures. Through quantitative illustration of the induced stresses, material deterioration and expansion variation, the analytical approach has helped in the understanding of the complicated structural effect of AAR.

The expansion due to AAR is stress-sensitive. This results in highly variable induced stresses, expansion and material deterioration within a structure. The variable feature of AAR affected concrete must be taken into account when conducting a structural assessment. In this aspect, analytical approach is indispensable.

The analytical approach described in the paper can be used in assisting site investigation. For example to determine suitable locations for concrete sampling; or in conjunction with core testing in various locations to infer the level of expansion and estimate the ultimate load capacity.

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