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PHYSICAL BEHAVIOUR OF AAR DAMAGED CONCRETE IN STRUCTURES AND IN TEST CONDITIONS

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1. ABSTRACT

For the structural appraisal and cost effective management of AAR damaged structures, Mott MacDonald have developed a range of insitu structural monitoring techniques and physical tests on concrete cores. This paper reports some of the techniques currently being used in the management of over 100 structures with AAR in the UK.

2. INTRODUCTION

For structural appraisal and the development of long term management strategies [1] the testing and monitoring of AAR affected structures must concentrate on quantifying the physical effects of the deterioration and especially its long term trends. It has been necessary to evolve, in parallel, both laboratory methods of measuring the structural effects (expansion, change in stiffness, strength and the magnitude of forces generated) and insitu determination of the rate of development and extent of damage. Methods of physical testing and structural analysis have been evolved since 1980 from first principles to complement the largely qualitative techniques of petrography and visual inspection. Some of these test methods are new, for others we have developed more rigorous procedures for established tests. This paper gives examples of data obtained from tests on two particular varieties of AAR in the UK; S.W. sea dredged with 2–6mm reactive chert in fine aggregate and Trent Valley with reactive chert and quartzite in the fine and coarse aggregate. One objective for the development of the overall test series is the provision of detailed data for the finite element analysis of the effects of AAR which we now carry out.

3. EVALUATION OF PHYSICAL DAMAGE

In order to make decisions on the management of structures with AAR it is necessary to evaluate both the 'expansion and damage to date' and the 'potential and rate of further expansion and damage'. The recommendations of the Doran Committee [2] provide a framework for this and give some interim guidance on methods, but they are not yet developed to cover detailed analysis and associated testing of serious cases.

While petrography, USPV and summation of crack widths provide indications for the estimation of 'expansion and damage to date', they are subjective, approximate and difficult to relate to physical properties used in appraisal. The development of AAR has been shown [3,4] to reduce the Youngs Modulus (E_c), USPV, and compressive and tensile strength of concrete. The non–destructive Youngs Modulus tests and tensile strength tests are particularly sensitive measures of 'damage to date' and have been developed and refined by Mott MacDonald in parallel with the simpler methods suggested by Doran.

4. STIFFNESS CHARACTERISTICS

The Stiffness Damage Test (SDT) is a non–destructive stress/strain test for both Youngs Modulus and other measures of non–linearity. The test involves the measurement of the uniaxial strain response of concrete under low cyclic load up to 5.5N/mm^2, to minimise damage to the core during testing. Details of the test apparatus and procedure can be found in references [5,6]. The dramatic change in stress–strain curves obtained during Stiffness Damage testing of two concrete cores from the same nominal mix but with different degrees of surface AAR cracking are shown in Figure 1. The characterisation of the stress–strain slope into Youngs Modulus (Ec) and the hysteresis into a Damage Index (DI) offers a very sensitive measure of degree of microcracking damage from expansion.

Figure 2 shows a plot of Ec against DI. The cores are again from the same mix but from pours with different levels of visible cracking. This is also being correlated with petrographic indices of microcracking. Cores from nominally uncracked pours show a high Ec and low DI while cores from cracked elements show a low Ec and high DI. After initial SDT a group of cores are sub–divided for either tensile or compressive strength determinations or expansion testing followed by a second SDT and then strength testing. The 'as cored' and 'expanded' stiffness characteristics (Ec and DI) are recorded and related to strength for use in appraisal.

5. STRENGTH CHARACTERISATION

For normal concrete all strength and stiffness properties can be related to cube or cylinder compressive strength. AAR destroys the normal relationships so more comprehensive testing is required. To determine the uniaxial compressive strength we use long concrete cores, i.e. with an aspect ratio of 2.5 or 3.0 to 1.0. Triaxial compression in short cores masks the effect of AAR. Figure 3 illustrates a selection of long core compression values compared to the DI obtained on the same core, showing a marked fall in compressive strength where DI is greater than 10.

There is evidence [3] that AAR reduces the tensile strength of concrete to a greater extent than the compressive strength. This adversely influences the shear strength of AAR affected elements without shear reinforcement as well as bond and anchorage behaviour, which are largely dependent upon the tensile properties of the concrete. Established tensile test methods are sensitive to specimen preparation and testing procedure and are difficult to relate to structural stress states. We have developed a test which subjects a concrete core to torsional loading which puts a representative volume of the concrete in a state of pure shear [7]. The state of surface stress in the test is similar to that occurring at the neutral axis or within flexurally cracked zones, in beams subjected to shear loading and leads to tensile fracture.

A programme of testing has been initiated to investigate the major parameters which affect shear (tensile) strength of concrete in non–deteriorated control concretes and a wide range of AAR damaged specimens. Figure 4 shows the relationship between the torsional shear strength and the DI on a selection of cores extracted from similar concrete pours with different levels of visual cracking. Figures 3 and 4 show that the DI provides a sensitive measure of the magnitude of current concrete strength. The larger variability in the torsion test results compared to the long cylinder compression is due to the increased sensitivity of shear strength to inherent defects. Increased variability of all properties is a consistent feature of AAR which must be considered in sampling and appraisal. The strength and stiffness test data presented in the figures is based on intact cores which results in an over–strong bias. The interpretation of data must also take into account core fractures during extraction.

6. POTENTIAL FOR FURTHER EXPANSION AND DAMAGE

The expansion of cores removed from structures provides a measure of the severity of reaction and potential for further damage from AAR. Our test procedures have evolved since those reported in 1986 [8]. The 38^{o}C/100% RH test condition although popular for diagnosis distorts the physical and chemical effects of the reaction. It is not appropriate for appraisal of structures. Testing at 5^{o}C, 13^{o}C and 20^{o}C and site ambient temperature regimes is more representative. These lower temperature tests need to be carried out over at least a 2 year period because the rate of expansion is slower although the overall expansion achieved is often greater.

The long term drift of demec readings from gauge wear etc needs to be rechecked and corrected relative to the apparent changes in a demeced steel plate control. The plate is also used as a check on weighing accuracy and to monitor thermal movements in site expansion tests. The high variability of expansions between the 6 or 9 50mm lengths measured on each core indicate that variability of expansion, not average expansion, is the major cause of damage from AAR. Uncertainty of moisture supply conditions has also proved a major difficulty in interpreting results. Weight changes are always monitored and we now establish the 'starting point' of the moisture uptake curve relative to the 'maximum' water content from vacuum saturated weight and oven dry weight, determined using ends cut from the core. The growing body of data from cores expanding in site exposure tests shows higher expansions than in most laboratory tests.

7. RESTRAINED CORE EXPANSION

In reinforced concrete structures the reaction can generate large forces within and between structural members when restraint is provided in the form of reinforcement or externally applied stress. Quantifying these stresses along with changes in strength is essential for appraisal [9]. The forces and stresses generated by the overall expansion can be judged from the restrained expansion test [8]. The further results since 1986 confirm that reinforcement or externally applied compression reduces the magnitude of axial expansion but it can yield reinforcement in some conditions. The expansion behaviour and forces generated are affected by the type of aggregate, Figure 5. Measurement of lateral expansions on matched cores in free and uniaxial restrained tests indicate that longitudinally induced compressive stress influences lateral expansions, but there is no simple poisson ratio. The effect of restraint on damage can be quantified by Stiffness Damage testing applied to samples in the restraint rig at different levels of induced stress.

8. COMPARING LABORATORY AND INSITU BEHAVIOUR

We are comparing the expansion behaviour of laboratory and site exposed cores with insitu concrete in structures we have monitored for up to 10 years. Site monitoring records movements of concrete and cracks as well as temperatures and relative humidity. Reference steel plates are essential controls in measuring long term trends reliably.

Results from strength and stiffness tests combined with the results from free and restrained expansion testing and structure monitoring form the basis for determining the constitutive relationships for AAR damaged concrete. These are now being used in finite element analysis to determine the structural effects for comparison with laboratory and site loading tests [10].

The greatest rates of deterioration are found in wet areas of structures with cores showing high expansions (> 1.0mm/m). Where all cores show little expansion (< 0.5mm/m) little cracking and very slow movement arises.

9. CONCLUSIONS

The evaluation of test methods to quantify the dimensional and strength changes in concrete with AAR now enables the physical effects to be analysed and related to traditional petrographic and chemical criteria.

The Youngs Modulus Ec and hysteresis Damage Index (DI) from the Stiffness Damage Test (SDT) provides a sensitive measure of microcracking damage in cores prior to strength testing both before and after expansion testing.

By relating SDT results to the testing of cores for shear tensile strength in torsion and long cylinder compression strength, (together with fractures during coring), strength characteristics can be determined for structural appraisal.

Expansion test data, covering dimensional and weight changes from the time of coring in a range of environments related to structure exposure including degree of restraint, are replacing unreliable 38°C "100% RH" tests for predicting the potential for future expansive strains and deterioration. The relationships between expansion test data with measured movements and structures are now starting to emerge.

The total physical test programme to date for UK structures being appraised by Mott MacDonald includes over 1000 free expansion tests, 100 restrained expansion tests, 300 SDT, 150 torsion tests, 100 long cylinder compression tests, together with associated USPV, weight change, petrography and chemical analysis.

With this data, current and future structural performance of buildings, dams, bridges etc suffering from AAR can be quantified so owners can be advised of appropriate management strategies.

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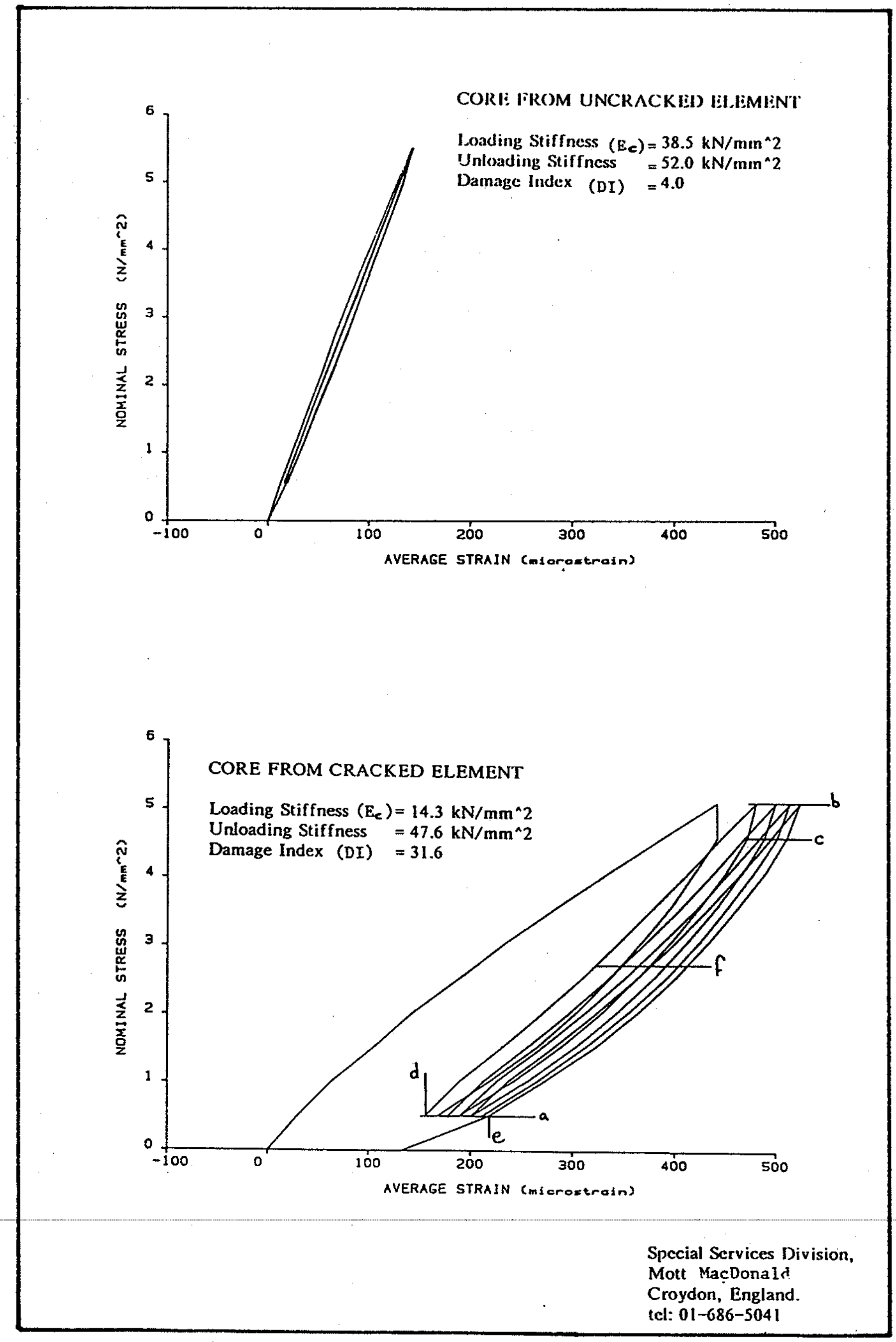
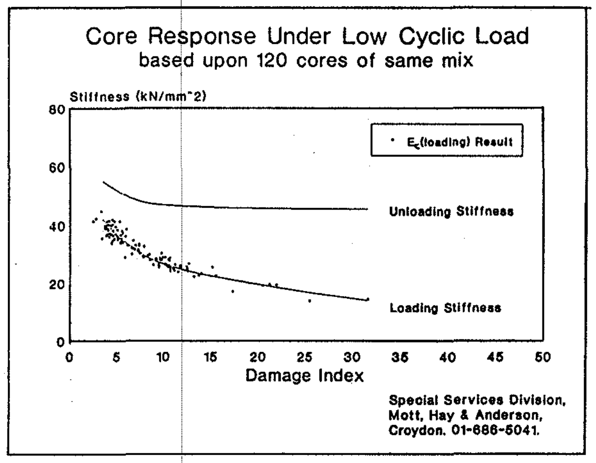
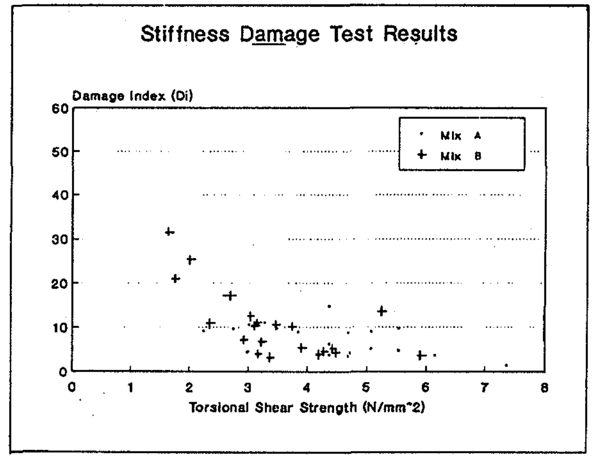


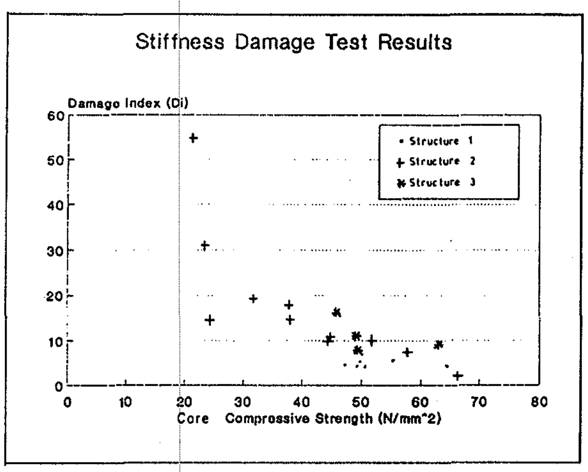
1. Low stress cyclic behaviour of cores



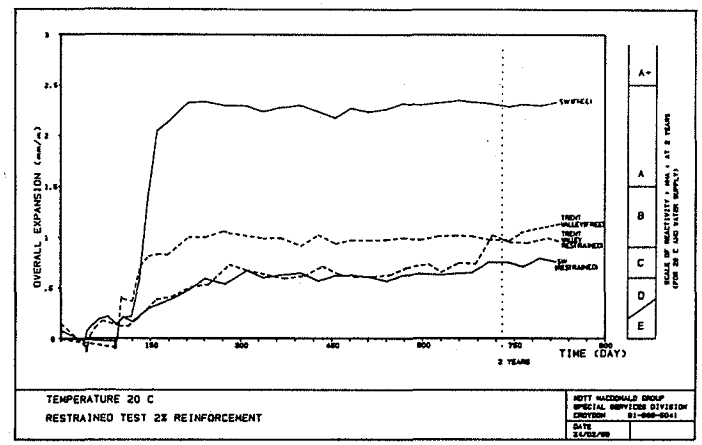
2. **Comparison of Ec and Damage Index**



4. **Comparison of Damage Index and Torsional Shear Strength**



3. **Comparison of Damage Index and Core Compression**



5. **Comparison of Behaviour of different UK Aggregate Types**