LABORATORY TESTING AND ASSESSMENT OF STRUCTURAL MEMBERS AFFECTED BY ALKALI SILICA REACTION

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Laboratory tests on structural members affected by ASR are described. These are tests on reinforced columns with two link details and shear tests on beams with poor end anchorage. ASR was induced by the addition of alkalis in the mix and conditioning at 38°C. Structural tests were carried out at four levels of expansion; zero, onset of expansion, low and high. The use of laboratory test data for the assessment of structures is discussed.

INTRODUCTION

Background

Alkali-silica reaction (ASR) has caused cracking and expansion in concrete structures in a number of areas of the United Kingdom. Little information exists on the structural assessment of ASR affected concrete which is one of the key issues to be considered in the management of these structures. In 1988, the Institution of Structural Engineers (ISE) published an interim report (1) which summarised the then current position regarding the structural effects of ASR and suggested that further experimental work was needed in this area. This confirmed the Department of Transport's own research strategy of which the research reported in this paper form a part. The paper deals with laboratory tests on columns and beams prone to brittle failure.

Assessment of affected structures

In general there are three approaches available to the structural engineer concerned with structural assessment:

i) loading tests
ii) analysis using revised material properties obtained from cores
iii) laboratory data from structural elements subjected to accelerated expansion due to ASR.

The assessment of the safety and serviceability of an ASR affected structure should be based on structural analysis. This will be aided by laboratory data and may be supported by a properly conducted loading test. If the structure behaves predictably under load and in accordance with the design requirements, and if the strains and deformations are of reasonable magnitude and largely recoverable then structural adequacy has not, at the time of the test, been affected. However, loading tests may be considered inappropriate for structures with sensitive structural details or liable to brittle failure. Load tests do not provide information on reserve of strength and for a non-ductile failure mode, this reserve could be small. Moreover, loading tests may not provide information on future loss of strength due to ASR.

Judgements on whether ASR expansion and cracking has reduced the safety margin of a structure or element are sometimes based upon analysis using material properties measured on extracted cores. Such an approach appears logical particularly for members subject to compression and for well detailed structures in general. However, Hobbs (2) suggests that this approach can lead to an unduly pessimistic view of the effect of ASR upon structural performance. This may be due to the removal of restraint which results in expansion of the core after removal from the structure. This expansion may cause a reduction in strength and stiffness in the core not typical of the structure. Clark (3) has published recommendations for assessment of ASR affected structures by relating the structural strength to basic first principles and proposing revisions to the design formulae given in BS5400 (4). A similar approach for assessing the anchorage bond strength has been suggested by Chana (5) and Chana and Korobokis (6). However, it is clear that none of the methods discussed can adequately and safely deal with structures containing sensitive details particularly those which are liable to fail in a brittle manner. In these areas, laboratory testing has a significant role to play.

PROGRAMME

This work was carried out in two phases. The preliminary work was primarily concerned with establishing basic information on ASR testing in the laboratory, and is described in detail by Chana and Korobokis (7).

The main programme was developed by considering practical details on bridge structures built in the UK since 1950 and identifying areas where test data were needed. These were:

i) lightly reinforced members
ii) compression members, e.g. columns
iii) poor end details (related to bond strength)
iv) bent-up bars
v) beams with lapped tension reinforcement
vi) shear strength of members without links
vii) strength under cyclic loads
viii) support regions of elements, i.e. beam ends and half joints with poor detailing.

This paper deals only with tests on columns and shear tests on beams with poor end anchorage. The remainder of the test programme is described in detail elsewhere (8).

EXPERIMENTAL METHODS

Concrete mix. Only one concrete mix was used in this investigation. It was proposed by Building Research Establishment as a structural concrete suitable for their programme on the appraisal of ASR affected structures. It has a 28 day cube strength of 55 N/mm^2. The details were as follows:

(a) Basic requirements of concrete mix:
30% Flint sand (Chertsey)
70% Inert coarse aggregate (limestone from Batts Coombe Quarry, Cheddar.
400 kg/m^3 OPC
W/C ratio = 0.5
Addition of alkalis to bring total content to 7 kg/m^3 Na_2O equivalent.

(b) Mix proportions per m^3 of concrete

Water	200 kg
OPC	400 kg
Sand (Chertsey)	555 kg
10mm (limestone)	425 kg
20mm (limestone)	855 kg
Total	2435 kg

Alkali addition:
Analysis of cement shows 0.64% Na_2O equivalent
= 2.56 kg/m^3
Balance of 7 kg/m^3 Na_2O equivalent
= 4.44 kg/m^3
11.77 kg sulphates to be added in solution, split as 2.12 kg/m^3 Na_2SO_4; 9.65 kg/m^3 K_2SO_4.

Control specimens. The following control specimens were cast to monitor the free expansion and to measure the material properties for each series:

three 100mm cubes for measuring cube strength,

three 100mm dia.x200mm cylinders for measuring tensile strength,

one 150 dia.x300mm cylinder for elastic modulus determination,

three 100mm dia.x200mm cylinders to monitor uniaxial compressive strength,

one 75 x 75 x 250mm prism for measuring free expansion and one large prism of the same cross-section as the test specimens and 900mm long for measuring 'true' free expansion.

Conditioning All the specimens were demoulded after 24 hours and cured under polythene sheets for a further 2 days. They were then moved into special insulated conditioning tanks and stored under water at 20°C for at least 28 days after which the water temperature was increased to 38°C for all the reactive specimens. The non-reactive specimens remained under water at 20°C in separate tanks.

Monitoring of expansion. The expansion of specimens was monitored periodically by measuring surface strains using Demec gauges. This was normally done both along the tension reinforcement and in the 'compression' zone, using a 200mm gauge length. The expansion of the control prisms was also measured at the same time using a 200mm gauge length.

Loading conditions as expansion develops. Chana and Korobokis (7) clearly demonstrated the effect of loading on the expansion during conditioning. Crack patterns, strain profiles and, in some cases, the ultimate strength of specimens were affected. Specimens were conditioned under load back to back in pairs. The applied load was calculated to simulate a typical dead load stress. This load was checked and adjusted at intervals. For the structural tests, the load was applied at the same location as during conditioning.

Levels of expansion. The performance of these members was determined at different expansion levels including onset of expansion because recent test data suggests that the most adverse effect of ASR may occur when expansion and cracking are initially induced and that thereafter the expansion may have a less adverse influence (9). Four levels of expansion were considered in this investigation; zero, onset, low and high. Onset of expansion is defined as the time before any surface cracking occurs when the unrestrained expansion measured from large control prisms is approximately 300-500 microstrains. Low expansion is defined as the time when the first cracks appear (i.e. onset of cracking), and the unrestrained mean expansion as measured from large control prisms is approximately 1000 microstrains; this occurred after 70 days of conditioning. The high level of expansion is when expansion ceases and the unrestrained mean expansion obtained from large control specimens is approximately 5000 microstrains.

Modified material properties

The structural strength of members generally depends on the uniaxial compressive strength, f_{cu}, and the tensile strength, f_t of the concrete. In Design Codes, strength is often expressed indirectly in terms of the concrete cube strength (f_{cu}) to the power of 1, ½ or ⅓. This is convenient because cube compressive strength is generally the sole strength parameter that is specified in design. Clark (3) has suggested that modified code equations, expressed in terms of f_c and f_t should be used for assessment since the effect of ASR on these material properties is different. The values of uniaxial compressive strength or tensile strength can be determined from cores (1) or by estimating the current expansion of the structure. In this programme, structural strength of reactive members has been calculated using f_{cu}, f_c or f_t obtained from cubes and cylinders cast and cured alongside the members.

TESTS ON SQUARE COLUMNS

Specimen details. All the columns were 150mm x 150mm section and 900mm long. Two levels of link reinforcement were provided representing links designed to BS5400 (4) and the other representing a lower level of links. Four replicates of each type were cast. The main steel represented 1.4% of the gross section.

All the specimens were conditioned under uniaxial load representing a stress of 5 N/mm^2 for the columns with a low level of links and 3 N/mm^2 for the columns with links designed to BS5400 (4).

Test arrangement. All the columns were loaded under an axial load in a compression testing machine.

Results

Expansion and cracking. These specimens were tested at four levels of expansion: zero, onset of expansion, low and high. Surface expansions were measured along and transverse to the axis of loading. The measured expansions are summarised in Table 1. Generally, cracks formed parallel to the direction of loading and parallel to the main reinforcement. However no delamination of cover was observed during conditioning. The transverse expansion was greater for columns with a low level of links while the longitudinal expansion was slightly reduced. The free expansion of the large control prisms was significantly higher than the small prisms. One possible explanation for this phenomenon could be leaching of alkalis from the small prisms leading to a lowering of reactive alkali content.

Structural tests. Table 2 summarises the failure loads and the material properties. As expected, the columns with the higher level of links are generally stronger compared to the specimens with low links. The reduction in load carrying capacity due to ASR is similar to the changes in cube compressive strength for free expansion levels up to 5mm/m.

All the specimens failed in a brittle manner; the mode of failure was unchanged due to ASR. The residual load (after failure) was greater for specimens with the higher level of links. It should be noted that no sign of delamination of concrete cover was observed. Where there is significant evidence of cover delamination, the cover concrete should be ignored in the strength assessment. It should also be noted that the slenderness ratio will then be altered and stability needs to be considered.

TABLE 1 : EXPANSION OF COLUMNS

	EXPANSION (Microstrains)					
	ONSET		LOW		HIGH	
	L	T	L	T	L	T
TEST SPECIMENS NORMAL LINKS	232	292	431	794	816	5713
TEST SPECIMENS LOW LINKS	178	337	348	1630	692	5886
LARGE PRISMS (1) 150x150x900mm	444		1010		5707	
SMALL PRISMS (2) 75x75x250mm	311		524		2308	

Notes:
(1) Single specimen
(2) Average of 3 specimens
(L) is Longitudinal expansion
(T) is Transverse expansion

TABLE 2 : COLUMNS - TEST RESULTS

EXPANSION	FAILURE LOADS (kN)		MATERIAL PROPERTIES			
	LOW LINKS	NORMAL LINKS	f_{cu} (N/mm^2)	f_{cyl} (N/mm^2)	f_t (N/mm^2)	E (kN/mm^2)
NON-REACTIVE	1150	1262	66	60	4.3	43.2
ONSET OF EXPANSION	1112	1129	60.3	44.9	4.1	32.6
% CHANGE	-3.3	-10.5	-8.6	-25.2	-4.7	-24.5
LOW	1002	1062	59.2	41.6	3.7	14.1
% CHANGE	-12.9	-15.8	-10.3	-30.7	-14.0	-67.4
HIGH	927	1043	55.2	32.5	3.5	9.8
% CHANGE	-19.4	-17.4	-16.4	-45.8	-18.6	-77.3

SHEAR TESTS ON BEAMS WITH POOR END ANCHORAGE

Specimen details. Shear tests were carried out on beams which were 200mm by 100mm in section. Both ends of the beam represented a poor end anchorage (five times bar diameter past centre line of support). Two types of reinforcement were involved: plain and ribbed bars; no links were included. Eight beams each were cast with plain and ribbed bars.

All beams were conditioned under load by strapping pairs of beams back to back. The conditioning load was 12.3 kN for beams with plain bars and 20.3 kN for the beams with ribbed bars.

Test arrangement. The beams were tested in an inverted position supported by a jack. The upward force from the jack was balanced by the two-end reactions, which were monitored by separate load cells. Both ends of the beams were tested giving two test results.

Results

Expansion and cracking. Four levels of expansion were considered in this series: zero, onset of expansion, low and high. Table 3 summarises the surface expansion results at the four expansion levels and also the unreinforced control specimens.

The crack pattern was similar for beams with plain and with ribbed bars and the ASR cracks ran predominantly parallel to the reinforcement.

Structural tests. The failure loads and the corresponding material properties are given in Table 4. In general, the mode of failure was not changed by ASR. For all the reactive specimens an ASR crack along the potential shear failure plane had formed during conditioning prior to testing. Figures 1 and 2 illustrate the effect of ASR expansion on shear resistance of beams with plain and ribbed bars respectively.

This test series was carried out primarily to investigate the effect of ASR on beams with poor anchorage (five times the bar diameter) and to obtain test data at low and intermediate levels of expansion. The maximum reduction in strength due to ASR is around 30% for plain bars and 23% for ribbed bars and is similar to the change in split tensile strength. The shear strength of beams at low and intermediate levels of expansion is not lower than at a high expansion level.

Shear failures are brittle in nature and any detrimental effect of ASR on the shear strength of a member is an area of major concern in structural assessment. In general these results are encouraging and the reduction in shear strength is modest given that the beams had poor anchorages. This may be due to the additional anchorage provided by the reaction at the support.

TABLE 3 : EXPANSION OF SHEAR BEAMS

	TIME (Days)	MEAN EXPANSION (Microstrain)			
		PLAIN BARS		RIBBED BARS	
		T(1)	C(2)	T(1)	C(2)
NON-REACTIVE	168	AVERAGE OF 300 $\mu\epsilon$			
ONSET (5)	23	-	-	53	35
LOW (5)	97	-	-	720	663
HIGH	168	1472	810	1368	832
SMALL PRISMS (3)		UNRESTRAINED EXPANSION (168 days) = 2800 $\mu\epsilon$			
LARGE PRISMS (4)		UNRESTRAINED EXPANSION (168 days) = 3560 $\mu\epsilon$			

Notes:
1. Average expansion for the tension zone
2. Average expansion for the compression zone
3. Average of 3 prisms, 75 x 75 x 250mm
4. Single specimen, 100 x 200 x 900mm
5. Beams with plain bars were tested at a high expansion level only.

TABLE 4 : SHEAR BEAMS : TEST RESULTS

TYPE OF SHEAR BEAMS	TYPE OF BARS	MEAN FAILURE LOAD (kN)	MATERIAL PROPERTIES			
			f_{cu} (N/mm^2)	f_{cyl} (N/mm^2)	f_t (N/mm^2)	E (kN/mm^2)
NON-REACTIVE (168 days)	P	47.1	71.6	66.2	4.79	39.9
	R	69.9				
ONSET (23 days)	P	39.2	70.8	59.6	4.80	32.7
	R	63.5				
% CHANGE	P	- 16.8%	-1.2%	-9.9%	+0.2%	-18.0%
	R	- 9.2%				
LOW (97 days)	P	33.2	66.6	45.4	3.770	29.6
	R	57.3				
% CHANGE	P	- 29.5%	-7.0%	-31.4%	-22.7%	-25.8%
	R	- 18.0%				
HIGH (168 days)	P	40.1	59.4	42.1	3.52	14.6
	R	54.1				
% CHANGE	P	- 14.9%	-17.0%	-36.4%	-26.5%	-63.4%
	R	- 22.6%				

Note: P = Plain;   R = Ribbed

CONCLUSIONS

1. Laboratory test results are particularly helpful in assessment of structures with sensitive details liable to brittle failures. Any reduction in load carrying capacity due to ASR is related to material properties obtained from cubes and cylinders cast and cured alongside the structural member.

2. The reduction in strength of columns for free expansion levels up to 5mm/m is similar to the change in the compressive strength obtained from parallel cast cubes. In the present test series, the effect of delamination of concrete cover due to ASR was not observed.

3. Shear tests were carried out on beams with poor anchorage. The maximum reduction in strength due to ASR is around 30% for plain bars and 23% for ribbed bars and

is similar to the change in split tensile strength. It seems that the reduction in shear strength is relatively modest even for beams with poor anchorage. This could be due to the additional anchorage provided by the reaction at the support.

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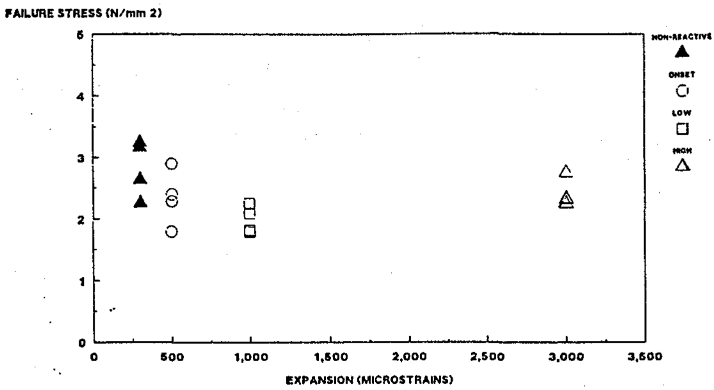

FIG 1 : COMPARISON OF RESULTS FOR SHEAR BEAMS WITH PLAIN BARS

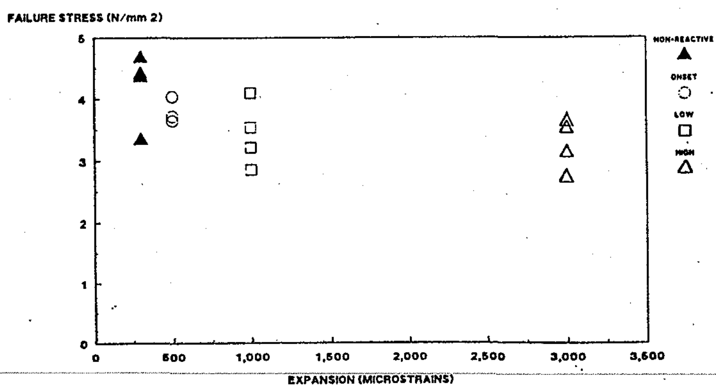

FIG 2 : COMPARISON OF RESULTS FOR SHEAR BEAMS WITH RIBBED BARS