THE INFLUENCE OF STRESS INTENSITY AND TIME OF APPLICATION ON THE MECHANICAL PROPERTIES OF ASR AFFECTED CONCRETE

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ABSTRACT

The paper describes an experimental investigation to examine the effects of different stress levels on the mechanical properties of alkali silica reactive deteriorated concrete cores. Two concrete blocks made with ASR concrete were left for one year during the period of reaction. The blocks were then cored perpendicular to the direction of casting and these cores were tested to determine stiffness damage parameters, ultrasonic pulse velocity, crushing strength and weight gain. The cores were then subjected to different stress levels and left in this stressed state for another whole year and were then tested again. The results indicate that the application of permanent stress to ASR cores when the ASR has effectively ceased, leads to a decrease in the damaged state of the cores. Higher levels of stress result in greater reductions in the damaged state.

Keywords: alkali silica reaction; concrete; stiffness damage test; stressed/unstressed cores; elastic modulus; core compressive strength; ultrasonic pulse velocity; water absorption; expansion; stress; strain; strength.

INTRODUCTION

Because cores can expand when they are extracted from a large block of ASR concrete, the properties of the cores quoted should not be taken to be directly representative of the concrete in the members from which the cores were taken. McLeish[9] pointed out that in most cases part of the core will be from the cover, which may be more badly deteriorated than the region of the member restrained by the reinforcement cage. This point is also illustrated by Imai et al.[6] who carried out an investigation on concrete piers supporting the Hanshin Expressway in Japan. The compressive strength and the Young's Modulus of cores obtained from deteriorated piers were about 65% and 20%, respectively, of those taken from sound piers. Results from these were compared with field loading tests on the piers from which cores had been extracted showed that the tested piers had adequate load carrying capacity. This conclusion was also demonstrated by Fujii et al.[4]. This would tend to support the view by Ono[10] that the difference between Young's Modulus of the concrete structure as a whole and that of cores drilled from the structure might be due to the different restraints that apply to each.

Hobbs[5] made the point that the cores may expand during and after coring and due to the possible damage arising from the coring process. He supported his viewpoint by an experimental test on two specimens which were restrained with an initial compressive stress of 2.5 N/mm^2 at 5 days after casting. He found that as the specimens expanded, the stresses increased to 3.5 N/mm^2 in one specimen and 4 N/mm^2 in the other. Once these stresses were attained, no further expansion occurred. On the removal of restraint the expansion continued.

However, Blight et al.[2] carried out a loading test and finite element analysis of a road bridge. They found that the modulus of elasticity measured in core tests, when used in the finite element analysis, gave deformational characteristics that correlated well with the behaviour of the bridge. An experimental study by Tomita et al.[13] on cores taken from restrained and unrestrained structural model specimens (300 x 300 x 500 mm) suggested that the future damage of existing concrete structures affected by ASR could be estimated from drilled cores. The recent study by Alexander et al.[1] indicate that the behaviour of ASR affected structures can be predicted on the basis of properties measured on sample cores.

The aim of the research reported here was to examine the effects of different stress levels on the mechanical behaviour of deteriorated concrete cores extracted from large blocks affected by ASR. The following parameters were measured in the cores over the two years of the research programme:

(1) The stiffness damage properties of Elastic Modulus (E_c), Damage Index (DI) and Plastic Strain (PS).
(2) The Water Absorption (WA).
(3) The Ultrasonic Pulse Velocity (UPV).
(4) The core compressive strength (f_c).

EXPERIMENTAL WORK

Concrete mix and materials

The basic concrete mix (ASR-I mix) was a 1: 1.57: 1.41 (cement: sand: coarse aggregate) by weight, with a cement content of 550 Kg/m^3 and a water/cement (W/C) ratio of 0.36. The cement was an ordinary Portland cement having an average alkali content of 0.60%. In order to accelerate the ASR reaction, the alkali content was raised to 12 Kg/m^3 by adding KOH to the mix. A second mix (ASR-II mix) was formed by replacing 11.9% by weight of the total aggregate in ASR-I mix, with fused silica. The detailed mix designs for the two mixes used are given in Table 1. Full details of the aggregate is given in Reference 11.

	ASR-I mix	ASR-II mix
Ordinary Portland Cement (OPC)	550 kg/m^3	550 kg/m^3
Coarse Aggregate (4.75 - 20 mm)	780 kg/m^3	780 kg/m^3
Fine Aggregate (< 5 mm)	865 kg/m^3	670 kg/m^3
Fused Silica (1.0 - 3.0 mm)	-	195 kg/m^3
Water/Cement Ratio	0.36	0.36
Alkali Equivalent	12 kg/m^3	12 kg/m^3

Table 1 - Concrete mix designs.

Sample size and curing conditions

The specimens used in this investigation were cored from concrete blocks that were 500 mm long by 500 mm high by 200 mm wide. Two concrete blocks were cast, one using the ASR-I mix and the other the ASR-II mix along with 100 mm cubes. After casting, the specimens were covered with hessian and polythene sheeting and left undisturbed in the casting room for 48 hours, after which the moulds were stripped. Subsequent to this the blocks were kept in water at 20 ± 1 °C for 2 days following which they were then removed to a water tank which was kept at a temperature of 38 ± 1 °C.

Direction of drilling

After one year, 16 cores of 74 mm diameter were taken from each block, the drilling was carried out perpendicular to the direction of casting. The trimmed cores were capped on both ends using the sulphur-carbon method as detailed in BS: 1881 part 120, 1983 section 5.3(3). All cores were produced with a L/D ratio of 2.5. Demec studs were then fixed along the length of core in three equally spaced rows at 120 degree intervals around the cores.

Application of preload

Four cores from each concrete mix were crushed to determine their strength. The remaining cores were then subjected to a variety of tests including the Stiffness Damage Tests (SDT), Ultrasonic Pulse Velocity (UPV) and weight determination (WA). Following this, the cores were subjected to a permanent compressive stress of either zero N/mm^2, 3.5 N/mm^2 or 7 N/mm^2. The cores were then placed in a curing tank at 38 ± 1 °C. The stress was applied through (170 x 170 x 8 mm) mild steel plates placed at both ends of the concrete core, as shown in Fig. 1. Each plate had one hole symmetrically drilled along each side to allow two 20 mm diameter mild steel rods, threaded at both ends, to be passed through and stressed against the plates. The rods were tensioned using a torque wrench and periodically retorque during the following 12 months to maintain the stress level. After one further year in the curing tank the cores were removed from the tank and the stress released. They were then tested again to determine the new stiffness damage properties, the Ultrasonic Pulse Velocity, weight change and core compressive strength.

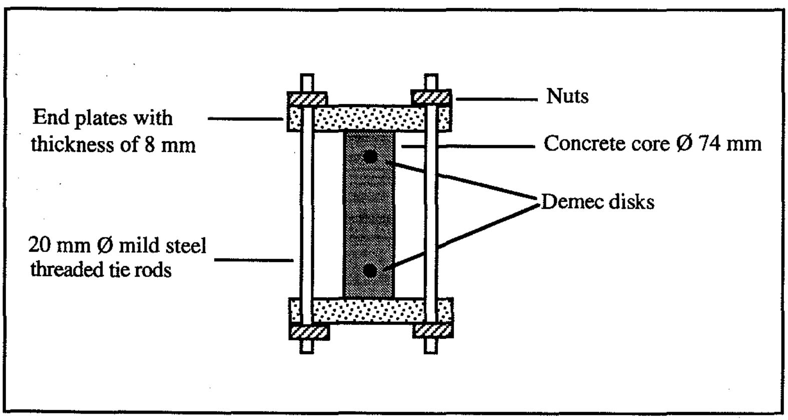

Fig. 1 - Stressed core.

TEST RESULTS AND ANALYSIS

The results presented were obtained in tests carried out on sixteen cores from each concrete mix. Four cores were subjected to the stress of 3.5 N/mm^2 and four to the stress of 7 N/mm^2 and another four cores were left unstressed as control specimens. The remaining four cores were crushed to determine the strength of the concrete at this time.

The results indicate the influence of permanent stress levels upon the mechanical properties of both types of reactive concrete used in the test programme and highlight the beneficial role that stresses due to imposed loads can play in ASR affected concrete structures.

The expansion data for the unstressed cores, shown in Table 5, indicates that the ASR had effectively ceased after the first year, so the changes in the mechanical properties resulting from the stressing are not significantly affected by continuing ASR within the concrete.

Elastic Modulus

The results given in Tables 2, 3 and 4 show that stresses applied after the ASR has virtually ceased cause significant changes to all the mechanical properties of ASR concrete. In the case of E_c, f_c and UPV these changes are very approximately linearly related to stress, regardless of the mix type. This could be explained by considering that the applied stress has closed up cracks that cross the direction of stress and that these cracks do not immediately re-open on removal of the stress.

In Table 4 the percentage increase in E_c in the two year old concrete cores that were stressed for twelve months is given relative to E_c for the two year old unstressed cores. It is seen that increasing stresses leads to increasing values of E_c. That is: $E_c\ (7\ N/mm^2) > E_c\ (3.5\ N/mm^2) > E_c\ (0\ N/mm^2)$

It is further seen from Tables 2 and 3 that the unstressed reactive specimens also show an increase in E_c for ASR-I and ASR-II concrete mixes during the second year of the test programme of 18% and 45% respectively. This increase in E_c in the unstressed cores is somewhat greater than would be expected for normal concrete and indicates that in certain circumstances ASR concrete exhibits appreciable autogeneous healing once the expansion is essentially complete. It is suggested that calcification of the gel results in a autogeneous healing process which causes E_c to increase(12). It is also seen that E_c for the stressed ASR-I mix is greater than for the stressed ASR-II mix.

		Age: One year	
		ASR-I mix Cores	ASR-II mix Cores
E_c	(kN/mm^2)	25.50 ± 2.15	19.83 ± 1.68
DI	(Dimensionless)	7.57 ± 2.73	11.56 ± 2.88
PS	($x10^{-6}$)	3.50 ± 1.30	4.73 ± 2.86
UPV	(km/sec)	4.31 ± 0.03	4.03 ± 0.07
f_c	(N/mm^2)	33.48 ± 3.04	26.27 ± 1.98

Table 2 - Mechanical properties of ASR concrete cores.

		Age: Two Years					
		ASR-I mix Cores			ASR-II mix Cores		
		Stressed to ($7N/mm^2$)	Stressed to ($3.5\ N/mm^2$)	Unstressed	Stressed to ($7N/mm^2$)	Stressed to ($3.5\ N/mm^2$)	Unstressed
E_c	(kN/mm^2)	35.02 ± 0.85	32.42 ± 1.90	30.18 ± 2.64	32.67 ± 2.10	30.10 ± 0.81	28.80 ± 3.11
DI	-	1.24 ± 0.58	1.48 ± 0.80	2.37 ± 1.64	2.03 ± 0.96	2.38 ± 1.62	3.51 ± 1.61
PS	($x10^{-6}$)	0.11 ± 0.90	0.56 ± 1.65	1.94 ± 1.56	1.02 ± 1.08	1.20 ± 1.52	4.50 ± 2.60
UPV	(km/sec)	4.47 ± 0.03	4.50 ± 0.01	4.52 ± 0.03	4.31 ± 0.02	4.34 ± 0.03	4.38 ± 0.03
f_c	(N/mm^2)	50.83 ± 2.18	48.84 ± 3.25	47.03 ± 2.00	44.40 ± 2.43	42.77 ± 2.02	41.28 ± 1.82

Table 3 - Effect of stress intensity on the mechanical properties of ASR concrete cores.

	ASR-I mix Cores		ASR-II mix Cores	
	Stressed to ($7\ N/mm^2$)	Stressed to ($3.5\ N/mm^2$)	Stressed to ($7\ N/mm^2$)	Stressed to ($3.5\ N/mm^2$)
% Ec	+ 16.03	+ 7.42	+ 13.43	+ 4.51
% DI	- 47.68	- 40.92	- 42.16	- 32.20
% PS	- 94.33	- 71.13	- 77.33	- 73.33
% UPV	- 1.10	- 0.44	- 1.60	- 0.91
% f_c	+ 8.08	+ 3.84	+ 7.55	+ 3.61

N.B. Minus (-) indicates % loss Plus (+) indicates % gain

Table 4 - Percentage difference in the mechanical properties after 2-years compared to their control cores.

Damage Index

It is known that the greater the DI the more damage present within the core[11, 12]. It is apparent that damage is likely to be less for a concrete with a high modulus than for a concrete with a low modulus. This assumption is confirmed by the results given in Tables 2, 3 and 4 where increasing modulus is in every case accompanied by decreases in the DI.

Plastic Strain

It is seen that: PS ($7\ N/mm^2$) < PS ($3.5\ N/mm^2$) < PS ($0\ N/mm^2$)

The maximum reduction in PS between the unstressed and the $7\ N/mm^2$ stressed case is 94% for ASR-I mix. This indicates that the stresses are causing a substantial reduction in the damage within the concrete. The PS is seen in Tables 2 and 3 to be greater with the ASR-II mix than with the ASR-I mix.

It is also noted that with both concrete mixes the unstressed cores also show a reduction in the PS during the second year of the programme; the maximum reduction being 44% in the case of ASR-I mix. This is again considered to be due to autogeneous healing of the microcracks[12].

Restrained Expansions

After one year, the measured expansions on blocks of ASR-I and ASR-II mixes were 1.32% and 2.25% respectively.

Table 5 shows that the immediate contraction for both ASR concrete mixes measured after applying the permanent stress, for the $7\ N/mm^2$ case was approximately twice that for the $3.5\ N/mm^2$ case indicating that the cores were behaving almost linearly elastic.

Subsequent further expansion was negligible or zero for the stressed cores during the second year. The unstressed cores continued expanding during this second year but only by 7% and 5% of the first year expansion for ASR-I and ASR-II respectively, indicating that the reaction was effectively exhausted.

Comparison of the immediate contraction figures with values calculated from the measured results for E_c given in Table 2 show that the former is approximately 2 to 3 times greater than the latter for both stress levels applied. This significant difference may be partly attributed to the limited accuracy of measurement of the former using a Demec Gauge. Another factor might be that a higher value of E_c is obtained from the Stiffness Damage Tests due to the results being obtained with a starting stress level of approximately $0.50\ N/mm^2$ which closes up some or all of the cracks and hence makes the core stiffer[12].

The results for immediate expansion on removal of the stress at the end of the second year are however in much better agreement with the values calculated from E_c obtained from the SDT carried out at that time. This tends to indicate that cracks did not substantially re-open upon removal of the stress.

		Immediately after preloading	After 12 months of preloading	Immediately after release of preload	Not preload
		ASR-I mix Cores			
Stressed to 7.0 N/mm^2	M1	- 0.051	0	+ 0.017	-
	M2	- 0.064	0	+ 0.025	-
	M3	- 0.072	0	+ 0.020	-
	M4	- 0.058	0	+ 0.022	-
	Average	- 0.061	0	+ 0.021	-
Stressed to 3.5 N/mm^2	M5	- 0.040	0	+ 0.013	-
	M6	- 0.032	+ 0.001	+ 0.017	-
	M7	- 0.038	+ 0.001	+ 0.018	-
	M8	- 0.030	0	+ 0.015	-
	Average	- 0.035	0	+ 0.016	-
Unstressed	M9	-	-	-	+ 0.110
	M10	-	-	-	+ 0.094
	M11	-	-	-	+ 0.082
	M12	-	-	-	+ 0.098
	Average	-	-	-	+ 0.096
		ASR-II mix Cores			
Stressed to 7.0 N/mm^2	N1	- 0.122	0	+ 0.027	-
	N2	- 0.096	0	+ 0.035	-
	N3	- 0.116	0	+ 0.040	-
	N4	- 0.115	0	+ 0.030	-
	Average	- 0.112	0	+ 0.033	-
Stressed to 3.5 N/mm^2	N5	- 0.051	+ 0.002	+ 0.028	-
	N6	- 0.080	+ 0.006	+ 0.022	-
	N7	- 0.056	+ 0.005	+ 0.020	-
	N8	- 0.070	+ 0.008	+ 0.024	-
	Average	- 0.064	+ 0.005	+ 0.023	-
Unstressed	N9	-	-	-	+ 0.110
	N10	-	-	-	+ 0.101
	N11	-	-	-	+ 0.143
	N12	-	-	-	+ 0.112
	Average	-	-	-	+ 0.116

N.B. Minus (-) indicates % contraction Plus (+) indicates % expansion

Table 5 - Expansions of stressed and unstressed cores.

Water Absorption

Table 6 shows the variation of Water Absorption (WA) with time for both concrete mixes. It is clear that the gel resulting from ASR-II mix absorbed twice the amount of water as the gel resulting from ASR-I mix. Though the variation in WA between the stressed and unstressed specimens is small, the results do suggest that increasing levels of stress might be associated with reduced water intake.

		ASR-I mix Cores			ASR-II mix Cores		
		Stressed to 7 N/mm^2	Stressed to 3.5 N/mm^2	Unstressed	Stressed to 7 N/mm^2	Stressed to 3.5 N/mm^2	Unstressed
WA (gram)	1st Year	1895.80	1884.80	1896.30	1795.10	1800.00	1796.10
	2nd year	1903.60	1893.82	1905.70	1810.44	1815.60	1813.30
Weight (%)		+ 0.41	+ 0.47	+ 0.50	+ 0.85	+ 0.87	+ 0.95

N.B. Plus (+) indicates % gain

Table 6 - Weight change determination.

This observation is in agreement with an experimental study carried out by McGowan and Vivian[8] on ASR mortar bars who found that increasing the magnitude of the applied force diminishes both the amount of water absorbed and the proportion of the volume change that causes widening of the crack plane which developed at right angles to the direction of the applied force.

Ultrasonic Pulse Velocity

In Tables 2 and 3, it is seen that the stressed specimens for both ASR-I and ASR-II mixes show an increase in UPV over the first year of approximately 5% and 8% respectively.

Comparing the stressed and unstressed specimens in Table 4, it is seen that the application of permanent stress during the second year results in only a small reduction in UPV.

Core Compressive Strength

One year after coring, four cores from each mix were crushed. The effect of permanent stress levels on the core compressive strength (f_c) of ASR concrete compared to that of unstressed cores is shown in Table 3. It is seen that:

$$f_c\,(7\ \mathrm{N/mm^2}) > f_c\,(3.5\ \mathrm{N/mm^2}) > f_c\,(0\ \mathrm{N/mm^2})$$

with f_c (7 N/mm^2) being nearly 8% greater than f_c (0 N/mm^2) for both ASR mixes. It is also seen that there are very significant increases in the values of f_c over the second year for the unstressed cores with increases in strength of 40% for ASR-I mix and 57% for ASR-II mix (see Tables 2 and 3). There are probably two main reasons for this gain in strength; calcification of the gel is considered to be the major factor with continuing hydration of the cement being expected to contribute an increase in strength of approximately 20% for both mixes.

An investigation by Koyanagi et al.[7] on ASR cylindrical specimens found that their crushing strength exhibited a significant increase from an age of 160 days. This increase was in their view due to ASR ceasing and further curing coming into effect.

Discussion and Conclusions

The results indicate that the application of permanent stress to ASR cores when the ASR has effectively ceased, leads to a decrease in the damaged state of the cores. Higher levels of stress result in greater reductions in the damage state. It is suggested that:

Damage (7 N/mm^2) < Damage (3.5 N/mm^2) < Damage (0 N/mm^2)

This can be explained as being due to the closure of the cracks within the core and autogeneous healing of the crack then taking place which has a beneficial effect in reducing the apparent damage within the core.

When a core is drilled from a structure, all the restraining stresses, due both to loading and the reinforcement, are released. This allows the core to expand and microcracks to develop during the period between drilling and testing the core. This research has demonstrated that applying a stress to the core for a period of time after coring but prior to testing has the effect of closing the microcracks that have developed both before and after drilling and hence result in less damage being identified by the Stiffness Damage Tests and other properties. This condition may more closely reflect the original damaged state of the concrete in the structure and so test results on such stressed cores may give a better indication of the true state of the concrete. A quantitative relationship between the damaged state of the concrete in-situ, prior to coring, and the condition of the stressed core at the time of testing, has obviously though not been established by this work.

While the test programme reported here was in progress McLeish[9] suggested that "if a core was subjected to a constant stress of 4 N/mm^2 for a period of time and was then increased to say 10 N/mm^2, then a higher modulus would be expected". He further stated that "this condition may be very similar to the stress state in a real structure".

The unstressed cores, exhibited the greatest damage but this damage decreased during the second year of the test programme but was still higher than was found in the stressed cores. The decrease in damage could be explained in part as being due to the calcification of the ASR gel.

Expansion along the vertical axes of the cores ceased for both concrete mixes on application of the stress. The unstressed cores did however continue to show a small expansion, but this was so slight that the reaction seemed to have been effectively exhausted.

Concrete cores from ASR-I mix exhibited less damage than those of ASR-II mix. Applying the stress tends to increase the stiffness of both mixes. However, the recovery of the stiffness for ASR-I mix was greater than that for ASR-II mix, bearing in mind that ASR-I mix was initially less damaged.

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