RESTRAINT EFFECTS ON THE PERFORMANCE OF VARIOUS ASR STRUCTURAL ELEMENTS

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ABSTRACT

Nearly all structural concretes that are affected by ASR were restrained during and subsequent to the ASR expansion. Therefore it is very important to consider the effects of external restraint on the behaviour of concrete elements affected by ASR. In this test programme, unreinforced cubes, cores and prisms were tested in this manner and various mechanical properties of the concrete determined both parallel and vertical to the direction of preloading. Test results from specimens with external restraint indicated a substantial reduction in damage compared to unrestrained specimens. The mechanical properties of the restrained samples were higher than those obtained from the unrestrained samples.
Keywords: axial load, crack modification, elastic modulus, external restraint, strength.

INTRODUCTION

It is well known that if ASR concrete is subjected to restraint from surrounding non-reactive concrete [1], reinforcement or applied stress then the dominant cracks form at right angles to the direction of the restraint as opposed to a random map cracking that occurs with unrestrained ASR expansion. It is therefore to be expected that the mechanical properties of ASR concrete will also be modified by restraint. Significant data has been published dealing with the effects of restraint on expansion [2-3] and expansion on compressive strength [4] but few authors have addressed the changes in other mechanical properties that are induced by restraint. Clark [5] who reported that restrained ASR specimens exhibited no reduction in their dynamic modulus of elasticity E_{cd} whereas similar unrestrained specimens exhibited 80% reduction in E_{cd} is one of the few authors to report this area. Chana [6] also reported that the loss of unrestrained elastic modulus due to ASR degradation was higher than the other mechanical properties.

TEST PROGRAMME

Size of the Specimens: The test programme was carried out using restrained cubes, prisms, cores, and reinforced concrete beams. The cubes were 100x100x100 mm, the prisms were 500x100x100 mm and the cores were 74 mm in diameter D and 200 mm in length L. In order to make the cores, blocks 250x250x200 mm were cast and four cores being taken from each block. The direction of drilling was also the direction of casting.

Mix Designs and Curing Conditions: The various mixes used were as detailed in Table 1. The cubes and prisms were made using mixes 1 to 6 of Table 1, whereas the blocks from which the cores were extracted used mixes 7 to 11. The fused silica was graded to pass through a 1 mm sieve, and the percentage of fine aggregate passing 0.6 mm was 55%. The particle sizes of the two aggregates were in the range of 4.8-20.0

mm and 4.8-10.0 mm. The ultimate expansion of the mixes at week 52 which were obtained from prisms are shown in Table 1 [7]. Ordinary Portland cement was used in this test programme and a sodium oxide equivalent level of 7.0 and 12.0 Kg/m^3 was achieved by adding KOH in the free water just prior to the mixing of the ingredients of the concrete. All the specimens were cured for four weeks in water at 20 °C from the day after casting and then transferred to the hot tank at 38 °C for another 48 weeks.

Table 1 - The proportion of various mixes used in the experimental work.

Mix No	20 mm Aggregate (Kg)	10 mm Aggregate (Kg)	Sand (Kg)	Fused silica (Kg)	Cement (Kg)	Water/ cement ratio	Na_2O equivalent (Kg/m^3)	Expan-sion (mm/m)
1	-	1060	300	240	550	0.41	12.0	15.54
2	-	1060	300	240	550	0.41	7.0	12.10
3	1060	-	300	240	550	0.37	7.0	12.82
4	-	1060	540	-	550	0.41	7.0	-
5	-	1060	540	-	550	0.41	-	-
6	-	1060	540	-	200	0.74	-	-
7	-	880	480	240	550	0.44	12.0	15.48
8	-	880	480	240	550	0.44	7.0	11.95
9	-	880	720	-	550	0.44	12.0	-
10	-	880	720	-	550	0.44	-	-
11	-	880	720	-	200	0.74	-	-

Preloading and Test Arrangements: The arrangements for preloading the samples is shown in Fig. 1. The intensity of preloading was 10 N/mm^2. The cores, were drilled from the blocks after they had been cured for 28 days at 20 °C. The cores were capped at both ends using the sulphur-carbon method. Half of the cores were restrained at 10 N/mm^2 and the rest unrestrained, after which they were all transferred into a hot tank at 38 °C for another 48 weeks. The cores were tested at week 4 and 52 to determine the modulus of elasticity and then compressive strength. The elastic modulus was found using the Stiffness Damage Test Procedure. In this method, incremental loads are applied up to 20 KN in 5 loops (cycles). In the calculation of the modulus of elasticity, only the average of the last 4 loops is taken into account.

Surface Characteristics of Restrained Cubes: The crack pattern in the restrained ASR concrete was significantly different from that of the unrestrained specimens. The restrained cubes exhibit a longitudinal macro crack which is continuous from one cube to the rest. This would suggest that ASR cracks will easily propagate along a single path from one part of an ASR damaged structure to another. The prisms and cores expanded at right angles to the direction of restraint and exhibited no signs of map cracking.

Performance of Cubes and Prisms under Stress: The cube is undoubtedly the most convenient specimen to use when large number of crushing test are required for concrete control purposes. Prisms on the other hand can give a much better estimate [8] of the uniaxial compressive strength of concrete. The performance of restrained and unrestrained cubes and prisms with various ASR and control mixes are presented in the Tables 3 to 4. The abbreviation used in this section are shown in Table 2.

TEST RESULTS

Cubes Test Results: Reference to the ASR mixes (1, 2 & 3) in Table 3, indicate that the compressive strength values of the restrained cubes of M1 and M2 are higher than that of identical unrestrained cubes (M). Results indicate that those tested parallel to the direction of restraint (M2) gain higher compressive strength compared to those tested perpendicular to the direction of restraint. The percentage increase of M1 and M2 ASR cubes for mix 1 (12 Kg alkali) were 8.3% and 25.7%, for mix 2 (7 Kg alkali) were 14.3% and 23.1% and for mix 3 (7 Kg alkali, gap graded mix) were 11.6% and 30.4% respectively. The ratio of the compressive strength of the restrained and unrestrained cubes of the ASR mixes in Table 4, columns 2 and 3 suggest that ASR mixes with lower levels of alkali gain more compressive strength due to restraint than the mixes with 12 Kg alkali. The compressive strength values of the control mixes 5 and 6 are shown in Table 3. It is seen that the cubes show no significant change in compressive strength due to restraint, regardless of the direction of restraint. However in the case of the mix 4 (control mix with excess alkali, Table 1), cubes tested both parallel (M2) and perpendicular (M1) to the direction of restraining indicate 21% increase in compressive strength with respect to the unrestrained cubes (M). The reason for the increase in compressive strength in this case is not understood particularly as it is noted both M1 and M2 cubes show similar increases in strength. It can be concluded therefore that ASR mixes exhibited higher compressive strength due to restraint and the increases differ depending on the direction of testing relative to the direction of the restraint.

Table 2 - Description of the symbols that have been used.

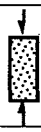
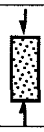
Letters	Description of the symbols	Letters	Description of the symbols
f_{cu}	Cube crushing strength.	M	Unrestraint cubes tested in a random direction.
P	Unrestraint prisms tested axially.	M1	Restrained cubes tested perpendicular to the direction of restraint.
P1	Restrained prisms tested axially		
E_c	Modulus of elasticity.	M2	Restrained cubes tested parallel to the direction of restraint.

Prisms Test Results: The values of the uniaxial compressive strength of the prisms are presented in Table 3. From the test results it is clear that the compressive strength values of the ASR prisms are lower than those of the controls. The mode of failure of the ASR prisms was progressive whereas in the case of the control prisms it was a sudden failure. Fig. 2 shows the types of the failure associated to the ASR and control prisms. It can be seen in Table 4 (column 1) that the uniaxial compressive strength of the restrained ASR prisms is greater than that of the unrestrained prisms. The level of alkali has an influential effect upon the increase in compressive strength as a result of restraint. When comparing the restrained and unrestrained prisms in Table 4 (column 1), it can be seen that with mixes 2 and 3 having 7 Kg alkali, the difference is 112.8% and 120.7% and in the case of prisms with 12 Kg alkali (mix 1) the difference is 49.1% only. Therefore the increase in uniaxial compressive strength in the restrained prisms with 7 Kg alkali is greater than the increase with 12 Kg alkali. It is seen in Table 4 that with control mixes 5 and 6 (column 1), the test values of the restrained and unrestrained uniaxial compressive strengths of the controls are similar to each other. Control mix 4 (with excess alkali) exhibited higher uniaxial compressive strength due to restraint but this increase is less significant than the increase associated with the ASR mixes.

Variation of Cubes and Prisms with respect to each other: The compressive strength of the cubes and prisms were compared with each other and the ratios are shown in the Table 4 columns 4 and 5. Regarding the unrestrained cubes and prisms in column 4, it can be seen that the ratios of the ASR mixes 1, 2 and 3 are higher than those of the control mixes 4, 5 and 6. The highest ratio of 181.6% belongs to mix 3 and the lowest ratio of 50.1% belongs to mix 4. The ratio of the 12 Kg alkali mix 1 is similar to that of the control mixes 5, and 6 yet the 7 Kg alkali mixes 2 and 3 do not show a similar ratio to the controls. Therefore the variation in ratio between the ASR and control mixes suggest that this ratio is higher for low level of alkali mixes. In columns 5 of

Table 4, the ratios of the restrained cubes and prisms are presented. These ratios unlike the unrestrained case in column 4, exhibit closer values between the ASR and control mixes. Therefore restraining did not show any adverse effect as far as these ratios are concerned. In column 1 of Table 4 the strengths of restrained prisms are compared with unrestrained prisms . In columns 2 and 3 the strengths of restrained cubes are compared with unrestrained cubes. It is seen that the gain in compressive strength due to restraint in the prisms is greater than in the cubes. The ratios in column 2 are lower than column 3 indicating that cubes tested parallel to the direction of restraint exhibit a higher strength than those tested perpendicular to the direction of restraint.

Table 3 - Typical test results of cubes and prisms of the alkali and normal mixes at week 52.

Names	1: Direction of restraining 2: Direction of testing		Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
	1	2	f_{cu} (N/mm^2)					
P Prisms	Unrestraint		15.1 17.0 18.7	14.9 15.0 15.1	11.6 12.5 13.3	34.7 39.3 40.2	35.4 41.3 43.6	19.1 20.7 21.7
P1 Prisms			24.6 24.9 26.0	29.8 32.0 37.4	24.9 25.8 29.1	44.8 47.2 51.0	39.8 42.9 46.2	19.4 20.8 22.6
M Cubes	Unrestraint		31.5 32.0 33.3 34.0	31.0 37.5 40.5 41.8	31.5 33.2 37.2 38.7	53.5 55.5 59.0 61.0	63.0 68.5 72.0 74.0	35.0 36.0 36.0 36.5
M1 Cubes			33.0 35.2 36.0 37.5	41.0 41.5 43.2 46.8	36.1 39.0 40.0 42.0	68.0 69.5 70.0 70.6	61.5 67.5 71.5 74.0	35.5 36.0 37.1 37.2
M2 Cubes			39.5 41.0 41.5 42.5	44.5 45.5 47.5 48.2	41.0 44.5 46.1 52.0	66.0 66.7 70.0 74.0	68.0 69.5 72.0 75.0	33.8 35.5 37.0 37.5

Stiffness of Cores under Stress: In the short-term and under rather low stress, concrete behaves nearly elastically. In the long-term it is more complicated as "creep" plays an influential role in the magnitude of strain under constant stress. According to BS 8110 [9] the elastic stiffness of structural concrete can be determined from an empirical expression related to the cube crushing strength. Such values do not take into account the individual constituents in the concrete, such as cement paste or aggregate. The residual stiffness of ASR concrete is usually assessed from cores taken from the structure concerned. Tables 5 and 6 present the experimental and theoretical values of the elastic modulus E_c of the test specimens. In Table 5 values of E_c at week 4 when the expansion was very small have been presented. At this stage all the samples were unrestrained. The values in Table 6 show the results at week 52 with some of the specimens being restrained from week 4. The test results at week 4 and 52 are compared with their theoretical values which have been obtained from the BS [9]. The British Standard recommends that, for concrete with an average, high quality dense aggregate, the modulus of elasticity at 28 days, $E_{c,28}$, is obtained from the cube strength at 28 days $f_{cu,28}$ by the following expression:

$$E_{c,28} = 20 + 0.2 f_{cu,28} \qquad \text{(see Table 5)}$$

and the modulus of elasticity of concrete at an age (t) by

$$E_{c,t} = E_{c,28}\ (0.4 + 0.6 f_{cu,t}/f_{cu,28}) \qquad \text{(see Table 6)}$$

Table 4 - Percentile ratios of the cubes and prisms.

Mix No	Percentile ratio %				
	1 $\frac{P1-P}{P}$	2 $\frac{M1-M}{M}$	3 $\frac{M2-M}{M}$	4 $\frac{M-P}{P}$	5 $\frac{M2-P1}{P1}$
1 (ASR), 12 Kg	49.1	8.3	25.7	93.4	63.1
2 (ASR), 7 Kg	120.7	14.3	23.1	151.3	40.2
3 (ASR), 7 Kg	112.8	11.6	30.4	181.6	72.6
4 (control)	25.1	21.5	21.0	50.1	45.1
5 (control)	7.2	-1.2	2.4	73.1	65.3
6 (control)	2.0	1.4	0.3	75.1	72.2

Column 1 Restrained prisms compared with unrestrained prisms.
Column 2 Restrained cubes tested perpendicular to the direction of loading compared with unrestrained cubes.
Column 3 Restrained cubes tested parallel to the direction of loading compared with unrestrained cubes.
Column 4 Unrestrained cubes compared with unrestrained prisms.
Column 5 Unrestrained cubes tested parallel to the direction of loading compared with restrained prisms.

Effect of ASR upon Elastic Modulus: In general the rate of expansion and the total expansion depend very much on the reactive aggregate, cement type, cement content and the environment [10]. Therefore the effect of ASR on the engineering properties of concrete and in particular, upon the elastic modulus cannot be generalised. In order to evaluate the elastic modulus of the ASR specimens, 2 ASR concretes were used and compared with 3 control mixes. The variation of the compressive strength of the mixes are also shown in the Tables 5 and 6 and used to find the theoretical elastic modulus of the mixes at week 4 and 52. The results clearly indicate a significant reduction in the elastic modulus compared to that of the controls. Factors that effect the elastic modulus of ASR concrete are discussed below.

Table 5 - Elastic modulus and compressive strength of cores at week 4.

Block No	Core No	Cube f_{cu} N/mm^2	Core E_c N/mm^2	Mean E_c N/mm^2	$E_{c,28} = 20+0.2 f_{cu,28}$ KN/mm^2	Mix details
A	A1, A2 A3, A4	34.5	18.6, 24.7 20.2, 21.4	21.6	26.90	Mix 7, ASR mix, 12 Kg alkali.
B	B1, B2 B3, B4		22.7, 20.7 22.2, 22.8			
C	C1, C2 C3, C4 C5, C6 C7, C8	38.2	22.6, 21.9 23.7, 25.1 24.0, 19.4 21.1, 22.4	22.5	27.64	Mix 8, ASR mix, similar to 3 but 7 Kg alkali.
D	D1, D2 D3, D4	36.5	36.3, 37.3 37.7, 39.6	37.8	27.30	Mix 9, control mix, 12 Kg alkali, no reactive aggregate.
E	E1, E2 E3, E4	57.0	43.4, 47.6 44.1, 44.5	44.9	31.40	Mix 10, control mix, no alkali, control mix.
F	F1, F2 F3, F4	30.6	36.6, 38.6 32.7, 36.9	36.2	26.12	Mix 11, control mix, no alkali, 200 Kg cement/m^3.

Effect of curing upon elastic modulus: The data in Table 5 indicates that at week 4 the values of compressive strength and elastic modulus of the ASR concrete are lower than that of the control mixes. ASR cores series A and B (mix 7 with 12 Kg alkali) have 39% and 52% lower compressive strength and elastic modulus than the cores series E (control mix 10). In the case of mix 8 (7 Kg alkali) these values reach 33% and 50% compared to the control cores series E. This indicates that the losses in compressive strength and elastic modulus at week 4 are similar, regardless of the alkali level. In Table 6 comparing the unrestrained ASR cores (i.e. A4, B1, B2 and C5 to C8) with the control cores (i.e. series D, E and F) at week 52, it can be seen that with 12 Kg alkali (i.e. A4, B1 and B2) the values of compressive strength and elastic modulus have dropped by 57% and 83% whereas with 7 Kg alkali (C5 to C8) the compressive strength and elastic modulus have reduced by 55% and 82% compared to the control cores (i.e. E3 and E4, mix 10). Therefore with both 7 and 12 Kg alkali the elastic modulus exhibited greater degradation than the compressive strength. Cores B3 and B4 in Table 5, have been kept out of water in the laboratory after week 4. It is seen that the modulus of elasticity of cores B3 and B4 are slightly higher than that of cores A4, B1 and B2 which have been cured at 38 °C.

Table 6 - Elastic modulus and compressive strength at week 52.

Core No	f_{cu} Cubes N/mm^2	f_{cu} Cores N/mm^2	f_{cu} Cores mean	E_c KN/mm^2	E_c mean KN/mm^2	$E_{c,t}$ KN/mm^2	Loading case
A1, A2 A3	44.4	45.4, 44.4 47.5	45.8	18.1, 14.4 20.4	17.6	25.3	Restrained
A4, B1 B2	32.5	24.8, 19.5 20.0	21.4	8.3, 9.5 7.0	8.3	20.8	Unrestrained
B3*, B4*	36.3	28.0, 28.7	28.4	8.3, 10.7	9.5	22.3	Unrestrained
C1, C2 C3, C4	45.2	47.3, 46.7 45.1, 48.6	46.9	17.3, 18.6 14.0, 15.2	16.3	25.0	Restrained
C5, C6 C7, C8	33.8	23.9, 25.4 24.3, 21.2	23.7	8.8, 9.9 9.0, 7.1	8.7	20.9	Unrestrained
D1, D2	66.6	59.0, 61.7	60.4	33.2, 33.5	33.4	56.5	Restrained
D3, D4	55.1	48.9, 50.1	49.5	27.9, 35.8	31.8	49.4	Unrestrained
E1, E2	75.2	64.8, 62.8	63.8	49.8, 49.2	49.5	53.5	Restrained
E3, E4	74.9	71.6, 65.4	68.5	49.2, 49.7	49.4	53.4	Unrestrained
F1, F2	44.5	38.9, 39.4	39.2	39.8, 47.1	43.4	52.6	Restrained
F3, F4	42.7	42.3, 36.4	39.4	44.0, 42.1	44.6	44.8	Unrestrained
*B3 and B4 cured in the laboratory condition							

Effect of alkali upon elastic modulus: Series D cores are made with mix 11 (control mix with extra alkali only). Comparing cores D and E (normal control mix), indicates that the enhancement of alkali has lowered the compressive strength and elastic modulus of the cores. The decrease in compressive strength and elastic modulus at week 4 are 36% & 16% and at week 52 are 26% & 36% respectively. This indicates that curing specimens for 52 weeks at 38 °C improves the compressive strength, compared to week 4 and reduces the elastic modulus. Cores series D and F (control mix, low compressive strength) at weeks 4 and 52 exhibits a similar effect.

Effect of restraint upon elastic modulus: All the specimens in Table 6 have been cured at 38 °C from week 4 to week 52. Half of the cores from each mix have been restrained from week 4 to week 52. It is seen that the elastic modulus of the restrained ASR cores are almost double than that of the unrestrained cores, in both 7 and 12 Kg alkali cores. In the case of the control mixes, the effect of the restraint is not significant, save in the case of cores series D, mix 9 (control mix with extra alkali only), where the elastic modulus of the restrained specimens is slightly higher than that of the unrestrained.

Comparison of the Theoretical and Experimental Values: Reference to the Tables 5, indicates that at week 4 the theoretical values of E_C in the ASR cores are higher than the experimental values, whereas in the case of the control mixes, experimental values are higher than the theoretical values. It is seen, in Table 6 that at week 52 the control mixes have lower experimental values of E_C than the theoretical values. In the case of the unrestrained ASR cores, with 7 and 12 Kg alkali they show 58% and 60% losses of elastic modulus compared to the theoretical value. However when the cores are restrained these losses reached 35% and 30% respectively. Therefore unrestrained cores exhibit greater loss of elastic modulus compared to the theoretical values, and when cores are restrained the loss of elastic modulus is lower.

CONCLUSION

[1] The expansion in the direction of stress is considerably reduced but increased expansion is exhibited in the direction at right angle to this. The cracking is also effected with cracks forming along the stress direction rather than the map cracking which occurs in unstressed concrete.
[2] The results of restrained cubes indicated that, preload decreased the amount of damage in both the parallel and perpendicular directions, however, the damage in the direction of preloading was less than the perpendicular direction.
[3] The loss of strength due to ASR is very much reduced in the direction of long-term stresses compared with the cross direction where the loss in strength is usually greater. The gain in compressive strength and elastic modulus in the uniaxial prisms due to restraint was higher than the gain in compressive strength from cubes.
[4] Application of external restraint modified the crack patterns on the surface of the ASR concrete. This indicates that a constant applied compressive stress can eliminate cracking in the direction perpendicular to the compression. A stress of 10 N/mm^2 was sufficient to stop the cracking in the lateral direction. Although lower stresses were not tried, lower stresses would be expected to give lower increases in the mechanical properties. Increase in the uniaxial compressive strength of the prisms was 120%, the increase in the elastic modulus of cores was 112% and the increase in the compressive strength of cubes was 30%.

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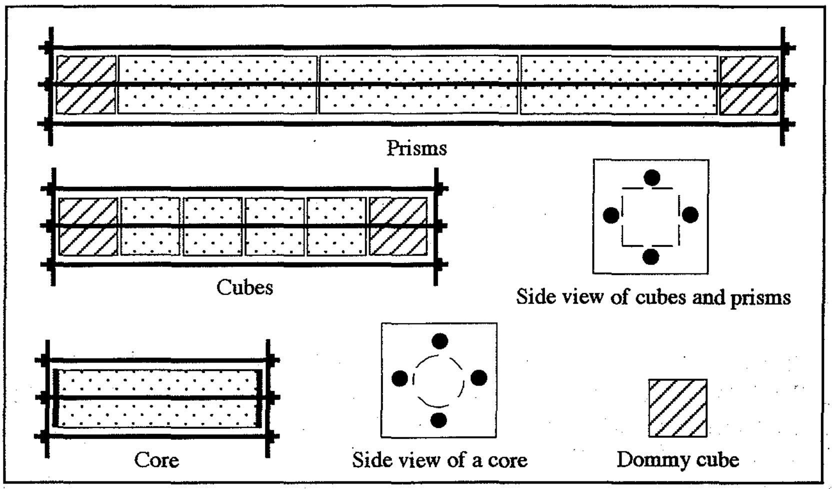

Fig. 1 - Method of applying external restraint on various specimens.

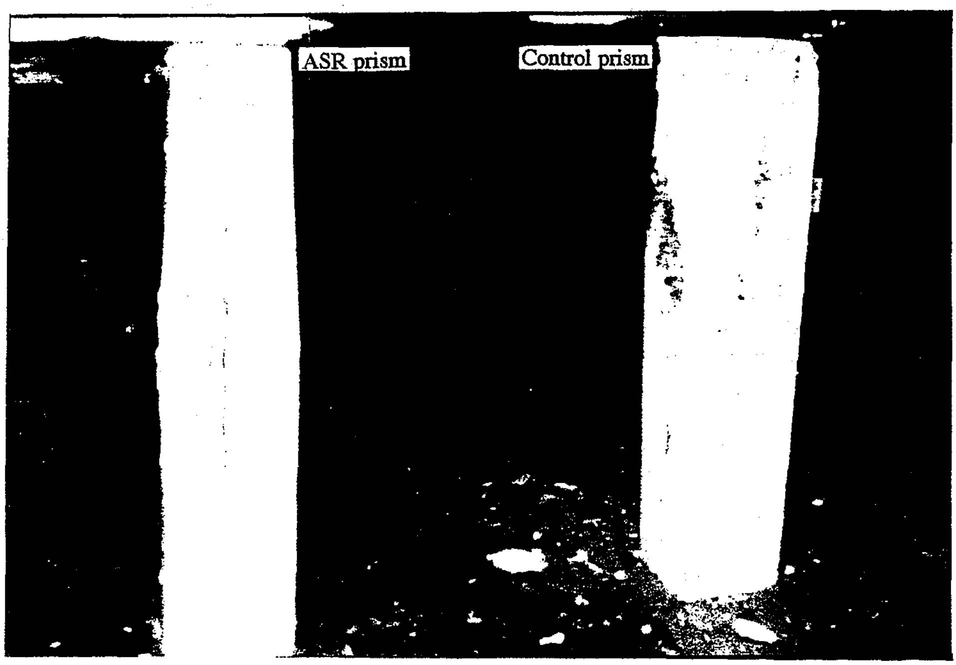

Fig. 2 - Failure of ASR and control concrete prisms.