THE INFLUENCE OF STRESS INTENSITY AND ORIENTATION UPON THE MECHANICAL PROPERTIES OF ASR AFFECTED CONCRETE

S.R. Rigden, J.M. Salam, E. Burley
Concrete Research Group, Department of Civil Engineering, Queen Mary and Westfield College, (University of London).

Three sizeable concrete blocks made with alkali silica reactive concrete were subjected to different stress levels for one year during the period of the reaction. The blocks were then cored in the three principal directions and these cores were tested to determine the stiffness damage parameters, ultrasonic pulse velocity and crushing strength. The results obtained clearly demonstrate major variations in concrete characteristics depending on stress level and orientation.

INTRODUCTION

The most direct and visible evidence of Alkali Silica Reaction (ASR) is external cracking. The crack pattern exhibited is influenced by the geometry of the structure, by the reinforcement detailing, by the nature and level of the stress in the structure and by cracking due to other causes (1).

Many load carrying reinforced concrete elements are in a state of near biaxial compression. Biaxial elements such as walls and slabs will be less willing to expand in plane because of the restraint provided by the reinforcement and the compressive state.

When the concrete member is free from external stresses, the cracking induced by ASR is in the form of "map-cracking" on the surface of the concrete, whereas in reinforced concrete beams and columns, they tend to appear parallel to the direction of the stress (2) and hence to the reinforcing steel (3).

Most structures are subjected to substantial long term dead and live loads, the stress patterns from which, affect the development of ASR cracking within the structure. It is therefore critical, when Engineers are carrying out investigations using laboratory ASR mixes, that the test specimens are subjected to an appropriate preload during the period that the ASR expansion is developing.

The aim of the research reported here was to examine the development of crack patterns in ASR concrete blocks subjected to different levels of uniaxial compressive stress and to study the physical properties of cores taken from the three principal directions of these preloaded blocks, once cracking had occurred. These cores were subjected to the full range of Stiffness Damage

Tests (S.D.T.) (4, 5), and their crushing strength (f_c) and Ultrasonic Pulse Velocity (U.P.V) were measured.

In order to investigate such affects, 3 blocks of concrete made from a mix which exhibits rapid ASR were cast. One of them was subjected to a stress of 8 N/mm^2 and another was subjected to a stress of 4 N/mm^2 while the other one was left unloaded. All of them were then kept in water at 38 ± 1°C for one year to accelerate the expansion. Reinforcement was not included in the blocks, the resulting crack pattern, therefore, being controlled only by the preload stresses that were applied. This paper then presents quantitative data which relates the various measured parameters to preload stress intensity and orientation.

TEST PROGRAMME AND DETAILS

Table 1 - Alkali Analysis in OPC

Na_2O	0.13%
K_2O	0.72%
Na_2O (equ.) = Na_2O + 0.658 K_2O	0.60%

Concrete mix and materials. The mix used consisted of 1 : 1.57 : 1.41 (cement: sand: coarse aggregate) by weight, having a cement content of 550 kg/m^3 and a water cement ratio of 0.36. The fine aggregate was a dried natural sand, and the coarse aggregate consisted of a river gravel with a 20 mm maximum size. The cement used was an ordinary Portland cement, with a sodium oxide alkali equivalent as shown in Table 1. In order to accelerate the ASR, the alkali content of the cement was enhanced by the addition of potassium hydroxide (KOH) to the mix, bringing the total alkali equivalent of the concrete to 12kg/m^3 and by using an amorphous fused silica, as partial replacement of the fine aggregate. The fused silica, which was in the size range of 1 mm to 2.8 mm, formed 11.9% by weight of the total aggregate in the mix. The natural sand and coarse aggregate were found to contain some reactive aggregates. Full details of the aggregate is given in Table 2.

Table 2 - Details of Aggregate

Coarse Aggregates (10-20 mm)	43.60% Flint. 2.80% Quartzite. 1.00% Sandstone, Limestone, ferruginous rock†.
Sand (0-4.75 mm)	26.4% Quartz. 2.85% Chert. 6.10% Quartzite. 2.00% Sandonstone, Silstone, Argillite. 2.00% Ferruginous rocks†. 1.35% Others.

† Possibly reactive if siliceous ironstone

Sample size and curing conditions. The main specimens used in this investigation were cored from concrete blocks that were 500 mm long by 500 mm high by 200 mm wide. Three concrete blocks were cast along with six 100 mm cubes.

After casting the moulded specimens were covered with wet hessian and polythene sheeting and left undisturbed for 48 hours. They were then stripped and Demec discs glued on to two faces to facilitate measurement of expansions in the X, Y and Z directions as shown in Fig. 1.

Application of preload. The compressive stresses of 4 N/mm^2 and 8 N/mm^2 were applied when the concrete blocks were 9 days old. The uniaxial stress was applied parallel to the direction of casting, through 550 x 250 x 40 mm mild steel plates placed at both ends of the concrete specimen, as shown in Fig. 2. Each plate had a set of holes symmetrically drilled along each side to allow 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 which was calibrated using a load cell, with an accuracy of $\pm$ 0.5 KN. The rods were tightened regularly to overcome creep that occurred in the system, hence the stress on the specimen was maintained at a fairly uniform level through the twelve months that the ASR and associated cracking was developing. It is acknowledged though, if more funds had been available, that a more controlled loading system would have been preferable.

ASR concrete behaviour under load. Unstressed areas of ASR mass concrete will exhibit "map cracking". If the concrete has been subjected to a directional stress during the period that it has undergone expansion and cracking then the map cracking is usually modified in some way. This cracking then reflects the direction of stress, restraint due to any reinforcing steel and end effects.

The above modification of the map cracking is readily demonstrated in the laboratory and observed in the field. An interesting example of this is provided by a number of water reservoir columns that have been extensively investigated by the Authors. Both reinforced and prestressed columns were investigated. They were 300 to 400 mm in width and between 7 and 8 m in length. The columns were subjected to a long term vertical stress of between 5 and 8 N/mm^2 and the cracks were noted to be all oriented parallel to the line of stress.

Smith and Wood (6) indicated that the development of such cracks may lead to reduced column stiffness and a much reduced load capacity as the vertical crack might effectively increase the slenderness of the columns.

In the present investigation, both of the preloaded blocks exhibited similar crack patterns, though in the case of the block stressed to 8 $N/mm^2$the cracks were more closely spaced.

In the case of the unloaded block the cracks caused by the ASR formed into individual three-armed shapes which joined up to produce the characteristic map crack pattern. This crack pattern is seen to be similar to that observed in unstressed areas of real concrete structures suffering from ASR.

Concrete expansions. Table 3 gives the average measured expansions for the three principal directions for all three blocks. It can be seen that the expansions in all three directions of the unloaded block were almost the same, but that they comply with the following inequality:

$$\Delta\% X > \Delta\% Z > \Delta\% Y$$

The differences however in these three values are less than the likely experimental error. It is also noted that on each face the expansions measured close to and parallel to the edges of a face were greater than those measured towards the centre of the face. This variation in expansion across a face was not consistently noted with the preloaded blocks.

The preloaded blocks did show a significant variation in the expansions exhibited in the three principal directions for both the 4 N/mm^2 and the 8 N/mm^2 loading cases. It is clearly seen that the minimum expansion occurs in the direction of uniaxial load. The greatest expansion occurs across the narrowest, 200 mm wide, face. The following inequality then relates to the observed expansions in the X, Z and Y directions for the preloaded blocks:

$$\Delta\% X > \Delta\% Z > \Delta\% Y$$

Increasing levels of preload resulted in reduced expansion in the Y direction.

The variation between the measured expansions in the two directions perpendicular to the applied stress at any particular stress level, is likely to reflect the difference in shape and length of the block in those two directions. The recent paper by Walton and Clayton (7) clearly indicates the substantial affect that size and shape can have on expansions. The effect of end restraint through the steel plates is also likely to have affected the expansions, in particular it is also noted that expansion in the Z direction on the largest face is noticeably greater midway between the two end plates, than adjacent to the plates.

The data in Table 3 indicates that the actual expansive strain in the Y direction was reduced, compared to the unloaded case, by 1.4 under 4 N/mm^2 of stress and 1.7 under 8 N/mm^2 of stress.

Direction of Drilling. After one year, 74 mm diameter cores were drilled in the three principal directions from each block, as shown in Fig.3. Vertically drilled cores were drilled right through the blocks and later cut into separate "top" and "bottom" cores, as recommended in Concrete Society Technical Report No. (CSTRll) (8), the top 10 to 15% of each vertically drilled core was trimmed off since this region is known to be weaker and to give inconsistent results. The trimmed cores were labelled and capped on both ends using the sulphur-carbon method as detailed in BS: 1881 part 120, 1983 section 5.3 (9). All cores were produced with an L/D ratio of 2.5, they were then wrapped in cling film, sealed in plastic bags and kept at normal room temperature until they were tested within one day.

TESTING PROCEDURES

The cores were subject to the full range of Stiffness Damage Tests, details of these tests and the apparatus used can be found elsewhere (5).

TEST RESULTS AND DISCUSSION

The results are presented in tabular form, each test result has been obtained from an average of four specimens. The results indicated that the influence of stress levels on the mechanical properties of the ASR concrete is as follows:-

Table 4 - Effects of Stress Level on Mechanical Properties of ASR Concrete

	BLOCK SUBJECTED TO ($8N/mm^2$)			BLOCK SUBJECTED TO ($4N/mm^2$)			BLOCK UNLOADED		
DIRECTION OF DRILLING	Y Cores	X Cores	Z Cores	Y Cores	X Cores	Z Cores	Y Cores	X Cores	Z Cores
Ec. (KN/mm^2)	22.95 ± 1.47	14.57 ± 1.21	11.41 ± 1.14	21.38 ± 2.23	17.30 ± 1.78	15.75 ± 1.76	18.96 ± 0.82	17.23 ± 0.75	15.34 ± 0.43
D.I. (No Unit)	10.34 ± 1.25	15.82 ± 2.56	31.12 ± 2.73	10.94 ± 2.96	11.71 ± 1.40	19.57 ± 2.84	11.02 ± 2.16	12.07 ± 1.37	17.95 ± 3.18
P.S. ($x\ 10^{-6}$)	4.48 ± 0.64	7.27 ± 1.30	9.64 ± 3.66	5.06 ± 2.03	5.58 ± 1.04	6.26 ± 1.97	5.68 ± 2.74	5.71 ± 2.10	5.78 ± 3.00
U.P.V. (Km/sec)	3.80 ± 0.01	3.53 ± 0.04	3.48 ± 0.02	3.77 ± 0.03	3.73 ± 0.05	3.70 ± 0.10	3.76 ± 0.01	3.75 ± 0.02	3.74 ± 0.10
f_c (N/mm^2)	27.90 ± 2.32	20.55 ± 1.20	18.64 ± 2.07	26.58 ± 1.51	23.25 ± 1.30	22.97 ± 2.11	25.62 ± 2.68	24.97 ± 3.01	23.71 ± 3.01

Elastic Modulus (Ec). It is known that the Elastic Modulus (Ec) exhibits a high sensitivity to ASR induced changes in the micro and macro structure of concrete (4, 5, 10). A comparison of the Ec results for the preloaded and unloaded blocks in Table 4 reveal a number of interesting points in relation to the structural behaviour of the specimens.

It is seen that in the direction of the preload the value of Ec increases as the preload increases. That is

$$Ec\,(Y)\,(8\ N/mm^2) > Ec\,(Y)\,(4\ N/mm^2) > Ec\,(Y)\,(\text{zero load})$$

Ec (Y) for cores taken from the $8N/mm^2$ block was on average over 20% higher than for the cores taken from the unloaded block.

It is also seen that Ec in the two directions perpendicular to the preload are similar for both the unloaded and the 4 N/mm^2 load case, but with a preload stress of 8 N/mm^2, Ec in the two perpendicular directions is substantially reduced compared to the unloaded core. That is:

$$Ec\,(X)\,(8\ N/mm^2) < Ec\,(X)\,(\text{zero load})$$

$$\text{and } Ec\,(Z)\,(8\ N/mm^2) < Ec\,(Z)\,(\text{zero load})$$

For all three load cases:

$$Ec\,(Y) > Ec\,(X) > Ec\,(Z)$$

with Ec (Y) being over 100% greater than Ec (Z) for the 8 N/mm^2 load case but only 24% greater for the unloaded case. The above again illustrates that preload, results in increasing stiffness in the direction of loading, but a reduction in stiffness in the two directions perpendicular to the load. The general relationship between Ec in the Y, X and Z directions is clearly compatible with the relationship between the expansions exhibited in the three directions for both the 4 and 8 N/mm^2 preloaded cases.

This relationship between Ec and the expansions is not though established by the results for the unloaded case. It is suggested that the variations in Ec for the unloaded case reflect the effects of casting direction and the size and shape of the concrete blocks.

Damage Index (D.I.). This represents the energy dissipated, normalised over the stress range, for a material subjected to limited uniaxial cyclic compression. It is a measure of the level of cracking within a concrete specimen, the more cracks being present the higher the damage index (4, 5).

It is seen from Table 4 that for preloads of 4 N/mm^2 and 8 N/mm^2 the following relationship might hold:

$$D.I.\,(Z) > D.I.\,(X) > D.I.\,(Y)$$

The relationship between D.I.(Y) and D.I.(X) for preloads of zero and 4 N/mm^2 is though somewhat inconclusive due to the size of the experimental error compared to the values obtained. At a preload of 8 N/mm^2 the relationship is though clearly established.

Increasing preload results in a small decrease in the D.I. in the direction of the preload. It is seen that D.I. (Y) (zero load) is over 6% higher than D.I. (Y) (8 N/mm^2). This small difference must be considered to be within the limits of experimental error but is compatible with the similar relationship seen for Ec.

D.I. (X) (zero load) and D.I. (X) (4 N/mm^2) are identical within the limits of experimental error but D.I. (X) (8 N/mm^2) is seen to be greater than D.I. (X) (zero load). The relationship between preload and the D.I. in the Z direction is though clearly seen to be:

$$D.I.\,(Z)\,(8\,N/mm^2) > D.I.\,(Z)\,(4\,N/mm^2) > D.I.\,(Z)\,(\text{zero load})$$

The above suggests that the application of preload to ASR concrete leads to decreased damage being suffered by the concrete in the direction parallel to the preload. The results further suggest that the application of preload leads to significant increases in the damage suffered at right angles to the direction of the applied stress but that shape and size characteristics of the concrete specimen might lead to an unequal distribution of damage between the two directions that exists perpendicular to the applied stress.

Plastic Strain (P.S.) This is defined as the non-recovered strain within a core which has been subjected to limited strain cycling and is related to the microcracking within the material. The more cracks within a core the higher the plastic strain measured.

It is seen from Table 4 that plastic strain is essentially the same in all three directions for zero preload. When preload is applied the following relationship starts to develop

P.S. (Z) > P.S. (X) > P.S. (Y)

The relationship becoming stronger with increasing preload such that for a preload of 8 N/mm^2, plastic strain (Z) is over 210% greater than plastic strain (Y).

The general relationship:

P.S. (Z) > P.S. (X) > P.S. (Y)

is not though fully established due to anomalous result for P.S. (X)

(4 N/mm^2)

D.I.(X) (4 N/mm^2) gave a similar result to break the pattern of varying damage index properties with increased stress levels. The variations in plastic strain are then seen to closely follow the variations in the damage index properties described previously

Ultrasonic Pulse Velocity (U.P.V). This is a non-destructive technique which is often used to provide additional information to that obtained by visual observation of deteriorating concrete and to give information in regard to the condition of the inner concrete, including the presence of microcracking. Relatively small changes in U.P.V usually reflect relatively large changes in the condition of concrete.

It is seen that for the unloaded case U.P.V in the Y, X and Z directions are essentially identical but for the 4 and 8 N/mm^2 preload case the following relationship is seen to exist.

U.P.V (Y) > U.P.V (X) > U.P.V (Z)

The relationship becomes more pronounced with increasing preload stress and for the 8 N/mm^2 case U.P.V (Y) is 9% greater than U.P.V (Z).

It is also seen that:

U.P.V (Y) (8 N/mm^2) > U.P.V (Y) (zero load)

and U.P.V (X) (8 N/mm^2) < U.P.V (X) (zero load)

and U.P.V (Z) (8 N/mm^2) < U.P.V (Z) (zero load)

A similar relationship has not been established for the case when the preload is only 4 N/mm^2.

Compressive Strength (f_c). The compressive strength of cores drilled in the X,Y and Z directions taken from the preloaded and unloaded blocks are shown in Table 4. These show that the application of uniaxial preload increases the compressive strength by a small amount in the direction of the load but reduces the strength in the perpendicular direction by a significant amount. Therefore

$$f_c\,(Y)\,(8\ N/mm^2) > f_c\,(Y)\,(4\ N/mm^2) > f_c\,(Y)\,(\text{zero load})$$

$$\text{and } f_c\,(X)\,(8\ N/mm^2) < f_c\,(X)\,(4\ N/mm^2) < f_c\,(X)\,(\text{zero load})$$

$$\text{and } f_c\,(Z)\,(8\ N/mm^2) < f_c\,(Z)\,(4\ N/mm^2) < f_c\,(Z)\,(\text{zero load})$$

When comparing the 8 N/mm^2 loaded block with the unloaded block a gain in strength in the (Y) direction of over 9% is noted but a loss of strength of 21% is seen in the (Z) direction.

The results also show a difference in the strength of the cores in the Y, X and Z directions at all these levels of preload. The relationship

$$f_c\,(Y) > f_c\,(X) > f_c\,(Z)$$

is therefore suggested. For the unloaded block $f_c(Y)$ is only 7% higher than fc (Z) but in the case of the 8 N/mm^2 block this difference has increased to nearly 50%. It is noted that the 7% difference lies within the limits of experimental error. The Y direction is also the direction of casting, therefore it is to be expected that fc would be greater than in the other two directions, even for the unloaded case.

Discussion and conclusions. The stiffness damage properties of Damage Index, Elastic Modulus and Plastic strain together with Ultrasonic Pulse Velocity and Strength that were determined in this investigation on preloaded alkali silica reactive blocks indicate that high levels of preload will increase the amount of damage recorded in the directions perpendicular to the uniaxial stress direction and decrease the amount of damage recorded in the direction of the uniaxial stress.

The following inequalities relating preload orientation and stress intensity to damage in alkali silica reactive preloaded concrete blocks of similar size and shape to those tested in this investigation are then suggested

$$\text{Damage (Z) } (8\ N/mm^2) > \text{Damage (Z) } (4\ N/mm^2 \text{ and } 0\ N/mm^2)$$

$$\text{Damage (X) } (8\ N/mm^2) > \text{Damage (X) } (4\ N/mm^2 \text{ and } 0\ N/mm^2)$$

$$\text{Damage (Y) } (8\ N/mm^2) < \text{Damage (Y) } (4\ N/mm^2 \text{ and } 0\ N/mm^2)$$

Where Y is the direction of the preload and X and Z are perpendicular to the preload.

The relationship that

$$\text{Damage (Y) } (8\ N/mm^2) < \text{Damage (Y) } (4\ N/mm^2) < \text{Damage (Y) } (0\ N/mm^2)$$

is also proposed. The similar inequality that might have been expected to apply to the X and Z direction was not found to hold in regards to the relationship between the zero and the 4 N/mm^2 load cases.

It is further suggested that

$$\text{Damage (Y)} < \text{Damage (X)} < \text{Damage (Z)}$$

for the three stress levels considered and that this inequality is particularly relevant at the higher, 8 N/mm^2, stress level. The X direction related to cores drilled into the length (500 mm) of the block and the Z direction related to cores drilled into the width (200 mm) of the block.

The implication of these inequalities is that large variations in the observed properties of ASR damaged concrete cores will occur depending not only on the basic severity of the reaction within the structure that the cores were taken from, but also upon the orientation of the cores to the applied load, the severity of the applied load and the general shape, size and geometry of the member that was cored. Low stress levels might not induce substantial variations in the damage suffered.

This paper does illustrate the importance of being aware of the orientation of cores relative to the applied stress when considering the results of tests on these cores.

Blight and Alexander (11) examined the behaviour in service of a deteriorated concrete pier supporting a bridge column. The large observed core strengths were in their opinion sufficient to demonstrate that the structure remained adequately strong even in its deteriorated condition. It is likely that their cores were taken in the direction perpendicular to the applied load, so the results from their coring would have related to the minimum core strength within the structure but if the cores had been taken in another direction they might not have identified the lowest concrete strength.

Though not investigated in the work covered by this paper directional restraint due to reinforcing steel is likely to result in similar variations in core test results to that shown to be related to the direction of loading.

Though the above results add to the body of knowledge in regards to the performance of ASR structures, it must be acknowledged that cores cut and removed from the stress environment experienced within the parent structure will suffer changes in strain immediately on removal and these changes would be expected to modify somewhat, the test parameters that describe the core. The application of an insitu test programme to real structures to obtain similar relationships to those discussed above would seem to have much merit.

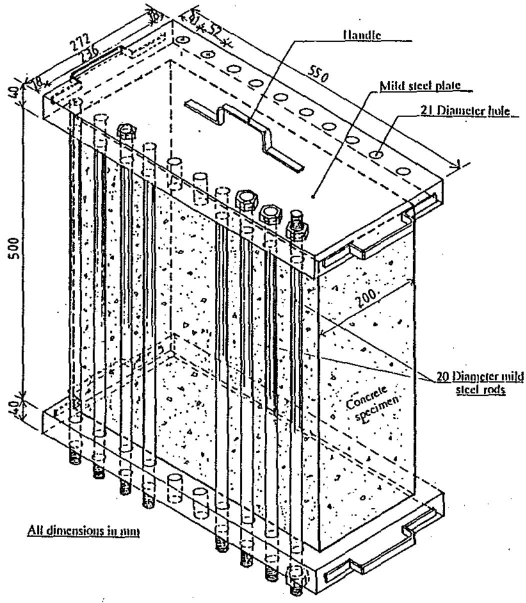


Figure 2 Preloading system

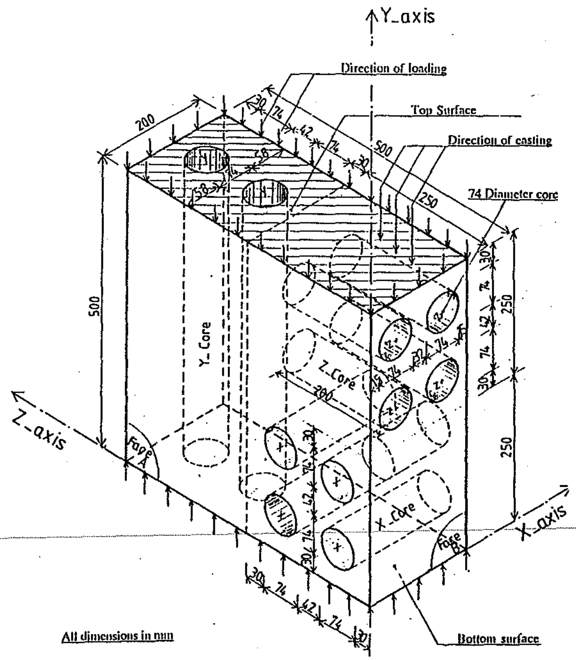
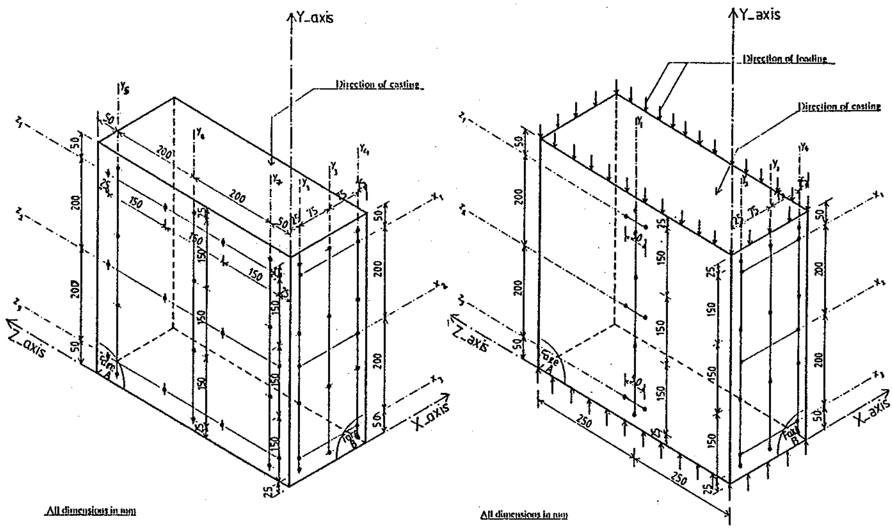


Figure 3 Direction of drilling



a) Unloaded block

b) Preloaded blocks

Figure 1 Locations of Demec dics on the blocks

Table 3 - Expansions in principal directions.

Preload (N/mm2)	Axis Lines	Y - Axis							X - Axis			Z - Axis		
		Y1	Y2	Y3	Y4	Y5	Y6	Y7	X1	X2	X3	Z1	Z2	Z3
	Faces	EXPANSION (%)												
Zero	A	-	-	-	-	2.14	1.98	2.24	-	-	-	2.42	1.91	2.30
	B	-	2.40	2.15	2.28	-	-	-	2.46	2.15	2.34	-	-	-
4	A	0.58	-	-	-	-	-	-	-	-	-	1.15	1.67	1.20
	B	-	1.02	1.38	0.80	-	-	-	2.02	2.14	1.98	-	-	-
8	A	0.25	-	-	-	-	-	-	-	-	-	1.16	2.40	1.21
	B	-	0.63	0.48	0.57	-	-	-	2.78	2.84	2.66	-	-	-

SYMBOLS USED

Ec = Elastic Modulus (KN/mm^2).

D.I.= Damage Index (dimensionless).

P.S.= Plastic Strain (dimensionless).

U.P.V = Ultrasonic Pulse Velocity (Km/sec).

f_c= Core crushing strength (N/mm^2).

REFERENCES

1. Somerville, G.S., 1985, "Engineering Properties of Concrete Affected by Alkali Silica Reaction", Interim Technical Report Note 8, Slough, England.

2. British Cement Association (B.C.A.), 1988, The Diagnosis of ASR", Report of a Working Party, Slough, England.

3. Swamy, R.S., 1989, "Structural Implications of ASR", Proceedings of the International Conference on A.A.R., Kyoto, Japan, 683.

4. Chrisp, T.M., Crouch, R.S., and Wood J.G.M., 1988, "The Stiffness Damage Test (S.D.T.)- A Quantitative Method of Assessing Damaged Concrete", The Life of Structures Conference, Inst.Struc.Engrs., Brighton, England.

5. Rigden, S.R., Salam, J.M., and Burley, E., "A Study of Variations in The Physical and Mechanical Properties of ASR Concrete over Time", Paper in The Course of Preparation.

6. Smith, D.N., and Wood, L.A., 1989, "The Structural Performance of Damaged Concrete Elements", The Life of Structures Edited by Armer, G.S.T., Clarke, J.L., and Garas F.K., 181.

7. Walton, C., and Clayton, N., 1989, "ASR Expansion Measurements on a Variety of Test Specimens", Building Research Establishment, London, England.

8. The Concrete Society, 1987, "Concrete Core Testing For Strength", Technical Report No.11, Including Addendum, London, England.

9. B.S. : 1881 Part 120, 1983, Method for Determination of The Compressive Strength of Concrete Cores. England

10. Swamy, R.N., and Al-Asali M.M., 1988, A.C.I. Mat. Jour., 367.

11. Blight, G.E., and Alexander, M.G., 1987, "Assessment of A.A.R. Damage to Concrete Structures. Proc. 7 th. Int. Conf. Concrete A.A.R. Ottawa, Canada, Edited by P.E. Grattan-Bellew, 121-125.