SECONDARY EFFECT OF ASR ON DURABILITY OF CONCRETE: FREEZE/THAW

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The durability of ASR infected concrete to cyclic freeze/thaw was investigated. It was discovered that high strength concrete, which is commonly regarded as "immune" from freeze/thaw damage, became susceptible due to the presence of ASR cracking. The ultimate expansion caused by ASR together with freeze/thaw was greater than that caused by ASR alone, and in some cases disintegration of the specimen was the final result.

INTRODUCTION

Analysis of all the confirmed cases of alkali-silica reaction (ASR) affected structures in the UK indicates a greater incidence occurring in the South West and the Trent Valley areas of the country. This national trend is reflected by British Rail's own experience of some 12 or so confirmed cases, and about an equal number of suspected structures, from its stock of over 3500 concrete bridges. The severity of ASR disruption varies throughout these 25 or so particular structures; the deterioration of two was judged to be sufficiently advanced to warrant replacement.

Monitoring of the remaining structures highlighted, in some instances, and apparent paradox in that although ASR activity showed a decline, the rate of deterioration of the concrete did not. Indeed in one particular structure where tests on extracted cores indicated negligible latent ASR expansion, the severity of cracking in terms of width rather than number increased dramatically between two site inspections. These particular observations were made at the beginning and end of an unusually severe winter giving rise to the suggestion that freeze-thaw action may have contributed to the continued deterioration of the concrete.

The secondary effects on the durability aspects of concrete that ASR may initiate or exacerbate were largely unknown at this time. This paper briefly outlines the study undertaken specifically devoted to the understanding of the behaviour of ASR affected concrete under freeze/thaw conditions.

BACKGROUND

As a means of coordinating research investigations into ASR, Building Research Establishment (BRE) developed two standard concrete mixes designed to produce significant levels of ASR induced expansion within a relatively short period. The two basic mixes were a "building" mix containing 300 kg/m^3 cement and a free W/C ratio of 0.6 (approximately equivalent to a C35 concrete), and a "bridge" mix containing 400 kg/m^3 cement and free W/C ratio of 0.45 (approximately equivalent to a C50 concrete).

The reactive mix selected was the C50 to better correlate with the BR affected structures. Thames valley sand was used as the reactive aggregate and limestone as inert aggregate. The proportion of reactive silica in the combined sand-limestone aggregate was the "pessimum" proportion so the reaction could be maximized. The mix proportions of the concrete are given in Table 1.

TABLE 1 CONCRETE MIX PROPORTIONS (by weight)

Free water	Thames Valley Grade M	Crushed limestone 5-10mm	Crushed limestone 10-20mm	O.P.C.
0.45	1.36	1.39	1.85	1.00

When the equivalent alkali level of the mix was raised to 7 kg/m^3 by adding sodium and potassium sulphates at the mixing stage, in the same proportion as in the cement, rapid ASR activity was obtained. This involved curing specimens initially at 20^{0}C for 1 month and then storing them at 38^{0}C and 100% RH which resulted in significant expansion occurring within a further two months.

SPECIMENS

For ASR specimens, the ordinary Portland cement was supplied by a cement manufacturer together with the alkali analysis. The air-dried aggregates were supplied by BRE from their stockpile at Garston. Water absorption values to achieve a saturated-surface-dry (SSD) stage had been determined and they were 0.35% for 10/20mm limestone, 0.40% for 5/10mm limestone and 1.3% for Thames valley sand.

Batch weights were adjusted to produce 0.034 m^3 of concrete in order to prepare 6 prisms and 2 cylinders. The ratio between sodium and potassium salts in the cement was determined and used to calculate the addition of sodium and potassium sulphates to raise the equivalent alkali content of the concrete to 7 kg/m^3.

For control specimens, either these could be made using the same aggregate but without alkali additions or alternatively by using a non-reactive aggregate (e.g. limestone coarse and fine) but with the same 7 kg/m^3 alkali level as the test specimens. Because of the possible effects of alkali additions on the properties of the concrete other than ASR the latter type of control has been favoured by other workers. In this study, both types of control were prepared to investigate whether the enhanced sulphate levels present in the 7 kg/m^3 alkali mix did introduce any secondary effect. The inert fine aggregate used was 0/5 mm limestone also supplied by BRE. Water absorption was estimated to be 2%.

As real structures suffering from ASR are very much restrained both from reinforcement and imposed loads and stresses, it is important that its effect be investigated. For simplicity, internal restraint was used in this study and was achieved in 4 prism specimens by using two 12 mm deformed bars, three 12 mm deformed bars, four 12 mm deformed bars and four 8 mm round bars respectively.

To prepare the specimens, the aggregates were batched into a Cretangle mixer, mixed for 30 seconds then wetted with 1 litre of water and re-mixed for a further 30 seconds. The mixing pan was sheeted over firmly with polythene to minimise evaporation and left for 30 minutes. The cement was then added to the aggregates and mixed for 30 seconds. The sulphate solution (ie. the additional alkalis dissolved in two litres of water) and the balance of the water were added slowly while mixing was continued for a further two minutes.

Six prism moulds and 2 cylinder moulds were filled and compacted on a vibrating table. Top surfaces were floated and covered with polythene sheet weighed down. Specimens were demoulded after 5 days and given an identification mark. Three lines of Demec targets were placed on the specimens before they were stored in a water bath maintained at 20 ± 2^0C.

TEST PROCEDURES

Measurement of ASR Activity

It has been established that some of the physical properties of concrete affected by ASR are compressive strength, tensile strength, elastic modulus, ultrasonic pulse velocity (UPV) and volume. The importance of not damaging the specimens prior to freeze-thaw cycling and the desire to use rapid methods resulted in linear expansion, UPV and weight change being selected to monitor ASR activity. Datum measurements of length, using 2" and 8" Demec gauges for the cylinders and prisms respectively, UPV with a PUNDIT and weight (SSD) were taken after 1 week.

After the initial 28 days water curing at 20 ± 2^0C 5 prisms from each batch were placed in a water bath maintained at 38 ± 2^0C. Three pairs of cylinders were also transferred to the 38^0C water bath while the remaining prisms and cylinders were retained in the 20^0C bath as controls.

Measurements made at BRE on specimens made with the same basic mix indicated the expansion should be detectable after 5 to 7 weeks at the elevated temperature and UPV reduction should occur at about the same time. The same information also indicated maximum expansions of 4 mm/m. It was decided to subject ASR damaged specimens to freeze-thaw action at 25, 50 and 100% of the predicted maximum expansion levels.

Freeze-Thaw Testing

The freezing and thawing of the prisms was achieved using an environmental chamber set to cycle between -20°C and +25°C. The cycle times for freezing and thawing were determined in advance by trial and error using a dummy prism with an embedded thermocouple. This resulted in a programme of 5 hours freezing followed by 3 hours thawing which enabled 3 complete cycles per day.

Saturation of the prisms was maintained by laying them in galvanised trays in which the water depth was kept between 20 and 4 mm. The cabinet was able to accommodate 3 trays each contained 3 prisms. This enabled up to 8 test specimens to be tested at any one time, the dummy prism being retained to check the performance of the cabinet.

The test specimens were removed once a week at the end of a thaw cycle and measured for length, UPV and weight changes.

RESULTS

Development of ASR

The results of length, UPV and weight changes recorded for each batch of prisms are shown graphically in Figures 1 to 3. There was a difference between the maximum expansion recorded for individual prisms as indicated by the batch ranges:

Batch	Expansion Range	Average mm/m
1	3.3-3.7	3.50
2	3.7-3.8	3.75
3	4.1-4.3	4.20
4	4.0-4.5	4.35
5	4.1-4.5	4.30
6	4.5-4.6	4.52

The lower results given by batch 8, as shown in Figure 1, reflect internal restraint against expansion arising from the included reinforcement. The results from the two controls 7 and 9 were combined because they showed no significant difference.

Visual detection of the first surface cracks was dependent on when the specimens were removed from the water bath for measurement. The earliest detection was at about 0.4 mm/m and the latest at 1.0 mm/m expansion.

The results of the UPV measurements are given in Figure 2 which indicates the very similar behaviour of batches 1,2,3,4 and 5 i.e. an initial increase in velocity peaking after about 6 or 7 weeks which then reduces markedly over the next 4 to 5 weeks reaching the lowest values at about 20 weeks after casting, thereafter showing a gradual increase. This contrasts with measurements obtained from the control, batch 7, which gave a steadily increasing UPV levelling out at about 5.2 km/s after 24 weeks or so.

Again, the results from batch 6 prisms differed from the other ASR active specimens. It can be seen that a sharper reduction in velocity occurs but at a much later age, i.e. 11 weeks, and that the minimum values of approximately 4.6 km/s are significantly lower than the main group, typically 4.7-4.75 km/s.

Weight changes recorded for the same batches show similar trends as can be seen in Figure 3. Again the main group of ASR active batches give broadly similar results, weight increasingly steadily reaching maximum values of 0.8 to 1.0% at about 20 weeks after which the weight stabilised or reduced marginally. Batch 6 prisms showed a slower initial rate of increase, but attained a similar maximum as the main group i.e. 0.8%.

The two control batches 7 and 9, while being markedly lower, were significantly different from each other, 7 having a final weight increase approximately 3 times that of 9.

The expansion results of the cylinder specimens stored at 38^{0}C are given in Figure 4. The plots represent the average values obtained from 2 cylinders for each batch.

Freeze-Thaw Testing

Prisms were selected at approximately 25, 50 and 100% ASR induced expansions levels for F/T testing. Each week 18 freeze/thaw cycles were achieved and the total number of cycles for each batch are given below. The behaviour of the prisms subjected to F/T is shown in Figures 5 and 6.

Batch/Prism	Weeks in Cabinet	No of Cycles
1	9	150
2	15	250
3	15	250
5	6	90
6/6	12	200
6/2	5	75
1/1*	11	180

* This prism has been stored at 20^{0}C for 18 weeks and then placed in the F/T cabinet for 11 weeks as a control. The expansions recorded at the end of each period were 0.14 mm/m and 0.04 mm/m respectively.

DISCUSSION

Development of ASR

The difference in the alkali levels in the first five batches can be summarised as:

Batch Nos.	Total Equiv Na_20	% Contributed by K_20
1 and 2	6.8 kg/m^3	75
3,4 and 5	7.0 kg/m^3	80

However, the recorded maximum expansions for these two groups was 3.6 and 4.3 mm/m respectively, the relative difference being greater than that between the total levels of equivalent alkalies. The explanation therefore would seem to be the greater proportion of potassium in batches 3,4 and 5 since this is known to be more reactive than sodium in most chemical reactions and the alkali-silica reaction would appear to be no exception. The reason for batches 1 and 2 reaching their maxima before 3,4 and 5 would, however, be due to the reduced level of total alkalis, the smaller amount being consumed or exhausted earlier.

No significant differences in expansion were recorded for the two controls, batch 7 with added sulphates and inert fines and batch 9, no sulphates but containing a potentially reactive sand. It would seem, therefore, that the abnormally high levels of sulphate does not affect the behaviour of the prisms in terms of expansion either at early stages or up to 23 weeks.

The behaviour of the cylinders was different as already noted. The overall expansion recorded for cylinders from batches 3 and 4 (range 5.4-6.0 mm/m and 5.7 mm/m average) is greater than that of the corresponding prisms (4.0-45 mm/m and 4.3 mm/m respectively). This has been attributed by other workers to how the expansion is measured relative to the direction of casting. Given that explanation then the results obtained here are in agreement i.e. greater expansion is given in the direction of casting.

The fact that batch 6 cylinders did not exceed the expansion of 3 and 4, unlike the corresponding prisms, is thought to be due to leaching out of some of the hydroxides. This is considered to be likely since the smaller cross-section of the cylinders would be liable to ion migrations and the greater frequency of cracking would also aid this process. The storage of the specimens, i.e. cylinders on their end and prisms face down on the floor of the water bath, may also be a contributing factor.

The UPV measurements were intended to detect and monitor ASR activity due to the formation of internal micro-cracks which, with all factors kept constant, should produce a reduction in pulse velocity. The initial increase recorded during the first six weeks or so is due to the continuing hydration of the cement producing a more dense matrix and water absorption. However, when this increase stops, as indicated by a departure from the expected pulse velocity given by the control batch 7, this can be interpreted as being due to ASR activity. This occurred at about 7 weeks which was some 2 to 3 weeks sooner than the first visual detection of surface cracks and any significant recorded expansion or weight changes.

UPV does therefore seem to be more sensitive at detecting the onset of ASR under laboratory controlled conditions. However, it is relatively insensitive at following the progression of the ASR induced expansion which is thought to be due to the cracks being filled with gel. The delayed onset of ASR in batch 6, as indicated by the later reduction in UPV relative to the main group, has already been discussed, but the lower final pulse velocity is presumably due to the greater overall expansion i.e. greater frequency and/or width of cracks.

Freeze-Thaw Testing

The disruption of F/T action is primarily due to the irreversible expansion caused by freezing concrete that is above the critical saturation point, normally taken to be 91.7% of its total saturation. The formation of ice crystals in the capillary pores generates pressure via a) hydraulic pressure as capillary pore solution is forced into the pore structure of the cement paste, and b) osmotic pressure caused by the increased ionic concentration of capillary pore solution (due to pure water being removed as ice) resulting in water moving into the capillary pore where it can be frozen enlarging the ice crystal further. Factors affecting this pressure include:

a) the permeability of the material through which the water is forced.
b) the distance from the capillary to avoid boundary.
c) the rate at which freezing occurs.

The latter can be assumed to be constant throughout the F/T testing adopted but (a) and (b) will be greatly influenced by the frequency, occurrence and nature of the ASR induced cracks. In theory their existence should provide escape routes to relieve the pressure generated by formation of ice crystals. However they should be partly or completely full of gel which at the lower temperatures may be quite viscous and hence resist pressure. The exact role that the ASR induced cracks will play in F/T exposure is therefore difficult to predict. What is obvious is that F/T does cause additional disruption as illustrated by Figure 5 where expansion has continued above and beyond that induced by ASR.

The mix used was designed to yield an approximate grade C50 concrete and a limited number of cubes were made and crushed at 6 months giving compressive strengths of 70 N/mm^2. Accepted wisdom is that concrete of such strength should not be susceptible to F/T action and this is borne out by the performance of prism 1/1 which, as already mentioned, only expanded 0.04 mm/m after approximately 180 cycles. The F/T disruption observed is therefore the result of the effect of the ASR induced expansion.

In real structures containing concrete capable of developing ASR, both disruptive mechanisms would be operating at the same time, at least during the winter months. It could be argued therefore that conducting the test in two distinct stages is not representative of real exposure. While this is true to a certain extent ASR susceptible concrete is more likely to suffer its greatest disruption from ASR activity during the non-freezing periods (and obviously no F/T attack) and vice versa.

The extent of the freezing should also be mentioned. The duration selected was of necessity short although with the benefit of hindsight a slightly longer F/T cycle might have been better. The depth of freezing would then have been more the -2^0C typically recorded at the centre of the dummy specimen which it was felt, whilst reflecting temperatures experienced by concrete structures, might not have been sufficient to freeze the pore solutions with their enhanced salt concentration and depressed freezing points due to being contained within a narrow pore.

The rates of disruption recorded were not constant and seem to be influenced by the extent of initial ASR induced damage. AT low levels, 1 to about 2.5 mm/m, the rate is progressive but reducing slightly until the total expansion reaches about 3 mm/m. At this stage the rate of disruption increased and is approximately linear with respect to the number of F/T cycles until the concrete approaches an expansion level of 5 mm/m or so. This marks the start of an unstable region where disruption becomes increasingly progressive causing spoiling and eventual disintegration.

CONCLUSIONS

Within the limited scope of this investigation a number of tentative conclusions can be drawn:

1) High strength concrete (C50+) that has been initially disrupted by ASR activity is susceptible to F/T action.
2) The initial level of ASR induced expansion, within the range 1 to 4 mm/m, does not influence the F/T susceptibility of concrete, but it does affect the rate of disruption.
3) At the lower levels of ASR induced expansion investigated the rate of F/T damage was less than that recorded for the higher values.
4) F/T attack of ASR affected concrete causes expansion in excess of that possible by ASR alone and will lead to eventual disintegration.

It should be borne in mind that the results obtained, and hence the conclusions drawn, are for plain unreinforced concrete and therefore might not be directly applicable to real structures.

Since this investigation also involved the development of ASR activity in concrete some secondary conclusions can be drawn:

1) ASR activity is governed by not just the total amount of alkalis present in the pore solution but also the Na/K ratio.
2) The form of additional alkalis introduced into a concrete can affect the rate and extent of ASR activity.
3) The extent of expansion caused is dependent on the direction of casting.
4) UPV is more sensitive to detecting the onset of ASR activity than expansion or weight changes.
5) Increasing the amount of restraint in concrete reduced the expansion caused by ASR.

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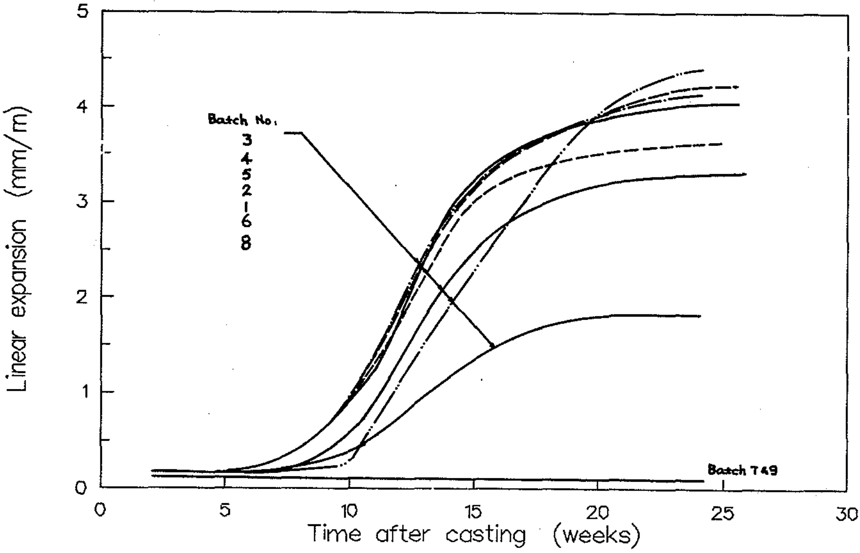

Figure 1 Batch average prism expansion measurements

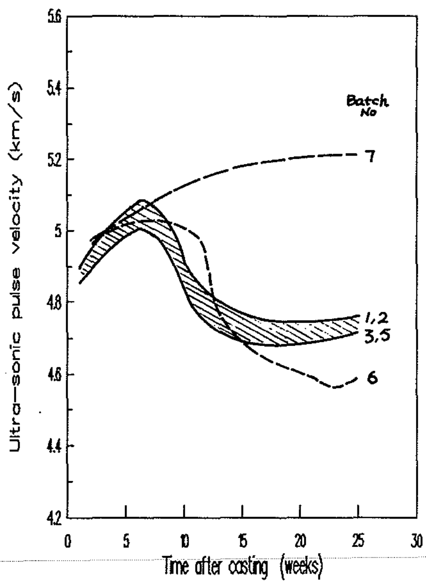

Figure 2 Batch average prism UPV measurements

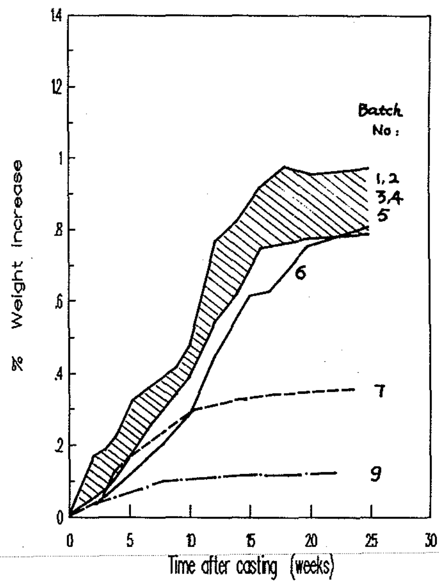

Figure 3 Batch average weight changes of concrete prisms

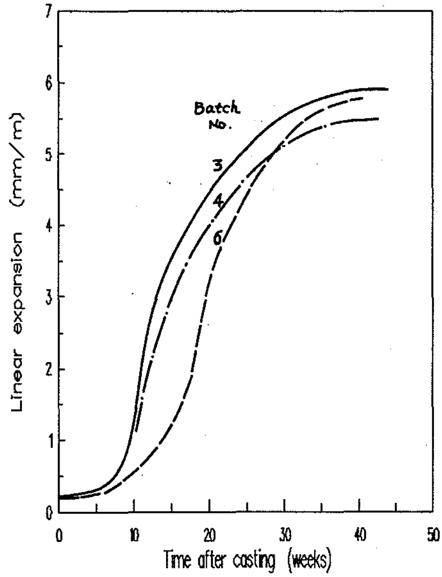

Figure 4 Batch average cylinder expansion measurements

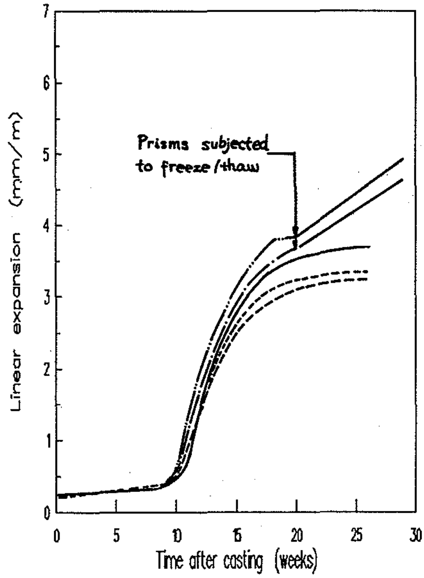

Figure 5 Expansion measurements of batch 1 concrete prisms

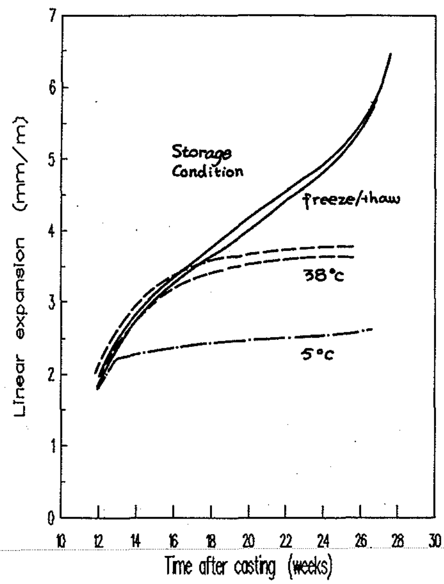

Figure 6 Expansion measurements of batch 2 concrete prisms