EVALUATION OF THE SUSCEPTIBILITY TO ASR OF CONCRETE MIXES CONTAINING MARINE DREDGED AGGREGATES

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A concrete prism expansion test has been used to evaluate the potential Alkali Silica Reactivity of combinations of siliceous aggregates. The effects of various aspects of the test method on the measured expansion have also been assessed. Large scale specimens have been exposed to an accelerated expansion test, demonstrating differential expansion between the surface and core. A mechanism for the origin of this differential expansion and its implication for observed ASR cracking in structures is proposed. The influence of the incorporation of PFA in concrete, on the reduction of measured expansion, is described.

INTRODUCTION

In support of the construction of the Sizewell B Nuclear Power Station, an extensive investigation was carried out using marine dredged aggregates, to establish the risk of deleterious expansion resulting from ASR. The study was initiated following the report (1) of a discrete example of ASR close to the location of Sizewell NPS. This was later identified as a Tank Block cast in the 1940s probably using beach sand and gravel and sea water and, therefore, not typical of structural concrete, and highlights the caution needed when evaluating examples of ASR. In addition to establishing the potential reactivity of the aggregates, the potential reactivity of concrete mix designs for use in structural elements has also been investigated. The programme was based largely on small scale concrete prism tests, but some large scale elements, representative of structural members, have also been tested. Tests using geologically similar land-won aggregates have also been included for comparative purposes.

At the start of the project in 1985, two test methods were considered, ASTM C289-81 (Chemical Method) (2) and ASTM C277-81 (Mortar Bar Method) (3), but previous experience with UK aggregates indicated conflicting results and poor correlation with observed performance in structures. Discussions were held with the Building Research Establishment (BRE), therefore, to identify a suitable test method. The, then current, draft British Standard method involved measurement of expansion of concrete prisms under accelerated conditions produced by increased levels of alkali and elevated temperature and this test was adopted. The test procedure has evolved throughout the project and the current procedure is described in a draft British Standard BS 812 part 123 (4).

The concrete prism expansion test may be used to evaluate a particular aggregate combination under standardised 'severe' conditions, using a high alkali reference cement (> 0.9% Na_2O equivalent), a high cement content (700kg/m^3), additional alkali if appropriate and an elevated temperature (38°C). This is the basis of the draft BS Test. Alternatively, the test can be used to assess the mix as a whole, by casting prisms with the Concrete Mix Design proposed for use in the structure (mix simulation). Acceleration of expansion can be achieved by increasing the temperature, increasing the level of alkalis in the mix or changing the source of one or other of the aggregate fractions. Both forms of testing have been undertaken in this test programme.

PRISM TEST PROGRAMME

The five stages of the test programme are summarised in Table 1. Mixes containing combinations of 2 coarse aggregates (A1, A2) and 3 fine aggregates (F1, F3, F4) were investigated. The fine and coarse aggregates (A1 and F1) used for Sizewell B were of marine origin, the remainder were land-won.

After 3 years, Stage 1 specimens exhibited no significant expansion regardless of mix design, alkali content (up to 6kg/m^3 with added KOH) or storage temperature. To determine the significance of this lack of

TABLE 1 - Outline of Overall Test Programme

STAGE	NO. PRISMS TESTED	NO OF MIX COMBINATIONS	ALKALI LEVEL (kg/m^3)	TOP UP ALKALI	STORAGE TEMP (°C)	COMMENTS
1	64	24	4, 6	KOH	20 38 65	Mix simulations based on then current BRE method (1985), mixes with and without 40% PFA. No significant expansions measured after 3 years.
2	16	6	6	KOH	20 38 65	Mixes without PFA incorporating combinations of proposed materials with inert coarse aggregates and known reactive sands. No significant expansion measured after 2 years.
3	24	2	7	KOH	20 38 65	Mix simulations without PFA.Modified storage conditions. Combinations of inert coarse/reactive fine and proposed materials. Insignificant expansion at 18 months.
4	52	25	3, 7	KOH K_2SO_4	38	Standard and simulated mixes to new draft BS (1987). Expansion of up to 3000 microstrain in reactive aggregate combinations. Differences in expansion due to different alkali contents and sources. PFA mixes show no expansion in 72 weeks.
5	16*	2	7	K_2SO_4	38	Expansion tests on prisms and large blocks to assess effects of scale and applied coatings.

* Including large blocks

expansion for aggregates with suspected ASR susceptibility, further tests were carried out (Stage 2) at the higher alkali content (again using KOH) on mixes incorporating a known reactive sand supplied by the BRE. Yet again no significant expansion was observed.

The evolution of the prism test method during the test programme indicated that higher total alkali contents were required to promote expansion and Stage 3 was undertaken at 7 Kg/m^3 Na_2Oeq (still using KOH) together with a modified storage regime (in pots similar to the current BS method). Again, no significant expansion was recorded after 18 months, even for aggregates of known reactivity. Since petrographic examination had suggested that the aggregates were potentially reactive and data from other laboratories using a further revision of the BS tests with K_2SO_4 in place of KOH also indicated the possibility of expansion, Stage 4 was initiated to establish the influence of the test method on measured expansion.

Various factors were investigated including:-

i) The alkali content of the Portland Cement
ii) The source of the 'Top Up' alkali, either potassium sulphate (K_2SO_4) or potassium hydroxide (KOH) added to the mix
iii) The relative quantities of alkali contributed by the cement and the top up source
iv) The aggregate source
v) The effects of PFA addition

Testing was carried out broadly in accordance with the draft Prism Test Method (4), using mixes with 700kg/m^3 of high alkali cement. A cement with a sodium oxide equivalent of 0.90% was used (Cement A).

To achieve the above objectives, it was necessary to depart from the standard mix proportions in some cases. Principally, this involved the use of the lower alkali cement used at Sizewell (0.67% Na_2Oeq Cement B) and some mixes with a cement content of only 350kg/m^3. By maintaining the overall alkali content at 7kg/m^3 Na_2Oeq and changing the cement type and content, the relative effects of alkalis from the cement and the top up source could be assessed. In addition, the alkali levels of some mixes were adjusted using KOH, as recommended in the earlier draft BS. Mix simulations containing 40% PFA were also investigated. On completion of Stage 4, selected prisms were examined using both optical and SEM techniques in order to confirm that the cause of any observed expansion was indeed ASR.

STAGE 4 TEST RESULTS

The mean prism expansions up to 72 weeks are presented in Table 2. Mixes 1-4 are almost identical to mixes 5-8, the only difference being the source of cement. All eight mixes have the same total alkali content of 7kg/m^3 Na_2O eq and use the same aggregate combination. These mixes examine the effects of cement content and source and top-up alkali type and content. Mixes 9-12 were fully compliant with the draft BS test (4), and were intended to assess the effects of different aggregate combinations.

TABLE 2 - Stage 4 Test Programme

MIX	CEMENT TYPE	CEMENT (kg/m^3)	% PFA	ALKALI TYPE	ALKALI kg/m^3 NaOeq	AGGREGATE TYPE		EXPANSION (x10^{-6})						
						Fine	Coarse	2 wk	4 wk	12 wk	24 wk	36 wk	52 wk	72 wk
1	B	350	-	K_2SO_4	7	F1	A1	-11	4	417	475	475	493	482
2	B	350	-	KOH	7	F1	A1	-8	4	-3	-2	0	21	7
3	B	700	-	K_2SO_4	7	F1	A1	-43	-40	-3	25	54	82	79
4	B	700	-	KOH	7	F1	A1	-7	-4	11	21	36	43	32
5	A	350	-	K_2SO_4	7	F1	A1	-114	-78	867	1014	1022	1046	1036
6	A	350	-	KOH	7	F1	A1	-60	-32	96	157	140	171	164
7*	A	700	-	K_2SO_4	7	F1	A1	14	50	339	1261	1600	1704	1757
8	A	700	-	KOH	7	F1	A1	22	88	442	1454	1718	1761	1786
9*	A	700	-	K_2SO_4	7	F1	A1	40	71	328	1193	1572	1668	1661
10*	A	700	-	K_2SO_4	7	F3	A2	32	86	1360	2993	3125	3179	3182
11*	A	700	-	K_2SO_4	7	F3	A1	25	64	300	1396	1722	1818	1871
12*	A	700	-	K_2SO_4	7	F4	A1	48	127	223	713	924	977	1009
24	B	408	40	KOH	3	F1	A1	11	-2	-82	-61	-65	-71	-71
13	B	408	40	KOH	3	F1	A1	-9	-23	-2	-34	-23	-37	-23
14	B	408	40	KOH	7	F1	A1	-11	-29	-25	-43	-43	-36	-32
15	B	408	40	KOH	7	F1	A1	57	40	171	157	132	161	132
16	B	368	40	KOH	3	F1	A1	14	-4	4	-11	-25	75	50
17	B	368	40	KOH	7	F1	A1	-15	-42	-83	-70	-77	-48	-63
18	B	368	40	K_2SO_4	7	F3	A2	-80	-49	-104	-84	-86	41	-59
19	B	368	40	K_2SO_4	7	F3	A1	-64	-43	-82	-72	-79	-54	-68
20	B	368	40	K_2SO_4	7	F4	A1	-32	-40	-86	-93	-90	-79	-93
21	B	368	40	K_2SO_4	3	F3	A2	-32	-57	-74	-74	-72	-64	-79
22	B	368	40	K_2SO_4	3	F3	A1	-6	-11	-36	-38	-25	-27	-25
23	B	368	40	K_2SO_4	3	F4	A1	-2	-43	-36	-68	-57	-41	-54
25*	A	700	-	K_2SO_4	7	F3	A2	59	54	990	2802	2977	3004	3028
26	A	700	40	K_2SO_4	7	F3	A2	-10	-35	-21	-28	11	11	5

Negative values indicate prism shrinkage
*Mixes fully compliant with BS 812 pt 123 draft

Influence of Cement Source. Expansions for mixes 1-4, with the low alkali Cement B used at Sizewell, were generally insignificant (Table 2), although mix 1, with a low cement content and high addition of potassium sulphate, achieved almost 500 microstrain. This expansion had largely occurred at 12 weeks, with little expansion thereafter and may have resulted from ettringite formation.

Using the high alkali Cement A with the same aggregate combination (and the same total alkali content) resulted in substantially higher expansions (Figure 1). This illustrates that expansion is not related solely to the total alkali content, and suggests that the alkalis originating in the cement make a more significant contribution to expansion than do the top-up alkalis (Figure 2).

Influence of Additional Alkalis. Mixes 1, 3, 5 and 7 are almost identical to mixes 2, 4, 6 and 8, the odd number mixes using K_2SO_4 as the top-up alkali, while the even number mixes used KOH. For the high cement content mixes (3 and 4; and 7 and 8), all of which required a relatively small quantity of top-up alkali, the difference in expansion as affected by the type of alkali added, was not significant. However, for the low cement content mixes (1 and 2; and 5 and 6), which required higher additions of top-up alkali, the difference was substantial. The two mixes containing K_2SO_4 yielded expansions of 482 and 1036 microstrain respectively, compared with only 7 and 164 microstrain for the mixes containing KOH.

Influence of Cement Content. From mixes 1-8, four mixes had a high cement content of 700kg/m^3, whilst the remaining four contained just 350kg/m^3. In most cases, comparable mixes exhibited higher expansions at higher cement contents. The only exceptions were mixes 1 and 2, where the high level of added K_2SO_4 resulted in much higher expansion in the lower cement content mix, possibly due to ettringite formation.

Expansion Characteristics. Two distinct types of behaviour were exhibited by those concretes which did expand. For mixes which contained a low cement content and high proportion of K_2SO_4 (mixes 1 and 5), the expansion occurred within the first 12 weeks, with no significant change thereafter. For those mixes which contained a higher cement content and a smaller amount of K_2SO_4, the expansion was more gradual, but ultimately higher, and continued up to about 52 weeks. The principal factor influencing the rate of expansion appears to be the quantity of added K_2SO_4, again suggesting that the mechanism may have been sulphate attack. Rapid expansion, followed by little change thereafter is a characteristic of prisms tested for sulphate attack (5).

Influence of Aggregate Combinations. Mixes 9-12 examined different combinations of coarse and fine aggregates. The purpose of these tests was twofold. Firstly, to verify that the BS test could discriminate between different aggregate combinations and, secondly, to classify the aggregate combinations in order of potential reactivity.

The combination of coarse aggregate A2 and sand F3 was clearly the most reactive, expanding by over 3000 microstrain in 72 weeks (Figure 3). The remaining mixes in this series contained coarse aggregate A1 in combination with 3 different sands. In combination with sands F1 and F3, the measured prism expansion was similar. With sand F4, expansion was approximately halved indicating clear discrimination between the performance of the different aggregate combinations.

INFLUENCE OF PULVERISED FUEL ASH (PFA)

All structural concrete for Sizewell B includes PFA, and PFA mixes have been investigated in each stage of the programme. There is still considerable debate in the UK about the benefits of PFA in reducing the risk of ASR, concerned primarily with the degree to which PFA contributes alkalis to the concrete. Based on research by Hobbs (6), using highly reactive opaline material, a contribution from PFA of $^1/_6$th of the acid soluble alkalis has been adopted in some UK specifications, and this value has been endorsed by the Cement Manufacturers and the Building Research Establishment. The authors are of the opinion that this is an over-conservative assumption resulting from tests which have introduced non representative behaviour, by creating a situation in which expansion occurs before the PFA has reacted to reduce the alkali content of the mix, as demonstrated by the results of Nixon et al (7). Furthermore in tests on many UK aggregates (7,8), PFA has been found to consistently eliminate deleterious expansion. In addition to the effect of the PFA in reducing the alkali level of the pore water as the pozzolanic reaction proceeds, the nature of the gel formed in a PFA system is of much lower calcium/silica (c/s) ratio than in OPC systems and it has also been shown that this low c/s ratio gel is more soluble and less expansive (9). Hence, even if gel is formed, significant expansion is unlikely.

Results obtained during the current investigation confirm the benefits of PFA in eliminating deleterious expansions. Having identified a highly reactive aggregate combination, with reproducible expansion in the Draft BS Prism Test, this was used to establish the effectiveness of PFA used to partially replace 40% of the OPC on a weight for weight basis. The alkali level was maintained at $7kg/m^3$ using K_2SO_4, assuming a contribution from the PFA of $^1/_6$th of the acid soluble alkali. The results, shown in Figure 2, demonstrate the ability of PFA to eliminate expansion, within the constraints of the materials and mixes used in this study.

It is also important to note that the effect of scale, discussed subsequently would also act in favour of PFA concretes, the long delay before expansion occurs in the bulk allowing the pozzolanic reaction to develop more fully.

EFFECT OF SCALE

The Stage 5 study was carried out to investigate the rate and magnitude of expansion in specimens of a size more representative of structural elements. Table 3 gives details of the specimens tested, the largest of which were 1x1x2m. The full range of four specimen sizes were cast using the simulated site mix, while the reactive mix (mix 10) was cast into two standard prisms and two 0.5x0.5x1.0m blocks only.

The specimens were stored in a purpose built chamber, maintained at a temperature of 38°C, and intermittently sprayed with recirculated water to keep their surfaces wet while avoiding leaching of alkalis. Strains were measured both internally, using embedded Vibrating Wire Strain Gauges (VWG's), and on the surface using a Demec demountable gauge. Measurements are reported here up to one year, but the tests are continuing. To date the simulated site mix, with an increase in alkali content to $7kg/m^3$ using K_2SO_4 has exhibited a net contraction, up to about 100 microstrain, confirming the results from earlier prism tests with PFA concretes.

TABLE 3 - Details of Scaling Test Specimens

Mix	Size	Comments
10	285mm x 75mm x 75mm	*Coated Lab Control Prism
10	285mm x 75mm x 75mm	Uncoated Lab Control Prism
10	1m x 0.5 x 0.5	Test Block
10	1m x 0.5 x 0.5	*Coated Test Block
Site	285mm x 75mm x 75mm	Lab Control Prism (x6)
Site	2m x 1m x 1m	Scaling Test Blocks (x2)
Site	1m x 0.5m x 0.5mm	Scaling Test Blocks (x2)
Site	0.5m x 0.25m x 0.25mm	Scaling Test Blocks (x2)

* Epigrip M253.

Significant expansions were exhibited by the reactive mix in the 0.5x0.5x1.0m block, as shown in Figure 4, but the strains were much less than recorded in the standard prisms. The expansion was greatest at the surface, reducing to the centre as shown in Figure 5. This might be expected, as the surface zone has preferential access to the water. However, while the surface has expanded by more than 1000 microstrain, no cracking has been observed. This is because the surface expansion is restrained by the bulk of the concrete which is receiving less water and is expanding more slowly.

If the above process occurs in the field then the map cracking, which is commonly associated with ASR, may be difficult to explain. However, if the mechanism is considered over longer periods, a process leading to map cracking can be developed.

Firstly, the restrained expansion which occurs at the surface generates compressive stresses in a relatively thin skin, in this case about 50mm or so, and this must be balanced by tensile stresses in the bulk. The average tensile stresses will be much lower than the average compressive stresses due to the ratio of areas (in a 500 x 500 section, the ratio is about 2:1). With time, the compressive stresses at the surface, and their balanced tensile stresses will be relieved by creep. Although the authors are not aware of any data for creep in ASR affected concrete, based on general knowledge of creep in concrete, it may be assumed that it is higher than in unaffected concrete. Hence, with time the surface compressive stresses reduce substantially, while moisture is slowly migrating beyond the surface zone, which by now has imbibed its full capacity. At a later stage, dependent on the rate of moisture movement, the bulk begins to expand against a surface skin which is now in a state of relatively low compression. The residual compressive stresses are overcome relatively quickly due to the relative area ratio being in favour of the expanding bulk, and with continued bulk expansion, the surface cracks.

The above mechanism explains why cracking may take many years to occur in a structure even though a prism specimen may crack in a few months. The delay in cracking occurs not necessarily because gel takes a long time to form, but because it takes a long time for moisture to penetrate beyond the surface zone. This mechanism is analogous to a thermal stress problem in which the material has a very high value of specific heat and density (ie, very low diffusivity) and high creep. Further studies are being undertaken to examine this hypothesis and if valid, the analysis of stress development may be used to determine when cracking is likely to occur in structures and more importantly, to select appropriate measures to avoid the problem.

CONCLUSIONS

Within the context of the results obtained it has been concluded that in concrete prism tests, the alkalis originating from the cement make a more significant contribution to expansion than do 'top-up' alkalis. Furthermore, the composition of the top-up alkali influences the measured expansion with K_2SO_4 being more effective than KOH.

The effectiveness of PFA in eliminating deleterious expansion was confirmed, even in concretes made using reactive aggregate combinations and a high total alkali content.

In large scale specimens, the rate of potential surface expansion was much greater than that of the internal bulk and the overall expansion was much less than that measured in standard prism tests. A hypothesis has been developed which may explain the difference in time to cracking between prisms and structures, based on stress development and redistribution in thick sections.

Although, in standard prism tests, the aggregates used for Sizewell B have been identified as potentially reactive, the use of a relatively low alkali OPC, in conjunction with PFA has resulted in concrete mixes with insufficient alkalis for deleterious expansion to occur.

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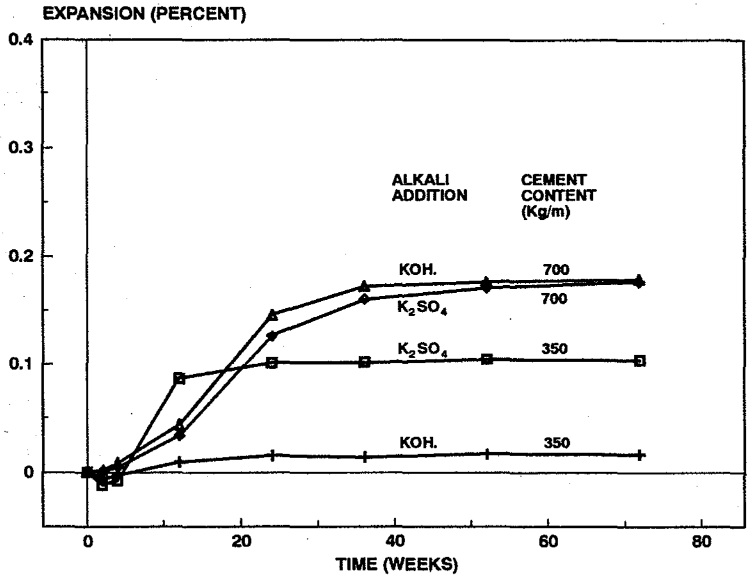

Figure 1. Comparison of the effects of Cement (A) content and top-up alkali type on mixes with 7kg/m^3 total alkali.

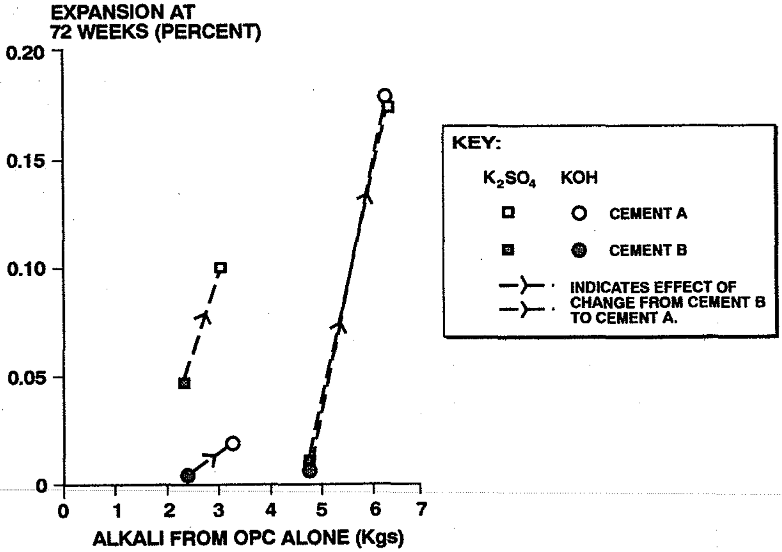

Figure 2. The relationship between 72 week expansion and the alkali contribution from OPC alone.

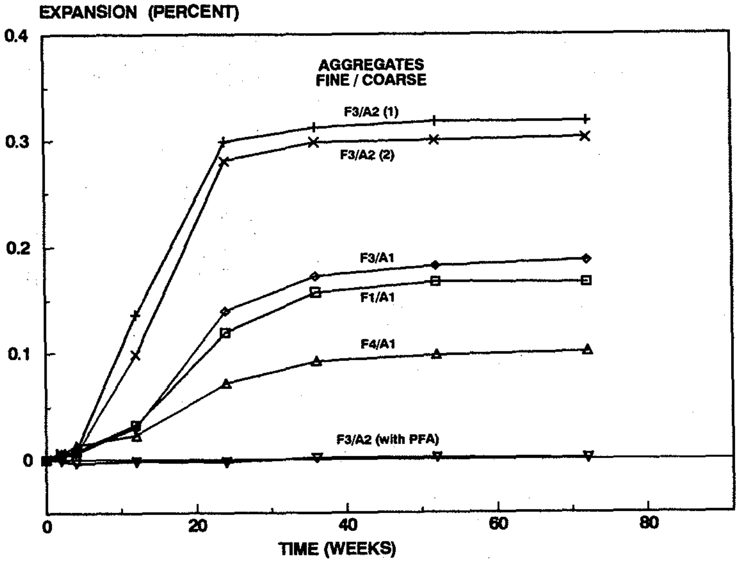

Figure 3. Measured expansion for different aggregate combinations using the BS prism test. (PFA mix also included).

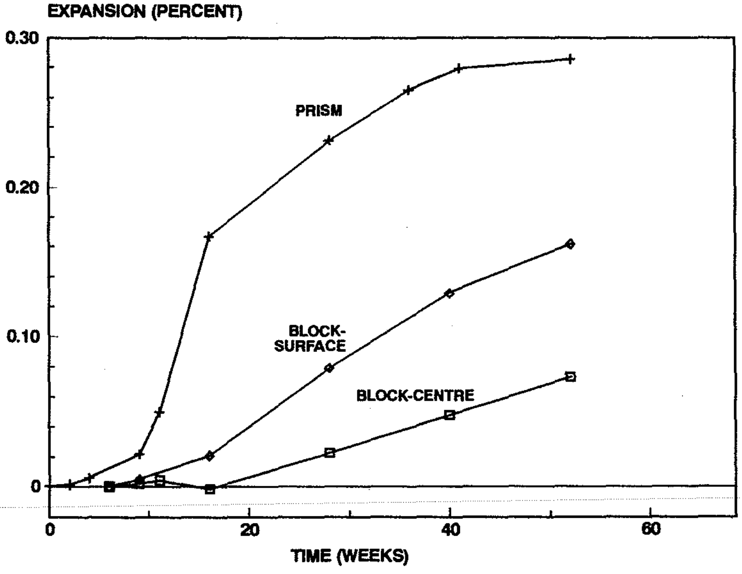

Figure 4. Expansions for reactive concrete (mix 10) measured in BS prisms and a 0.5x0.5x1m block.

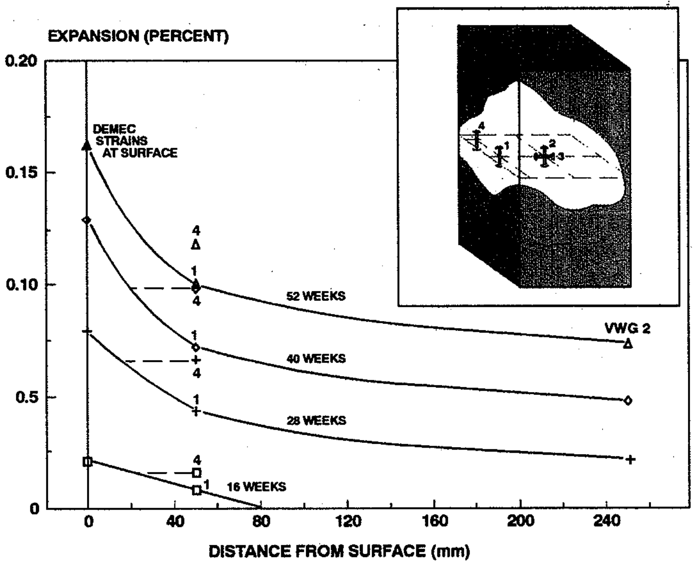

Figure 5. Variation of expansion through a 0.5x0.5x1m block using the reactive concrete.