ALKALI - AGGREGATE REACTION
IN A CONCRETE WATER STORAGE TANK

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ABSTRACT:
A large reinforced concrete water storage tank, built in 1982, has shown signs of distress in the form of map-cracking in the walls, and vertical cracking in many of the 42 internal columns supporting the roof of the tank. The cracking was noted 4 years after the tank was constructed and has progressively worsened.
The cracking was most severe in the cylindrical columns, but was also evident in the walls of the structure. A second tank of similar age is also exhibiting the same symptoms.
Cores were extracted from various parts of the structure for diagnostic purposes using petrographic methods, scanning electron microscopy, and evaluation of residual expansion of the concrete.
The investigations have shown that the schistose hornfels aggregate used in the concrete has undergone a severe alkali-aggregate reaction, causing the observed cracking. The residual expansion of the cores appeared low and indicated that the reaction has probably levelled off, and that remedial action can be contemplated. Preliminary steps taken towards repairing the structure will also be discussed.
Keywords: Alkali-Aggregate reaction, expansion, Cracking, Concrete Water Tank.

INTRODUCTION:
A large reinforced concrete tank approximately 41 metres in diameter and 5 metres high is a major component in potable water storage for the City of Mildura. The tank has a wall thickness of 300 mm and contains 42 columns, of 500 mm diameter, concentrically arranged in three circles on which the 300 mm thick roof of the tank has been cast. The roof has been cast so that it rests on the columns and the wall of the tank but is not integral with the walls. The columns are sitting on reinforced ring beams (platforms) of 2400 mm diameter. The floor of the tank is 150mm thick reinforced concrete. The construction of the tank was completed in 1982 and cracking of the columns and walls was noticed in 1986. The cracking progressively became more evident.
The columns have developed more severe cracking than the walls. Some cracking features of the water tank are illustrated in Figure 1. Another tank of the same age is also showing the same symptoms. Alkali- aggregate reaction (AAR) was suspected as a possible cause of cracking.
Records kept of the construction project revealed the concrete mix to contain 380 kg/m³ of a general purpose Portland cement. This cement is known to be of high alkali content, generally above 0.8 % Na_2O equivalent, although the alkali content of the cement used has not been recorded. The coarse aggregate was an imported schistose hornfels and the fine aggregate a local fine river sand. The water/cement ratio was 0.45 and the average concrete slump 55 mm. The concrete also contained a water reducing chemical additive (Embecon ALF30) at a dosage rate of 400 ml/100 kg cement. The chemical composition of this admixture is not available.
The purpose of this study was to identify whether AAR was the cause of the observed cracking and accordingly propose some remedial action to prevent further deterioration of the structure.
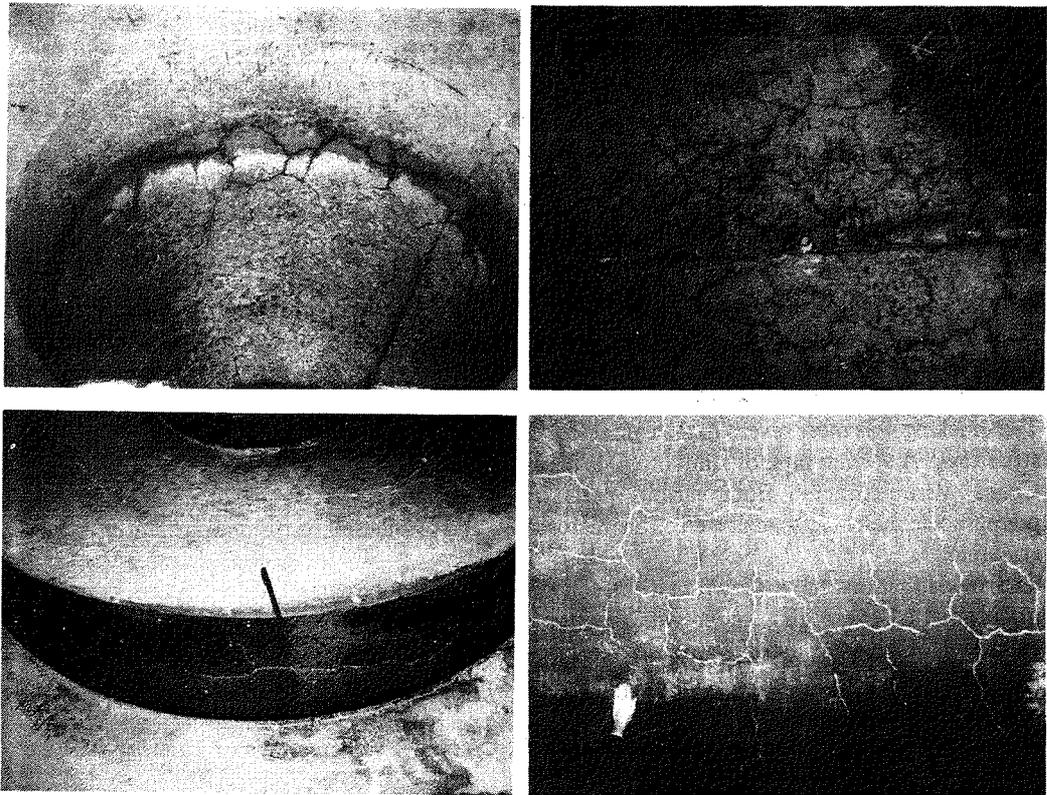
Figure 1 - Some cracking features of the various parts of the water tank. Clockwise from left: cracked column, column ring beam, top of column joining the ceiling, the ceiling and wall. Cracks in columns are wider than other cracks.
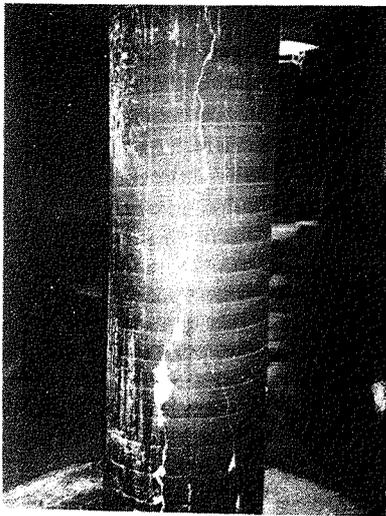
EXPERIMENTAL WORK

Samples of the coarse and fine aggregates were obtained from the same sources as the original materials, and tested independently for alkali- reactivity. Core samples 100mm in diameter and varying in length, depending on their location, were taken from various parts of the tank. Table 1. shows the location of the cores and the condition of the concrete zones sampled. The drilled cores were used for petrographic examination and measurement of their residual expansion. The petrographic examination included preparation of thin sections from slices of concrete sawn from the cores and impregnated with a yellow-stained, fluorescent epoxy resin to show up the micro cracking. Scanning electron microscope (SEM) examination of the concrete specimens was done on the concrete slices, that included the fracture surface of the cores, where reaction rims and gel products were evident.

MORTAR BARS - ACCELERATED TEST
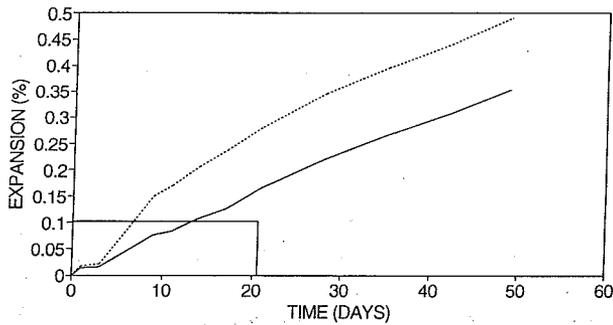
Figure 2. Accelerated mortar bar test results for the coarse (dotted line) and fine (solid line) aggregates showing them to be potentially reactive. Time refers to $N^{\underline{o}}$ of days in 1M NaOH solution at 80°C.

Figure 3. View of a fracture surface of a core showing reacted aggregate particles with dark outer rims and white inner rims. The matrix is impregnated with AAR gel. A void on the LHS is filled with white AAR product.
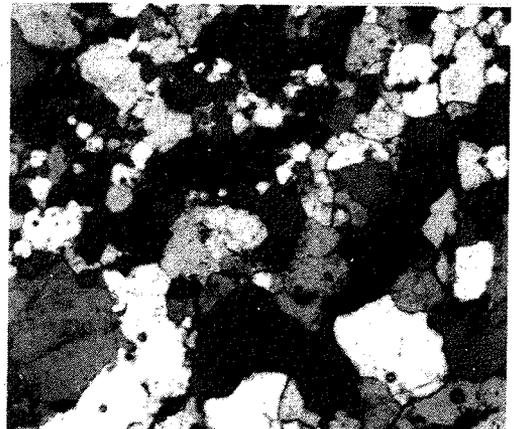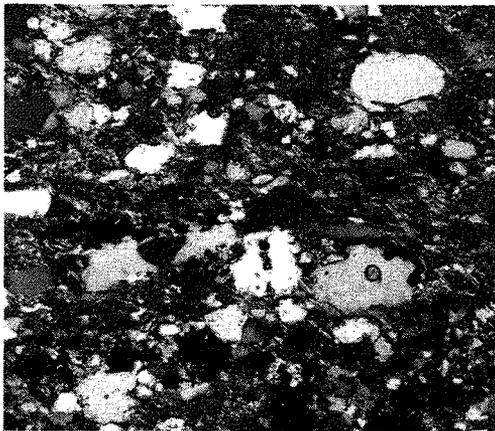
Figure 4. Some petrographic features of the reactive hornfels in cross polarized light showing schistosity and varying grain size (left) in a matrix of chlorite and mica, and bands with quartzitic features (right). Cordierite was sometimes completely sericitised in a fine quartz, mica, chlorite matrix (magnification 37 x).

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Table 1. - Location of core samples.

Core No.	Location	Condition
1	Drilled from the roof into the top of column 17	Minor crazing on roof top
1a	Drilled 300 mm away from core 1 into column 17	Minor crazing on roof top
2	Drilled externally from wall near column 17	Crazed
3	Platform at base of Column	Cracked
3a	Near Core 3	Cracked
4	Shoulder height on Column 2	Cracked
5	Drilled from floor into ring beam under Column 2	Widely spaced cracks
6	Base of Column 12	No visible cracking

For the measurement of the residual expansion potential of concrete, cores of suitable length were trimmed to a length of 150 mm, and two sets of demec disks were glued to each core (on opposite sites) with a gauge length of 100mm. A moisture and alkali-resistant epoxy resin was used for gluing the demec disks and allowed to harden for one week. The cores were then immersed in a solution of 0.5 M NaOH solution for 24 hours at 23°C before taking the initial length reading. After this treatment the cores were wrapped in a wet cloth and then in plastic sheeting and stored over water in sealed containers at 40°C. Two segments of 150 mm length were cut from Core 6, one was soaked in 1 M NaOH and the other wrapped in a wet cloth and plastic sheeting (both at 23°C), with the initial length reading taken 24 hours later. These were then stored at 40°C for monitoring their expansion. The core specimens were allowed to recover overnight at 23°C before each expansion measurement. The reason for soaking the specimens in 0.5 M NaOH was to allow the specimens to absorb moisture so that this is not counted towards AAR-related expansion, and at the same time not to unduly dilute the pore solution of concrete, which usually contains a high concentration of alkali hydroxide. This depends on the alkali content of the cement used. A cement of 0.8% Na_2O equivalent could result in a pore solution concentration of about 0.6 M NaOH in a mortar with sand/cement ratio of 2 and water/cement ratio of 0.5 under sealed conditions. The soaking treatment was thought appropriate for the concrete of the water tank which is constantly in contact with water and remains wet.

RESULTS AND DISCUSSION

Aggregate Specimens: The coarse and fine aggregates originally in the concrete were allegedly required to comply with the then Australia Standard test methods AS 1465 (outdated) but no problem with alkali reactivity of the aggregates had been established. It must be noted that the alkali-reactivity tests included even in the current Australia Standard methods AS 1141-38 (mortar bar test) and AS 1141-39 (quick chemical test) have been shown to be inappropriate for determining the alkali-reactivity of many Australian aggregates (Shayan, 1992). The newly acquired aggregate samples were tested according to the more suitable test procedure and criteria developed for Australian aggregates (Shayan et al. 1988) consisting of storage of mortar bars in 1M NaOH solution at 80°C for 21 days. Expansions of 0.1% or greater at 10 days of storage in the NaOH solution indicate reactive aggregate and the same level of expansion at 21 days of storage in the NaOH solution indicates slowly reactive aggregate. Expansions less than 0.1% in 21 days indicate non-reactive aggregate.

Figure 2 shows that the schistose hornfels is classed as reactive and the river sand as slowly reactive. Therefore these aggregates would not have been accepted for use in concrete, without adequate precaution, had the new test method and criteria been in effect at the time of construction. As a matter of interest the more reactive coarse aggregate was subjected to the chemical test (AS 1141-39) and was erroneously classed as innocuous (Sc=33 and Rc=31 m moles/l)

Concrete Specimens: Most cores showed fracture surfaces that contained aggregate particles with distinct reaction rims and much gel on the mortar phase (Fig. 3.). Some of the aggregate particles on the sides of the cores were internally cracked which sometimes extended into the matrix.

a) **Microscopic Examination**
Thin sections made from the various cores have shown the coarse aggregate to be a fine-to medium-grained schistose rock containing quartz rich bands with foliated mica (biotite and muscovite) and other bands containing foliated biotite, muscovite, chlorite quartz and cordierite. Some cordierite grains were seen to be completely sericitised. Some quartz grains showed a small degree of undulatory extinction. Figure 4 shows some of the petrographic features of the reactive hornfels.
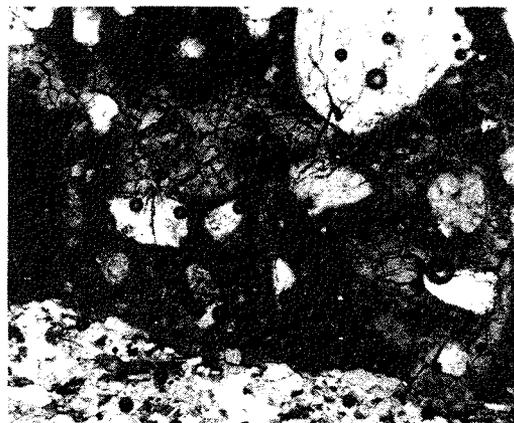The metamorphosed nature of the rock and the microcrystalline nature of the quartz may have made the aggregate reactive to alkali in the concrete. The presence of large amounts of mica in the aggregate implies that some potassium may have been contributed to the concrete from the aggregate, increasing the concentration of alkali-hydroxide in the pore solution of the concrete, and providing more favourable conditions for AAR to occur.
Figure 5 shows the presence of AAR gel in thin sections of the cores, occurring both at the aggregate interfacial zone (Fig 5A) and in the matrix (Fig 5B) probably filling micro-cracks. The sand grains also appear to have reacted although the observed AAR gel may have originated from the nearby coarse aggregate (Fig 5B,bottom). The AAR gel has also filled air bubbles in the vicinity of the reacted particles (Fig 5C).

Figure 5. *Some Petrographic features of the AAR-affected concrete in plane polarised light (magnified 40x).*
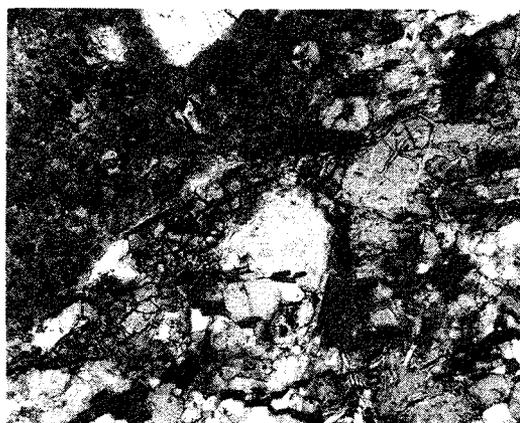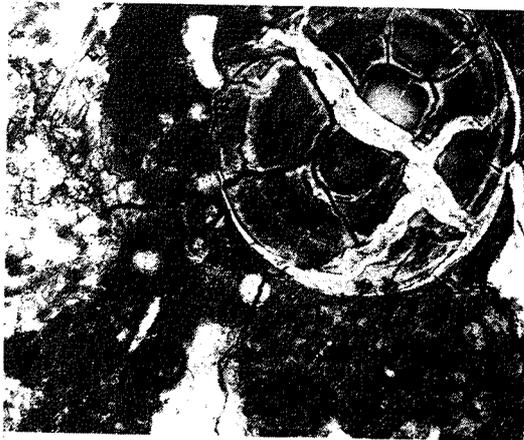

(5A)   *gel at aggregate/matrix interface*   (5B)   *gel in the matrix near sand grains*
   *and above coarse aggregate*
(5C)   *pore filled with AAR gel from the coarse*   *(bottom)*
        aggregate on the LHS (next page)

(5C)

Scanning electron microscopy of specimens taken from the cores revealed various morphological features of the reaction products. Figure 6 shows both amorphous AAR gel and crystalline products, the latter often forming in the white inner rim observed around reacted coarse aggregate. Energy dispersive X-ray analysis of the AAR products showed that the gel in contact with the mortar phase was richer in Ca than K, whereas the crystalline products are very rich in K. All the cores contained AAR products similar to those in Fig 6 although the amount of gel in the visually uncracked column was much less, and no crystalline product was detected. The latter forms in the more advanced stages of AAR, such as in the cracked columns and the wall of the tank. Occasionally, some mats of ettringite were found at the aggregate interfacial zones and in air bubbles, but this has no connection with the cracking of the concrete. These AAR features are the same as those observed in many AAR-affected concretes in Australia and around the world.
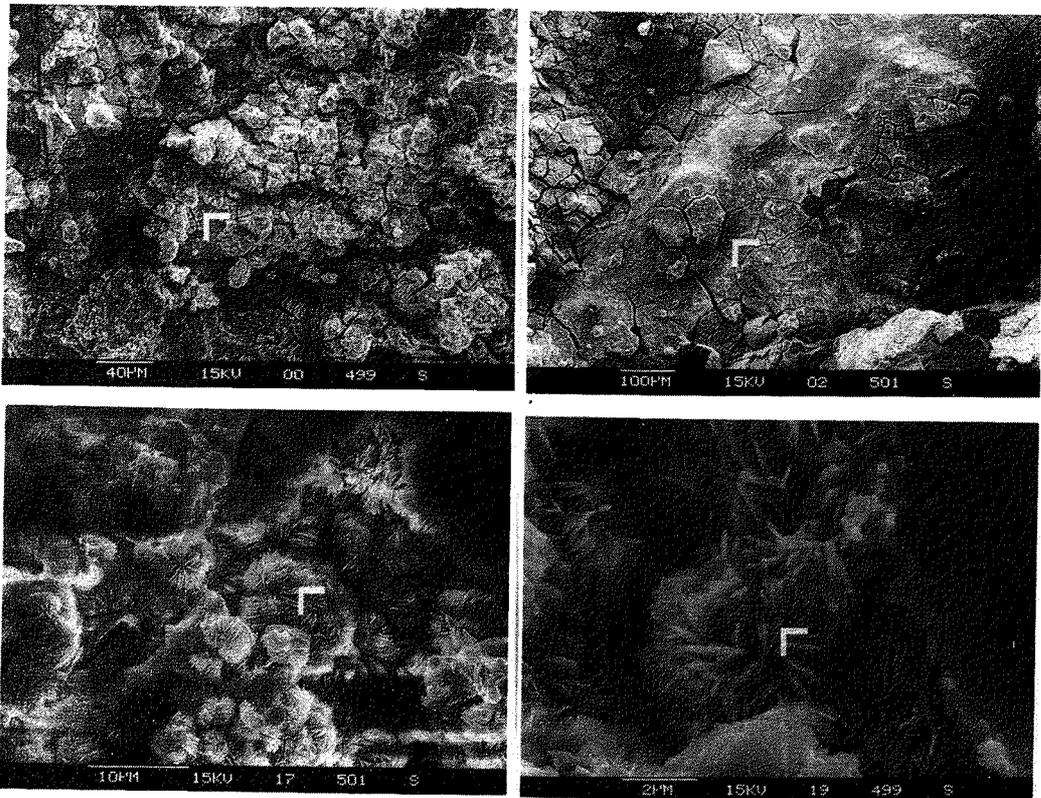
Figure 6. Representative morphological features of AAR gel (top) and crystalline products (bottom). The gel contains high Ca due to contact with the matrix, whereas the crystalline products are high in K.

RESIDUAL EXPANSION OF THE CORES

Results of expansion measurements on cores up to 68 weeks are represented in Figure 7.

Cores 1 and 1a behaved similarly, with a trend of continuing gradual expansion, although Core 1 which had a piece of reinforcement bar expanded less than Core 1a without any reinforcement piece. The initial faster rate of expansion may have been due to water absorption by both the AAR gel and the cementilious phase, but the gradual expansion is likely due to continuing AAR. Core 2 from the exterior of the wall showed a high initial rate of expansion which levelled off over a few weeks. This probably means that despite the presence of reacted aggregate, the moisture supply was inadequate in the structure, but when exposed to more water rapid expansion took place. However it is not possible to translate this behaviour to that of the heavily reinforced wall of the tank. The presence of reinforcement has a considerable effect on restraining the AAR expansion (Hobbs 1988). Cores 3, 3a and 5, all from reacted zones inside the tank, showed a rapid initial expansion over the first four weeks, probably due to moisture uptake, which levelled off and did not continue, indicating little residual expansion potential from such zones. For Core 6, the piece continually soaked in 1 M NaOH solution is continuing to expand, indicating the presence of reactive components, and the piece that was only kept moist without soaking continues to expand at a very slow rate, but this may not result in cracking in the column itself. The shape of the expansion curves for the cores together with the fact that the structure is reinforced indicates that future expansion of the concrete in the structure would probably be low, and that remedial measures could be taken to prevent further deterioration of the cracked concrete, without much risk of re-cracking.
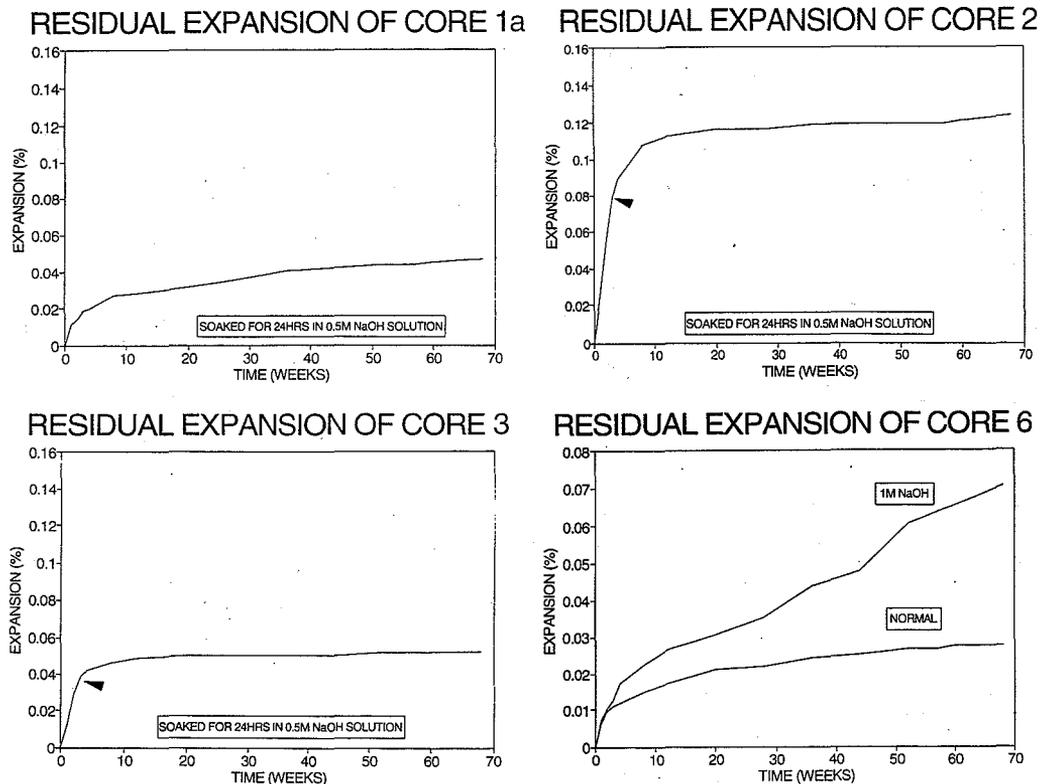
Figure 7. Residual expansion of representative cores initially treated as indicated, then wrapped in wet cloth and plastic sheeting and stored over water at 40°C in sealed conditions.

REPAIR OF THE WATER TANK

The element of the tank which has exhibited the greatest degree of cracking has been the cylindrical columns with pattern cracking towards the top and multiple single vertical cracks typically 1.0 mm wide along the length of column. The roof, walls and floor have a varying degree of cracking over their surface area and are best described as hair line in width. So far only the columns have had a repair/protective treatment.

This treatment has been applied for two reasons :-

- To restrict the water supply to columns and prevent further AAR expansion
- To prevent or reduce corrosion of the steel reinforcement

As the AAR reaction is water dependent it was decided to encase each partially dried column in a waterproof membrane. This approach will probably meet the two criteria above.

The technique used was :-

- drain the tank
- clean the column surface with a fine grit blast
- dehydrate the structure internally by allowing it to dry under forced ventilation and heat for a period of 28 days
- apply a fibreglass coating

The effects of this treatment is currently being monitored.

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