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CRACKING IN PRECAST, PRESTRESSED DECK PLANS IN TWO RTA BRIDGES: CAUSES OF CRACKING, CONCRETE CHARACTERISTICS AND REHABILITATION OPTIONS

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ABSTRACT

Precast, prestressed concrete (PSC) planks in the decks of two RTA bridges, referred to MC and BC bridges, have exhibited cracking in the soffit of the planks and alkali-aggregate reaction (AAR) was suspected. Two PSC planks from each bridge have been examined to identify the causes of the cracking and determine their remedial needs based on the residual strength and residual expansion properties.

Based on petrographic examination and scanning electron microscopy, strong AAR was found to be the cause of cracking for both bridges. Investigation of strength properties of the concrete cores showed that significant loss in strength properties had occurred, of the order of 30% in compressive strength and up to 50% in elastic modulus. Residual expansion of the cores was determined in the laboratory under conditions of elevated temperature and humidity, and it was found that the expansion potential of the cores examined was relatively small.

The in-situ cast columns of MC bridge were also examined and found to be free of AAR, of adequate strength and in sound condition. Options for the rehabilitation of the structures have been discussed. Remedial action would need to consider the economy of replacement of the whole deck. Strengthening of the affected planks using recently developed retrofitting techniques may not be a desirable long-term option for these particular structures.

Keywords: alkali-aggregate reaction, prestressed concrete, cracking, concrete strength, expansion

1. INTRODUCTION

Recently some bridges under the control of the Roads and Traffic Authority (RTA) in New South Wales have been identified in which prestressed, precast concrete planks have shown signs of distress in the form of longitudinal cracking and exudation of white materials which cover parts of the soffit of the deck planks. Alkali-aggregate reaction (AAR) was suspected as a cause of cracking. The planks are typically about 11.8 x 0.6 x 0.35 m and are placed 10 mm

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apart over each span to form the deck. The spaces between the planks are filled with a sealer, and a layer of in-situ cast concrete (around 140 mm) forms the wearing course of the deck.

The cracking of the deck planks may influence the load-bearing capacity of the decks, and this paper reports on an investigation undertaken on two of the bridges to find out the causes of cracking and to determine the current properties of the concrete to assist with decision making on appropriate remedial measures for the decks.

Although columns in the two bridges are, at present, free of cracking, they were also included in the investigation to determine whether or not they would develop cracking in the future.

2. THE BRIDGES

Two bridges were investigated and are referred to MC bridge and BC bridge which were built in 1989 and 1977, respectively. They have 6 and 4 spans, and 16 and 17 planks per span, respectively. Figure 1 shows the cross section of the deck at a pier for MC bridge, and Figure 2 shows details of steel reinforcement in the planks, which are similar for the two bridges. The top surface of the deck, consisting of in-situ cast concrete, has developed longitudinal parallel cracking which is more extensive in MC bridge than BC bridge, and the soffit of the PSC planks also exhibit this type of cracking as seen in Figure 3. Other bridges of similar construction have also shown similar cracking features.

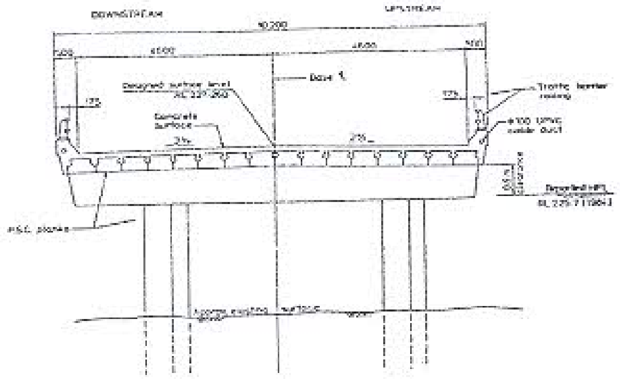

Figure 1 Cross section of the bridge deck at a pier, showing arrangement of planks

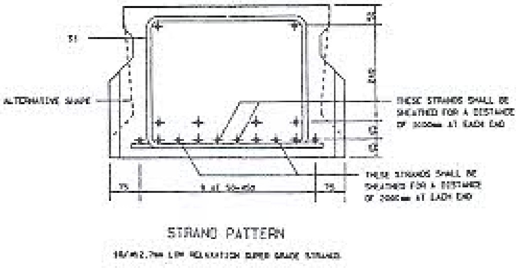

Figure 2 Cross section of a plank showing details of reinforcement and prostrating wires

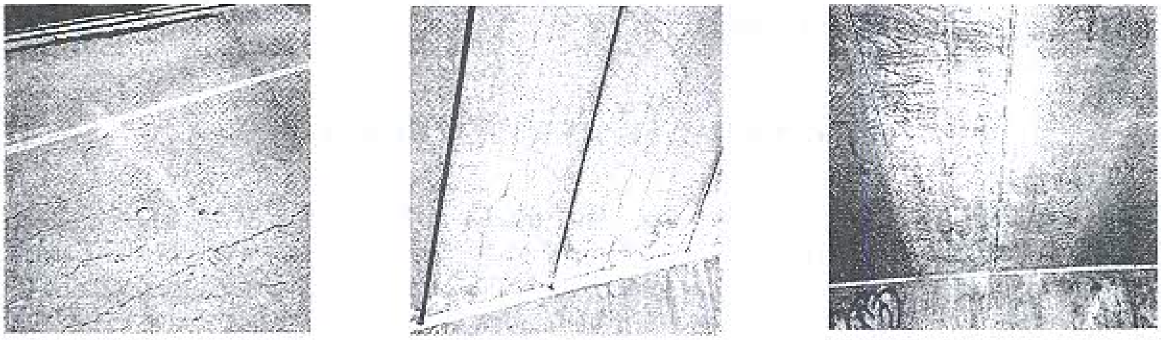

Figure 3 Cracking of the wearing course concrete (top) and beam plank (center) of MC bridge, and beam plank of BC bridge

Documentation on the drawing of the PSC planks for MC bridge specifies a minimum 28-day compressive strength of 40 MPa with a transfer strength of 35 MPa. The calculated hog of 40 mm at 28 days was based on the following assumptions that had been made at the time of construction:

Density = 2600 kg/m^3; elastic modulus at transfer = 36.7 GPa; steam curing at 70°C for 8 hours; plank self weight = 6.5 tonnes (with no external load); storage after steam curing in open air at 20°C average temperature, and RH of 50-75%. Although no such documentation was found on BC bridge planks, it can be expected from the similarity in design that they had similar concrete mix designs and strength properties.

The columns in the bridges were all cast-in-situ reinforced concrete of 30 MPa strength grade, which is adequate for their non-aggressive exposure conditions.

3. CORE SAMPLES

3.1 Sampling of PSC Planks

In MC bridge, the soffit of many planks showed cracking which was worse at the two ends of the planks where they rest on the cross beam, and where there is more water leakage. The cracking of the wearing course concrete and the presence of joints at the cross beams may have caused enhanced AAR in the planks in these areas by allowing more water penetration to the planks. Two planks in the southernmost span were selected and two cores of 95 mm diameter drilled in each. These were designated cores M1-M4. Cores M1 and M3 were from the first plank west of the bridge centre-line and cores M2 and M4 from the second plank west of it.

In BC bridge, cores B1 and B2 were taken from cracked planks under a cracked area of the wearing course near the center-line of the bridge, and cores B3 and B4 from uncracked planks near the kerb.

3.2 Sampling of Columns

The columns of both bridges are free of cracking. However, it was suspected that similar materials must have been used in their manufacture, and it was necessary to identify whether or not the columns may develop distress in the future. Therefore two cores were taken from each of the two representative columns in MC bridge for AAR determination and strength testing. These were designated MC-1 to MC-4.

4. VISUAL FEATURES OF CORES

4.1 MC Bridge

The aggregate in all the four cores from PSC planks in MC bridge is a hornfels or meta-sediment, and exhibits internal cracking, typical of AAR. Many aggregate particles show a wet-looking appearance due to AAR gel impregnation. The fracture surfaces of cores show AAR rims which vary in thickness from core to core. Some cracks and air voids appear to be filled with AAR products. Cracks about 25-30 mm deep are present in some cores. Strong AAR seems to present in the cores.

Cores taken from the columns of MC bridge showed no sign of AAR and no visible defect.

4.2 BC Bridge

The aggregate in all the four cores from BC bridge contain crushed quartz gravel with other sedimentary rocks and meta-sediments.

In cores from uncracked planks no unusual feature is present in the concrete. In cores from cracked planks, strong AAR rims are present at the fracture surfaces of the cores. Many aggregate pieces show internal fractures parallel to the core surface, and some are partially filled with AAR products. Strong AAR exists in the latter cores.

Examples of the visual features of cores are given in Figure 4 and Figure 5 for MC and BC bridges, respectively. These features suggest that strong AAR has occurred in the cracked planks of both bridges.

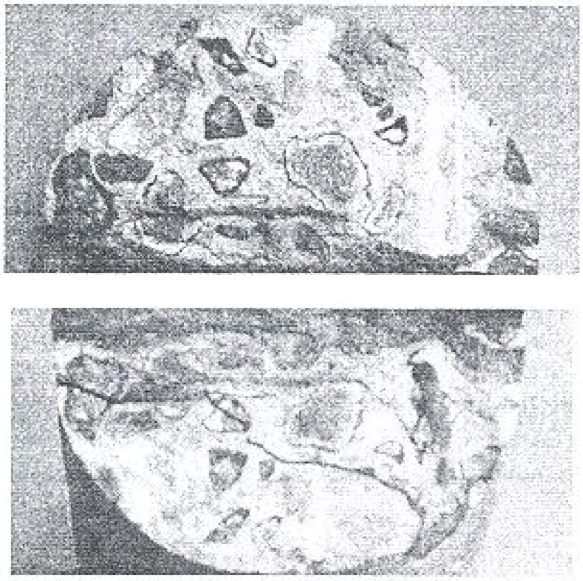

Figure 4 Fracture surfaces of core M1 (above) and two segments of core M2 (right) showing strong AAR rimming. AAR gel covers the steel/concrete interface in M2, and fills some voids in M1

Figure 5 Fracture surfaces of core B1 with strong AAR rims (top), and core B3 free of AAR

5. INVESTIGATION OF CORE SAMPLES

Detailed examinations and testing were carried out on all the cores. Those from the PSC planks were subjected to petrographic examination, Scanning Electron Microscopy (SEM) combined with Energy-Dispersive X-ray (EDX) analysis, determination of residual alkali content, modulus of elasticity, ultrasonic pulse velocity, compressive-strength, expansion potential at 100% RH 40°C and in 1M NaOH solution at 40°C. Due to the small amount of core samples available not all the tests could be done on the samples available. Cores from the columns were also used for these tests, except modulus, pulse velocity and expansion tests. Results of the above examinations and tests are summarised below.

5.1. Petrographic examination

Cores M3 and M4 representing the two planks of MC bridge, and cores B1 (with AAR) and B4 (free of AAR) representing the two planks of BC bridge were examined petrographically. Representative cores from the columns of MC bridge were also examined, and the results are summarised below.

5.1.1 Cores M3 and M4

The coarse aggregate in these cores appears fissile and shows orientation and banding when seen by the unaided eye. Under the petrographic microscope, the aggregate is a fine to medium-grained hornfels with a non-uniform texture. Some quartz rich zones are separated by bands of micaceous zone giving the banded appearance. The size of the quartz grains varies from very fine to medium, and some aggregate pieces are entirely of a very fine mixture of quartz, micaceous materials with some iron oxide staining. The latter is present in most aggregate pieces giving them a slight brownish tinge. Feldspar is also identifiable in aggregate pieces which have a coarser grain size.

Quartz grains show some elongation in the coarser aggregate pieces, in which some quartz patches exhibit quartzitic features with welded joints and lenticular appearance, indicating the metamorphic nature of the aggregate.

The sand fraction consists of rounded to angular quartz grains of which some are monocrystalline and some polycrystalline. All show moderate to high undulose extinction angles. The sand also appears to have a metamorphic nature.

Both the coarse and the fine aggregate are considered to be susceptible to AAR. Microcracking is evident in the aggregate itself as well as partially around it and extending into the matrix. Fine microcracking is seen throughout the matrix. Some coarse aggregate particles have AAR gel on their periphery, and some cracks appear to be partially filled with the gel. Some of the sand grains also appear to have reacted.

5.1.2 Cores MC-1 and MC-3 from columns

The coarse aggregate in the columns was different from that in the PSC planks, but still of a metamorphic nature of gneissic type. Both the coarse and fine aggregates contain significant amounts of moderately to highly strained quartz which are considered to be susceptible to AAR. However, no sign of AAR could be detected by the petrographic examination. This indicated that the progress of any AAR would depend on the amount of available alkali in the concrete.

5.1.3 Cores B1 and B4

The coarse aggregate particles show a variety of features probably indicating different origins. Among these, some particles are heavily stained by iron oxide and have a very fine texture similar to chert. Some other particles are of medium-grained sandstone texture with tightly packed and well sorted quartz crystals and some iron oxide staining. A large proportion of the quartz grains show undulatory extinction. Some other particles show extreme deformation with highly strained, elongated quartz that have highly sutured boundaries and show considerable recrystallization of microcrystalline quartz at the grain boundaries. Yet other particles appear to be of a deformed granitic nature (gneissic), with highly strained quartz.

The fine aggregate is a natural sand probably of the same origin as the coarse aggregate and shows similar petrographic features. These features are indicative of strong alkali reactivity in concrete. The matrix of core B1 shows considerable microcracking which has resulted from AAR, and some of the cracks appear to contain AAR gel. Signs of reactivity are seen with many coarse aggregate pieces as well as with sand grains. No wide microcracking is seen in the section from core B4, although a considerable number of fine microcracks are present in the matrix running between sand grains and sometimes originating from the coarse aggregate. These microcracks may be due to thermal shock that may have affected the concrete element as a result of steam curing. No visual signs of AAR are present in core B4.

6. SEM AND EDX ANALYSIS

Examination by SEM, and EDX analysis of the reaction products, clearly showed that strong cases of AAR exist in the concrete of the cracked PSC planks in both bridges. In addition, secondary or delayed ettringite (hydrous calcium-sulfoaluminate) was also detected, but the latter was much less prevalent than the AAR products. Moreover, the ettringite in MC bridge was largely in the pores and only in a few locations was indicative of expansive ettringite.

whereas ettringite in BC bridge was more similar to the delayed formation of ettringite, albeit in small amounts. No evidence of AAR was found in the cores from the columns of MC bridge.

A representative example of extensive formation of AAR gel is shown in Figure 6. This gel forms within the aggregate causing expansion and stress build up that eventually causes cracking in the aggregate and mortar phases of the concrete. The gel impregnates the surrounding mortar and part of the cracks that may be formed around the aggregate. Many sites of this nature were observed in the affected concretes of both bridges. The white reaction rims on the reacted aggregate contain crystalline AAR products (Figure 7), which is indicative of advanced reaction in both concretes. Some other Na-rich phases (Figure 8) are indicative of a high alkali, Na-rich cement in the concrete.

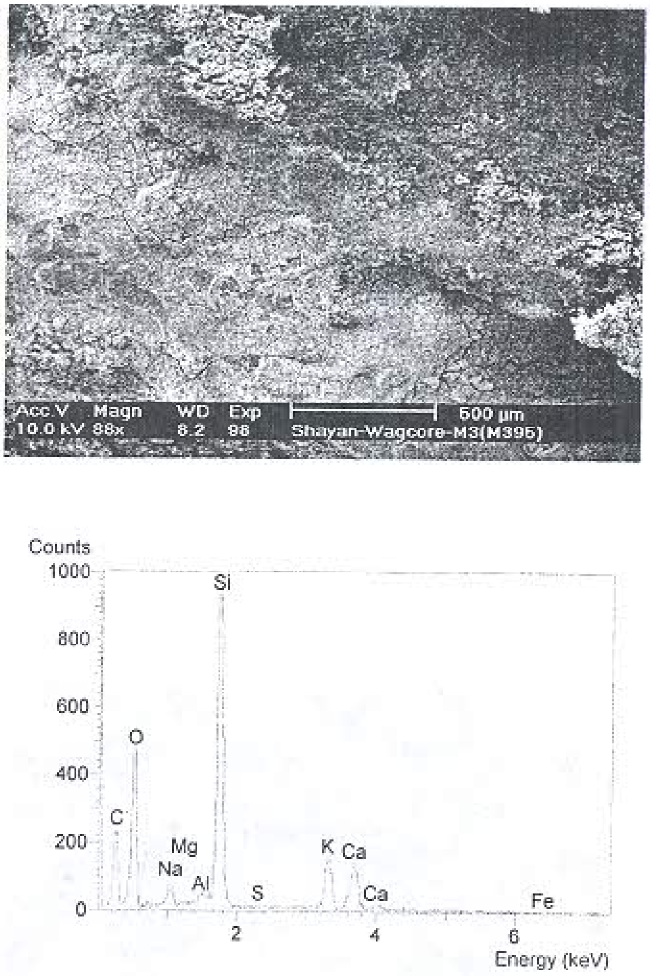

Figure 6 AAR gel formation covering a larges area around the reacted aggregate site. The composition of the cracked gel is rich in Na and Si as indicated by the EDX spectrum

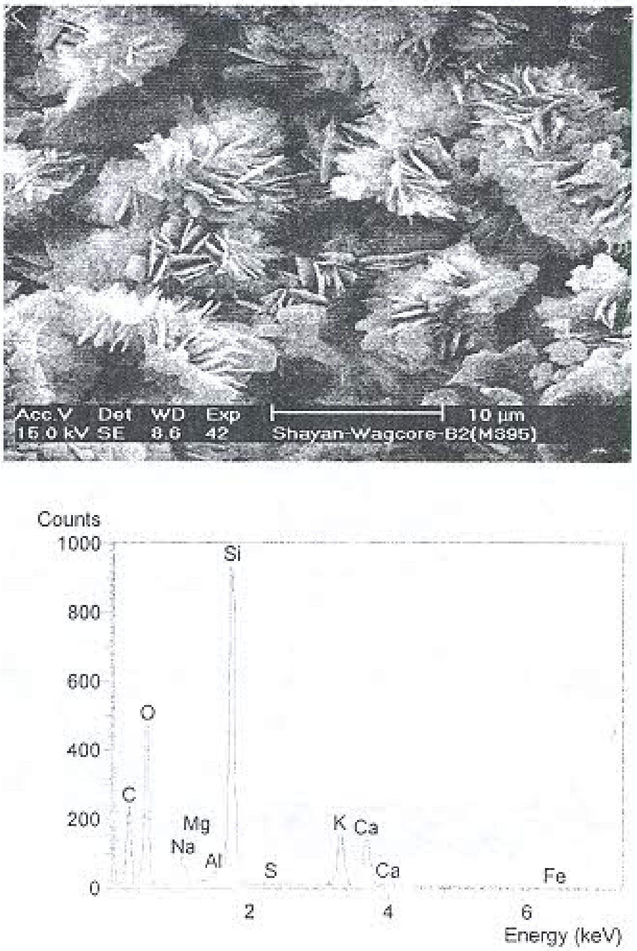

Figure 7 Crystalline (Rosette) AAR products in the white reaction rims seen within the aggregate boundaries

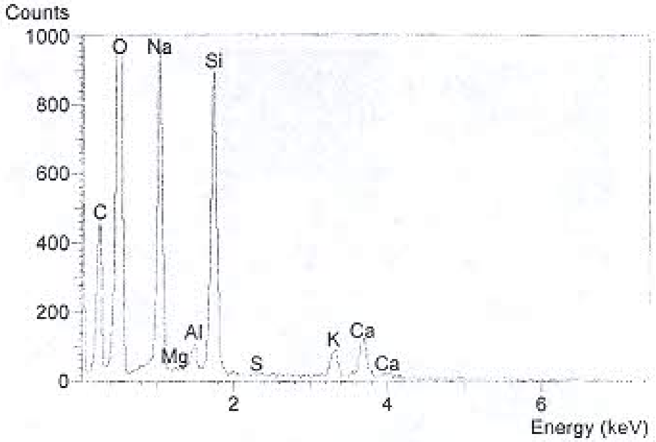

Figure 8 AAR product highly enriched in Na, indicative of high Na content in the cement

Other than the usual form of ettringite lining in some air voids, a few locations were seen in MC bridge concrete, where the form of ettringite at the cement/aggregate interface (Figure 9) may indicate expansive ettringite as judged from its radial growth at the reaction site into the interfacial paste. In BC bridge concrete, locations were seen where AAR products were associated with ettringite, as indicated by the composition of the materials seen in Figure 10. The ettringite appears to have been formed at a later stage than the AAR gel in cracks at the aggregate interface, as seen in Figure 11, where ettringite crystals are shown below the layer of AAR gel at the aggregate surface. Figure 12 shows another site of ettringite formation where it could indicate some contribution to concrete expansion, by its compact form that has filled a gap at cement/aggregate interface. Such locations were far less frequent than the AAR sites, in both bridges, and it appears that AAR is by far the main cause of the observed cracking.

Figure 9 Expansive ettringite formed at the cement/aggregate interface of MC concrete

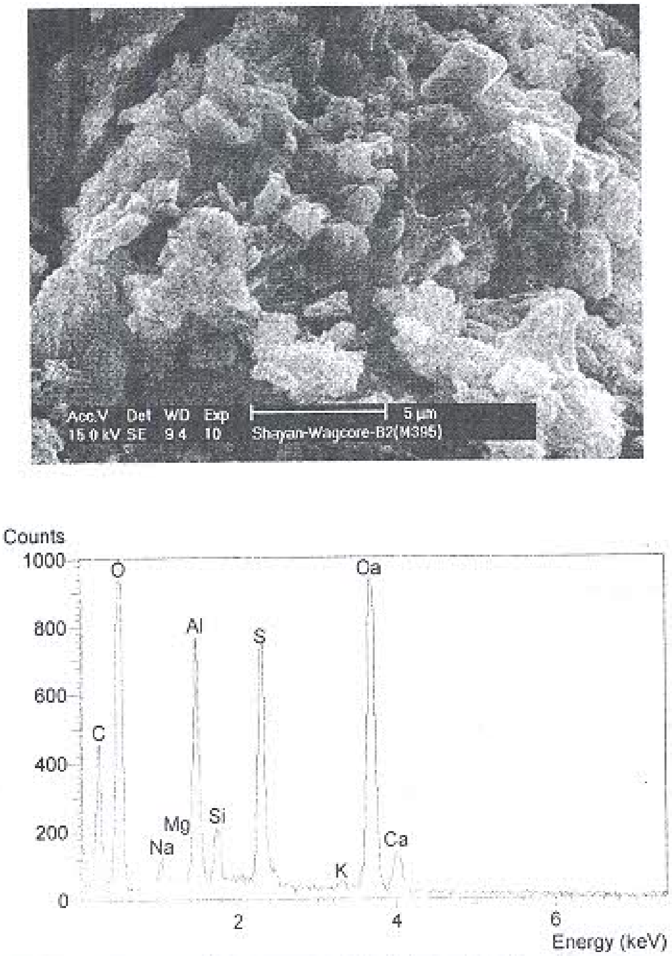

Figure 10 Mixture of AAR and ettringite

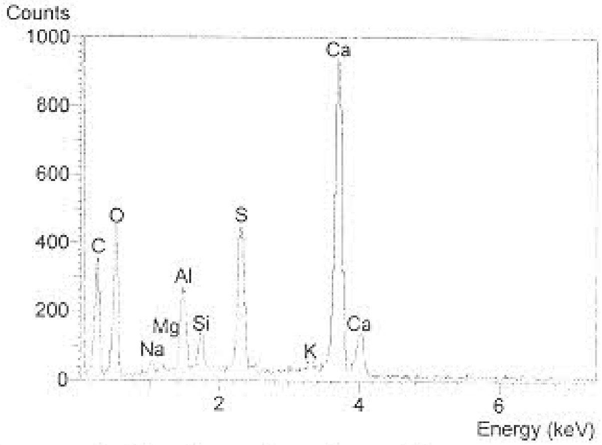

Figure 11 Ettringite crystals forming under a layer of AAR gel at the aggregate surface, indicating its later formation than the AAR products

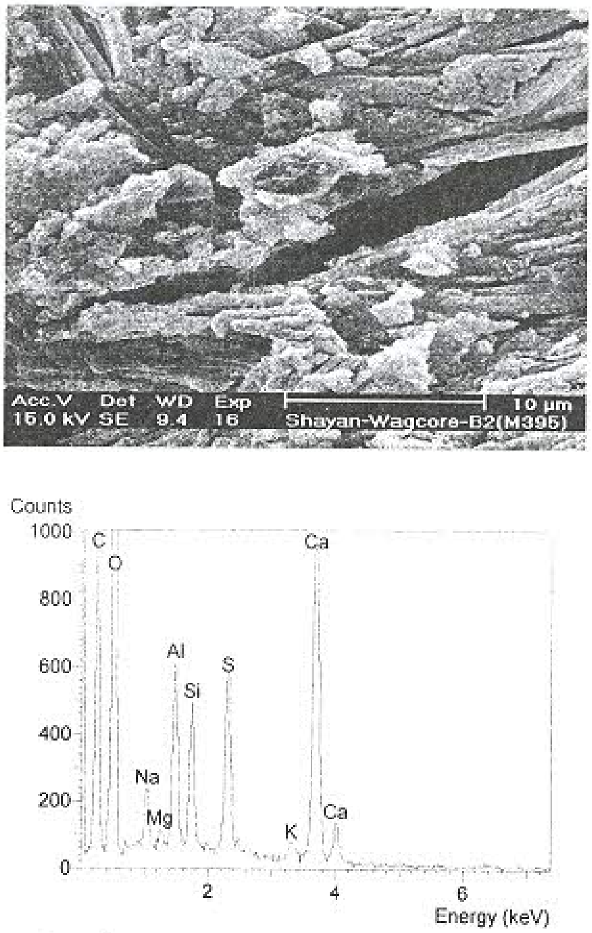

Figure 12 Ettringite layer found at aggregate interface, and mixed with small amounts of AAR gel

Cores B3 and B4 from the uncracked PSC plank of BC bridge were free of both AAR product and secondary ettringite. The hydrated cement paste in the bulk concrete and at the aggregate interfaces was low in alkali and silica, and rich in Ca, compared to the AAR products shown earlier. Although the aggregate types in the two PSC planks are the same, the cement type in the plank represented by cores B3 and B4 must have been different, and probably low in alkali for AAR not to have occurred.

7. STRENGTH PROPERTIES OF CONCRETE

Before destructive testing of the core specimens, their Ultrasonic Pulse Velocity (UPV) was measured, and using estimated values of Poisson's ratio values of elastic modulus were calculated. These values are given in Table 3. Sound concrete of 40 MPa strength is expected to have UPV values of around 4300 m/s, and it is apparent that the AAR-affected cores have reduced velocities due to the presence of micro-cracks in them, but that cores B3 and B4 (free of AAR) have much higher UPV values.

Table 3 UPV and elastic moduli of core specimens

Core	Diameter mm	Length mm	Volume Cm^3	Mass g	Density kg/m^3	UPV m/s	Estimated Poisson ratio	Elastic Modulus E (GPa)
M1	94.1	241	1671	4008.73	2399	3933	0.30	27.4
M2	94.0	135	936	2222.06	2374	3820	0.30	21.1
M3	94.1	193	1341	3209.01	2393	4072	0.38	25.5
M4	94.1	184	1280	3072.00	2400	3953	0.37	21.2
B1	94.4	174	1214	2843.2	2342	3991	0.37	21.1
B2	94.4	222	1544	3654.6	2367	4173	0.41	18.0
B3	95.7	232	1682	3996.4	2376	4764	0.14	51.5
B4	95.7	224	1631	3816.5	2340	4609	0.16	46.6

The estimated E values may not be reliable due to possible errors in the estimation of the Poisson's ratio. Structural calculations for the MC bridge planks at the time of construction had assumed an elastic modulus of 36.7 GPa at transfer of prestress. The E values in Table 3 for the AAR-affected concretes are much smaller than 36.7 GPa, and the loss of elastic modulus may have arisen from damage caused by AAR.

Core M4 was subjected to compressive strength testing and static measurement of elastic modulus. The compressive strength was 37.2 MPa and modulus of elasticity of 15.5 GPa. The compressive strength after steam curing was expected to be 40 MPa, which should have increased with time. Therefore, it can be concluded that the stiffness of the AAR-affected planks in MC bridge has been significantly reduced (by 50% on average). As shown later for BC bridge, the compressive strength of core B3, free of AAR, was 57.2 MPa at the time of testing, having increased from the specified 40 MPa with age. Therefore, there has been a 35% reduction in the compressive strength.

It is worth noting that AAR affected cores from both BC bridge and MC bridge have similar UPV values, with an average of 3990 m/s, which is 85% of the average UPV for the sound concrete (4687 m/s). However, comparison of the elastic moduli values of the AAR affected cores B1 and B2 with those of AAR-free cores B3 and B4 shows a massive reduction in stiffness by about 60%. This indicates a significant deterioration in the engineering properties of the AAR affected PSC planks.

Elastic moduli of Cores B2 and B3 and their compressive strength were also measured by the static method. Core B2 (with AAR) had a compressive strength of 41.5 MPa and an elastic modulus of 15.5 GPa, whereas Core B3 (no AAR) had a compressive strength of 57.2 MPa and modulus of elasticity of 24.5 GPa. Based on these values the strength and modulus for BC bridge planks have been reduced by about 28% and 37%, respectively. These significant reductions should be taken into account in making decisions regarding rehabilitation of the structures.

The cores from the column of MC bridge had compressive strengths ranging between 33 and 35 MPa with an average of 34 MPa. Considering the benign environmental conditions of this bridge, this strength is adequate for continued service life of the columns.

8. RESIDUAL ALKALI CONTENT OF CONCRETE

The soluble alkali was extracted from the concrete and analysed to determine the residual alkali content in the concrete. The results are given in Table 4.

The amount of residual alkali in the PSC planks is considered high and adequate to sustain further reaction in the concrete. Therefore, provided that reactive components are still present in the concrete (which is usually the case), further expansion and cracking is likely in the concrete. Core B3 which is free of AAR has the least amount of residual alkali, and at this level would not support development of AAR in the concrete. Therefore, this plank would remain free of cracking.

The amount of soluble sulfate in the concrete is relatively high, particularly if converted into ettringite, and it is likely that some additional ettringite precipitation may take place within the existing micro-cracks. However, this may have only a marginal effect on the magnitude of future expansion.

Table 4 Residual alkali and sulfate contents of cores

Core	Na_2O%	K_2O%	Na_2O equiv. %	Concrete density kg/m^3	Na_2O equiv. kg/m^3	Corrected Na_2O equiv.* kg/m^3	SO_4 %	SO_4 kg/m^3
M1	0.088	0.047	0.119	2399	2.71	2.36	0.052	1.25
M2	0.094	0.055	0.130	2374	2.93	2.58	0.053	1.26
M4	0.097	0.065	0.140	2400	3.20	2.85	0.054	1.30
B2	0.090	0.053	0.125	2367	2.96	2.81	0.057	1.35
B3	0.031	0.098	0.095	2376	2.26	2.11	0.026	0.62
M-C-2	0.032	0.022	0.047	2412	1.12	0.77	—	
M-C-3	0.027	0.013	0.036	2412	0.86	0.51		

* an estimated 0.35 kg Na_2O/m^3 has been deducted for contribution from the metamorphic aggregate, and 0.15 kg/m^3 for the gravel aggregate.

From the data in Table 3 it is clear that the cements used in the PSC plank represented by core B3 is different from the others. Firstly, the nature of alkalis in the concretes are different. B2 and all MC cores being rich in Na_2O while B3 containing more K_2O. Secondly, the other cores contain more than twice the amount of SO_4 in B3. The residual alkali values indicate that further deterioration could be expected in the affected planks, but the uncracked plank would remain sound.

The amount of residual alkali in the columns appears to be very low, indicating that although the aggregate is reactive, AAR is unlikely to develop due to the insufficient amount of alkali. The cement used for the manufacture of the columns must have been a low alkali cement.

9. RESIDUAL EXPANSION POTENTIAL OF CONCRETE

Residual expansion measurements were conducted on the remaining portions of the cores. Portions of cores M1 and M3 and a portion of core B1, (each 150 mm long), representing one of the planks from each bridge were separated and prepared for expansion measurement. After the initial conditioning, core M3 and B1 were stored at 40°C, 100% RH conditions and core M1 in 1M NaOH solution at 40°C, and their expansion was measured regularly. Expansion under the former storage conditions provides information on the residual expansion of concrete under the existing alkali levels, and expansion in 1M NaOH, 40°C indicates whether reactive components are still present in the concrete, and also the maximum expansion potential of the concrete.

Figure 13 shows the expansion curves obtained under the two storage conditions. Core M1 in 1M NaOH, 40°C continues to expand, indicating the presence of reactive components, and will continue until the maximum expansion potential is reached. Expansion of core M3 under 100% RH 40°C, has been slower and smaller, as expected, and has reached 0.07% at 340 days of storage, of which around 0.04% could be due to water absorption rather than AAR expansion. Assuming 0.03% residual expansion, each affected plank (600 mm wide) will expand laterally by 0.24 mm which could be accommodated by the sealed gap between the planks. However, this could cause further longitudinal cracking in the planks. Due to the prestressing effects, the longitudinal expansion may be less than the lateral expansion.

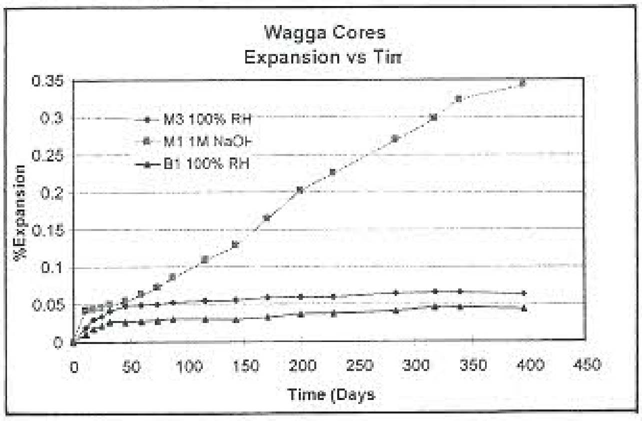

Figure 13 Expansion curves for core segments under the conditions indicated

Expansion of core B1 has reached 0.045% at 340 days of storage, of which 0.025% is probably due to water absorption, and the remaining 0.02% is the residual AAR expansion. This lower expansion compared to core M3 is probably because the BC plank has already undergone more extensive AAR than the MC plank. The expected lateral expansion of the plank (600 mm wide) of 0.12 mm could also be accommodated by the gap between the planks, otherwise the movement across the deck would be 2.0 mm if all the planks expand to this level. Actually, some of the planks are not expansive. These movements should be taken into account in any rehabilitation program.

10. OVERALL ASSESSMENT OF CONCRETE AND SUGGESTED REMEDIAL ACTION

10.1 MC bridge

Visual, petrographic and SEM examinations have shown that the PSC planks examined have significantly suffered from alkali-aggregate reaction and, in one core segment, the steel/concrete bond has been lost and AAR gel accumulated at the interfacial zone. Measurement of ultrasonic pulse velocity, strength and modulus of elasticity have shown that the strength properties of the AAR-affected concrete planks have significantly deteriorated as a result of the reaction.

A large number of the planks are affected by the AAR, and due to the method of construction their individual replacement is very difficult and costly. Considering the advanced stage of AAR, and existing potential for further expansion and cracking, strengthening of the planks using techniques such as composite fibre-epoxy bonding may not be advisable. In any case the wearing course of the deck would need major rehabilitation, including water-proofing and reconstruction. Another option may be replacement of the whole deck, which may be less expensive in the long term. The economy of each option needs to be considered before taking any remedial action.

The columns in MC bridge are sound and of adequate strength. No remedial action seems to be required for the columns.

10.2 BC bridge

A survey of the deck is needed to determine the number of the affected planks. If the number is large the remedial actions would be similar to those suggested for MC bridge. A few affected planks could probably be tolerated after in-situ strengthening.

11. CONCLUDING REMARKS

Two PSC planks from each of MC and BC bridges have been examined for AAR and residual strength and potential for further expansion. For MC bridge both planks were found to have suffered strong AAR, and their strength properties significantly deteriorated such that the compressive strength was reduced by 35% and elastic modulus by about 50%. For BC bridge, one of the planks was free of AAR and in sound condition, whereas, the other had undergone a strong AAR and its compressive strength and modulus of elasticity have been reduced by 28% and 37%, respectively, compared with the sound plank. The residual expansion of the affected planks appear to be small, but not insignificant.

It has been suggested that individual AAR-affected planks could be replaced if there are only a few of them, although they could also be strengthened. However, where many of the planks are affected, the rehabilitation should include placement of an impermeable layer on top of the deck, and application of epoxy-bonded composite fibre sheet to the soffit of the planks to increase their load-bearing capacity. This would require structural calculations to determine the amount and distribution of the composite materials. The disadvantage of this method is that AAR could progress and cause further damage over many years.

Another option would be to replace the whole deck, and an economic evaluation of these option would be needed before taking any remedial action. In any case, the columns appear to be sound and of adequate strength for supporting a new or a rehabilitated deck.