CONCRETE PILE DURABILITY IN SOUTH ISLAND BRIDGES

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Summary

Routine maintenance inspections of prestressed concrete piles on two coastal bridges in the South Island of New Zealand revealed extensive cracking that was not related to reinforcement corrosion. Investigations revealed that the damage was probably caused by alkali silica reaction (ASR), exacerbated by delayed ettringite formation (DEF).

This paper describes the damage and the procedures used to investigate the cause of the cracking, discusses the combination of factors that led to the deterioration of the affected structures, and investigates the risk of ASR/DEF in other South Island structures. It also recommends changes to current industry recommendations for minimizing the risk of ASR in New Zealand in order to improve the durability of precast concrete piles in future structures.

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INTRODUCTION

When deciding what to do with a damaged structure it is necessary to understand how the damage is likely to affect the structure’s current and future performance. In addition, repairs must address the underlying cause of the damage. Correct diagnosis of the cause of damage is, therefore, essential for effective management of the asset.

Corrosion of steel reinforcement is the most common type of deterioration encountered in reinforced concrete structures, particularly those in marine or coastal environments. Consequently, cracks appearing in concrete after several years of exposure to seawater or sea spray are commonly assumed to be caused by reinforcement corrosion. Occasionally, however, such cracks may be caused by mechanisms other than corrosion, as has been reported from overseas [1, 2, 3], and observed recently in two coastal bridges in the South Island of New Zealand [4].

By describing these two New Zealand cases, this paper aims to help asset owners and managers distinguish this type of cracking from cracking related to reinforcement corrosion, and to help them appreciate the type of investigation needed to confirm the cause, the nature of the results that may be obtained, and how the results are interpreted.

These two bridges represent the first cases of alkali silica reaction identified in the South Island. The paper also describes a current investigation of the likelihood and severity of this type of deterioration in other South Island structures, with the aim of minimising the risks in existing and future structures.

The structures

The two bridges are in an estuarine environment, exposed to tidal conditions and onshore winds. They were built in 1969 under separate contracts and are critical to the operations of an industrial facility. Details of the bridges are given in Table 1. The piers consist of precast prestressed square concrete piles supporting a pile cap (crosshead). The piles are approximately 17 inches square in cross section. Different precasters made the piles for each bridge, except for a few of the piles from Bridge A that were made by the Bridge B precaster. The concrete was not air entrained. The same aggregate source was used by both precasters. Figure 1 shows Bridge B.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Details of bridges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bridge A</td>
</tr>
<tr>
<td>Length</td>
<td>1200 m</td>
</tr>
<tr>
<td>No. of spans</td>
<td>139</td>
</tr>
<tr>
<td>Piles/pier</td>
<td>Mostly 2 (total ~376)</td>
</tr>
<tr>
<td>Cage shape</td>
<td>circular</td>
</tr>
<tr>
<td>% of piles with symptoms</td>
<td>≤ 33%</td>
</tr>
<tr>
<td>Concrete comp strength</td>
<td>45 MPa (design)</td>
</tr>
</tbody>
</table>

The symptoms

Inspections in the early 2000s revealed cracking, splitting and spalling near the corners of the concrete piles in both bridges. The cracks extended from the tidal zone to below low tide level and sometimes below bed level (Fig. 2). Efflorescence and rust staining were absent from these cracks,
unlike cracks caused by reinforcement corrosion (Fig. 3). Many of the cracks were very fine, and were obscured by marine growths (Fig. 4). The damage on some piles of Bridge A was more severe, the concrete reportedly soft and able to be broken away by hand or already eroded (Fig. 5).

Possible causes of the deterioration

Although reinforcement corrosion had caused cracking and spalling on many piles, the cracks on the corners of the piles were related neither to steel reinforcement corrosion nor to obvious structural causes. Cracking was more severe on Bridge A, where the reinforcement cage in the square pile was circular. These features suggested that the cracking was caused by expansion of the concrete that was not restrained by the reinforcement. The most likely causes were alkali silica reaction (ASR) and/or delayed ettringite formation (DEF), which other authors have reported in precast piles on marine structures [1, 2, 3]. Bruce et al [4] summarised the mechanisms of these types of deterioration and their incidence in New Zealand.

ASR has not previously been identified in any structure in the South Island. On this basis, and supported by limited laboratory testing, the New Zealand concrete industry has assumed that all South Island aggregates are non-reactive. Nevertheless, the aggregate source reportedly used in both concretes is an alluvium that contains a wide variety of rock types, including acid and intermediate meta-volcanic rocks. High alkali cements were available at the time of construction, and the need for relatively high concrete strengths may have resulted in the use of concrete with high cement (and alkali) content. Consequently, the possibility of ASR could not be ruled out.
‘DEF’ refers to the gradual formation of ettringite in hardened concrete that was subjected to elevated temperatures during curing. Ettringite is a normal product of the early stages of Portland cement hydration at normal ambient temperatures. If the concrete temperature exceeds about 70°C during the early stages of curing then ettringite does not form until the concrete has cooled, and then only if sufficient water for reaction and void space for crystallisation are available. The delayed crystallisation of ettringite could generate expansive stresses in the concrete if the void space in the hardened cement paste is insufficient to accommodate it. Curing temperatures are now closely controlled by precasters (and in mass concrete cast in situ) to reduce the risk of DEF, but these bridges were built before the risk was widely recognised. Both precasters are believed to have steam cured the piles but the curing temperatures are not known. DEF is, therefore, a possible cause. The localised nature of the damage suggests that curing temperatures may have varied between piles and along the length of individual piles, possibly as a result of uneven curing temperatures (‘hot spots’).

The softening and erosion observed on the most severely damaged piles was reminiscent of microbial attack, which results in softening of concrete, as has been observed in buried portions of piles and on immersed surfaces [5]. The progression of damage from cracking to softening and erosion, however, suggested microbial attack was not the principal cause.

Scope of investigation

The first stage of the investigation aimed to identify the cause of the deterioration, and then to predict whether the condition of damaged piles was likely to worsen and whether undamaged piles may deteriorate in future. This information would allow appropriate plans to be developed for managing the structures. The concrete and the damage on both bridges were very similar. Thus, both bridges were investigated together to determine the cause of the damage, even though they have different owners.

The second stage of the investigation, initiated once the cause of the deterioration was identified, aims (a) to ascertain whether more South Island structures are affected, and (b) to identify the factors that contributed to the deterioration, in order to minimise the risk in structures that will be built in future. This work is due to be completed by the end of 2010. The associated report will describe in more detail the investigation methodology and the deterioration mechanisms.

METHODOLOGY

Stage 1

Nineteen concrete core samples were taken from bridges A and B to identify signs of expansive chemical reactions in the concrete (such as ASR and DEF), features of the concrete mix design and materials that might increase the risk of ASR or DEF, differences between concretes from cracked and uncracked piles, differences amongst cracked piles, and the likelihood of future expansion.

The cores were examined visually to compare concrete quality and aggregates in the different piles. Petrographic thin sections were then prepared from selected cores and examined by polarising microscope to identify the aggregate types and evidence of ASR, DEF, or other expansive chemical reactions. Selected specimens were examined by scanning electron microscope (SEM) and energy dispersive x-ray analysis to positively identify reaction products. Sub-samples were taken for chemical analysis to determine the cement content and source (from which the original concrete alkali content was estimated), and the remaining soluble alkali content of the concrete. Other cores were used to measure the potential for future expansion. Bruce et al [4] describe in detail the sampling regime and the methods of testing and examination in the first part of the investigation.

In addition to the laboratory testing, construction records and historical records of cement composition were searched to identify factors that might have contributed to the deterioration.

Stage 2

To identify the likelihood of ASR in other structures in the same region as bridges A and B, the potential alkali reactivity of coarse aggregates used in the two bridges, and of similar sand and coarse aggregate from currently-used sources, were measured by accelerated expansion tests on mortar bars at 80°C (RTA T363) and on concrete prisms at 60°C (RILEM AAR-4).

The risk of ASR/DEF in other regions of the South Island was assessed by a geologist’s review of principal South Island rock types and aggregate sources. In regions where potentially reactive aggregates were thus identified, precast bridge piles in tidal or immersed conditions were then
inspected for signs of ASR/DEF. Core samples were then taken from a wharf and a bridge in the Nelson region (‘B’ and ‘M’), and from a wharf and three bridges in Otago/Southland (‘T’, ‘Wh’, ‘O’ and ‘Wp’). The cores represented cracked piles and piles (cracked or uncracked) representing different aggregate assemblages observed on site. As in stage 1, the cores were examined visually and by microscope to find out how the various concrete aggregates have contributed to the risk of ASR/DEF, and thereby how this type of deterioration may be avoided in structures built in the future.

RESULTS

Examination of core samples from bridges A and B

Visual examination of the core samples from bridges A and B showed that the concrete in all piles was of good quality, with the same predominantly rounded aggregates and similar aggregate contents.

Petrographic examination of 13 cores found the aggregate was predominantly sandstone/siltstone and greywacke showing signs of low to medium grade metamorphism, plus quartzite and some tuff-like materials. Minor constituents included acid, intermediate and basic volcanic rock types (including partly metamorphosed varieties), phyllite, breccias, and shell fragments. Potentially alkali reactive minerals in these rock types included strained quartz, microcrystalline quartz, and chalcedony.

ASR was unequivocally identified in two cores from cracked piles, possible signs of ASR were identified in six cores and no signs of ASR were seen on five cores. DEF was unequivocally identified in two cores, both of which showed signs of ASR. ASR and DEF were both unequivocally identified in one core only. ASR and DEF were neither severe nor extensive in any of the cores examined. DEF indicates that curing temperatures exceeded 70°C.

Chemical analysis from bridges A and B

Cement contents measured in concrete samples from both bridges were approximately 320 kg/m³. Chemical analysis of the cementitious binder suggested that the cement may have been from Milburn’s Burnside plant. Alkali contents of cements from this plant were typically around 0.4-0.5% Na₂O equivalent, corresponding to about 1.3-1.7 kg/m³ of concrete. This is much lower than the maximum limit of 2.5 kg/m³ usually applied to minimise ASR-related cracking. Similarly, the sulfate, alumina, magnesium and alkali contents of the cements likely to have been used did not indicate a significant risk of DEF when compared to published criteria [6].

Residual expansion of cores from bridges A and B

The residual soluble alkali content was less than 2.5 kg/m³, indicating a low risk of further ASR. Four cores stored at 38°C, 100% RH (conditions designed to accelerate ASR) expanded less than 0.005% in 12 months, suggesting that ASR was unlikely to cause further expansion in the piles represented by these cores. The length of time since construction suggested that without further ASR expected, further DEF expansion is also unlikely.

Potential alkali reactivity of South Island aggregates

Petrographic examination of the concrete from bridges A and B (see above) and of aggregate currently won from a nearby source confirmed that aggregates currently used may also be potentially reactive [7]. The review of principal South Island rock types identified similar assemblages of rock types in alluvial gravels throughout Southland and from at least one river in Nelson/Marlborough [7].

Aggregate was extracted from spare cores taken from bridges A and B, and an alluvial sand currently used for concrete manufacture was obtained from a nearby source. Expansions recorded in accelerated mortar bar tests at 80°C exceeded 0.10% (coarse aggregate) and 0.15% (sand) in 21 days. This indicated that the extracted aggregate, and the sand, were both ‘slowly reactive’ (Fig. 6). Aggregates that exceed these limits at 10 days are considered ‘highly reactive’.

Expansions recorded in concrete prism tests at 60°C were less than 0.02% after four months (Fig. 7). Aggregates that produce expansions greater than 0.03% at 4 months are considered potentially reactive. Thus the results indicated that neither the extracted coarse aggregate, nor similar aggregate from a current supply, nor the alluvial sand were likely to cause significant ASR expansion in concrete.
The combination of results from the mortar and concrete tests suggested that steam curing at temperatures of 70-80°C may induce ASR in concrete containing these aggregate types if sufficient alkali is available, but that these aggregates may not react at temperatures of 60°C or lower.

![Accelerated mortar bar tests](image)

**Figure 6.** Accelerated mortar bar tests show that aggregate extracted from cores from bridges A and B, and sand from the same alluvial source, are both slowly reactive.

![Accelerated concrete prism tests](image)

**Figure 7.** Accelerated concrete prism tests show that neither coarse aggregate extracted from the cores, nor coarse aggregate nor sand from the same alluvial source, are potentially reactive.

The review of South Island aggregates identified several phonolites and trachytes in the Dunedin Volcanic Group in eastern Otago that have silica contents greater than 50% and high levels of sodium and potassium [7, 8]. Some of these rock types may be alkali reactive. At the time of writing we do not know whether these rock types have been used as concrete aggregate. To our knowledge they have not been tested for potential alkali reactivity.

**Incidence of ASR/DEF in other South Island bridges**

Inspection of piles above ground level and water level on about 50 bridges in Southland and Nelson/Marlborough in March 2009 revealed no further severe cases of deterioration similar to that observed on bridges A and B. Nevertheless, up to four bridges with precast piles cracked below high tide level were seen: up to three in Nelson and possibly one in Southland. Only one of these structures, M, in the Nelson region, exhibited widespread longitudinal pile cracking that was not related to reinforcement corrosion. The cracking had previously been identified during routine bridge inspections, but the cause had not been identified. Two other bridges in the Nelson region and one in Southland exhibited minor isolated cracking that was not obviously related to reinforcement corrosion and was not severe or extensive enough to raise concerns about durability or structural performance.

**Preliminary examination of core samples from other Nelson and Southland bridges**

The following observations are subject to verification by SEM and further petrographic microscopy.

Stereoscopic examination of cores revealed mild indications of the presence of some form of ASR product near or within some aggregate pieces in the concrete. These indications were strongest in the cores from structure M, where extensive pile cracking was observed on site.

Petrographic examination of thin sections showed that the aggregates in cores from structures Wh, T, B and M comprised siliceous aggregates, meta-sediments, and some acid igneous/tuff particles that contained highly strained quartz and microcrystalline quartz and are, therefore, considered to be potentially reactive. The cementitious matrix contained microcracks resembling ASR cracking, and in some parts appeared to contain gel-like materials. Some pores could also have contained ASR products, and some were filled with ettringite crystals, which could indicate DEF. Clearly-defined ettringite rims, characteristic of DEF, were seen around some aggregate particles in concrete from structure M. These signs of ASR and DEF were strongest in the cores from structure M.

Cores from structures Wp and O contained one type of coarse aggregate: a crystalline andesite/basalt, possibly with some strained quartz crystals and with considerable alteration of feldspar to finely divided masses of chloritic and ferromagnesian minerals. These cores also contained a coarse polycrystalline gneissic sand with highly strained quartz crystals. The strained quartz in the coarse and fine aggregate is considered potentially reactive. Mild microcracking was seen in the matrix and adjacent to some coarse aggregate pieces, but the presence of ASR gel was not verified.
DISCUSSION

Although the laboratory investigation of samples from bridges A and B revealed signs of ASR and DEF, they were less distinct and more isolated than we had expected from the extent and severity of the damage to the piles. Other authors have also reported inconsistent observations between different elements of a structure with suspected DEF damage [9]. Different authors report DEF occurring under different physical and chemical conditions, and therefore have different opinions about the relative importance of the factors that contribute to DEF. This suggests that DEF is sensitive to small changes in physical and chemical conditions, so may not be distributed evenly throughout a single concrete placement, let alone a whole structure. Consequently, evidence of DEF may be present in some samples of concrete from an affected structure but not from others, making it difficult to determine whether DEF contributed significantly to the damage observed on a structure. This section describes how apparently inconsistent laboratory observations and results from the investigation of bridges A and B were interpreted, and gives an example of how ASR/DEF damage may be repaired.

Did ASR and DEF occur in bridges A and B and the other structures, and if so, why?

DEF and/or ASR were observed in cores from bridges A and B. Yet neither the chemical compositions of the cements likely to have been used nor the estimated original concrete alkali contents suggested an obvious risk of ASR or DEF. Mild to moderate evidence of in-situ alkali reactivity of these aggregates in six other structures of similar age was observed, yet no cases had previously been reported. Why then did ASR/DEF occur in these piles? Are they different in some way from those showing no signs of reaction, or are all piles affected to some degree?

Bruce et al [4] discuss the factors that contributed to ASR and DEF in bridges A and B, and the relationship between the two reactions.

The risk of ASR in concrete containing South Island alluvial aggregates has been overlooked until now because the potentially reactive rock types are a minor constituent in such aggregates. Observations made in this investigation suggest that ASR cracking in South Island structures is indeed rare. Uneven and widely scattered distribution of the reactive constituents within a concrete element means that if ASR occurred its effects would be minor and localised. The elevated temperatures used to steam-cure precast elements in the late 1960s would have increased the risk of ASR, but the temperatures in the concrete may have varied within a single element and between elements, further localising the reaction. Such localised reactions are easily missed when taking samples from a structure, particularly when the reaction products may be masked by subsequent reactions such as DEF. This is why evidence of ASR in the cores examined in this investigation was not widespread.

We believe from experience and literature review that ASR precedes DEF except in rare cases where all the high risk factors in mix composition are combined with high curing temperatures [10]. Thus when ASR is localised as described above, evidence of DEF may also be missed when taking samples for examination. Again, this is probably why only minor evidence of DEF was seen in the cores examined from bridges A and B.

The accelerated mortar expansion tests at 80°C showed that the Southland alluvial aggregates tested were slowly reactive. Such aggregates may not react unless the concrete alkali content is relatively high [11]. The accelerated concrete tests at 60°C showed that a high alkali content alone was not enough to cause ASR; curing temperature over 60°C was also needed. Therefore, the concrete in the piles investigated may not have contained sufficient alkali or not been cured at high enough temperature for these slowly reactive aggregates to cause widespread significant deterioration.

We concluded that high temperatures used to cure the precast piles on bridges A and B initiated isolated and relatively minor ASR associated with minor constituents of the aggregate. The potential alkali reactivity of the aggregates used had not previously been recognised. The curing temperatures were high enough to also initiate DEF in concrete subsequently exposed to wet conditions, despite the cement chemistry not inherently presenting a high risk of DEF. The sensitivity of DEF to variations in conditions within the concrete, the overall minor extent of ASR and DEF and the difficulty of obtaining a representative sample of such an inhomogeneous material explain why the observations of ASR and DEF varied between cores from the same pile. If all piles contained the same amount of the reactive aggregate constituent and were subject to the same curing regime, then ASR and DEF would probably have occurred to some extent in all piles. Similar comments probably apply to piles from bridge M, and possibly also to the piles from structures Wh, T and B.
Did ASR/DEF cause the cracking in bridges A and B?

Although ASR and DEF were neither extensive nor severe in the cores examined from bridges A and B, the distribution and pattern of cracking indicated that it was caused by ASR/DEF:

• the cores that exhibited signs of both reactions were both from the tidal zone;
• the cracks were only observed in wet concrete, i.e. below high tide level;
• crack patterns indicated an expansive stress (although piles on both bridges were square, damage was less severe in Bridge B piles, where the square reinforcing cage provided more restraint to expansion than the round cage in Bridge A piles).

Thus we believe that minor and localised ASR caused by curing temperatures higher than 70°C produced expansive stresses and microcracking. DEF in the wet concrete below high tide level subsequently induced or extended microcracking, which eventually developed into visible cracks.

Potential for ASR/DEF in other structures

Alkali-rich phonolites and trachytes from the Dunedin Volcanic Group may also be potentially alkali reactive. Their use and alkali reactivity in concrete has not been investigated (other than by examination of the cores taken from structures Wp and O), and no evidence of ASR damage on concrete structures has been reported from the Otago region.

Completion of the petrographic and SEM examinations of the cores from the six structures sampled in Stage 2 will reveal whether ASR/DEF is widespread in existing structures. If it is widespread, then the reactions may also occur in structures built in the future from similar materials. Current evidence suggests that the risk of damage is low. Nevertheless, if ASR/DEF has occurred in other structures, then industry standards and guidelines should be amended to acknowledge the potential reactivity of the South Island aggregates concerned, and to limit curing temperatures to less than 60°C when potentially alkali reactive aggregates are used in concrete.

Likelihood of ongoing deterioration in bridges A and B

ASR damage caused by slowly reactive aggregates usually develops within 10-20 years of construction. DEF damage usually also appears within 20 years, but laboratory testing indicates the rate and extent of DEF in different concretes varies widely with different concrete composition and exposure [12]. This is why different authors report different DEF behaviour in different structures [9].

Expansion tests on cores from bridges A and B indicated little risk of further ASR cracking or damage due to DEF. Yet an inspection in 2006 revealed cracking not seen in previous inspections. This may be a result of inspections being more focussed once the deterioration was recognised, with cracks being observed or reported for the first time, rather than being 'new'.

The concrete in all piles sampled appeared similar. It was, therefore, considered prudent to assume that further cracking will be identified in the future, although this may be a feature of the inspection regime rather than evidence of ongoing deterioration.

Other deterioration mechanisms

Chloride ion profiles in the splash and atmospheric zones indicate a risk of chloride-induced corrosion on the piles of Bridge B, although reinforcement and pre-stressing exposed at the cracks on the pile corners was in good condition. The cracks attributed to ASR/DEF will facilitate the ingress of chlorides, oxygen and moisture in the tidal and splash zones, further increasing the corrosion risk. The risk is expected to be similar on Bridge A.

Remedial options for cracked piles

ASR and DEF cannot be stopped once they have started because all the reactants are already in the concrete. The only practical means of repair is to jacket affected piles to restore their strength and to prevent or significantly delay reinforcement corrosion. Jacketing won’t, however, prevent further expansion [13, 14] unless the reactions are almost complete when the jacket is installed.

Seventeen piles on Bridge A were previously repaired because the deterioration had resulted in sufficient pile section loss to compromise structural integrity. The repair consisted of a substantial cast in situ reinforced concrete jacket which was carried from approximately 300mm below bed level to at
At least 1 metre above high tide to encase all visible cracks (Fig. 8). To date, no remedial work has been carried out on the Bridge B piles as the pile cracking has not progressed to a stage where loss of structural integrity is likely.

Figure 8. Piles jacketed in concrete, Bridge A

Freitag et al [15] describe other aspects related to the repair and maintenance of piles affected by ASR/DEF.

SUMMARY AND CONCLUSIONS

Prestressed concrete piles on two Southland bridges (A and B) and one bridge in Nelson (M) exhibited longitudinal cracking below high tide level that was not related to reinforcement corrosion.

Laboratory examination of concrete core samples by petrographic microscope revealed the presence of potentially alkali reactive rock types as minor aggregate components in the concrete in bridges A, B and M. Similar aggregate had been used in uncracked prestressed concrete piles.

Petrographic and scanning electron microscopy revealed definitive signs of ASR and DEF in some, but not all cores for the cracked piles on bridges A, B and M. Moderate signs of ASR/DEF were also seen in cores from uncracked piles on these and other bridges.

The occurrence of DEF in some piles indicates that these piles were cured at temperatures over 70°C.

Laboratory testing on coarse aggregate separated from concrete core samples from bridges A and B, and on alluvial concrete sand from the same original source as the coarse aggregate, indicated that the sand and coarse aggregate were slowly alkali reactive. Tests at elevated temperatures on mortars and concretes made from these aggregates showed that they may have undergone ASR at the elevated curing temperatures indicated by the occurrence of DEF.

Chemical analysis of concrete samples from bridges A and B indicated that the original alkali content of the concrete was less than 1.8 kg/m³, therefore the concrete was unlikely to have undergone ASR at normal ambient temperatures.

The ASR and DEF observed in the cores were neither extensive nor severe, despite the presence of reactive components in the aggregate, because the alkali content of the concrete was very low. Nevertheless, the combination of ASR and DEF is the most likely cause of the cracking in piles on bridges A, B and M.

The uneven distribution of ASR and DEF in the cores highlights the importance of sampling sufficient concrete when investigating potential cases of these reactions.

Although the aggregates used in the concretes sampled from bridges A, B and M are widely used for concrete in Southland and Nelson, little evidence of similar cracking was seen in piles of other bridges of similar age and design, apart from possibly two bridges in Nelson and one in Southland. This is probably because of the low concrete alkali contents and lower curing temperatures generally used.
Bridges A, B and M appear to represent isolated cases of ASR/DEF, where the combination of unusually high curing temperatures and moist in-service exposure conditions have facilitated ASR.

Alkali-rich phonolites and trachytes from the Dunedin Volcanic Group may also be potentially alkali reactive. Their use and alkali reactivity in concrete has not been investigated in depth, and no evidence of ASR damage on concrete structures has been reported from the Otago region. It is unlikely that all the factors promoting ASR would be present in many structures, but the occasional case may have occurred and not been recognised or reported, as has happened elsewhere.

Industry standards and guidelines should be amended to acknowledge the potential reactivity of the South Island aggregates identified in this investigation, and to limit curing temperatures to less than 60°C when potentially alkali reactive aggregates are used in concrete.

Residual alkali contents and expansion tests on core samples from bridges A and B indicated that ongoing deterioration of the concretes in these two bridges was unlikely. Therefore, recent reports of 'new' cracks may be a feature of improved inspection techniques.

ACKNOWLEDGEMENTS

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REFERENCES


