Concrete pile durability in South Island bridges

September 2011

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NZ Transport Agency research report 454

ISBN 978-0-478-38049-1 (print)
ISBN 978-0-478-38048-4 (electronic)
ISSN 1173-3756 (print)
ISSN 1173-3764 (electronic)

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Freitag, SA[1], SM Bruce[1] and A Shayan[2] (2011) Concrete pile durability in South Island bridges. *NZ Transport Agency research report 454.* 56pp.

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Keywords: alkali silica reaction, bridges, concrete aggregate, concrete, concrete durability, concrete piles, delayed ettringite formation, New Zealand, precast concrete

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Acknowledgements

The authors wish to thank the following organisations and their representatives for their assistance during this investigation:

- New Zealand Transport Agency, Invercargill City Council, Southland District Council, Nelson City Council, Tasman District Council, Southport, Port Marlborough NZ Ltd, Port Nelson Ltd, and their respective asset management consultants MWH Global and Opus International Consultants, for providing access to structures of interest and information about them for this research.
- Firth Industries, Allied Concrete Ltd and Southern Aggregates for providing information on past and present aggregate sources in the Invercargill area, and Allied Concrete Ltd for providing aggregate samples for testing.
- Bill Page and Associates for advising the researchers of pile cracking that had been observed during routine maintenance of a bridge in the Nelson area. The original enquiry was not related to this research, but ensured that we paid equal attention to the risk of pile deterioration in the northern South Island and in the Southland/Otago area (where the only other known cases had previously been identified).

Abbreviations and acronyms

AMBT-80	accelerated mortar bar test (specific test method)
ASR	alkali silica reaction
CPT-60	accelerated concrete expansion test (specific test method)
DEF	delayed ettringite formation
GNS	GNS Science Ltd
MoW	Ministry of Works
NZTA	New Zealand Transport Agency
RTA	Roads & Traffic Authority (Australia)

Contents

Executive summary

Background and scope of research

In 2006, routine inspections of two critical Southland bridges 'A' and 'B' (both with a pile bent substructure and exposed to marine conditions) revealed extensive cracking, spalling and surface erosion of precast prestressed concrete piles below high tide level. The damage significantly reduced the cross section area and therefore the load capacity of some of the affected piles.

An investigation carried out for the owners of bridges A and B found that the damage was caused by the interaction of two chemical reactions in the concrete that caused it to expand: alkali silica reaction (ASR), and delayed ettringite formation (DEF). This type of deterioration, referred to herein as ASR/DEF, is not easily detected or identified until it is well advanced, which means that other cases may exist but not have been recognised. This is particularly true for buried or immersed parts of piles, which are not often closely inspected. Until it was observed on these two bridges, ASR had been generally considered not to affect South Island concrete, further increasing the likelihood of cases being overlooked.

Repair and replacement of affected elements or structures is expensive. Therefore designers of new structures need to understand the potential risk so they can optimise cost and durability when selecting raw materials and mix designs for concrete structures.

To address the potential risks in both existing and future structures, this research aimed to

- identify the extent and severity of ASR and DEF in South Island precast concrete bridge elements, to enable affected structures to be managed effectively so that they remain safe and serviceable
- examine how ASR and DEF are influenced by aggregate type, construction practice and in-service exposure conditions, to reduce the chance of future structures being affected.

It involved:

- evaluating the potential alkali reactivity of South Island aggregate sources
- identifying the number of South Island concrete road bridges that might be more susceptible to ASR/DEF because of their location, age and pile design, and inspecting susceptible structures for signs of damage
- examining concrete core samples from piles on selected structures to identify whether ASR/DEF had occurred (whether or not damage was observed).

Potential alkali reactivity of South Island concrete aggregate

Accelerated mortar bar and concrete prism tests showed that aggregates from Oreti Beach and nearby alluvial deposits are potentially alkali-reactive but may react slower than fresh volcanic materials, and concrete temperatures may need to exceed 60ºC to produce deleterious expansion even if the concrete contains sufficient alkali.

The alkali reactivity is associated primarily with strained quartz and microcrystalline quartz in rocks from specific geological terranes. The reactive rock types include minor acid and intermediate volcanics, sedimentary rocks containing volcanic constituents, and partly metamorphosed sediments and volcanics.

Similar assemblages are found in alluvium throughout Southland and southeast Otago, and in the Waimea and upper Motueka River catchments in the northwest of the South Island.

Alkali- and silica-rich phonolites and trachytes in east and central Otago may be alkali-reactive, but it is not known whether they have been used as concrete aggregate.

No other sources of potentially alkali-reactive South Island aggregate were identified.

Incidence of ASR/DEF damage

The most likely structures to be affected are those built between about 1955 and 1970 (when high- and medium- alkali cements were available), with precast piles in damp or wet conditions, eg in waterways. Approximately 55 state highway bridges are in this category.

Routine maintenance inspections and specialist inspections of 51 such bridges and two wharves, mostly of pile bent design, revealed very few cases of pile damage resembling that caused by ASR/DEF. Extensive cracking was seen on one structure, less widespread cracking was seen on another four structures, and unexplained efflorescence was seen on a sixth structure.

Cracking was only seen on piles on marine or estuarine structures. This is probably coincidental, but may be a result of interactions between hardened cement paste and seawater exacerbating ASR expansion.

Dirt and biological growth must be removed before inspecting piles on marine/estuarine structures to detect cracking and other defects below high-tide level.

If removal of dirt and biological growth from such piles reveals more cases of ASR/DEF cracking, then the possibility of such cracking affecting buried piles should be examined.

Incidence of ASR/DEF

Core samples were taken from six structures in Southland/Otago and the northwest of the South Island, representing two aggregate assemblages containing microcrystalline quartz and strained quartz:

- mixed alluvial aggregate (Southland and northwest South Island)
- crushed andesite coarse aggregate with quartzitic sand (Southland and Otago).

Evidence of ASR reaction products was found by microscope examination of cores from five of the structures, but evidence of DEF was seen in samples from only one. ASR therefore appears to be more common than DEF.

ASR products were observed in cores from cracked piles and uncracked piles, but were more widespread in cores from cracked piles. Therefore ASR may be relatively common, but does not necessarily cause sufficient expansion to visibly crack the concrete unless sufficiently severe and widespread.

Microcracks were seen in all cores, but their extent was not clearly related to the presence of ASR or DEF reaction products, so they may have been caused by other mechanisms.

The most widespread cracking was seen on piles that had been cleaned before inspection, but ASR products were also present in samples from piles on which no cracks were seen. On these apparently uncracked piles, either the reaction was not extensive enough to crack the concrete, or cracks may have been obscured by dirt and biological growth.

The relatively widespread incidence of ASR suggests concrete temperatures during curing often exceeded 60°C, which is supported by the occasional observation of DEF.

The observed widespread occurrence of ASR also raises the question whether New Zealand greywacke aggregates containing microcrystalline quartz or strained quartz might also react in similar circumstances to the aggregates examined in this research.

Recommendations for NZTA bridge inspection and management practice

- Partly immersed precast concrete piles on bridges in marine/estuarine conditions should be cleaned to remove dirt and biological growth before every Detailed Inspection or at least every second Detailed Inspection.
- If the practice of cleaning partly immersed piles before inspection reveals more cases of suspected ASR/DEF, then buried precast piles on selected structures with piles in damp ground should be excavated and cleaned before Detailed Inspections to enable them to be inspected for cracks, and sampled to see whether ASR/DEF products are present in these elements. This will indicate whether the risk of ASR/DEF is similar in buried piles.
- If damage resembling ASR/DEF is observed on a structure, then its cause and extent should be identified by specialist examination of core samples, the likelihood of future deterioration determined by laboratory testing of core samples, and the implications for durability and structural performance determined by engineering assessment.
- Investigation of the potential alkali reactivity of New Zealand greywacke should be considered to find out whether the risks of ASR/DEF in precast concrete identified in this research also extend to concrete made with greywacke aggregate.

Recommendations for New Zealand concrete industry practice

The current New Zealand guidelines for managing ASR expansion (CCANZ 2003) recognise the potential reactivity of quartzite and strained quartz, but would benefit from updating to acknowledge the findings of this investigation, in particular the ASR cases observed, the sources of potentially alkali-reactive South Island aggregates identified, the effectiveness of different test methods for detecting potential reactivity of different rock types, and the influence of concrete alkali content and elevated curing temperatures on ASR expansion.

The guidelines would also benefit from general revision to take into account local experience gained and international developments in the 10 years since they were written. The wider concrete industry may wish to consider whether curing practices and quality management can be improved to reap the benefits of improved concrete quality and durability that can be achieved by ensuring concrete temperatures during curing are consistent and remain below 70°C.

Abstract

Alkali silica reaction (ASR) has, until recently, been considered to present a low risk to concrete in the South Island of New Zealand. The discovery in 2006 of evidence of ASR and delayed ettringite formation (DEF) associated with extensive deterioration of precast piles on two South Island structures prompted further investigation to identify the extent and severity of ASR and DEF in other South Island precast concrete bridge piles. The aim was to ensure affected structures could be managed effectively and thereby remain safe and serviceable, and to help identify effective means of minimising the risk of ASR/DEF in future structures. The work was carried out in New Zealand between 2008 and 2011.

The research found that despite the availability and use of potentially alkali reactive concrete aggregates in the Southland and Nelson areas, ASR/DEF was relatively uncommon and associated damage was generally minor, although cleaning of piles prior to routine inspection may reveal more cases in future. The findings suggested that ASR/DEF may be associated with the use of curing temperatures higher than those now specified, and recommended that current industry guidelines be amended to acknowledge the existence of alkali reactive aggregate in the South Island and the risk associated with elevated curing temperatures.

1 Introduction

1.1 Background

1.1.1 The problem – durability of concrete piles

In 2006, routine inspections of two critical Southland bridges ‘A’ and ‘B’ (both with pile bent substructures and exposed to marine conditions) revealed extensive cracking, spalling and surface erosion of precast prestressed concrete piles below high tide level. An investigation carried out for the owners of bridges A and B found that the damage was caused by the interaction of two chemical reactions in the concrete that caused it to expand: alkali silica reaction (ASR) and delayed ettringite formation (DEF). The investigation and its findings are described by Bruce et al (2008) and Freitag et al (2009; 2010).

The damage significantly reduced the cross section area and therefore the load capacity of some of the affected piles. The cracks may also render the concrete susceptible to other types of degradation such as freeze thaw attack and reinforcement corrosion. About a quarter of the piles on each bridge were affected to some degree. It was not practical to replace them. Structural repairs to extend their service life another 20 years were estimated at the time to cost about $10,000 per pile. It is not known why some piles were damaged more than others, so it was assumed that the number of affected piles would increase with time as the structures aged, or with increasing vigilance during routine maintenance inspections. Similarly, no unique features were found on the piles, so it was assumed that other bridges could be affected.

This type of deterioration, referred to herein as ASR/DEF, is not easily detected or identified until it is well advanced, which means other cases may exist but not have been recognised. The damage initially resembles cracking caused by corroding reinforcement and could easily be mistaken for this. As the deterioration continues, the cover concrete may soften and/or spall, resembling impact damage, surface abrasion/erosion, or chemical attack.

Pile damage directly affects load-carrying capacity. Where a structure has severe ASR/DEF damage, the owner will need to determine whether load restrictions are required, and whether the structure needs to be repaired or replaced. Where a structure exhibits minor or moderate damage, the owner will need to identify the likely rate of deterioration and the appropriate remedial options available to maintain an acceptable level of service for the remaining life of the structure.

Remedial treatments for surface degradation, structural defects, reinforcement corrosion, or abrasion/erosion may be inappropriate for ASR/DEF damage. At least one case of cracking in a South Island bridge has been treated as a structural deficiency, without investigating possible causes related to concrete durability. If the cracking had been observed in a North Island location where potentially reactive aggregates were available, then the possibility of ASR would have been considered. The possibility of ASR/DEF must be recognised to ensure that appropriate remedial techniques are used in future.

Repair and replacement of affected elements or structures is expensive. Therefore designers of new structures need to understand the potential risk so that cost and durability can be optimised when selecting raw materials. Ready-mixed concrete producers have to demonstrate how they manage ASR risk, so they need to know the reactivity of their aggregates. Existing laboratory tests for aggregate reactivity can be costly and time-consuming and can underestimate or overestimate the potential risk. Examination of existing structures built from concrete containing a particular aggregate therefore provides a practical way to assess its reactivity. Testing can then be limited to special applications where the risk is potentially higher or less acceptable.

1.1.2 Mechanisms of ASR/DEF deterioration

ASR is a chemical reaction between alkalis in hardened cement paste (mostly from Portland cement) and particular types of silica minerals that occur in some rock types found in concrete aggregate. In moist conditions, the reaction product takes up water and expands. The expansion can generate sufficient stress to crack the concrete if the reaction is sufficiently extensive. The New Zealand guidelines for managing the risk of ASR damage (CCANZ 2003) summarise the general principles of ASR.

Ettringite is a reaction product of Portland cement hydration at normal in situ curing temperatures. A different product forms when the temperature of the concrete exceeds about 70°C during the early stages of curing. This may happen, for example, in mass concrete or in accelerated curing if temperature increases are not well managed. Once cooler temperatures are restored, it will convert back to ettringite if sufficient water is available. Ettringite takes up more space than the original product so the conversion generates internal stress, which, like ASR, can be enough to crack the concrete. Quillan (2001) summarises the general principles of DEF. The risk of DEF is determined primarily by the early age curing temperatures, although some cement compositions and aggregate types may further increase the risk (Brunetaud et al 2007).

DEF is very sensitive to small changes in physical and chemical conditions, so the reaction and its effects may be highly localised within a structure, leading to inconsistent observations that make it difficult to determine the cause of damage even when DEF is suspected (Thomas et al 2008). DEF does not necessarily crack the concrete unless sufficient expansive stress is generated. It may, however, expand or extend microcracks initiated by other mechanisms, such as wetting and drying, thermal stress, freezing and thawing, dynamic loads, or localised high stresses in prestressed elements (Collepardi 2003; Ekolu et al 2007; Tosun and Baradan 2010).

DEF is often associated with ASR, and there has been considerable debate about the relationship between the two reactions. Where both occur, ASR generally precedes DEF, providing microcracks in which ettringite can crystallise, and a chemical environment in which ettringite is stable. DEF can occur without ASR if all high-risk parameters are present (Shayan and Xu 2004). Bruce et al (2008) summarise the relationship between ASR and DEF as applied to the case of structures A and B.

DEF does not proceed to a sufficient extent to crack concrete unless enough water is available. Therefore, severe DEF deterioration is generally limited to concrete elements such as piles or foundations that are immersed or partly immersed in water, although elements exposed to rain can also develop DEF. Thus wharves and bridges with foundations in a waterway are more susceptible than other structures. Such elements are also difficult to inspect, so this type of damage may easily be overlooked, particularly in the early stages when it may be masked by biological growth or surface abrasion/erosion.

ASR may be a precursor to DEF damage, but also causes cracking itself. ASR needs less moisture than DEF, and therefore affects not only immersed concrete elements but also any element exposed to rain, run-off, soil moisture, condensation or high humidity. To date it has been assumed that South Island concrete aggregates do not cause ASR in practice, despite some aggregates containing rock types known to be reactive overseas, high alkali cements being produced in the South Island between 1958 and 1968, and medium alkali cements being manufactured between the early 1950s and the early 1970s (St John 1988). This assumption was based on the absence of monolithic acidic and intermediate volcanic aggregates that are highly reactive (see section 1.1.3), and the absence of reports of ASR in South Island concrete.

Bridges A and B were built in 1969. The alkali content of the concretes used in the piles, calculated from the measured cement content and records of cement composition, was less than 2.0kg/m^3, well below the level of 2.5kg/m^3 currently considered to increase the risk of ASR damage. Measured concrete alkali contents of two concrete samples were slightly higher, probably because they included sodium and potassium from seawater, but both were less than 3.0kg/m^3. Therefore ASR and DEF in the two aforementioned Southland bridges probably resulted from too high temperatures being reached when the precast elements were cured, rather than simply from the original concrete alkali content being higher than 2.5kg/m^3.

DEF is now managed by better control on curing temperatures than when these two bridges were built, but other structures from the same era may be similarly affected. DEF is much more likely to damage concrete that is already affected by ASR.

In contrast, practices for minimising the risk of ASR damage have paid relatively little attention to the influence of elevated concrete curing temperatures.

1.1.3 Previous research

Until the early 1980s, very few New Zealand cases of ASR had been reported, and the reaction was believed to have been prevented by precautions introduced by the Ministry of Works (MoW) in the 1940s. Following the discovery of isolated cases of ASR in Taranaki, investigations in the 1980s to determine the incidence of in situ ASR in the North Island were carried out by concrete specialists specifically looking for damage that might have been caused by ASR. These surveys found that the MoW precautions were generally effective when followed, but still identified many previously unreported cases. Most were of cosmetic significance only, but they reinforced the need to take precautions when using certain aggregates. CCANZ (2003) summarises the history of previous ASR research in New Zealand.

Awareness of the potential for ASR to occur if precautions are not taken has become increasingly important because of changes over the last 20 years or so in technology and the commercial and regulatory environments involving concrete construction. Thus now:

- no single organisation has oversight of public works
- a wider range of raw materials and concrete mix designs are used
- new concrete structures are required by default to have specified intended lives of 50 years and some asset owners, such as the NZ Transport Agency (NZTA), require a specified intended life of 100 years
- infrastructure asset owners want to extend the life of existing concrete infrastructure beyond 50 years
- many concrete designers, specifiers and suppliers do not realise ASR is not a major problem in New Zealand only because precautions have previously been taken to prevent it.

The 1980s investigations also highlighted the need to consider the potential for further ASR expansion in structures being considered for upgrading or repair. Consequently, ASR investigation has now become more common in structures where ASR has caused minor or moderate damage.

The main reactive aggregates in the North Island are acidic and intermediate volcanic materials. Most consist of a single rock type from a readily identifiable source (eg ‘Egmont andesite’), so were easy to identify when ASR was first discovered in the USA in the early 1940s. The 1980s investigations also found that these materials sometimes cause ASR even when they are only minor constituents of the aggregate. In the South Island these rock types are not found as monolithic aggregates, so the risk of ASR in the South Island has always been assumed to be minimal. Consequently, the 1980s investigations did not include South Island structures. Similar rock types are, however, found as minor constituents in some South Island alluvial aggregates, particularly in Southland, as reported by Shayan (2007a).

Extending the 1980s North Island work by identifying such aggregates and investigating whether they had been associated with in situ ASR was, therefore, desirable to determine whether this assumption was appropriate. It also would determine whether the two affected Southland bridges represented a unique combination of materials, design and construction practice, or whether they were symptomatic of a wider problem.

1.2 Aim and scope of current research

International guidelines exist for assessing the risk of ASR based on knowledge of the general rock type. Following these guidelines may result in excessive or inadequate precautions being taken to minimise the risk associated with a particular aggregate, because the risk of ASR is related to the specific characteristics of individual aggregate sources.

After identifying the cause of deterioration on bridges A and B, we did not want to unnecessarily raise construction costs or concern about the risk to other New Zealand structures. Therefore, we believed it was important to find out more about the potential reactivity of South Island aggregates and how widespread and severe ASR/DEF is in other existing structures before considering any changes to current New Zealand practice. The research therefore aimed to provide practical information specific to New Zealand needs. Its purpose was to:

- improve the safety of existing concrete structures by identifying the extent and severity of a concrete durability problem recently identified in New Zealand
- improve the durability of new concrete structures by developing appropriate strategies to reduce the chance of future structures being affected.

The objectives of the research were to:

- identify the extent and severity of two chemical reactions in South Island precast concrete bridge elements: alkali silica reaction (ASR) and delayed ettringite formation (DEF). These findings will enable affected structures to be managed effectively so that they remain safe and serviceable.
- examine how ASR and DEF are influenced by aggregate type, construction practice and in-service exposure conditions. These findings will help to identify means of minimising the associated risks in new structures.

The research involved:

- evaluating the influence of South Island aggregate sources by geological assessment and laboratory testing.
- identifying structures on which ASR/DEF were considered more likely because of their location, age and pile design, reviewing routine inspection reports from these structures, and inspecting them specifically for signs of ASR/DEF.
- examining concrete core samples from piles on selected structures to identify whether ASR/DEF had occurred and had caused cracking or other signs of damage to the pile.
- identifying appropriate means of communicating the research findings to asset managers and to designers, contractors and concrete suppliers/manufacturers involved in new concrete construction.

This report is divided into three sections each covering a distinct aspect of the project:

- evaluation of the potential alkali reactivity of South Island aggregate sources

- identification of the incidence of ASR/DEF damage in South Island concrete structures
- identification of the incidence of ASR/DEF in South Island concrete structures (whether or not damage was observed).

The conclusions consider whether ASR and DEF are likely to have occurred on many structures, and whether the effects of the reactions are likely to have damaged the concrete. They also consider how risks associated with ASR/DEF might be minimised in structures built in the future.

Recommendations based on the research findings are given for minimising the risks associated with ASR/DEF in new and existing structures.

The research did not:

- evaluate the effects of ASR/DEF on the durability or structural performance of individual affected structures
- identify the concrete mix design, aggregate and cement sources, or pile manufacturing process used for each individual structure, and therefore did not evaluate how concrete alkali content might have influenced the potential reactivity and expansion of the concrete
- consider remedial options for affected structures (collectively or individually).

This report uses geological definitions to describe rock types and groups of rock types. These terms will be familiar to the geologists engaged by New Zealand concrete practitioners to describe the composition of specific aggregate sources. Practitioners involved in concrete supply and the design, construction and management of concrete structures do not need to understand these definitions, and therefore they are not explained in this report.

Territorial boundaries created for regulatory purposes, such as the NZTA's regional network boundaries, may change with time and may differ between agencies. Although this report focuses on road bridges, the findings are also relevant to other concrete structures. Therefore the geographical terms used in this report refer to general geographical locations rather than to specific road controlling authorities. Thus 'Nelson' refers to the northwest corner of the South Island, and includes the areas under the jurisdiction of Nelson City Council and Tasman District Council.

1.3 Project details

This research was carried out by Opus International Consultants Ltd (Lower Hutt, New Zealand) between 2008 and 2011.

Specialist consultancy services were provided by:

- GNS Science Ltd: identification of sources of potentially alkali-reactive rock types in the South Island, New Zealand (Skinner et al 2009)
- ARRB Group Limited: testing concrete aggregate samples from Southland for potential alkali reactivity, identification of potentially alkali-reactive aggregates and evidence of alkali silica reaction and delayed ettringite formation in concrete core samples (Shayan 2010).

2 Potential alkali reactivity of South Island concrete aggregates

This part of the investigation involved two phases:

- determining whether the aggregates used in bridges A and B were potentially alkali reactive
- identifying other sources of potentially alkali-reactive aggregates in the South Island.

2.1 Reactivity of aggregates used in bridges A and B

2.1.1 Methodology

2.1.1.1 Samples

Petrographic analysis of concrete from bridges A and B carried out during the investigation for the bridges' owners found that the aggregate was predominantly sandstone/siltstone and greywacke showing signs of low-grade to medium-grade metamorphism, plus quartzite and some tuff-like materials. Minor constituents included acidic, 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.

The aggregate used in the piles of bridges A and B was most likely to have been alluvial material from the Oreti River near Branxholme/Wallacetown, which was the main source of concrete aggregate in the 1960s and 1970s. Dune sand from Taramoa was also sometimes used. (Information from Firth Industries and Southern Aggregates, pers comm, October 2008).

Because concrete aggregate from the same source appeared to have been used in both bridges, it seemed reasonable to combine aggregate from both bridges to provide a sample for aggregate testing in the current investigation. Thus a combined sample of aggregate was extracted by crushing several cores from bridges A and B and physically separating the coarse aggregate pieces. A portion of the extracted aggregate was then crushed, and the fraction smaller than 5mm graded for accelerated mortar bar testing. The remainder, ranging in size from 5mm–15mm, was used for concrete prism testing.

Most concrete aggregate is now sourced from coastal beach deposits at Oreti Beach. This material is very similar to the Branxholme aggregate, but has shelly layers and may contain minor limestone and iron-stained constituents from tributaries downstream from Branxholme (Southern Aggregates, pers comm, October 2008).

Samples of 19mm and 13mm coarse aggregate and concrete sand from Oreti Beach were supplied by Allied Concrete in October 2008 for testing in this investigation to compare the potential reactivity of the Branxholme and Oreti Beach sources. These samples were used in the gradings 'as supplied' to make concrete and mortar specimens. They were identified by Opus Central Laboratories sample numbers 4-08/298 (19mm), 4-08/299 (13mm) and 4-08/300 (sand).

Type GP cement from Blue Circle Southern was used to make the concrete and mortar test specimens. The cement used complied with the Australian cement standard current at the time (AS 3972), which was almost identical to the New Zealand cement standard current at the time (NZS 3122), and was very similar to typical type GP cements made in New Zealand. In addition, the results of the tests carried out were influenced more by the test conditions than the composition of the cement used to make the test specimens. Therefore the use of an Australian cement in the tests was considered unlikely to produce misleading results for the New Zealand market.

2.1.1.2 Test methods

The potential alkali reactivity of the aggregates was assessed by an accelerated mortar bar test (AMBT-80) and an accelerated concrete expansion test (CPT–60). Overseas, both tests have been shown to produce results that correlate with in situ concrete performance (Lindgard et al 2010; Shayan et al 2008).

The AMBT-80 test method used was Roads & Traffic Authority (RTA) T363 (RTA 2001). This test involves storing mortar bars in a 1 mole/litre solution of sodium hydroxide at 80ºC for 21 days, and monitoring their length during that time. It is similar to ASTM C1260, which runs for 14 days. Shayan and Morris (2001) found that for rock types such as gneissic granites, gneissic quartz gravels, and basic meta-volcanics (which are similar to rock types found in the Oreti alluvial material, and which may react more slowly than fresh volcanic reactive materials), extending the test period to 21 days detects potential reactivity that may not be apparent at 14 days. RTA adopted the 21-day test rather than ASTM C1260 because many of New South Wales' reactive aggregates are of this type. Shayan (2007b) developed criteria by which the results could be used to define aggregate reactivity. These are given in section 2.1.2.

The CPT–60 method involves casting prisms from a standard concrete mix design with extra alkali added to the mix in the form of sodium hydroxide, storing them at 60ºC 100% relative humidity (RH) for 20 weeks (4 months), and monitoring their length during that time (Shayan et al 2008). Features of the concrete mix design are as follows:

19mm coarse aggregate	550kg/m^3 (note 1)
13mm coarse aggregate	550kg/m^3 (note 1)
Sand	725kg/m^3
Cement	420kg/m^3
Cement alkali content	0.42% Na_2O equivalent
Sodium hydroxide added	0.92% Na_2O equivalent by weight of cement (note 2)
Water to cement ratio	0.42
Air content	1% approximately

Note 1: for the combined aggregate extracted from the cores a total of 1100kg/m^3 of the combined material was used.

Note 2: added to increase concrete alkali content to 1.4% Na_2O equivalent by weight of cement (5.9kg/m^3 of concrete). This is much higher than the alkali content of most commercially produced concretes (generally less than 3.0 kg/m^3), but is necessary to accelerate expansive reactions to obtain results within a practical time.

The combination of AMBT-80 and CPT-60 tests was required because:

- Some aggregates could react in AMBT-80's high temperatures and alkaline storage conditions and thereby be classed as 'potentially reactive' even though they do not react in normal in situ exposure conditions. In addition, crushing coarse aggregates to a suitable particle size for AMBT-80might induce fractures in the aggregate particles and release reactive components that might not be available in the coarse aggregate form. Both of these effects would increase the reactivity of the test sample, so an aggregate might react more aggressively in AMBT-80 than in the CPT-60 test. Consequently, it is generally recommended that AMBT-80 be used to accept aggregates, but not to reject them, on the basis of their potential reactivity (unless the risk of 'false positive' results is acceptable). Thus in this programme, if the new alluvial sand tested as non-reactive by AMBT-80 but CPT-60 produced significant expansions, then the CPT-60 expansions would be assumed to have been associated with reactivity of the coarse aggregate.

- CPT-60 is performed at a lower temperature than AMBT-80, and does not require coarse aggregates to be crushed; therefore the test conditions are less aggressive than AMBT-80 conditions. Consequently, CPT-60 results may represent the reactivity of aggregates under normal site conditions more accurately than AMBT-80 results. In other words, an aggregate classed as 'potentially reactive' by AMBT-80 will not necessarily react at normal in situ exposure conditions, but if CPT-60 finds an aggregate to be potentially reactive then it is likely to react under normal in situ exposure conditions. Therefore, results from CPT-60 take precedence over AMBT-80 results when assessing aggregate reactivity.
- The combination of both tests might indicate the influence of temperature on potential alkali reactivity. CPT-60 uses the same temperature as some accelerated curing procedures. The AMBT-80 temperature is hotter than recommended curing temperatures and is in the range where the risk of DEF becomes significant.
- Most importantly, the AMBT-80 gives indicative results within four weeks, compared with months or years for CPT-60 or other concrete tests. Thus decisions about the next stage of work that are based on aggregate reactivity can be made sooner.

Table 2.1 shows the test regime used.

Table 2.1 Test regime for determining potential aggregate reactivity

Aggregate	Tests carried out	Purpose
Coarse aggregate extracted from cores, plus new alluvial sand	CPT–60	Did the piles on bridges A and B contain a potentially alkali-reactive coarse aggregate?
New coarse aggregate, plus new alluvial sand	CPT–60	Are alluvial aggregates currently being sourced potentially alkali-reactive?
Coarse aggregate extracted from cores, crushed to sand size	AMBT-80	Did the piles on bridges A and B contain a potentially alkali-reactive coarse aggregate?
New alluvial sand	AMBT-80	Is alluvial sand currently being sourced potentially alkali-reactive?

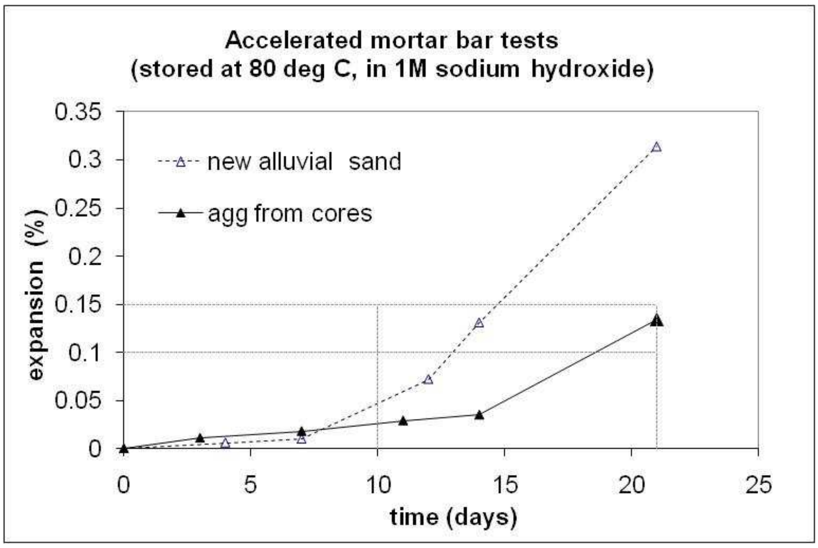
2.1.2 Results

Results from AMBT-80 and CPT-60 are given in figures 2.1 and 2.2.

The AMBT-80 results indicate that the aggregate extracted from the cores, and the new alluvial sand, are both 'slowly reactive'.

The CPT–60 results indicate that the coarse aggregate extracted from the cores, the new coarse aggregate and the new alluvial sand are all unlikely to cause significant ASR expansion in concrete at normal in situ exposure temperatures, even with elevated concrete alkali contents.

Figure 2.1 Accelerated mortar bar test results. Criteria for assessing results are at right



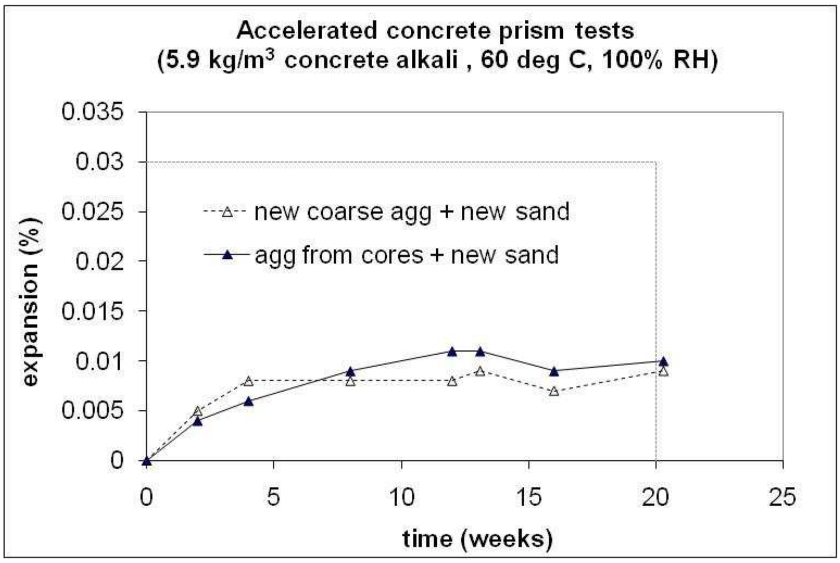
Sand:

Non-reactive:	<0.15% at 21d
Slowly reactive:	≥0.15% at 21d
Reactive:	≥0.15% at 10d

Coarse aggregate:

Non-reactive:	<0.10% at 21d
Slowly reactive:	≥0.10% at 21d
Reactive:	≥0.10% at 10d

Figure 2.2 Accelerated concrete prism test results. Aggregates that produce expansions greater than 0.03% at 20 weeks are considered potentially alkali-reactive



2.1.3 Discussion

The expansion limits used to interpret AMBT-80 and CPT-60 results indicate whether ASR is likely in concrete cured at, and subsequently exposed to, natural environmental temperatures. They do not indicate reactivity at elevated temperatures, although it is widely accepted that the risk of reaction increases with temperature. Similarly, most guidelines for managing ASR risk (including TR3 (CCANZ 2003)) are based on limits that minimise ASR expansion of concrete cured at and exposed to normal environmental conditions, rather than at elevated temperatures.

In this investigation, the mortar bar tests were carried out at 80°C, and the concrete prism tests at 60°C. An excess of alkali was available in both types of test. The difference between the results from mortar and concrete tests probably reflects the different test temperatures. Thus the combination of results from these mortar and concrete tests suggests that 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 are less likely to react at curing temperatures of 60°C or lower, even in concrete with high alkali content. DEF is unlikely to occur at temperatures lower than 60°C, but may occur at temperatures over 70°C. The amount of DEF expansion is determined primarily by the maximum concrete temperature, and the duration over which it occurs; other aspects of mix design and materials are secondary (Brunetaud et al 2007). Therefore it is reasonable to assume that curing temperatures exceeding 70°C increase the risk of expansions caused by a combination of ASR/DEF (if not ASR alone) in concrete containing these aggregates.

Hanson (1963) found that the internal temperature of 12” x 6” concrete cylinders during steam curing could be 10°C higher than the enclosure temperature, depending on curing temperature and heating rate. This highlights the importance of monitoring and controlling the temperature inside the concrete during curing, not just the applied temperature or the mould temperature. Steam curing to accelerate hardening and strength development of precast units such as beams was a relatively new process in New Zealand in the 1960s when structures A and B were built. At that time, curing temperatures were not always closely monitored or controlled (former Ministry of Works project engineer, pers comm), so the magnitude of temperature differentials may not have been appreciated.

As described in section 1.1.2, the ASR and DEF observed in bridges A and B was probably associated with inadequate management of steam curing temperatures, with the concrete temperature exceeding 70°C during the curing of some piles (as indicated by the presence of DEF in some of the samples examined). The results presented in this section support this conclusion.

2.2 Other potentially reactive South Island aggregates

Unless otherwise indicated, the contents of this section were based on work carried out as part of this project by GNS Science (‘GNS’). GNS’s methods and findings were reported by Skinner et al (2009) to Opus.

2.2.1 Methodology

As part of the original investigation of the cause of the pile deterioration on bridges A and B, core samples from the piles were examined by petrographic microscope to identify the type of aggregate in the concrete and whether it contained potentially alkali-reactive components (Shayan 2007a).

To assess the risk of ASR associated with current aggregate sources from the Invercargill area, GNS re-examined three of the bridge A and B thin sections described by Shayan (2007a), and compared them with the aggregate samples from Oreti Beach described in section 2.1, which GNS examined visually by hand lens.

To assess the risk of ASR/DEF in other regions of the South Island, GNS reviewed information from geological maps and various summaries of aggregate resources to identify South Island rocks that may be potentially alkali-reactive when used as concrete aggregate.

Determining whether such rock types have been used as concrete aggregate, or measuring their potential reactivity was, however, beyond the scope of this research.

2.2.2 Results and discussion

2.2.2.1 Southland/southeast Otago aggregates

ARRB's petrographic examination of the concrete from bridges A and B found that 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 acidic, 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 (Shayan 2007a).

Skinner et al (2009) found that the mixed alluvial aggregates in the three thin sections from bridges A and B consisted of quartz, quartzite, quartz vein clasts, greywacke sandstone and siltstone, tuff, volcanic particles, dioritic and granitoid clasts, potassic and calcic feldspar fragments and, in one section, shell fragments. All rock clasts except the greywacke sandstone were described as weathered, iron stained and partly corroded. Skinner et al (2009) considered that the aggregates described by Shayan (2007a), and the aggregates represented in the thin sections they re-examined, were consistent with being derived from the Mataura, Oreti and Makarewa river systems.

Skinner et al (2009) found that the new aggregate samples from Oreti Beach consisted of a mixture of materials. This was as they expected from the origins of the Oreti Beach deposit, which is supplied by gravels from the Oreti, Makarewa and Aparima rivers and their tributaries and watersheds, and from the Waiau catchment and Fiordland (by longshore drift). Thus the gravel samples comprised a mixture of four main rock types: dark to medium grey 'greywacke' sandstone and siltstone, possibly from the Caples terrane[1] (27%); coarse volcanic rock, tuff and diorite (32%); pale grey-brown fine-grained greywacke (17%); and quartzite, quartz vein and quartzose granitoid pebbles (24%). These rock types are similar to the aggregate mixture seen in the thin sections from bridges A and B.

Figure 2.3 shows the distribution of South Island basement rocks (see also Mortimer and Smith Lyttle 2001). The Southland/Otago basement on the east of the Alpine Fault is characterised by five typical lithologies: Caples terrane, Dun Mountain-Maitai terrane, Murihiku terrane, Brook St terrane and the Median Batholith. Displacement of the earth's crust along the Alpine Fault means the same sequence appears to the west of the fault in the northwest of the South Island. Overlying these basement rocks in the Southland/Otago region are younger sedimentary deposits from the Cenozoic period.

Southland and southeast Otago are drained by five main river systems. From east to west these are: the Mataura-Waikaia, Oreti-Makarewa, Aparima and Waiau rivers, plus, in the northeast, the Clutha River system including the Pomahaka River. These rivers each drain several of the geological terranes shown in figure 2.3, each supplying characteristic lithologies to their gravel deposits.

Erosion of the basement rocks by the river systems in their headwaters, together with erosion of older glacial deposits and alluvial terraces in the upper and middle reaches of the river, produce large alluvial gravel deposits that overly the basement rocks over much of the plains and coastal areas in Southland, Canterbury, Marlborough, Nelson and Westland. These gravels retain the characteristic lithologies of the parent terranes, but vary with location and time of deposition because of the variation in hardness of the different rock types in each terrane. Thus the amounts of softer rocks (such as those from Cenozoic sediments) and more veined or schistose rocks (as in Caples terrane lithologies) decrease with distance downstream from their original

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[1] Terrane: a fragment of the earth's crust that has formed on or broken off one tectonic plate and accreted ('sutured') to crust lying on another plate. The crustal fragment preserves its own distinctive geological history, which is different from that of the surrounding areas (Wikipedia February 2009).

source because they are broken down by fluvial abrasion. Consequently, the proportions of potentially alkali-reactive aggregate may vary between sites and with time at individual sites.

Table 2.2 lists the five terranes of the Southland/Otago basement from north to south (youngest to oldest), the river catchments that traverse them, and their principal potentially alkali-reactive constituents.

Skinner et al (2009) described the Oreti Beach samples they examined as consisting of a mixture of Caples, Dun Mountain-Maitai, Murihiku and Brook St terrane lithologies, as well as lithologies of the Median Batholith and Fiordland. They considered that the present-day Oreti Beach aggregates had a similar lithological range to the aggregate in the concrete from bridges A and B, and therefore would have a similar potential for ASR.

Skinner et al (2009) considered that other alluvial gravels throughout Southland would contain similar assemblages of rock types, though varying with the time of deposition and distance downstream. For example, veined/schistose rocks and softer Cenozoic sediments are less common in downstream and coastal deposits. Therefore in the absence of data from investigations from specific sites, all Southland/Otago gravels containing this assemblage should be assumed to have similar potential for ASR.

In addition to identifying potentially alkali-reactive constituents in the alluvial aggregates, Skinner et al (2009) also observed that zeolites in the low-grade metamorphic rocks of the Dun Mountain-Maitai, Murihiku and Brook St terranes may be dimensionally unstable with wetting and drying. This would make such rock types weaker and susceptible to being broken down by alluvial transport processes, when being processed for use as aggregate, or when being mixed into concrete.

2.2.2.2 Nelson/Marlborough aggregates

Skinner et al (2009) reported that in Nelson/Marlborough, aggregate has been extracted from river gravels in the lower reaches of the Wairau and Motueka Rivers, and from the Waimea River and its tributaries and floodplain.

The Wairau River gravels are predominantly unweathered indurated sandstones from the Torlesse terrane, and were considered unlikely to include alkali-reactive rock types.

The Motueka River gravels contain Moutere Gravel, Separation Point granite and Dun Mountain ultramafics, which are all weathered materials that provide poorer quality aggregate. Concern was raised that weathered material in the lower Motueka River gravels may break down on exposure to salt water.

Waimea River gravels that consist mainly of Torlesse greywacke sandstone are unlikely to be alkali-reactive. Waimea River gravels containing sandstones and other materials from the Murihiku and Maitai terranes may include potentially alkali-reactive vitric and lithic tuffs and volcaniclastic sandstone. Therefore, Waimea River gravels containing these materials were considered potentially reactive.

2.2.2.3 Eastern and Central Otago aggregates

Skinner et al (2009) noted that aggregate quarried from the Dunedin Volcanic Group in central and eastern Otago is of consistent quality, particularly the basalts with silica contents less than 50%.

They also noted that some alkali phonolites and trachytes found in scattered occurrences within the Dunedin Volcanic Group in eastern Otago have silica contents of 55%–60% and high levels of sodium and potassium (Coombs et al 2008). Basaltic rocks with silica contents exceeding 50% may be potentially alkali-reactive because they may contain residual glass, and some basaltic rocks with high levels of sodium and potassium may react with the cementitious binder in the concrete and thereby release alkalis into the pore solutions in the concrete (CCANZ 2003). Therefore these phonolites and trachytes with high silica and alkali contents may be alkali-reactive themselves, or contribute alkalis that may react with alkali-reactive aggregate. To our knowledge they have not been tested for potential alkali reactivity and we do not know whether they are used as concrete aggregate. Skinner noted that they would be easily identified by petrographic microscopy and suggested they be treated as potentially highly reactive.

Aggregates from the Taieri and Waitaki River catchments were considered unlikely to contain alkali-reactive materials.

2.2.2.4 Canterbury and North Otago aggregates

Skinner et al (2009) reported that most aggregate in Canterbury and North Otago is alluvial gravel. In Canterbury, indurated greywacke from the Torlesse terrane provides high-quality aggregate, while Holocene gravels in South Canterbury and North Otago may provide suitable concrete aggregate. These materials are unlikely to contain alkali-reactive rock types.

They considered that basalt from Halswell Quarry, used for sealing chip, is unlikely to be alkali-reactive, as are alkaline and tholeiitic basalts from the Timaru Basalt and Oamaru Volcanic groups, which were used for port works at Timaru and Oamaru.

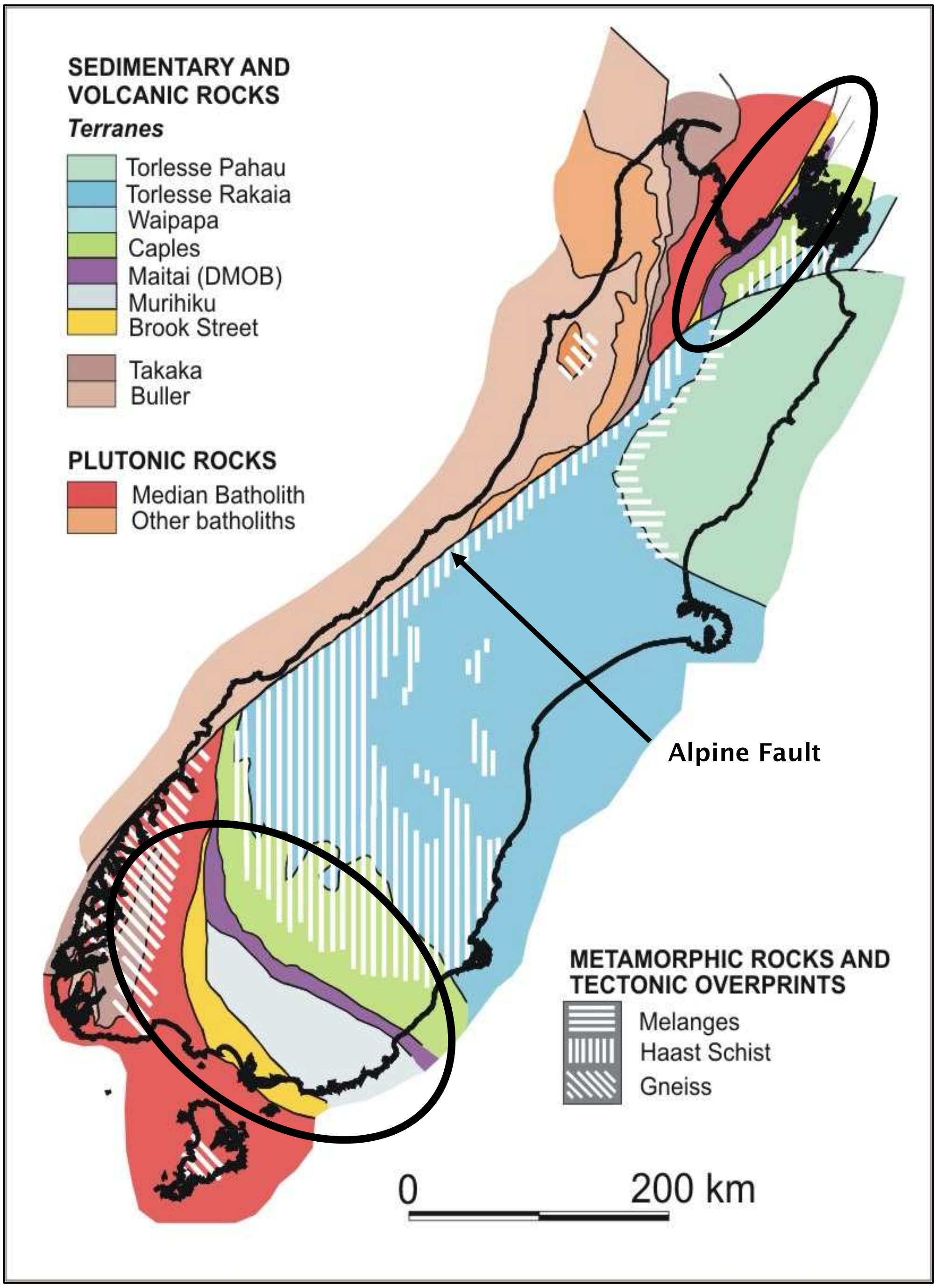
2.2.2.5 West Coast aggregates

Skinner et al (2009) reported that on the West Coast most aggregate is sourced from river beds, river terraces, and (locally) from gold dredge tailings. Gravels from the Grey and Buller river systems consist largely of unweathered granite from the Karamea and Paparoa batholiths, whereas gravels from south of the Grey River are predominantly indurated greywackes from the Rakaia terrane and Greenland Group. Schist and gneiss from the Alpine Schist and Greenland Group greywacke are found in minor quantities. None of these rock types were considered potentially alkali-reactive.

Table 2.2 Basement terranes in Southland/Otago and Nelson/Marlborough (from youngest to oldest; north to south in Southland/Otago)

Terrane	River catchments (Southland/Otago)	River catchments (Nelson/Marlborough)	Potentially alkali-reactive constituents
Caples	Upper Mataura/ Pomahaka Upper Oreti	Upper Waimea	Chert Andesite Dacite Rhyolite (all are minor constituents)
Dun Mountain-Maitai	Mataura Upper Oreti Upper Aparima	Waimea Upper Motueka	Vitric and lithic rhyolitic tuff Hyaloclastites Spilite and keratophyre with glass and cryptocrystalline silica
Murihiku	Mataura Oreti Aparima	Waimea	Felsic vitric and lithic tuff Rhyolitic tuff Sandstone derived from ignimbrite, andesite, trachydacite and rhyolite
Brook St	Aparima Lower Waiau (also beneath the Bluff-Greenhills area)	-	Calc-alkaline andesite/rhyolite Volcanic tuffs Spilite and keratophyre (as above)
Median Batholith/ Fiordland lithologies	Upper Oreti Waiau	-	nil

Figure 2.3 South Island basement rocks



Note: The three terranes likely to provide sources of potentially alkali-reactive materials in Southland/Otago and Nelson/Marlborough are Dun Mt-Maitai ('Maitai'), Murihiku and Brook St (circled). The basement rocks are overlain with gravels in much of Southland, Canterbury and Westland. (Map by N. Mortimer, GNS, based on Mortimer (2004)).

2.3 Summary – potential alkali reactivity of South Island aggregates

2.3.1 Southland/southeast Otago mixed alluvium

AMBT-80 and CPT-60 tests showed that aggregates from bridges A and B and aggregates currently sourced from Oreti Beach are potentially alkali-reactive, but may react more slowly than fresh volcanic materials, and may need temperatures exceeding 60ºC to produce deleterious ASR expansions even if the concrete contains sufficient alkali.

Petrographic examinations of aggregates from bridges A and B and of aggregates currently sourced from Oreti Beach indicated that they include potentially alkali-reactive rock types containing strained quartz, microcrystalline quartz, chalcedony, glass and devitrified glass (eg sandstone and siltstone; fresh and partly metamorphosed acidic, intermediate and basic volcanic material; quartzite).

Potentially reactive rock types from South Island basement terranes that may be found as major constituents of Southland and southeast Otago gravels include:

- hyaloclastites, spilites and keratophyres from the Dun Mountain – Maitai terrane (Mataura River catchment, headwaters of Oreti and Aparima rivers)
- felsic lithic and vitric tuffs, rhyolitic tuff, volcaniclastic sedimentary rocks from the Murihiku terrane (Mataura, Oreti and Aparima rivers)
- calc-alkaline andesite-rhyolite, sodic spilite tuff and lava, and keratophyre from the Brook St terrane (Aparima and Waiau rivers).

2.3.2 Nelson–Marlborough

Waimea River gravels may contain potentially reactive vitric and lithic rhyolitic tuffs from the Murihiku and Maitai terranes.

Aggregates sourced from the lower Wairau and Motueka Rivers are unlikely to contain alkali-reactive materials, but weathered materials from these sources may produce poorer quality aggregate.

2.3.3 Eastern/Central Otago

Alkali- and silica-rich phonolites and trachytes from localised sources in the Dunedin Volcanic Group may be alkali-reactive, but to our knowledge they have not been tested for potential alkali reactivity, and we do not know whether they are used as concrete aggregate.

2.3.4 Other sources

No other sources of potentially alkali-reactive aggregates were identified in other areas including Canterbury, North Otago and the West Coast.

3 Has ASR/DEF damaged concrete piles on many South Island structures?

Having determined that the risk of ASR/DEF in South Island concrete was probably limited to Southland/Otago and Nelson/Marlborough because of the composition of the aggregates in those areas, the next steps were to find out how many structures were potentially affected and whether ASR/DEF had actually damaged structures in these areas.

Even if concrete contains potentially alkali-reactive aggregate, ASR will only cause damage if the concrete contains sufficient alkali and if the environment provides enough moisture. As shown in the previous section, elevated temperatures will increase the chance of ASR if sufficient alkali and moisture are available. High and medium alkali cements were manufactured in New Zealand from the early 1950s to the early 1970s (St John 1988), which coincides with the introduction of steam curing of precast units. DEF usually is preceded by ASR and requires the concrete to have a relatively high moisture content (ie constantly damp or wet).

Therefore the structures most likely to be affected by ASR are those built between 1958 and 1968, when high alkali cements were available, and with precast concrete piles (or other elements exposed to moisture). Of these, the structures with piles in waterways (ie piers) are most likely to be affected by DEF.

To ascertain whether ASR/DEF had occurred on any structures, selected structures were inspected for signs of the reactions. To maximise the chance of seeing signs of ASR/DEF, the site inspections focused on structures with ‘pile bent’ piers, particularly those built from precast piles between 1955 and 1970.

Overseas, ASR/DEF damage has been reported on wharf piles as well as on bridge piles. Wharf piles are often more accessible and therefore easier to inspect than bridge piles, so ASR/DEF damage may be more readily detected on wharf piles. Therefore, wharves were included in the investigation to increase the likelihood of identifying the risk of ASR/DEF to New Zealand concrete structures in general.

Thus, evaluating the incidence of ASR/DEF damage in the South Island involved:

- identifying structures in Southland/Otago and Nelson/Marlborough that would be most susceptible to ASR/DEF, by:
  - examining the NZTA’s Bridge Data System
  - consulting asset managers in port companies, NZTA and local authorities (and/or their consultants)
- asking bridge and wharf asset managers in Southland/Otago and Nelson/Marlborough about the condition of concrete piles in their structures as observed in routine inspections
- inspecting ‘pile bent’ structures for signs of ASR/DEF that may not have been reported during routine maintenance inspections.

Anecdotal evidence reported that piles on bridge A (and probably on bridge B) had been steam cured. No attempt was made to find out whether piles on other individual structures had been steam cured.

3.1 Identification of structures most likely to be affected by ASR/DEF

3.1.1 Methodology

Bridges considered most susceptible to ASR/DEF were those with precast reinforced concrete piles, built between 1955 and 1970, and particularly those with piers in a waterway. Of those, structures with abutments and piers of a 'pile bent' design were of particular interest because they would be much easier for the researchers to inspect (and take samples from) than those supporting a separate abutment/pier wall or diaphragm.

In January 2009, the NZTA's Bridge Data System was searched for bridges meeting all of the following categories:

- in regional networks Nelson (5B), Marlborough (5C), Central Otago (7A), Coastal Otago (7B) and Southland (7C)
- over waterways
- with driven reinforced concrete piles
- built between 1955 and 1970
- with more than one span (ie with at least one pier)
- foundations or piers consisting of 'piles and pile cap', or piers 'formed by foundation'.

Asset managers from the NZTA, local authorities and port companies were contacted directly and asked to identify pile bent structures built between 1955 and 1970. They were also asked to identify any structures on which pile damage resembling that caused by ASR/DEF had been observed in routine maintenance inspections (a copy of Bruce et al (2008)) was provided to assist them). Local authorities and port companies were not asked for details of the age and design of their overall bridge/wharf stock.

Organisations involved in this consultation (including their consultants) were:

- NZTA
- Nelson City Council
- Tasman District Council
- Port Nelson
- Port Marlborough
- Invercargill City Council
- Southland District Council
- Southport.

Local knowledge and anecdotal evidence were also sought from Opus International Consultants' asset management teams in Nelson, Marlborough, Southland and Otago.

3.1.2 Results

3.1.2.1 Likely numbers of structures affected

Table 3.1 shows the number and distribution of relevant structures in the Nelson and Southland/Otago areas, as indicated by the database search and consultation with asset managers.

The Bridge Data System and the consultation process indicated that in these areas, approximately half the state highway bridges with driven concrete piles and crossing waterways were built between 1955 and 1970, a total of about 103. Of these, five were pile bent structures, similar to those on which ASR/DEF damage had previously been reported.

A further 18 pile bent structures were reported from local authorities, including five built between 1955 and 1970.

3.1.2.2 Extent and severity of ASR/DEF damage reported from routine inspections

Only one case of damage resembling that caused by ASR/DEF was reported from routine maintenance inspections of structures in Nelson and Southland/Otago. The bridge concerned was a pile bent structure built in 1968 in the Nelson area, referred to herein as ‘structure M’ (see chapter 4). A routine Detailed Inspection[2] in 2008 revealed cracks that were not related to corrosion of reinforcing. The piles were subsequently water blasted to remove marine growths and then re-inspected. Longitudinal cracks were seen in the tidal zone on 65% of its piles. At least two faces on each of these piles were cracked. The inspector contacted Opus to find out what might have caused the cracks, but did not consider them to be structurally significant, so did not recommend to the NZTA that they be investigated for operational purposes. The cracks were, however, considered significant in terms of this research project, so the bridge was considered top priority for specialist inspection and sampling (see section 3.2 and chapter 4).

3.1.3 Discussion

If the main risk is indeed to piles in pile bent structures crossing waterways (and built between 1955 and 1970), then the findings above suggest a low risk of ASR and ASR/DEF in concrete piles of South Island bridges, with just 10 bridges in that category and only one of them with reported damage.

If buried piles are also affected, the risk may be higher: up to 55 state highway bridges built between 1955 and 1970 cross waterways and have precast piles supporting their piers. Damage to these piles would not be observed without excavating and cleaning the piles, which may be why no such damage has been reported.

Until the early 1980s, ASR was widely believed not to occur in New Zealand bridges (or other infrastructure). This belief resulted from public works specifications dating from the 1940s that were designed to ensure precautions were taken to minimise the risk of ASR when potentially reactive aggregates were used in concrete. In the 1980s, investigations by concrete specialists familiar with ASR revealed that the reaction was occurring in some North Island structures, including bridges, reservoirs and pavements. A lack of damage reported from routine inspections of South Island structures may, therefore, represent a lack of damage considered severe enough to required further attention, rather than a lack of any damage at all.

Thus a critical part of the research was the inspections by concrete specialists of the structures identified in section 3.1 as most likely to be affected by ASR/DEF. These inspections are described in section 3.2.

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[2] General, Superficial, Detailed, and Special Inspections are specific types of inspection defined by NZ Transport Agency (NZTA 2011, SP/SS6:2011 110706).

Table 3.1 Structures with driven (precast) piles, and structures with piers consisting of pile bents, all over waterways

	NZ Transport Agency[(a)]					Local authorities		Port companies		Total
	Nelson 5[(b)]	Marlborough 5[(c)]	Central Otago 7[(a)]	Coastal Otago 7[(b)]	Southland 7[(c)]	Nelson area	Southland/ Otago area	Nelson area	Southland area	
Bridges with driven piles	19 (7 built 1955–1970)	22 (8 built 1955–1970)	15 (6 built 1955–1970)	44 (26 built 1955–1970)	99 (56 built 1955–1970)	n/a	n/a	n/a	n/a	199 (NZTA) (103 built 1955–1970)
Bridges with driven piles and more than 1 span	12 (6 built 1955–1970)	12 (5 built 1955–1970)	11 (5 built 1955–1970)	34 (19 built 1955–1970)	43 (20 built 1955–1970)	n/a	n/a	n/a	n/a	112 (NZTA) (55 built 1955–1970)
Pile bent piers ('formed from foundations' or 'piles and pile cap' or 'multiple rc column')	1 (built 1968)	1 (built 1966)	0	3[(b)] (built 1961,1962, 1965)	4 (built 1978-1984)	7 (1 built 1968)[(c)]	11 (4 built 1969–70, 7 built since 1970)	2 (built 1974–5 and 2000)	1[(d)] (built 1969)	>30 (11 built 1955–1970)

a Data from Bridge Data System, January 2009.

b The pier construction of the 1962 bridge was incorrectly described in the Bridge Data System as 'rc wall or diaphragm'.

c The other six bridges were built since 1970. The age of four of them was recorded as '1980s'. The asset manager thought this date referred to the superstructures, which had been replaced on existing substructure. The date of original construction was not recorded.

d Southland and Otago port companies were not asked for information on their structures, but one pile bent structure was identified during site investigations for other purposes.

3.2 Specialist inspections

3.2.1 Methodology

Concrete technologists from Opus Central Laboratories carried out two field surveys in late March 2009: one in Southland/Otago and the other in the Nelson area. The Nelson survey took two days and the Southland/Otago survey took three days. The inspections were planned around visiting the pile bent structures built between 1955 and 1970 that had been identified by the NZTA Bridge Data System and by bridge asset managers (see section 3.1) and were carried out at low tide where possible.

Inspections of Otago bridges were limited to pile bent structures in Coastal Otago, where the aggregates may have contained potentially alkali-reactive rock types from the Dunedin Volcanic Group.

Inspections of ‘Nelson’ bridges also included bridges between Blenheim and Nelson, because precast elements in this area may have been cast by the same precaster that had made the bridge piles on which cracks had been observed during routine inspection (see section 3.1.2).

As time permitted, all bridges built between 1955 and 1975 over waterways were inspected along some stretches of state highway. This was because a few discrepancies were noted between entries in the Bridge Data System entry and the structures observed on site, and it was hoped that some additional useful observations might be made by inspecting the extra structures.

To include as many structures as possible in the surveys, inspections of bridges were brief, involving only visual examination from road level and riverbed/river bank/floodplain (depending on access conditions at each site). Binoculars were used where needed and the inspection team wore gumboots to allow access to piles in shallow water.

Removal of biological growths from the pile surfaces before inspection was beyond the means of the project, but the inspection team manually scraped such material from small areas on individual piles where they could get close enough to do so.

To avoid risks associated with working in deep or swiftly flowing water and to minimise the duration of each inspection, waders were not used. Similarly, inspection by boat or diver, or excavation of piles were considered to be beyond the scope of this research because of the time and costs involved.

Wharf structures were inspected by concrete technologists from Opus Central Laboratories during other investigations being carried out for the wharves’ owners. One of the wharves was also inspected by contractors familiar with the ASR/DEF damage on bridges A and B.

The main sign of damage the inspection teams were looking for was cracking (not obviously related to other causes) on elements exposed to moisture (deck edges, abutments, piles, piers, external beams). The orientation of cracks caused by expansive mechanisms like ASR/DEF is determined by the reinforcement configuration, because the concrete can only expand in directions where it is not restrained. Crack patterns considered as possible indicators of ASR/DEF were longitudinal cracks below the top of the splash zone on piles, and random cracks or grids of cracks on abutments and wingwalls. Efflorescence may or may not be associated with such cracking.

3.2.2 Results

The number of bridges inspected in each area is shown in table 3.2. One wharf in each area was also inspected.

The inspections largely confirmed the observations from the routine maintenance inspections, ie that very few bridges exhibited signs of ASR/DEF (table 3.3).

Table 3.2 Numbers of bridges inspected

Area	Total	1955–1970	Precast piles visible but not pile bents[(a)]	Precast pile bent structures [(a)] [(b)]
Nelson	21	15	2 (built 1963)	7 (2 built 1955–1970)
Southland/Otago	30	19	2 (built 1957, 1958)	16 (8 built 1955–1970)

a Assumed to be precast.

b Piles on one pile bent structure inspected in Southland had board marks on all faces so were assumed to be cast in situ and were not included in this tally.

Table 3.3 Signs of ASR/DEF

Area	Cracks on precast piles	Minor cracks on wingwalls	Other
Nelson	3 (1 built 1955–1970)	3 (2 built 1955–1970)	–
Southland/Otago	2 (built 1961–1965)	4 (built 1965–1970)	1 (built 1970)[(a)]

a Occasional very small spots of efflorescence on piles

The only structure to exhibit extensive and widespread pile cracking that may have been caused by ASR/DEF was structure M in the Nelson region, on which cracks had been identified by routine inspection. On the other four structures on which pile cracks were observed, the cracking was seen on only a few piles.

All piles on which cracks were observed were exposed to tidal conditions. No cracks were seen on piles on inland bridges.

Other possible signs of ASR seen were minor random cracks (with and without efflorescence) on wingwalls of seven bridges, and efflorescence not associated with cracks (one bridge). These could have been caused by other factors.

Figures 3.1 to 3.4. demonstrate the range of signs of possible ASR seen in this investigation and (for completeness) in the preceding investigation of bridges A and B (see chapters 1 and 2).

Figure 3.1 Examples of ASR/DEF cracking (bridge A, prior to this investigation)

Figure 3.1a Pile cracks caused by ASR/DEF (wider and more common below high-tide level)

Figure 3.1b Pile cracks caused by reinforcement corrosion (typically wider above high-tide level)

Figure 3.1c Minor ASR/DEF cracking (arrowed)

Figure 3.1d Extensive ASR/DEF damage

Figure 3.2 Extensive pile cracking (structure M, Nelson; see also chapter 4)

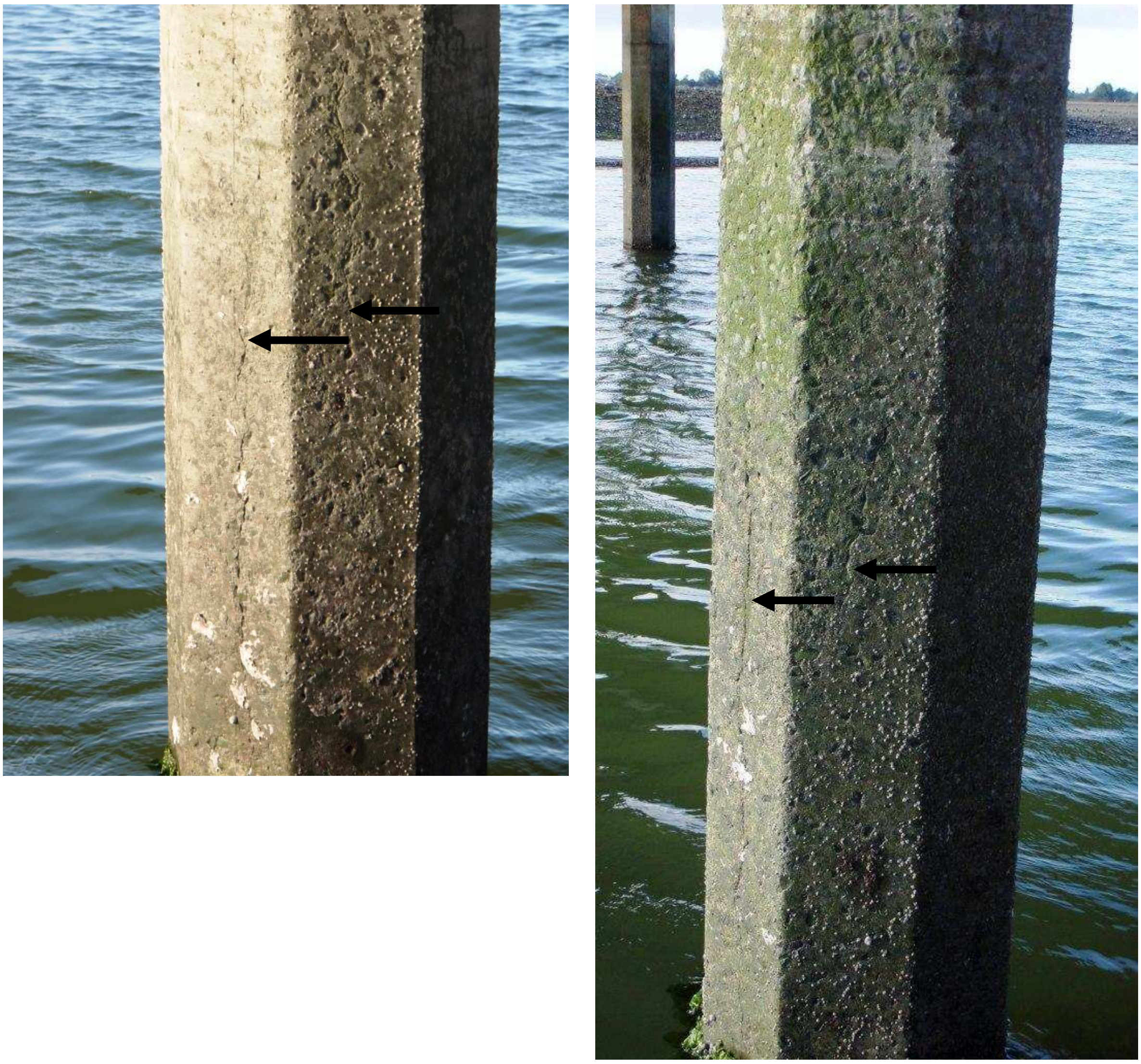
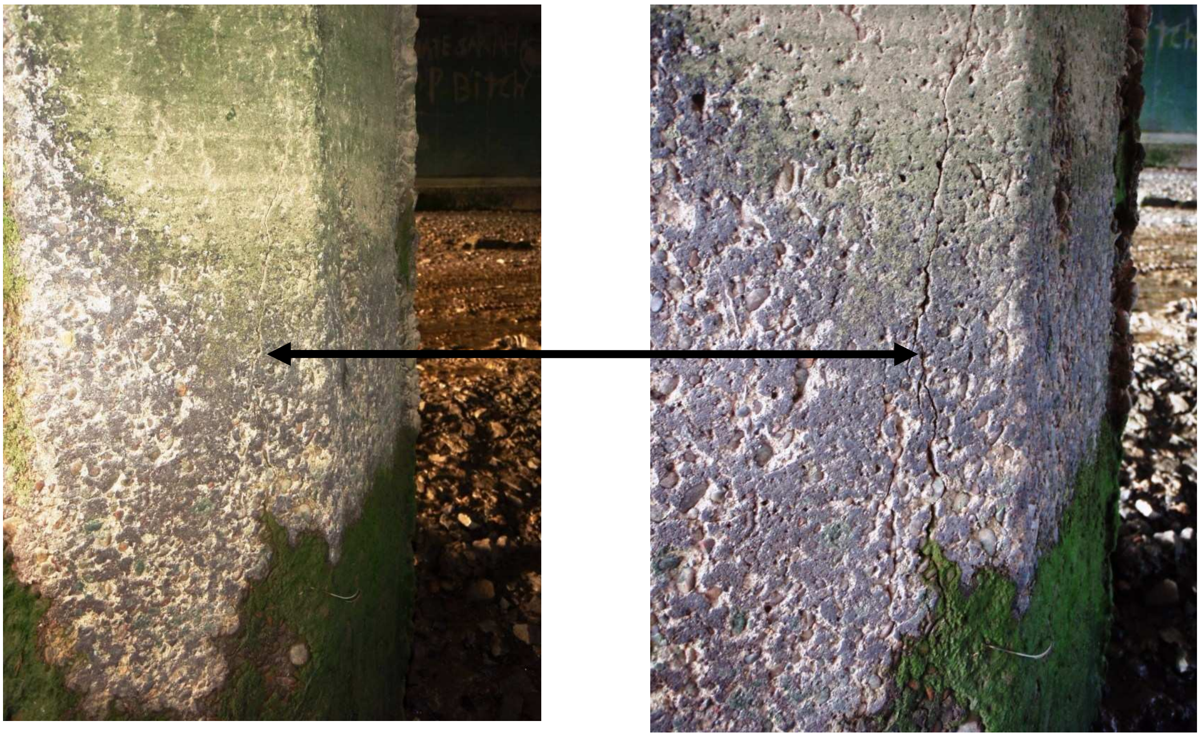


Figure 3.3 **Minor pile cracking at and below tidal zone (structure Wh, Southland; see also chapter 4)**



(close-up of crack)

Figure 3.4 **Signs of possible minor ASR**

Figure 3.4a **Triple point crack (or large-scale craze crack?) on bridge abutment wingwall (Nelson)**

Figure 3.4b **Efflorescence on uncracked pile (structure 'O', Southland; see also chapter 4)**

3.2.3 Discussion

Signs of ASR/DEF were seen on piles of six structures, all bridges. All piles on which cracks were seen were exposed to tidal conditions. Many reported cases of ASR/DEF in piles overseas are also associated with marine/coastal structures, so similar mechanisms of deterioration may be involved in the New Zealand structures examined.

Did exposure to seawater influence the risk of ASR expansion? The reaction of sodium chloride in seawater with the calcium aluminate phases of hardened cement paste to produce Friedel's salt involves the release of hydroxide ions, which may exacerbate ASR expansion (Shayan 2006). Shayan et al (2010), however, reported that for slowly reactive aggregate with similar reactive constituents to those in the Southland/Otago and Nelson alluvial aggregates, ASR expansion was influenced less by exposure to seawater than by temperature, concrete alkali content and aggregate reactivity. Therefore it is probably a coincidence that, in this investigation, pile cracking was only seen on marine or estuarine structures.

The only structure to exhibit extensive and widespread pile cracking considered likely to have been caused by ASR/DEF was structure M, on which the cracks had previously been identified by routine inspection. On the other bridges on which pile cracks were observed, the cracking appeared to affect only a few piles. Nevertheless, on one of these bridges (structure Wh; see chapter 4), observations from a subsequent inspection of piles carried out from a boat (for a different purpose) suggested that some cracks initially assumed to be related to reinforcement corrosion may in fact have been caused by other factors, such as ASR/DEF.

Minor random cracking was seen on wingwalls of another seven bridges but was not investigated further because such cracking is relatively common even in areas where aggregates are non-reactive.

The observations from the two surveys largely supported those from routine inspections, ie that few structures exhibited signs of ASR/DEF. It may be significant, however, that the only structure on which extensive pile cracking was observed was the one where biological growths on the piles had been removed by water blasting prior to inspection by boat, and the cracking affected parts of the piles that were above water level and ground level. This may mean that such cracking exists on piles that we could not inspect because they were either buried, below tide level, in the middle of a waterway, or because the concrete surface was obscured by dirt or biological growth.

Removal of dirt and biological growth before each Detailed Inspection or at least every second Detailed Inspection is, therefore, recommended to improve the accuracy of all observations made during the inspection, not just those relating to ASR/DEF. If cleaning reveals more cases of ASR/DEF damage, then buried piles on selected structures may also need to be exposed so that they can be inspected for cracks or other damage. The implications of such 'undetected' evidence of ASR/DEF are discussed further in chapter 4.

Determination of how the observed cracking affects the future durability and structural performance of affected piles would require more detailed investigation of the condition of the piles, and was beyond the scope of this project. Even if an engineering assessment was to find no reduction in structural performance, it would be reasonable to expect the cracks to facilitate the ingress of chloride ions and oxygen, and thereby increase risks associated with reinforcement corrosion. This is also discussed in chapter 4.

3.2.4 Summary – incidence of ASR/DEF damage in South Island structures

The greatest risk of ASR/DEF in South Island structures is to driven (ie precast) concrete piles in waterways on structures built between 1955 and 1970 in the Nelson and Southland/Otago areas. Approximately 55 state highway bridges are in this category.

Relatively few of these bridges have piles that are readily visible without excavation: 10 bridges with 'pile bent' piers were identified in this investigation, five on state highways and five on roads maintained by local authorities.

Observations from routine inspections by bridge controlling authorities and from specialist inspections of 51 bridges and two wharves carried out during this research indicated very few bridges built between 1955 and 1970 showed signs of ASR/DEF damage. Only one of these, structure M, had suspected ASR/DEF cracking on more than half its piles. Less widespread cracking was seen on piles on structure Wh, which also exhibited damage associated with reinforcement corrosion, and on another three structures. A further structure had unexplained efflorescence on some piles.

The five structures on which cracks were seen were all exposed to marine or estuarine (ie tidal) conditions. This is probably a coincidence, although interactions between hardened cement paste and seawater may exacerbate ASR expansion.

The piles on structure M had been cleaned before inspection. The cracks may not have been visible on prior inspections carried out without cleaning. All other structures were inspected without cleaning the piles first. This suggests that exposed piles on structures in the 'at greater risk' category should be cleaned to remove dirt and biological growth before every Detailed Inspection or at least every second Detailed Inspection. If such cleaning reveals more cases of suspected ASR/DEF, then buried piles on selected structures may also need to be exposed for inspection.

Overall, the findings suggest ASR/DEF has not damaged many South Island structures. Observations may have been different had piles been cleaned before inspection, or had piles not visible during our surveys been excavated or viewed at low tide. The effect of the observed pile cracking on durability and structural integrity was not assessed, but it is reasonable to expect it to increase the risks associated with reinforcement corrosion.

Nevertheless, it was considered important to find out whether the signs of ASR/DEF were indeed caused by ASR/DEF, and whether ASR/DEF had occurred in apparently undamaged piles in the 'high-risk' category. This would identify whether there was a possible risk to other concrete structures, including those to be built in the future.

This work is described in chapter 4.

4 Has ASR/DEF occurred in concrete piles on many South Island structures (with or without causing visible damage)?

ASR and DEF do not necessarily cause damage unless sufficiently severe or extensive, and, as reported in section 3.2, the damage is often minor. Therefore, it was considered important to find out whether the damage observed on the piles inspected was indeed caused by ASR/DEF, and whether ASR/DEF had occurred in apparently undamaged piles in the ‘high-risk’ category. This would identify whether there was a possible risk to future concrete structures.

Core samples were taken from selected structures and examined using specialist microscope techniques to identify whether ASR or DEF had occurred, the aggregates associated with ASR, and whether the extent of the reactions was likely to have caused the damage observed.

4.1 Methodology

Six structures were selected for core sampling. All were built between 1955 and 1974 and had precast piles forming pile bent piers. They were chosen to represent different pile conditions and aggregate types. Five were in marine or estuarine environments, and the sixth, structure O, crossed a major river prone to flooding.

Core samples were approximately 40mm diameter and at least 80mm long. Larger diameter cores (at least 75mm) are normally preferred because they give a more representative sample of the concrete. For example, a large core may be needed to obtain a representative sample of the aggregate, particularly when the aggregate contains a mixture of rock types. In addition, features that are not necessarily common or widespread in the concrete, such as microcracking and reaction products, can easily be missed by small samples. Small diameter cores were taken for this project despite their shortcomings, because they allowed samples to be taken with minimal damage to the closely spaced reinforcement and prestressing in the piles.

Up to six cores were taken from each structure, but only one or two were examined in detail. More than two cores would normally be examined when investigating the cause and extent of damage on an individual structure. The purpose of this investigation was to obtain a ‘snapshot’ of a population rather than of any individual structure, so the aim was to examine up to 10 cores in total. If the cores indicated cause for concern about a particular structure then this could be investigated separately if requested by the asset manager.

Cores were collected from the structures in December 2009/January 2010. They were dampened then wrapped in clingfilm and stored in plastic bags in a laboratory fog room, protected from direct contact with moisture (that could leach alkalis from the concrete), and from atmospheric carbon dioxide (that would react with cementitious binder and products of ASR, and make the reaction products difficult to detect).

Table 4.1 describes the cores that were collected.

Table 4.1 Core details

Structure	Sample identification				Source(b)	Length (mm)	Test(c)
	Opus		ARRB	(a)			
Wh	4-10/003	A	C10/2067	1	S pier, pile 1 from E, above high tide	120	-
		B		2	S pier, pile 2 from E, above high tide	155	-
		C		3	S pier, pile 3 from E, above high tide	140	-
		D1		4	Broken pile, tidal zone	170	Petro/SEM
		D2		-	Broken pile, tidal zone	115	-
Wp All samples from North pier	4-10/004	A	C10/2076	-	Pile 2 from W, upper, above high tide	135	-
		B		1	Pile 2 from W, lower, tidal zone	145	Petro/SEM
		C		2	Pile 3 from W, upper, above high tide	140	-
		D		3	Pile 3 from W, lower, tidal zone	145	SEM
O All samples from 3rd pier from East	4-10/005	A	C10/2077	1	Pile 2 from S, above flood level	150	-
		B		-	Pile 3 from S, above flood level	150	-
		C		2	Pile 3 from S, below flood level	135	SEM
		D		3	Pile 4 from S, above flood level	110	Petro
		E		4	Pile 4 from S, below flood level	150	-
T(d)	4-10/12	A	C10/2078	1	Raked pile, tidal zone	90	-
		B		2	Raked pile, tidal zone	80	-
		C		3	Vertical pile, tidal zone	80	Petro/SEM
		D		-	Vertical pile, tidal zone	75	-
Br	4-10/21	A	C10/2079	1	Bent 39, pile G, tidal	115	SEM
		B		2	Bent 39, pile G, tidal	105	Petro
		C		3	Bent 40, pile G, tidal	123	-
		D		-	Bent 40, pile G, tidal	100	-
M All samples from East pier	4-10/002	A	C10/2080	1	Pile 1 from u/s, upper, tidal zone	100	-
		B1		2	Pile 1 from u/s, lower, tidal zone	85	-
		B2		-	Pile 1 from u/s, lower, tidal zone	80	-
		C		3	Pile 2 from u/s, upper, tidal zone	95	Petro
		D		4	Pile 2 from u/s, lower, tidal zone	145	SEM
		E		5	Pile 3 from u/s, upper, tidal zone	100	-
		F		6	Pile 3 from u/s, lower, tidal zone	155	-

a Cores indicated by '–' were retained by Opus

b S=south, W=west, E=east, u/s = upstream

c Petro = petrographic microscope; SEM = scanning electron microscope

d Cores were provided by contractor, and were assumed to be from lower part of tidal zone

Once cores had been obtained from all structures, they were visually examined and photographed at Opus Central Laboratories, then re-wrapped and sent to ARRB Group for specialist examination. One core from each structure was retained by Opus for future reference.

No attempt was made to find construction records or other historical evidence about the concrete materials, mix designs or construction methods used to manufacture the piles on individual structures.

ARRB examined one or two cores from each structure to:

- identify the aggregate types present
- identify the extent of ASR/DEF in the concretes
- identify the most likely alkali-reactive aggregate constituents
- assess the likelihood of ASR in each concrete, based on comparisons with other concretes examined
- identify structures or individual samples that might warrant further investigation for potential alkali reactivity.

One thin section was taken along the length of the cores selected and examined by petrographic microscope to identify the rock types present in the aggregate, their potential for alkali reactivity, and microcracking and reaction products that might indicate ASR/DEF had occurred. Scanning electron microscope examinations and associated energy-dispersive x-ray analysis provided more detailed information on the microstructure and composition of observed phases, including ASR/DEF products. No laboratory tests were carried out to determine potential alkali reactivity of the aggregates, or the potential for future expansion.

Two cores from the deck of an additional Southland marine structure, I, were found near the structure and were collected out of interest. Structure I was not accessible for inspection and the condition of its piles is not known. The structure was built in the late 1960s. The cores were examined in hand specimen to see whether the concrete was similar to the concrete sampled from other structures and thereby to gain a better understanding of the range of materials used in the area. The cores were not examined by microscope.

4.2 Observations

Figure 4.1 presents photographs of some of the core samples, showing the different aggregate assemblages represented.

Table 4.2 summarises the observations of aggregate type and evidence of ASR/DEF from site observations, laboratory examination and microscope investigation.

Examination of the core samples in the laboratory revealed no obvious shortcomings in concrete mix design, handling or placing. The occasional piece of reinforcing or prestressing steel cut by the core, or imprinted at the inner end of the core, appeared in good condition except for rust on the freshly cut surface (which was assumed to have developed after the cores were cut).

No obvious signs of ASR (cracks or gel) were seen on the cores when they were unwrapped and examined visually.

Potentially alkali-reactive rock types or minerals in the aggregates were seen in all core samples: strained quartz, microcrystalline quartz and/or quartzite.

The concretes from structures Br and M (both from Nelson) had similar aggregates, except the maximum aggregate size was larger and more angular in the concrete from structure M. Both appeared to contain more coarse aggregate than the other concretes.

The concretes from structures O and Wp both contained similar coarse and fine aggregates, but the colour of the mortar fraction in the concrete from structure O was distinctly yellow-beige compared with the grey colour of the mortar in structure Wp. This may reflect the use of sand from slightly different sources and/or different cements.

Concretes from structures T and Wh contained similar coarse aggregates but different fine aggregates: the sand in Wh probably being from the same beach deposit as structures A and B (see chapter 2) and crusher dust being used in structure T.

Overall, the Southland/Nelson mixed alluvium observed in structures Br, T, M and Wh was similar to that observed in structures A and B in the previous investigations (Bruce et al 2008; Freitag et al 2009; 2010).

The two cores from structure I appeared to contain a mixed alluvial fine aggregate, with no shell fragments visible by naked eye. The coarse aggregate in one of the cores was a mixed alluvial gravel like that used in structures T and Wh. The coarse aggregate in the other core was a dark, crushed material thought to be from Bluff Hill. A quarry on Bluff Hill was used briefly in the 1960s during the development of the port facilities at Bluff. The rock type quarried there may be older than that won from other sources, representing rocks of the Median Batholith. Skinner et al (2009) considered these rocks unlikely to contain potentially reactive components (see table 2.2). No further comment can be made about the potential for ASR/DEF in the concretes from this structure.

Samples from structure Wp exhibited extensive microcracking. Microcracking in samples from structures Br, M, O, T and Wh was less extensive.

The strongest signs of products of ASR were seen in the samples from structure M, which was the only structure to have widespread pile damage that was not obviously related to reinforcement corrosion. Samples from structures Br and Wh also showed definite signs of mild to moderate reaction, while samples from structures O and T had possible signs of weak to mild ASR. No definite sign of ASR was seen on samples from structure Wp.

The samples from structure T were the only samples to show signs of DEF.

Table 4.2 Summary of observations on core samples (table continued on next page)

Overall aggregate type	Overall pile condition	Structure (location)	Date built	Pile shape	Aggregate details	Evidence of ASR/DEF on site	Evidence of ASR/DEF in core[(a)]	Overall extent/ severity of ASR/DEF[(b)]
Southland/Nelson mixed alluvium (rounded)	Uncracked	Br (Nelson) Marine	1974	Square	CA: sandstone, siltstone, greywacke, metasediment, gneiss[(c)] FA: crusher dust (as for CA)	nil	Microcracking ASR gel (some Al-rich, some Mg-rich)	Mild/moderate ASR No DEF
		T (Southland) Marine	1969	Octagonal	CA: meta-sandstone/greywacke, tuff, acidic meta-volcanics[(c)] FA: crusher dust	This pile was uncracked, but one raker pile on the same bent was cracked.	Microcracking Minor ASR gel, carbonated Dense ettringite mats	Possible weak/mild ASR (masked by DEF and carbonation?) DEF definite
	Cracked	M (Nelson) Estuarine	1968	Octagonal	CA: sandstone, siltstone, tuff, acidic igneous porphyry, altered quartzite/arenite[(c)] FA: as for CA.	Extensive cracking, apparently unrelated to reinforcement corrosion, affecting 13 of 20 piles	Microcracking ASR gel and crystalline reaction products (some Mg-rich)	Moderate ASR No DEF
		Wh (Southland) Estuarine	1962	Octagonal	CA: sandstone, siltstone, greywacke, acidic metavolcanics, tuff, metaquartzite[(c)] FA: quartz, feldspar, rock fragments as in CA, shell	Extensive cracking, some cracks related to reinforcement corrosion	Microcracking ASR gel around aggregate particles	Mild/moderate ASR No DEF

Overall aggregate type	**Overall pile condition**	**Structure (location)**	**Date built**	**Pile shape**	**Aggregate details**	**Evidence of ASR/DEF on site**	**Evidence of ASR/DEF in core(a)**	**Overall extent/ severity of ASR/DEF(b)**
Otago andesite (crushed)	Uncracked	O (Southland) Inland river	1970	Octagonal	CA: crushed andesite with minor microcrystalline quartz FA: monocrystalline quartz and feldspar; gneissic polycrystalline quartz and quartzite	Localised white efflorescence on surface of a few piles above flood level	Microcracking Minor Al-rich gel	Possible weak /mild ASR No DEF
		Wp (Otago) Estuarine	1961	Square	As in structure O	nil	Extensive microcracking Localised Al-rich gel	ASR unlikely No DEF

a Aluminium-rich gels may form as a result of reaction of aluminium-rich minerals such as feldspars, and are not, strictly speaking, 'ASR'. They produce similar expansion to alkali silica gels. Magnesium-rich gels are thought to result from ion-exchange between alkali gels and sea water, and may produce smaller expansions than the original alkali-rich gels.

b ASR or DEF are considered to have occurred if reaction products and characteristic microcracking patterns are both observed. The extent of reaction is described as 'possible' if reaction products can't be positively identified or if the cracking patterns aren't distinct.

c Aggregate contains strained quartz and/or microcrystalline quartz, which are likely to be alkali-reactive.

Figure 4.1 Examples of core samples

Structure Br (coarse aggregate ≤25mm)

Structure T (coarse aggregate ≤25mm)

Structure M (coarse aggregate ≤40mm)

Structure Wh (coarse aggregate ≤25mm)

Structure O (coarse aggregate ≤30mm)

Structure Wp (coarse aggregate ≤30mm

4.3 Discussion

4.3.1 Potential reactivity of aggregates

Two main aggregate assemblages were identified in the samples examined:

- Mixed alluvial (rounded) coarse aggregates, with fine aggregate consisting of crusher dust or beach deposits of similar composition. Found in Southland and Nelson structures.
- Crushed andesite coarse aggregate combined with predominantly quartz/quartzitic sand. Both coarse and fine aggregates are likely to be from the Dunedin area. Found in Southland and Otago structures.[3]

The principal reactive constituents in potentially alkali-reactive North Island aggregates are glass, cryptocrystalline silica, cristobalite and tridymite (CCANZ 2003). These minerals are usually associated with relatively rapid ASR, which may occur at lower concrete alkali contents than threshold values used to manage ASR in many aggregates overseas, including non-volcanic aggregates.

These highly reactive minerals were not observed in the two South Island aggregate assemblages. Instead, the fine and coarse aggregates in both groups contained microcrystalline quartz, and/or quartz with a crystal structure that has been distorted by heat or pressure (ie ‘strained quartz’). These forms of quartz have been associated with cases of ASR overseas, including in slowly reactive Australian aggregates (Shayan 2007b) and are, therefore, the most likely alkali-reactive constituents of the two aggregate assemblages. They were observed in the following rock types within the aggregates:

- quartzite and meta-quartzite (in quartz/feldspar/gneissic sand, and in mixed alluvium)
- siltstone (in mixed alluvium)
- acidic meta-volcanics (in mixed alluvium)
- tuff-like particles (in mixed alluvium)
- gneissic material (in quartz/feldspar/gneissic sand and in mixed alluvium)
- andesite.

4.3.2 Occurrence of ASR/DEF

ASR is considered to have occurred if the concrete contains potentially alkali-reactive aggregates, and if reaction products are present in microcracks in the vicinity of reacted aggregate particles, and/or in air voids. Microcracking around or through aggregate particles and through the cementitious binder between aggregate particles is a characteristic of ASR expansion, but not conclusive evidence unless ASR reaction products are also present.

DEF is considered to have occurred if ettringite is present as dense mats in cracks and voids. The more usual needle-like form of ettringite is a common product of normal processes of dissolution and recrystallisation related to moisture transport through the concrete, is not necessarily a sign of DEF, and does not generate expansive stress.

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[3] The material described as ‘andesite’ exhibited localised microtextures that are characteristic of trachyte, but its mineral and chemical compositions were not determined. Therefore we do not know whether it corresponds to any of the ‘trachytes’ or ‘trachyandesites’ that Coombs et al (2008) identified as having elevated silica contents (see section 2), or whether it corresponds with crushed volcanic aggregates currently used in the Dunedin/Otago area.

Examination by petrographic microscope revealed characteristic ASR microcracking in samples from all six structures. ASR reaction products were identified in samples from the four structures containing the mixed alluvial aggregate (Br, M, Wh and T). Amorphous gels in the samples from the structures containing the andesitic aggregate (O and possibly Wp) were enriched in aluminium, and may have resulted from reaction between alkalis and aluminium-bearing minerals (such as feldspars), rather than from reaction with silica minerals.

Evidence of DEF was seen only in the concrete from structure T.

ASR was, therefore, relatively common. In contrast, DEF was either more unusual, or its reaction products were highly localised within affected concrete.

Similarly, not every core from bridges A and B showed evidence of ASR and DEF. Of the 13 cores examined, ASR was unequivocally identified in two cores, signs of possible ASR were seen in six cores, and no signs of ASR were seen in 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. Neither reaction was severe or extensive in any of the cores examined.

In both this investigation and the investigation into bridges A and B, ASR was highly localised in all the concretes examined. This is because sufficiently elevated temperatures and potentially alkali reactive constituents in the aggregates were unevenly distributed within individual piles and between piles on the same structure. DEF is even more sensitive than ASR to small variations in curing conditions and concrete composition. Thus reaction products and damage may be present in a pile, but not necessarily at the precise locations from which cores are taken. The absence of evidence in one core may simply mean the reactions occurred at a location other than the location sampled. Therefore in these investigations we considered that clear evidence of ASR or DEF in some but not all cores representing the aggregate type (or element, or concrete mix design) of interest was sufficient to conclude that the reactions had probably occurred.

4.3.3 Influence of ASR/DEF on pile condition, durability and structural performance

The microcracks observed in the concrete thin sections may have been caused by ASR/DEF, but may also have been caused by other factors such as thermal effects (if the piles were steam cured), drying shrinkage (particularly if the concrete was not cured adequately before being allowed to dry), or overloading (eg by over-stressing or dynamic loading). The same concrete compressive strength was specified for piles in structures Br, M, O and Wp, and a slightly higher strength was specified for structure T. The use of at least two different mix designs suggests that drying shrinkage or other factors related to mix design may not be the sole cause of the microcracking, although actual mix designs were not investigated. Similarly, the incidence of microcracking on piles from all six structures suggests it was not caused by overloading.

ASR reaction products were ‘moderate’ and ‘mild/moderate’ in samples from structures M and Wh respectively. Macrocracks possibly related to ASR/DEF were visible on the piles of both structures. Therefore ASR may have contributed to the cracking on structures M and Wh.

ASR products were also ‘mild/moderate’ in samples from structure Br, and evident but only ‘weak/mild’ in concrete from structures O and T. No macrocracks were observed on the piles of these structures. Therefore the ASR that occurred in these concretes was either not sufficiently extensive to crack the concrete, or cracks were present but not observed because the piles were not cleaned prior to being inspected.

ASR products were least distinct in the samples from structure Wp. The piles were not cracked, but microcracking was widespread in the concrete. Therefore the microcracking in these concretes may have been caused by factors other than ASR/DEF. Nevertheless, aluminium-rich reaction products were observed in these concretes, so the possibility of the microcracks being caused by an expansive alkali aggregate reaction cannot be discounted.

Some of the gel observed in structures M and Br was enriched in magnesium. When ASR gel is exposed to seawater, either because of prolonged exposure or because seawater penetrates cracks in the concrete, magnesium from seawater substitutes for the alkali in ASR gels. The resulting magnesium-enriched gels do not appear to expand as much as ‘normal’ ASR gel (Shayan 2006), so ongoing concrete expansion and cracking may be limited. Seawater is likely to have penetrated the visible cracks in structure M, and unseen cracks, or cracks caused by reinforcement corrosion, in structure Br.

The extent of macrocracking on structures M and Wh suggests that further investigation of the cause and likely continuation of pile cracking should be carried out as part of the strategic management plans for these two structures. Such investigations should include accelerated expansion tests to find out whether cracked and uncracked piles are likely to deteriorate further, and could also include further examination of concrete from cracked and uncracked piles to ascertain whether the presence or absence of cracking is related to the amount of ASR/DEF reaction products present.

As mentioned in section 3.2.3, the effect of the observed cracking and microcracking on durability and structural performance of affected structures was not assessed as part of this investigation, but it is reasonable to assume that cracks and continuous networks of microcracks would increase the risk of reinforcement corrosion. These effects should also be investigated as part of the strategic management plan for each affected structure[4].

The apparent absence of damage to the piles on structure Br suggests that the piles should be cleaned before their next inspection, because the evidence of ASR under the microscope was as strong as on samples from cracked piles from structures M and Wh.

Indeed, as noted in chapter 3, the history of cracks first being observed after the piles on bridges A and B (in the previous investigation) and structure M were cleaned prior to close inspection suggests that partly immersed precast concrete piles on bridges in marine/estuarine conditions should be cleaned to remove dirt and biological growth before every Detailed Inspection or at least every second Detailed Inspection. A similar cleaning and inspection regime should be adopted for other types of structure with immersed elements.

Buried piles (and other buried elements) are more difficult to inspect. Therefore, as also noted in chapter 3, it is suggested that if the practice of cleaning partly immersed piles before inspection reveals more cases of ASR/DEF, then buried precast piles on selected structures with piles in damp ground should be excavated and cleaned before Detailed Inspections. This will enable them to be inspected for cracks and sampled to see whether ASR/DEF products are present in these elements, and therefore will indicate whether the risk of ASR/DEF is similar in buried piles. Other buried precast elements could also be inspected in this way.

Although the findings suggest that ASR is relatively common in precast concrete piles containing the two aggregate assemblages used in the six structures sampled, the reaction is generally mild and does not necessarily cause damage unless sufficiently extensive. DEF, on the other hand, is neither common nor widespread within individual elements and therefore is less likely to have contributed to the observed pile

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[4] An investigation into the risk of reinforcement corrosion and future ASR cracking on the piles of structure M is currently underway. The ability to carry out accelerated expansion tests on core samples is limited, however, by the close spacing of the reinforcement. This may be a problem on other structures too.

damage. Nevertheless, its occurrence is significant because it indicates that curing temperatures may have been high enough to cause ASR expansion.

The findings of this investigation raise the question of whether the potential reactivity of New Zealand greywackes has previously been underestimated. Greywacke is likely to contain microcrystalline quartz and strained quartz, and greywackes have been found to be alkali reactive overseas and in accelerated mortar bar tests in New Zealand (Freitag et al 2000). A high incidence of ASR damage caused by greywacke is unlikely because no damage has been reported from routine maintenance inspections. Petrographic microscope examination of greywacke concretes cast in situ between 1955 and 1965 revealed microcracking that increased with cement content, but no ASR gel, and accelerated core expansion tests indicated that future ASR expansion was unlikely (Freitag et al 2000). Nevertheless, the findings of the current research suggest it may be appropriate to review the potential alkali reactivity of New Zealand greywacke in case similar risk factors to those of the Southland and Nelson alluvial aggregates are involved, eg elevated curing temperatures and damp or wet exposure conditions. A similar laboratory investigation to that described in section 2.1 would be a practical starting point.

4.3.4 Implications for managing the risk of ASR/DEF damage in new concrete

Alkali silica reactions with the forms of silica observed in the concretes sampled in this project tend to be slower than the ASR associated with glass in fresh volcanic rock and other amorphous types of silica. Consequently, the reactivity of aggregates containing these more crystalline forms is not always detected by the ASTM C289 quick chemical test. Therefore, in countries where ASR has been associated with the more crystalline silica forms, more aggressive tests (such as the rapid mortar bar tests described in chapter 2) are now used instead of ASTM C289 as rapid screening tests for alkali reactivity. In contrast, ASTM C289 has to date proven relatively reliable for identifying potentially reactive aggregates in New Zealand, where most reactive aggregates are glassy volcanic rocks. New Zealand's traditional reliance on ASTM C289 as an aggregate screening test, combined with the lack of reports of South Island structures requiring repair to ASR damage (until recently), may be why the potential reactivity of the more crystalline silica forms has largely been ignored in local aggregates.

Nevertheless, the current guidelines for managing ASR in New Zealand (CCANZ 2003) acknowledge that the lack of reports of in situ damage could also mean ASR damage is present but very minor, or not observed, or not recognised, or not identified by investigation prior to applying traditional repairs. They also recommend that if local experience with an aggregate is limited and similar materials overseas have been shown to be reactive, then the aggregate should be tested before using in concrete with high alkali cement.

In addition, CCANZ (2003) specifically refers to potential risks associated with quartzite, which it lists as a potentially reactive aggregate. It cites one quartzite that tested as reactive by ASTM C289 but was not believed to have been used in concrete, and one from another source that was quarried but had not been tested.

Therefore, the discovery of ASR associated with South Island rocks containing microcrystalline quartz and/or strained quartz is not a complete surprise. Instead, the findings of this investigation indicate these rocks may be reactive under particular circumstances, as described in chapter 2. The findings also indicate that although the incidence of ASR may be more common than originally thought, the reaction is generally not sufficiently severe or widespread to damage the concrete significantly.

The measured cement contents of concrete samples from bridges A and B were about 320kg/m^3. Typical alkali contents of the cements likely to have been used were less than 0.6% sodium equivalent, suggesting that the original alkali content of the concretes was less than 2.0kg/m^3 (Bruce et al 2008). 45MPa concrete was specified for bridge A.

Measurements of concrete cement and alkali content were beyond the scope of this investigation, but construction drawings for five of the structures sampled indicated that the piles were cast from concrete with specified compressive strengths of 38–45MPa. Therefore it is reasonable to assume the cement contents in their piles were similar to (or less than) those in bridges A and B, and that on the three structures built after 1968 (Br, T and O) the alkali contents of the pile concretes were probably also less than 2.0kg/m^3. If, however, the concrete contained as much as 420kg/m^3 of low alkali cement, then the concrete alkali content would have exceeded CCANZ's (2003) current limit of 2.5kg/m^3.

When structures Wp and Wh were built, high alkali cements were being manufactured in Southland and Golden Bay (St John 1988). If these cements had been used in the pile concretes, concrete alkali contents would have exceeded 3.0kg/m^3 at a cement content of 320kg/m^3.

Structure M was completed shortly after a period when high and medium alkali cements were produced at Golden Bay (St John 1988). Depending on when the piles were manufactured, they may have been made with high alkali cement. If so, the concrete alkali content may have been as high as 2.9kg/m^3 at a cement content of 320kg/m^3.

Use of high alkali cements in structures M and Wh could explain why ASR was sufficiently extensive to cause cracking on their piles. But the extensive ASR/DEF cracking on bridges A and B, made with similar aggregate to structures M and Wh, could not be related to high alkali cement. Therefore the curing temperature seems to be a stronger factor than cement/concrete alkali content in determining the incidence of ASR in concretes made with the Southland/Nelson alluvial aggregates.

The service environment to which the concrete is exposed is also an important factor. Elements exposed to water such as piles, piers, pier/pile caps, wingwalls and abutments are more susceptible to ASR than those that are generally dry, such as beams. But elements exposed to high humidity may also be at risk, such as beams on bridges with low clearance over waterways.

Overall, the findings of this investigation indicate that the guidelines given by CCANZ (2003) are not misleading, but would benefit from being updated to acknowledge that:

- ASR associated with South Island aggregates containing microcrystalline quartz and strained quartz has been observed.
- Dunedin Volcanic Group rocks containing more than 50% silica may be alkali-reactive.
- ASR appears to have caused visible damage to precast concrete piles containing alluvial aggregates from Southland and Nelson, which contain quartzite, meta-quartzite, acidic meta-volcanics, andesite, tuff-like material, gneissic material and siltstones of a particular composition.
- Limited laboratory testing suggests that Southland alluvial aggregates may be reactive in concrete cured at temperatures higher than 60°C if the concrete contains sufficient alkali.
- Typical concrete mix designs used in the 1960s and 1970s for manufacturing precast piles for road bridges in the South Island do not present a significant risk of ASR expansion unless concrete is exposed to curing or service temperatures exceeding 60°C. The risk increases at temperatures higher than 60°C and is then determined by temperature (especially if the temperature is high enough to induce DEF), concrete alkali content and the reactivity of the specific aggregate.
- To minimise the risk of ASR-related expansion in concrete containing Southland and Nelson alluvial aggregates, and other rock types with a history of expansive ASR overseas, concrete temperatures during curing should not exceed 70°C.

High concrete temperatures during curing increase not only the risk of ASR, but also the risk of other problems related to excessive, non-uniform and variable temperatures, such as DEF, microcracking and inconsistent concrete quality. Therefore, ensuring that concrete temperatures during curing[5] are consistent and remain below 70ºC can improve the overall quality and durability of the hardened concrete. The wider concrete industry may wish to consider whether curing practices and quality management can be improved to reap these benefits.

The rate and duration of heating (and cooling) may also influence ASR as well as DEF. This aspect was not investigated.

4.4 Summary – incidence of ASR/DEF in South Island structures

The investigation found that fine and coarse alluvial aggregates used in concrete in Southland and Nelson structures contained microcrystalline quartz, and/or strained quartz. Overseas, these quartz forms have been found to be alkali-reactive.

Another common aggregate assemblage found in Southland/Otago, consisting of crushed andesitic coarse aggregate combined with predominantly quartz/quartzitic sand, also contained microcrystalline and strained quartz.

The potential reactivity of rocks containing these quartz forms is best assessed by accelerated mortar bar tests such as AMBT-80 described in section 2.1.1.2. It may not be detected by the quick chemical test traditionally used to identify the potential reactivity of New Zealand rocks.

Petrographic examination of core samples taken from precast piles on two Nelson structures and four Southland/Otago structures revealed evidence of moderate or mild/moderate ASR in concrete from three of the six structures, and weak/mild ASR in two structures, but uncertain signs in the sample from the sixth structure. Samples from one of the structures also showed signs of DEF.

Microcracks were seen in all cores. Their extent was not clearly related to the presence of ASR or DEF reaction products, so they may have been caused by other mechanisms such as shrinkage or thermal effects.

Cracks were seen on the piles of two of the structures in which moderate or mild/moderate ASR was seen, and therefore may have been associated with ASR/DEF. ASR/DEF may have occurred in the uncracked piles without generating enough expansion to damage the concrete.

It is also possible that cracking may have been obscured by dirt and biological growths on the piles. Therefore it is recommended that precast piles in marine/estuarine conditions be cleaned to remove such material before Detailed Inspections, as recommended in chapter 3. This will improve the accuracy of all aspects of pile condition assessments, including the incidence of ASR/DEF.

A review of the risk of ASR associated with New Zealand greywacke, which probably also contains microcrystalline and/or strained quartz, should also be considered.

Overall, the findings suggest that ASR is relatively common in precast concrete containing the two aggregate assemblages used in the six structures sampled, but that it does not necessarily cause damage unless sufficiently severe or extensive. On the other hand, DEF appears to be neither common, nor widespread within individual elements. Therefore it is less likely to have contributed to the observed pile

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[5] Measuring the temperature of the steam or water used to heat the concrete may underestimate the maximum temperature attained by the concrete itself.

damage. Nevertheless, its occurrence is significant because it indicates that curing temperatures may have been high enough to cause ASR expansion.

It is not known whether the observed cracking is likely to become more extensive or how it might affect the durability and structural performance of affected piles. These aspects should be investigated as part of the strategic management plans of the affected structures.

Current industry guidelines for managing the risk of ASR acknowledge the potential reactivity of quartzite, so the ‘discovery’ of ASR in South Island concrete is not surprising. To reduce the risk of ASR damage in future structures, the guidelines should be updated to acknowledge the findings of this investigation, in particular the:

- cases of ASR observed
- sources of potentially reactive South Island aggregates
- effect of elevated curing temperatures
- appropriateness of different test methods for detecting potential alkali reactivity of different rock types
- possible effects of mix design.

5 Summary and conclusions

5.1 Potential alkali reactivity of South Island concrete aggregate

Accelerated mortar bar and concrete prism tests showed that aggregates from Oreti Beach and nearby alluvial deposits are potentially alkali-reactive but may react slower than fresh volcanic materials, and concrete temperatures may need to exceed 60°C to produce deleterious expansion even if the concrete contains sufficient alkali.

The alkali reactivity is associated primarily with rock types containing strained quartz and microcrystalline quartz that are found in the Caples, Dun-Mountain/Maitai, Murihiku and Brook St geological terranes. The reactive rock types include minor acid and intermediate volcanics, sedimentary rocks containing volcanic constituents, and partly metamorphosed sediments and volcanics.

Similar assemblages are found in alluvium throughout Southland and southeast Otago, and in the Waimea and upper Motueka River catchments in Nelson.

In east and central Otago, alkali- and silica-rich phonolites and trachytes may be alkali-reactive, but it is not known whether they have been used as concrete aggregate.

No other sources of potentially alkali-reactive aggregate were identified in Canterbury, north Otago, or the West Coast.

5.2 Incidence of ASR/DEF damage

The most likely structures to be affected are those built between 1955 and 1970 (when high and medium alkali cements were available), with precast piles in damp or wet conditions, eg in waterways. Approximately 55 state highways bridges are in this category.

Routine maintenance inspections and specialist inspections of 51 such bridges, mostly of pile bent design, revealed very few cases of pile damage resembling that caused by ASR/DEF. Extensive cracking was seen on one structure, less widespread cracking was seen on another four structures, and unexplained efflorescence was seen on a sixth structure.

Cracking was only seen on piles on marine or estuarine structures. This is probably coincidental, but may be a result of interactions between hardened cement paste and seawater exacerbating ASR expansion.

Removal of dirt and biological growth prior to inspection of piles on marine/estuarine structures is essential to detect cracking and other defects below high-tide level.

If removal of dirt and biological growth from such piles reveals more cases of ASR/DEF cracking, then such cracking may also affect buried piles.

5.3 Incidence of ASR/DEF

Two aggregate assemblages were represented in concretes sampled from structures in Southland/Otago and Nelson regions:

- mixed alluvial aggregate (Southland and Nelson)
- crushed andesite coarse aggregate with quartzitic sand (Southland and Otago).

Both contained microcrystalline quartz and strained quartz.

Evidence of ASR reaction products was found by microscope examination of cores from five out of six structures, but evidence of DEF was seen in samples from only one of the structures. ASR therefore appears to be more common than DEF.

Microcracks were seen in all cores, but their extent was not clearly related to the presence of ASR or DEF reaction products, so they may have been caused by other mechanisms.

ASR products were observed in cores from cracked piles and uncracked piles, but were more widespread in cores from cracked piles. Therefore ASR may be relatively common, but does not necessarily cause sufficient expansion to visibly crack the concrete unless sufficiently severe and widespread.

The most widespread cracking was seen on piles that had been cleaned before inspection, but ASR products were also present in samples from piles on which no cracks were seen. On these apparently uncracked piles, either the reaction was not extensive enough to crack the concrete, or cracks may have been obscured by dirt and biological growth.

The relatively widespread incidence of ASR suggests that concrete temperatures during curing often exceeded 60°C, which is supported by the occasional observation of DEF.

The observed widespread occurrence of ASR also suggests that New Zealand greywacke aggregates that contain microcrystalline quartz or strained quartz might also react in similar circumstances to the aggregates examined in this research.

The current New Zealand guidelines for managing ASR expansion (CCANZ 2003) recognise the potential reactivity of quartzite and strained quartz, but would benefit from updating to also acknowledge the:

- ASR cases observed in this investigation
- sources of potentially alkali-reactive aggregates in the South Island
- effectiveness of different test methods for detecting potential reactivity of different rock types
- influence of elevated curing temperatures on ASR expansion
- effects of concrete alkali content.

6 Recommendations

6.1 Recommendations for the NZTA bridge inspection and management practice

The following recommendations are proposed as a means of managing an identified risk to the performance of New Zealand concrete bridges (and other structures), particularly those with precast piles exposed to damp or wet conditions.

- Partly immersed precast concrete piles on bridges in marine/estuarine conditions should be cleaned to remove dirt and biological growth before every Detailed Inspection or at least every second Detailed Inspection.
- If the practice of cleaning partly immersed piles before inspection reveals more cases of suspected ASR/DEF, then buried precast piles on selected structures with piles in damp ground should be excavated and cleaned before Detailed Inspections to enable them to be inspected for cracks, and sampled to see whether ASR/DEF products are present in these elements. This will indicate whether the risk of ASR/DEF is similar in buried piles.
- If damage resembling ASR/DEF is observed on a structure, then its cause and extent should be identified by specialist examination of core samples, the likelihood of future deterioration determined by laboratory testing of core samples, and the implications for durability and structural performance determined by engineering assessment.
- Investigation of the potential alkali reactivity of New Zealand greywacke should be considered to find out whether the risks of ASR/DEF in precast concrete identified in this research also extend to concrete made with greywacke aggregate. Such an investigation should begin with a combination of laboratory examination and testing of aggregate and then, depending on the results, proceed to evaluation of in situ concrete performance.

6.2 Recommendations for New Zealand concrete industry practice

The findings of this investigation suggest that the guidelines given by CCANZ (2003) for minimising the risk of ASR would benefit from being amended to acknowledge that:

- ASR associated with South Island aggregates containing microcrystalline quartz and strained quartz has been observed.
- Accelerated mortar bar and concrete testing is required to assess the potential alkali reactivity of such aggregates, for which the quick chemical test may be less reliable.
- Dunedin Volcanic Group rocks containing more than 50% silica may be alkali-reactive.
- ASR appears to have caused visible damage to precast concrete containing alluvial aggregates from Southland and Nelson that contain quartzite, meta-quartzite, acid meta-volcanics, andesite, tuff-like material, gneissic material and siltstones of a particular composition.
- Laboratory tests suggest that Southland alluvial aggregates are non-reactive in concrete cured at temperatures less than 60ºC, but may react at curing or service temperatures exceeding 60ºC if the concrete contains sufficient alkali.

- Typical concrete mix designs used in the 1960s and 1970s for manufacturing precast piles for road bridges in the South Island do not present a significant risk of ASR expansion unless concrete is exposed to curing or service temperatures exceeding 60ºC. The risk increases at temperatures higher than 60ºC, and is then determined by temperature (especially if the temperature is high enough to induce DEF), concrete alkali content and the reactivity of the specific aggregate.
- To minimise the risk of ASR-related expansion in concrete containing Southland and Nelson alluvial aggregates, and other rock types with a history of expansive ASR in New Zealand and overseas, concrete temperatures during curing should be monitored and should not exceed 70ºC. This applies particularly to heat-cured concrete and to mass concrete.

The guidelines would also benefit from general revision to take into account local experience gained and international developments in the 10 years since they were written. This is of lower priority than the recommended amendments.

The wider concrete industry may wish to consider whether curing practices and quality management can be improved to reap the benefits of improved concrete quality and durability that can be achieved by ensuring concrete temperatures during curing are consistent and remain below 70ºC.

7 References

American Society for Testing and Materials (2007) Standard test method for potential alkali reactivity of aggregates (mortar-bar method). *ASTM C1260*.

Bruce, SM, SA Freitag, A Shayan, R Slaughter and R Pearson (2008) Identifying the cause of concrete degradation in prestressed bridge piles. *Corrosion and Prevention 2008*. Wellington New Zealand.

Brunetaud, X, R Linder, L Divet, D Duragrin and D Damidot (2007) Effect of curing conditions and concrete mix design on the expansion generated by delayed ettringite formation. *Materials and Structures 40*: 567–578.

Cement and Concrete Association of New Zealand (2003) Alkali silica reaction. Minimising the risk of damage to concrete – guidance notes and recommended practice. *CCANZ technical report TR3 (second edition)*. 84pp.

Collepardi, M (2003) A state of the art review on delayed ettringite attack on concrete. *Cement & Concrete Composites 25*: 401–407.

Coombs, DS, CJ Adams, BP Roser and A Reay (2008) Geochronology and geochemistry of the Dunedin Volcanic Group. *NZ Journal of Geology and Geophysics 51*: 195–218.

Ekolu, SO, MDA Thomas and RD Hooton (2007) Implications of pre-formed cracking in relation to the theories of DEF mechanism. *Cement and Concrete Research 37*: 161–165.

Freitag, SA, SM Bruce, A Shayan, R Slaughter and R Pearson (2009) Concrete degradation in precast concrete piles. *Coasts and Ports 2009*. Wellington New Zealand.

Freitag, SA, SM Bruce, A Shayan, R Slaughter and R Pearson (2010) Concrete pile durability in South Island bridges. *The New Zealand Concrete Industry Conference October 2010*. Wellington, New Zealand.

Freitag, SA, DA St John and R Goguel (2000) ASTM C1260 and the alkali reactivity of New Zealand greywackes. *11th International Conference on alkali aggregate reaction (ICAAR),* Quebec, Canada, 11–16 June 2000.

Hanson, JA (1963) Optimum steam curing procedure in precasting plants. *Journal of the American Concrete Institute Proceedings 60*, no.1.

Lindgard J, P Nixon, I Borchers, B Schouenborg, B Wigum, M Haugen and U Akesson (2010) The EU partner project – European standard tests to prevent alkali reactions in aggregates: final results and recommendations. *Cement and Concrete Research 40,* no.4: 611-635.

Mortimer, N (2004) New Zealand's geological foundations. *Gondwana Research 7*, no.1: 261–272.

Mortimer, N and B Smith Lyttle (2001) New Zealand's geological foundations. Poster. Dunedin: Institute of Geological and Nuclear Sciences.

NZ Transport Agency (NZTA) (2011) Bridge and other highway structures inspection policy. S6.2011. Accessed August 2011. *www.nzta.govt.nz/resources/bridges-structures-inspection-policy/docs/bridges-structures-inspection-policy.pdf*

Quillan, K (2001) Delayed ettringite formation: in-situ concrete. *BRE Information Paper IP 11/01*.

Roads & Traffic Authority (2001) Accelerated mortar bar test for AAR assessment. *RTA test method T363.*

Shayan, A (2006) Expansion of AAR-affected concrete under aggressive marine conditions: a look at possible effects of complex interactions. *Marc-Andre Berube Symposium on alkali aggregate reactivity in concrete.* Montreal, Canada.

Shayan, A (2007a) Unpublished ARRB contract report VC 72964, confidential to Opus International Consultants.

Shayan, A (2007b) Field evidence for inability of ASTM C1260 limits to detect slowly reactive Australian aggregates. *Australian Journal of Civil Engineering 3,* no.1: 13–26

Shayan, A (2010) Unpublished ARRB contract report 002348, confidential to Opus International Consultants. Australia.

Shayan, A. and H Morris (2001) A comparison of RTA T363 and ASTM C1260 accelerated mortar bar test methods for detecting reactive aggregates. *Cement and Concrete Research 31*: 655–663.

Shayan, A and A Xu (2004) Effects of cement composition and temperature of curing on AAR and DEF expansion in steam-cured concrete. *12th International Conference on Alkali Aggregate Reaction*, *(ICAAR)* Beijing. China, 15–19 October 2004. pp773–788.

Shayan, A, A Xu and H Morris (2008) Comparative study of the concrete prism test (CPT60°C 100%RH) and other accelerated tests. *13th International Conference on Alkali-Aggregate Reaction (ICAAR)*, Trondheim, Norway, 16–20 June 2008.

Shayan, A, A Xu, G Chirgwin and H Morris (2010) Effects of seawater on AAR expansion of concrete. *Cement and Concrete Research 40*: 563–568.

Skinner, DNB, RL Brathwaite and AB Christie (2009) Review of south Island aggregate sources in terms of their potential for alkali silica reaction. GNS Science Consultancy report 2009/12, confidential to Opus International Consultants.

St John, D (1988) Alkali aggregate reaction and synopsis of other data on AAR. *New Zealand Concrete Construction*: 7–14.

Thomas, M, K Folliard, T Drimalas and T Ramlochan (2008) Diagnosing delayed ettringite formation in concrete structures. *Cement and Concrete Research 38*: 841–847.

Tosun, K and B Baradan (2010) Effect of ettringite morphology on DEF-related expansion. *Cement & Concrete Composites 32*: 271–280.