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Progress in the Evaluation of Alkali-Aggregate Reaction in Concrete Construction in the Pacific Northwest, United States and Canada

Chapter K of

Contributions to Industrial-Minerals Research

Bulletin 2209–K

U.S. Department of the Interior
U.S. Geological Survey

Progress in the Evaluation of Alkali-Aggregate Reaction in Concrete Construction in the Pacific Northwest, United States and Canada

By Fred H. Shrimer

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Contributions to Industrial-Minerals Research

James D. Bliss, Phillip R. Moyle, and Keith R. Long, Editors

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Progress in the Evaluation of Alkali-Aggregate Reaction in Concrete Construction in the Pacific Northwest, United States and Canada

By Fred H. Shrimer[1]

Abstract

The supply of aggregates suitable for use in construction and maintenance of infrastructure in western North America is a continuing concern to the engineering and resources-management community. Steady population growth throughout the region has fueled demand for high-quality aggregates, in the face of rapid depletion of existing aggregate resources and slow and difficult permitting of new sources of traditional aggregate types. In addition to these challenges, the requirement for aggregates to meet various engineering standards continues to increase.

In addition to their physical-mechanical properties, other performance characteristics of construction aggregates specifically depend on their mineralogy and texture. These properties can result in deleterious chemical reactions when aggregate is used in concrete mixes. When this chemical reaction—termed "alkali-aggregate reaction" (AAR)—occurs, it can pose a major problem for concrete structures, reducing their service life and requiring expensive repair or even replacement of the concrete. AAR is thus to be avoided in order to promote the longevity of concrete structures and to ensure that public moneys invested in infrastructure are well spent.

Because the AAR phenomenon is directly related to the mineral composition, texture, and petrogenesis of the rock particles that make up aggregates, an understanding of the relation between the geology and the performance of aggregates in concrete is important. In the Pacific Northwest, some aggregates have a moderate to high AAR potential, but many others have no or only a low AAR potential. Overall, AAR is not as widespread or serious a problem in the Pacific Northwest as in other regions of North America.

The identification of reactive aggregates in the Pacific Northwest and the accurate prediction of their behavior in concrete continue to present challenges for the assessment and management of geologic resources to the owners and operators of pits and quarries and to the users of the concrete aggregates mined from these deposits. This situation is complicated by the length of time typically required for AAR to become noticeable in concrete construction in the Pacific Northwest, commonly on such a scale that other deterioration mechanisms may have masked the effects of AAR. Distinguishing between the effects of AAR and those related to other problems in concrete is important for understanding the nature and severity of AAR throughout the Pacific Northwest. Furthermore, developing an understanding of the extent of the problem will assist efforts to maximize the intelligent and stewardly use of aggregate resources in the Pacific Northwest.

This chapter illustrates the current "'state of the art" of AAR studies in the Pacific Northwest, a region with a common geologic heritage as well as many distinct geologic elements. The optimal use of aggregates in the construction of concrete structures that will achieve their design life is possible through an understanding of the engineering and geologic properties of these aggregates and of their geologic setting.

Introduction

This chapter has a twofold focus: (1) to review current research on the evaluation of alkali-aggregate reaction (AAR) in concrete structures from Alaska to Oregon (the "Pacific Northwest"), and (2) to assess AAR test data for aggregates throughout this region. I briefly appraise the problems and trends in AAR research in the Pacific Northwest region, together with a discussion of test methods, the specification limits applied throughout the region, and the various solutions that are available for managing AAR in concrete.

AAR is a chemical reaction that occurs in portland-cement concrete, involving alkalis that are present in the pore solutions of concrete and certain mineral phases in the aggregates with which the concrete is made. The typical pH of pore solutions in concrete is about 12 to 13. Several minerals are more soluble at a pH of more than 9 to 10 and thus are susceptible to attack by alkalis; most of these minerals are forms of quartz, or silica-rich minerals, although some carbonate species, zeolites, and certain clay minerals have also been reported to be alkali reactive. Depending on which minerals are involved, AAR is subdivided into alkali-silica reaction (ASR) or alkali-carbonate reaction (ACR). Worldwide, ASR is the more common form of AAR. No ACR occurrences have been reported in the Pacific Northwest.

The most AAR susceptible forms of silica are generally those with a more disordered crystalline structure, including

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chalcedony, flint, chert, opal, tridymite, cristobalite, strained quartz, fragmented/sheared/shredded quartz, quartz overgrowths, and quartz cement. In addition, other silicate minerals, such as micas and clays, and some hydrous silicates, such as zeolites, have also been reported as AAR susceptible. Feldspar, the most abundant rock-forming silicate mineral, has not been reported as alkali reactive in concrete. Quartz-deficient rocks generally are not alkali reactive, except some carbonate rocks.

Analysis by stereobinocular microscope or thin section alone, however, may be inadequate to characterize the AAR potential of some rocks. For example, Shrimer (1996) described a mafic rock, considered to be quartz deficient on the basis of thin-section petrographic analysis, that was determined to be alkali reactive. Further analyses using scanning electron microscopy (SEM) and X-ray analysis determined that an extremely fine grained quartz phase was present in the rock (a metadiabase), as a result of metamorphism. This fine-grained, nearly undetectable quartz proved to be significantly reactive in the diabase aggregate.

Typically, AAR occurs in concrete between a reactive silica (or silicate) mineral and alkali compounds derived from the cement, producing an alkali-silica gel (fig. 1) that absorbs water from the concrete pores and subsequently swells. Swelling of the alkali-silica gel generates tensile stresses in the concrete that, if sufficiently great, may cause cracking. In other words, if enough reactive aggregate, alkalis, and moisture are present in concrete, expansion and cracking of the concrete may occur, affecting its serviceability or structural capacity. Features associated with AAR include cracking of concrete (figs. 2, 3) and leaching or "efflorescence" of carbonate and alkali-silica gel out of concrete through cracks (fig. 4).

The typical timeframe for AAR is measured in years, rather than days or months. Some strong reactions can cause noticeable, even serious, damage in concrete structures within a short timeframe, for example, within 5 years of construction (Rogers, 1986). The typical length of time for AAR to become noticeable in structures in the Northwestern United States and western Canada, however, is 25 years or more. Other natural processes (freeze-thaw cycles, wind) and anthropogenic processes (traffic load, salt applications, impact) can contribute to the deterioration of concrete elements throughout the lifetime of concrete structures. AAR may rank as more severe than other causes if its effects are significant and are manifested early, and as less severe if the effects are not evident or serious before other deterioration mechanisms become evident. The prediction of whether various cement-aggregate combinations will produce no, slight, moderate, or severe reaction of this type is of greatest concern to owners of concrete construction, to concrete design professionals, to concrete producers, and to aggregate producers.

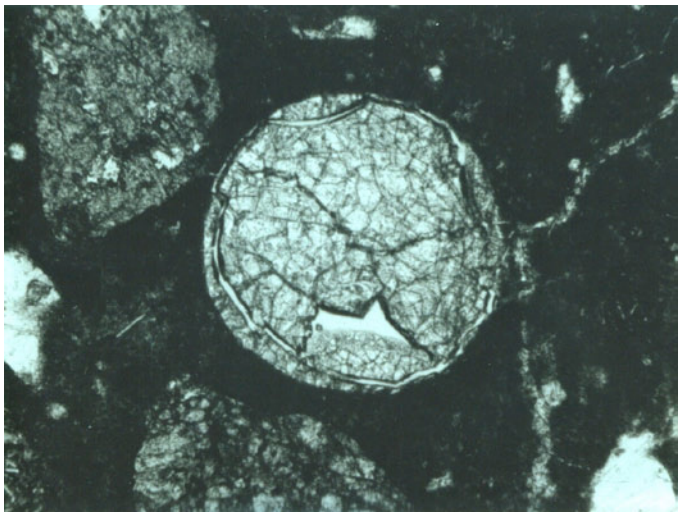

Figure 1. Scanning electron photomicrograph of air void in concrete filled with alkali-silica gel. Note microcracks leading from gel-filled void, resulting from extrusion of gel into concrete-paste matrix. Magnification, 100×.

Figure 2. Concrete column in Stanley Park, Vancouver, British Columbia, showing typical "map" cracking throughout entire column, induced by expansion of concrete due to swelling alkali-silica gel. Reactive aggregates include andesite and dacite from Mount Garibaldi near Whistler, British Columbia, as well as quartzite, chert, and granodiorite. Concrete was cast in the 1920s; specific aggregate source (that is, location of pit) is unknown.

Depending on the nature of the concrete structure or element, and its intended service life, the effects of AAR may range from merely cosmetic (no significant structural effects) to serious (requiring extensive repair). In some cases, these effects may be limited to unsightly cracks and some efflorescence in concrete construction such as a sidewalk or a retaining wall (fig. 4), and the degree of damage may not be significant enough to warrant any particular repairs if the structure remains serviceable and safety is not an issue. In other cases, however, the effects of AAR can weaken the concrete altogether and reduce its structural capacity to such an extent that the concrete may require either significant and costly repairs or outright replacement. For such major civil structures as bridges (fig. 5), dams, and tunnels, this degree of damage can be particularly problematic, affecting not only serviceability and operation but also safety. At the costly end of the scale of repairs is the technique of cutting vertical slots in dams that exhibit expansion due to AAR, to relieve the pressures generated by swelling alkali-silica gel. These repair programs are expensive, sometimes costing millions of dollars. For example, Mactaquac Dam in New Brunswick, Canada, is a well-documented case of such a remediation scheme (Curtis, 2000).

For smaller concrete structures, load capacity may be compromised, requiring expensive repair or replacement. For example, Shrimer (2000b) reported on a dock facility in which relatively small concrete elements were affected by AAR (fig. 6), reducing their structural capacity and requiring the replacement of more than 150 precast-concrete beams at a cost of more than $2 million.

Three "ingredients" (or conditions) are required for AAR to occur: (1) reactive aggregate, (2) alkalis content sufficient for the reaction to be significant, and (3) moisture. Should all three of these conditions not be present in the concrete, AAR will not occur. These conditions are normally met only when the concrete contains sufficient cement to elevate alkali levels to some threshold value (such as when the cement content is high or where high-alkali cement is used), and only when the

Figure 3. Pier in Seattle harbor, showing well-defined "map" cracking induced by alkali-aggregate reaction. Reactive aggregates includes andesite from the Mount Rainier-Mount St. Helen's area, Wash., as well as sandstone, chert, and quartzite of unknown provenance. Field of view, 1 by 1.3 m.

Figure 4. Wall in Stanley Park, Vancouver, British Columbia, showing white deposits of leachate emanating from cracks in concrete. These "efflorescence" deposits are composed of a mixture of alkali-silica gel and calcium carbonate.

concrete structure is located in an environment that exposes it to moisture. Typically, these moist conditions would be present outdoors and, if indoors, only in a setting where moisture was common (for example, a carwash, sewage plant, industrial facilities). Thus, AAR damage is more likely to occur in such structures as dams, bridges, reservoirs, dock facilities, and walls located at or near water than in those that are protected from the elements or located away from sources of moisture. In short, most residential and commercial construction, as well as some types of industrial facilities, generally is less AAR susceptible.

When AAR begins, and as it progresses over a period of time, either the alkalis in the concrete are consumed thereby ending the reaction (even though reactive aggregate remains), or the reactive aggregate is consumed, and the reaction ceases (while alkalis are still left in the concrete). Furthermore, if the supply of moisture is interrupted, swelling of the alkali-silica gel will cease, even if the reaction between the alkalis and reactive aggregate continues. AAR is specifically a chemical reaction that occurs between the minerals and the alkali solution, while water is the agent that enables or produces expansion of the concrete.

Evidence of AAR is determined through various means, such as macroscopic examination of the concrete structure, and microscopic examination and chemical analyses of concrete samples obtained from the structure. Visual evidence includes reaction rims (figs. 7, 8), cracks induced by the pressures exerted by swelling alkali-silica gel (fig. 9), and the presence of alkali-silica gel (figs. 1, 8).

Background

In the Pacific Northwest, the level of effort directed toward the identification, remediation, and prevention of AAR in concrete has been inconsistent. Some of the earliest studies of AAR in North America were conducted in this region. During the late 1930s and early 1940s, for example, Tremper (1941) and Coombs (1942) identified reactive aggregates in the Mount Rainier area and Puget Lowlands of western Washington. Their studies of cracked concrete in bridges and concrete pavements in central and eastern Washington and Oregon identified reactions that were attributed to the presence of opaline and chalcedonic silica in aggregate derived from Columbia Plateau basalt flows.

Holland and Cook (1953) described reactive aggregate in Oregon derived from the Clarno Formation, which consists of andesite-rhyolite flows and tuffs of Oligocene through Eocene age. More recently, Shrimer and Jones (2000) described examples of AAR in Washington and British Columbia. Overall, however, the level of effort directed towards the identification of AAR in concrete structures or toward the characterization of AAR-susceptible aggregates in the Pacific Northwest has been lower than in eastern North America, where AAR is recognized as more of a problem.

Control Specifications and Testing for Alkali-Aggregate Reaction

The testing and research efforts during the 1930s and 1940s led to the development of a widely adopted specification geared to the control or prevention of AAR in new concrete structures in Washington and Oregon. The primary requirement was the use of low-alkali-content cement in concrete, because a link had been found between the use of cements with an alkali content greater than 0.6 weight percent Na_2O equivalent and a higher or more severe incidence of AAR. This specification, which was adopted throughout

Figure 5. Old Alexandra Bridge in Fraser Canyon, near Boston Bar, British Columbia, showing piers and abutments damaged by both alkali-aggregate reaction and freeze-thaw cycles.

Figure 6. Part of a dock structure in Vancouver, British Columbia, showing "map" cracking. Reactive aggregates include Mount Garibaldi volcanic rocks, opal (in volcanic vugs), granitic rocks, and quartzite. Aggregate was derived from the now-closed Britannia Pit, located near Squamish, British Columbia.

the Northwestern United States, is widely used as a general rule-of-thumb in concrete construction. To some extent, application of this specification has been successful because relatively few cases of serious AAR have been reported in the Northwestern United States for many years. This success rate may be largely coincidental because cement supplies in western North America generally have low alkali contents. With lower alkali contents, AAR has not been as frequent or as pronounced in the Pacific Northwest as in other regions, where cements with higher alkali contents are more commonly used.

Besides the general requirement for the use of low-alkali cement, other standard practices specific for the control of AAR were not adopted within the Pacific Northwest during approximately the 1940s to well into the 1990s, because no serious problems due to AAR damage in concrete had been diagnosed or, if so, they were poorly understood within the region. Generally, the use of low-alkali-content cement with the required limit of 0.6 weight percent Na_2O equivalent was effective in preventing widespread AAR damage in concrete throughout the Pacific Northwest.

Figure 7. Polished section of a concrete core drilled from an alkali-aggregate-reaction-damaged dam in southern British Columbia. Darkened reaction rims on aggregate particles indicate that reaction with alkalis has taken/is taking place. Field of view, approximately 30 by 50 mm.

Figure 8. Fracture surface on a sample of core drilled from alkali-aggregate-reaction-damaged concrete, showing dried white gel patches on several aggregate particles. Darker "reaction rims" also are clearly visible on many aggregate particles. Field of view, approximately 60 by 100 mm.

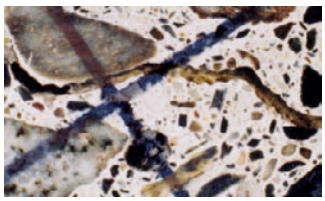

Figure 9. Polished sample of concrete, showing cracking induced by pressure from swelling alkali-silica gel. Crack extends through sand/cement matrix and passes by several coarse aggregate particles. Field of view, 20 by 55 mm.

During much of the 1950s to1990s, few cases of AAR were reported in the Pacific Northwest. Some examples surfaced, but the incidence was low enough that the general concrete-construction community did not give AAR much consideration. This situation began to change in the 1980s and 1990s as cases of AAR became more apparent throughout the Pacific Northwest (British Columbia Ministry of Transportation and Highways, 1995). In some cases, AAR damage was merely cosmetic, with cracks appearing in the surfaces of concrete elements but without serious structural weakening of the concrete. In other cases, however, AAR-damaged concrete structures were removed from service or demolished, or needed costly repairs.

In practice, many of the aggregates used for making concrete were, in fact, determined to be quite reactive, but owing to the lower alkali contents in Pacific Northwest cements, AAR did not set in and become noticeable until considerable time had elapsed. By the time damage was noted and investigated, frequently the deterioration had been attributed to the effects of freeze-thaw cycles, which can closely resemble those of AAR.

Currently, the primary methods used for evaluating AAR potential are the accelerated mortar-bar test (AMBT), referenced in American Society for Testing and Materials (2002) as ASTM C 1260 and in Canadian Standards Association (2004) as CSA A23.2–25A; and the concrete-prism test (CPT), referenced as ASTM C 1293 and CSA A23.2–14A. Other methods that have been used in the past include the "Potential Alkali-Silica Reactivity of Aggregates" ("Quick Chemical") test (ASTM C 289) and the "Mortar-Bar Test for Potential Reactivity of Cement-Aggregate Combinations" (ASTM C 227), both of which have been shown to be largely unreliable indicators of AAR potential, and so they are no longer recommended for this purpose. Thus, the AMBT and the CPT are the currently preferred methods for evaluating AAR potential in the United States and Canada.

Geology and Reactivity of Aggregates

The low incidence of AAR in the Pacific Northwest is probably due more to the historical use of low-alkali cement than to the use of nonreactive Pacific Northwest aggregates. Recent research has shown that, in many areas of the Pacific Northwest, aggregates actually have an AAR potential which (in some areas) ranges from "moderate" to "high" as defined in CSA A23.1/2–04 and by ASTM. This observation is based on testing of aggregates from throughout the region, and on comparison of the geology of tested aggregates with that of aggregates from areas where little or no testing has been conducted (for example, Alaska, Oregon).

Aggregates used in the Pacific Northwest for the manufacture of ready-mix and precast concrete generally are derived from sand and gravel deposits of glaciofluvial or fluvial origin. Of the quarried supplies of aggregates in the Pacific Northwest, few are regularly used primarily as concrete aggregate. Some amount of crushed quarry rock or over-

size gravel may be blended in with natural, rounded gravel to increase concrete strength and durability, but as a rule, the use of concrete coarse aggregates composed of 100 percent crushed quarried stone is rare.

For aggregates produced from sand and gravel deposits, the geologic composition of the aggregates reflects the regional (or "upstream") geology of the area in which the deposit is located. Because the AAR potential of an aggregate is a direct function of its mineralogy and lithology, an understanding of the geology of the aggregates, their provenance, and their mode of deposition is important. This information also is required if an overall appraisal of the engineering geology is desired.

Generally, the following rock types in Pacific Northwest aggregates are considered to be "potentially reactive," that is, susceptible to or associated with AAR in concrete:

- *Volcanic rocks of Cascadian origin*, including intermediate-composition to acidic rocks (rhyolite-andesite). One of the most reactive aggregates discovered to date in the Pacific Northwest is in the former gravel pit at Britannia, British Columbia, which contains a significant amount of volcanic rocks derived from Mount Garibaldi, situated at the north end of the Cascade Range (Hickson, 1994).
- *Basaltic volcanic rocks*, such as Columbia River flows, which contain chalcedonic quartz as amygdule fillings or vug linings, basaltic pebbles with opaline coatings, and rocks from the Chilcotin Plateau, Anahim Belt, and Wells Grey-Clearwater volcanic fields in British Columbia, particularly those that contain chalcedony, opal, or zeolites.
- *Quartzite pebbles* of widespread and varied provenance. In British Columbia and western Washington, some quartzites may originate from the Canadian Rocky Mountains and the Purcell Mountains. Other quartzite formations in Washington and British Columbia likely also have contributed.
- *Sandstone pebbles* of widespread provenance, some from the Rocky Mountains, and many from southwestern British Columbia and western Washington, including chert-rich sandstone, greywacke, and lithic sandstone.
- *Chert pebbles* in Fraser River gravels, which may have been derived from radiolarian chert beds in the vicinity of Cache Creek, British Columbia, as well as numerous other sources. Fraser River gravel cherts have been determined to be reactive in concrete. Chert, which is generally a reactive rock type, occurs in many formations of the Pacific Northwest.
- *Some plutonic rocks*, such as granitic rocks of the Coast Plutonic Complex in British Columbia, that have been associated with AAR in concretes 40 or more years old. Therefore, though rarely, other plutonic rocks within the Cascades or other areas in the Pacific Northwest may exhibit some AAR potential as well.
- *Metamorphic rocks* in which cataclastic fabrics are present (Wigum,1996) or that contain strained quartz, owing to their disturbed crystalline lattice.

Rock types that generally are considered to be nonreactive include:

- *Most plutonic rocks*, particularly if little or no disturbed or strained quartz is present. Mafic plutonic rocks generally exhibit little or no AAR potential. Coastal gravel deposits that contain a high proportion of Coast Plutonic Complex rocks generally exhibit a low (that is, "safe" level of) AAR potential, such as in the large gravel pits near Sechelt, British Columbia, where the deposits are primarily derived from bedrock sources within the Coast Plutonic Complex.
- *Carbonate rocks*, provided they are not dolomitic, siliceous, or argillaceous. Special tests have been devised to identify reactive carbonate rocks. Numerous limestone deposits are mined throughout the Pacific Northwest for cement or agricultural use: a few of these deposits have been evaluated for their AAR potential, and thus far, have been found to be nonreactive.
- As noted above, *mafic, quartz (chalcedony, tridymite, cristobalite, opal)-deficient volcanic rocks* have generally exhibited low or no AAR potential. However, careful diagnosis is required to verify that these potentially reactive forms of silica are absent.

On a finer scale, even within deposits, AAR potential may vary significantly as production penetrates different strata. Individual strata exposed within one section of a pit may differ lithologically from other strata above or below, with corresponding shifts in the proportion of reactive rock types. Typically, hydraulic sorting and a change in flow direction (with a corresponding change in upstream provenance) are responsible for these variations. Aggregate suppliers working these types of gravel deposits commonly consider their deposits to be nearly homogeneous, but, in fact, this is not always so. A more thorough evaluation of the lithology and AAR potential within individual pits or deposits may be appropriate in these cases.

In one pit in southern British Columbia, evaluation over a 5-year period showed reaction levels ranging from low ("safe for use") for one year's production to high ("very reactive") in tests conducted for another year's production. To explain such seemingly inconsistent test results requires detailed petrographic analysis of the aggregates produced over the various time periods. In this pit, various rock types, provenances, and AAR potentials are represented, including Cascade volcanic rocks (reactive), quartzite and sandstone (reactive), chert (reactive), Coast Plutonic Complex and Cascadian plutonic rocks (nonreactive), metamorphic rocks (some reactive, some nonreactive), greenstone (nonreactive), and Interior Plateau basalt (mostly nonreactive). As the proportion of reactive rock types changed from one years' production to another, the AAR potential also changed. For example, chert content within the pit ranged from ~7 to ~20 percent, and AAR potential ranged from low to high, respectively.

Therefore, even within a single aggregate deposit, seemingly small changes in lithology may be associated with significant changes in some engineering characteristics of the aggregate produced, including AAR potential. Thus, aggregate producers may need to regularly evaluate and test deposits in order to monitor such characteristics as AAR potential. Without such test data available, management of the aggregate resources to its optimal and best use becomes difficult.

In Washington, virtually all the aggregate sources tested in accordance with ASTM C 1260 have been identified as "potentially reactive" (Shrimer and Jones, 2000). Very few of these aggregate supplies have been evaluated by using the long-term, more definitive ASTM C 1293 test, and so no clear indication of the actual AAR potential of these aggregates is known. This question requires further assessment in Washington.

In British Columbia, approximately 80 percent of the aggregates tested in accordance with ASTM C 1260 have been identified as "potentially reactive" (Shrimer, 2000b). When tested in accordance with ASTM C 1293, however, the proportion of aggregates identified as "potentially reactive" is only approximately 40 percent of the total. Some pits have been identified that contain aggregates with an AAR potential low enough to be considered "nonreactive," generally those pits in deposits with a high content of Coast Mountain Pluton (intrusive) rocks and low contents of volcanic rocks, chert, quartzite, and sandstone (Shrimer, 2001). For information on individual pits, it is best to contact the pit operator and request current and historical AAR test data, before assuming anything about the AAR potential of a particular supply of aggregate.

Alkali-Aggregate Reaction in Concrete in the Pacific Northwest

In the Pacific Northwest, varying levels of effort have been applied to the discovery of AAR in concrete structures, depending largely on previous experience. In areas where a serious problem stemming from the occurrence of AAR in an important structure was uncovered, the owners and managers of such structures were or are more vigilant in the recognition of other cases of AAR. In general, more effort in identifying AAR in existing structures has been applied in Washington and British Columbia than in Alaska, Oregon, or northern California. Interest in the discovery of new sites of AAR in the Pacific Northwest has risen since the early 1990s, as more and more old structures have been reported to be affected by AAR.

In some cases, AAR has made the structure all but useless, requiring its demolition or replacement. For example, in the central Fraser Valley of southern British Columbia, two water reservoirs were demolished because of serious leaking resulting from AAR-induced cracks. In Fraser Canyon, the Alexandra Bridge (fig. 5), built in 1926, has been affected by both freeze-thaw cycles and AAR; the heavily cracked and deteriorated concrete is essentially unsalvageable. Management of the structure has become a source of concern for the British Columbia Ministry of Transportation and Heritage Canada, who have joint custody of and responsibility for the bridge.

In a recent study of a dam in southern British Columbia, Shrimer (2003) reported that its safe operation was being compromised by the expansion of concrete elements, resulting in poor operation of the radial gates. The typical condition of some AAR-affected concrete elements—efflorescence, discoloration, and "map" cracking (fig. 10)—illustrates the potentially serious effects of AAR. At the time of the study, the dam was 47 years old.

In other structures, extensive repairs have been required to reestablish the serviceability of the concrete. For example, repair of 40-year-old concrete support beams at a Vancouver, British Columbia, grain terminal was considered to be an unworkable solution, owing to the extent of AAR-induced cracking and the reduction of structural capacity. In these beams, andesite, quartzite, and chert were the primary reactive aggregates. Reactive opal was also identified as vug linings in basaltic aggregate in the concrete. Replacement of the beams cost more than $2 million.

In many structures, the effects of freeze-thaw cycles commonly accompany the damage incurred by AAR in concrete, such that the AAR damage is "masked" by freeze-thaw damage. Rarely, in other structures, the observed damage was first attributed to AAR, but upon conducting a detailed investigation, the primary cause was identified as freeze-thaw action. In some cases, AAR is diagnosed in the concrete but may be only incidental.

The Washington State Department of Transportation (WSDOT) has identified AAR in some structures as part of their routine inspection of their infrastructure. Affected structures include bridges and pavements in various locations throughout the State, such as the Manette Bridge (fig. 11) in Kitsap County, the Woodward Creek Bridge near Walla Walla in southeastern Washington, and the historic Monroe Street Bridge in Spokane (figs. 12–14). In total, as many as 150 sites of suspected occurrence of AAR have been identified in WSDOT-owned structures. The confirmation of whether AAR is present, and to what extent, remains to be determined at these sites in Washington. At the time of this writing, additional studies to make such determinations have not yet been undertaken.

In British Columbia, more than 125 structures have been reported to be affected by AAR in concrete, including bridges and tunnels (owned by the British Columbia Ministry of Transportation in all parts of the Province), tunnels (south coast and Fraser Canyon), dams (south, southwestern, and north-central British Columbia) (Shrimer, 2003), port facilities (Vancouver, Prince Rupert), reservoirs (south and north coast regions), and privately owned structures in various locations.

Correct evaluation of AAR in a concrete structure is best achieved through a multicomponent investigation, carried out by an individual experienced in this type of work. Typically, such an investigation will involve a detailed inspection of the concrete and include a review of construction records, plans, and repair-and-maintenance records, as well as a laboratory evaluation of concrete samples from the structure. AAR can be evaluated by specialized methods, such as petrographic analysis of hardened concrete, (ASTM C 856), the American Association of State Highway Transportation Officials' uranyl acetate test (AASHTO T–299), and other methods that have been developed more recently, such as the damage-rating-index test (Dunbar and Grattan-Bellew, 1995; Shrimer, 2000a).

Testing the Alkali-Aggregate-Reaction Potential of Pacific Northwest Aggregates

Despite the awareness of AAR since the 1930s and 1940s, Pacific Northwest aggregates were generally not tested for AAR potential on a routine basis, except for

Figure 10. Section of a wall in a dam in southern British Columbia, showing well-developed "map" cracking and efflorescence, both indicators of alkali-silica reaction. Concrete was about 47 years old at time of photograph.

Figure 11. Manette Bridge in Kitsap County, Washington, which was diagnosed with alkali-silica reaction in its piers and abutments.

Figure 12. Monroe Street Bridge in Spokane, Wash., undergoing rehabilitation work in fall 2003.

Figure 13. Closeup of Monroe Street Bridge, Spokane, Washington, showing section of main arch. Concrete removed from demolished sections was determined to have been affected by alkali-silica reaction.

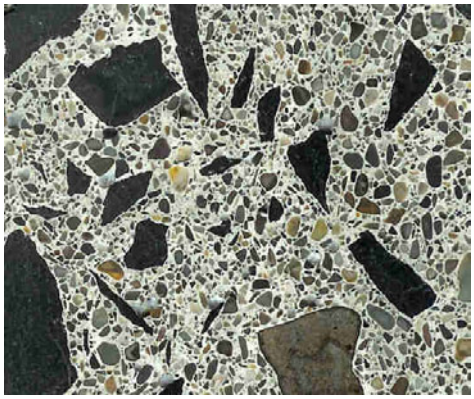

Figure 14. Polished sample of concrete from the Monroe Street Bridge in Spokane, Wash., showing reaction rims on andesitic aggregate particle and on smaller aggregate particles, indicating reaction with alkalis in concrete.

specific projects, in contrast with other regions of North America, where a clear and more widespread AAR problem was recognized. In those regions (for example, Ontario, Quebec, central/eastern Canada, New Mexico, Virginia, and other Eastern and Southern States), testing of aggregates for AAR potential was more common, and aggregate producers were not only accustomed to having the testing done but also familiar with the AAR potential of their aggregate supplies.

As more evidence of the occurrence of AAR was identified in some areas, a desire to understand the problem and avoid it in new or rehabilitated concrete structures arose, leading to a renewal of interest in testing both existing and proposed aggregate resources. This level of interest has generally not characterized aggregate engineering in the Pacific Northwest since the 1950s. The recent renewal of interest, in turn, has resulted in the revision of specifications for concrete construction materials by transportation and highways departments, by municipal, district, or county governments, and by hydro, rail, port and other infrastructure authorities.

Another factor that has generated further interest in AAR evaluation has been the importance and use of aggregates in areas where specification requirements differ and are more stringent than at the source, for example, the sale of aggregates from British Columbia to the Washington and California markets. The sale and transport of British Columbia aggregates to the United States has occurred since the late 1990s, partly owing to the favorable exchange rate between Canadian and U.S. currencies, as well as the growing demand in California for high-quality construction aggregates. Generally, the U.S. market requires a higher level of testing and prequalification than in British Columbia, and so Canadian aggregate supplies needed to be evaluated for AAR potential in advance of their acceptance for use in the United States. Additionally, the limit for AAR-induced expansion in ASTM C 1260 is lower than that specified in the equivalent Canadian CSA A23.2–25A. As a result, the chances of exceeding the U.S. expansion criteria are higher in the American test than in the Canadian test.

Recent Alkali-Aggregate-Reaction Test Data

Since about 1990, testing of Pacific Northwest aggregates for AAR potential has been done mostly in Washington and British Columbia. Because the Alaska and Oregon Departments of Transportation currently have no prequalification requirements specifically for the AAR potential of aggregates intended for use in new concrete construction, few aggregate supplies have been tested for AAR potential in those States, although some testing of aggregates from neighboring areas has been carried out. For example, WSDOT has conducted testing of four aggregate supplies from Oregon and four aggregate supplies from British Columbia, all of which were proposed for use in WSDOT projects. All of the Oregon aggregate supplies and three of four British Columbia aggregates tested by WSDOT were rated as "potentially reactive" when tested in ASTM C 1260.

AAR test data (Shrimer, 2000b; Shrimer and Jones, 2000) generally indicate that many Pacific Northwest aggregates have a moderate to high AAR potential. Because of the length of time (1 year) required to run a CPT, many aggregates have been evaluated with the AMBT, which requires only 2 to 3 weeks to complete. Although the AMBT is faster, it also can be quite severe, and so it is generally considered by the aggregate-testing industry to be better used as a screening test. (The CPT, as discussed below, is considered to be a more accurate predictor of AAR potential in aggregates.) As a result, many aggregates exceed the limits in the AMBT. In Washington, for example, current data indicate that 98 percent of the aggregates tested exceeded the maximum-expansion limit of 0.10 percent specified for this test. In British Columbia, where the higher CSA limit of 0.15 percent is used, 82 percent of the aggregates tested exceeded this limit.

The AMBT data listed in table 1 are based on the number of samples tested, which varies for the three States and one Canadian Province involved. The Alaska and Oregon datasets are based on very few tests, whereas the Washington dataset currently represents about 100 AMBTs, and the British Columbia dataset more than 250 tests. Recent testing of aggregates in neighboring Montana has also identified several potentially reactive aggregates, a result consistent with what has been determined in the adjacent, geologically similar regions of Alberta, British Columbia, and Washington.

The sparsity of available CPT data reflects the low incidence of use this longer-term test in Pacific Northwest States. The British Columbia dataset currently consists of more than 100 CPT results. Of the two current methods, the CPT is considered to be a more accurate and reliable predictor of the AAR potential of aggregates. The 1-year time requirement for running a CPT, however, exceeds the typically short timeline for preparation for many construction projects, such that the project might be well underway or even finished before the test is completed. Thus, many aggregates are evaluated by using the AMBT instead.

To overcome this dilemma of "quick/harsh versus slow/better test," it is recommended that aggregate supplies be evaluated initially by using both methods, so that a "calibration" for the short-term versus the long-term test is established. Some specifications require a CPT to be run at least annually. After a reasonable track record of data has been achieved for a specific aggregate source, the 1-year requirement might appropriately be relaxed to every 2 years (or longer, for smaller-output supplies) provided that no obvious changes are observed in the aggregate's geology, as determined by petrographic analysis.

To assist aggregate and concrete producers, specifying agencies, such as State departments of transportation, could issue a "qualification requirement" to suppliers of concrete, concrete products and concrete aggregates. Any aggregate and concrete suppliers who wished to provide their products to State or Provincial transportation projects would be given a 1-year-long period in which to conduct CPTs on their sup-

Table 1. Summary of alkali-aggregate-reaction test data for selected aggregates in the Pacific Northwest, United States and Canada.

[All values in percent. n/a, not available]

Area	Accelerated mortar-bar test (C 1260[1]): expansion after 14 days				Concrete-prism test (C 1293[1]): expansion after 12 months			
	Low	High	Average	Limit	Low	High	Average	Limit
Oregon	0.28	0.63	0.46	0.10	n/a	n/a	n/a	0.04
Washington	.08	.75	.31	.10	.03	.095	.063	.04
British Columbia	.01	1.07	.42	.15	.004	.360	.067	.04
Alaska	.16	.52	.32	.10	n/a	n/a	n/a	.04

[1]Method defined by American Society for Testing and Materials (2004).

plies of aggregates. In this way, the necessary information could be obtained in a timely fashion, and the high "failure rate" observed in the AMBT could be accounted for. The specifying agencies could then review the submitted data and assess the test results to determine the acceptability of various aggregate sources for use in concrete construction.

After an initial set of AAR tests has been compiled, and once a CPT has been begun, an AMBT can be conducted to determine the AAR potential of current production aggregates by comparing the new data with historical calibration data. This approach has been used with success by aggregate quality-control staff in central Canada (De Grosbois and Fontaine, 2000). Such an approach generally requires a concurrent petrographic analysis to provide data on the consistency of the mineralogic and geologic composition of the aggregates under study.

WSDOT currently has a framework in place requiring that aggregate suppliers submit samples of their aggregates for testing, in the quick, 2-week ASTM C 1260. Aggregates that pass this test may be included on the State's "Aggregate Source Approval" listing, whereas those that fail are excluded. This approach is somewhat similar to that used in Ontario, where the Provincial Ministry of Transport requires that suppliers of concrete and aggregates provide certified test data to demonstrate that their aggregate supplies will not cause deleterious AAR-induced expansion in concrete.

The Federal Highways Administration, which has extensively studied the AAR problem in publicly owned transportation infrastructure, provides helpful information and detection advice in their *Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures* (Federal Highways Administration, 1991).

Summary

AAR has been found to vary in occurrence, location, and severity throughout the Pacific Northwest. Although the geology of Pacific Northwest aggregate supplies commonly supports the occurrence of AAR because of their moderate to high AAR potential, the geology of much of the carbonate source rock used to manufacture local Pacific Northwest cements has resulted in the production of cements with low alkali contents, helping the region avoid a far more serious AAR problem.

Recommendations

More concrete structures that have been affected by AAR are anticipated to be detected in the Pacific Northwest. Repair or replacement strategies should be developed on a case-by-case basis. An assessment of each occurrence can be facilitated through detailed field and laboratory methods, including petrographic analysis (ASTM C 856), damage-rating-index test (Shrimer, 2000a) and determination of the "potential for future expansion" (Berube and others, 1995).

Continuing evaluation of the AAR potential of aggregates throughout the Pacific Northwest will be required to more completely understand the reactivity of available aggregate sources. Although reactive aggregates may be the only choice for use on some AAR-sensitive projects, effective methods to suppress AAR in new concrete construction are currently available, holding promise for many reactive aggregates to be declared "safe for use" with respect to AAR. These methods include the use of such mitigative materials as fly ash, silica fume, and certain lithium products. Nonetheless, it is recommended that individual combinations of aggregate be evaluated with the proposed mitigative material(s) before acceptance of the aggregate for use. These mitigative materials have generally been found to be effective in making many potentially reactive aggregates safe for use; however, authorities typically require that reactive aggregates be carefully evaluated before being their approval for use. Caution is the safest approach when dealing with potentially reactive aggregates in the concrete that is required to build safe, durable, and economic structures or constructed works.

Implementation of these types of mitigative material would extend the service life of existing aggregate resources that may otherwise be reactive in concrete. If potentially reactive aggregate supplies throughout the Pacific Northwest were abandoned in favor of nonreactive aggregate supplies only, some areas would be left with few or no alternative aggregate resources and would need to transport aggregates into the market area, at significantly greater cost.

Therefore, the use of local, potentially reactive aggregates, in properly designed, AAR-mitigated concrete mixes, would alleviate the need to transport nonreactive supplies from other, more distant areas. The use of local versus nonlocal aggregates would reduce costs to projects and communities, would mitigate the potentially greater negative effects on livability and the environment within the region, and is consistent with a more stewardly use of aggregate resources.

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