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Mitigation of the Effect of Alkali-Silica Reaction in Concrete Structures: A Review

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Abstract

Unexpected or premature concrete deterioration due to alkali-aggregate reactivity is a widespread problem worldwide. The most common management actions for concrete structures affected by ASR can generally be grouped into activities to (1) control moisture access to the concrete by improving drainage systems or applying physical barriers or a variety of waterproof coatings, (2) slow down the process of ASR through chemical treatments such as the use of lithium-based compounds, (3) restrain expansion forces using physical containment, post-tensioning, encapsulation, and (4) try to accommodate the deleterious effect of AAR expansion by releasing stresses using slot-cutting. The effectiveness of the above methods has been shown to vary widely from one application to another; however, it is generally recognized that most of the above remedial measures are temporary solutions that may help to save some time and money until the deleterious process of AAR expansion has stopped.

Keywords: Alkali-aggregate reaction; alkali-silica reaction; remedial measures; repair of concrete.

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1 Introduction

The properties of aggregates greatly affect the strength, durability and structural performance of concrete. In concrete, aggregates are subjected to a highly basic and alkaline environment where some mineral phases, generally stable in normal environmental conditions, can produce significant deterioration as a result of deleterious chemical reactions commonly called alkali-aggregate reactions (AAR). Alkali-silica reaction (ASR) is the most commonly recognized form of AAR worldwide; it refers to chemical reactions between alkali hydroxides (Na^+, K^+ - OH^-) in the concrete pore fluid and certain siliceous phases present in the aggregate materials. The reaction results in the formation of a secondary calcium-rich alkali-silica gel that has a strong affinity with water. As the gel absorbs water, internal swelling pressure develops causing volume change and fracturing of the reacting aggregate particles, cracking of the surrounding cement paste and subsequent deterioration of the concrete, which in turn can result in a significant reduction in the service life of affected concrete structures. The extent and the rate of ASR-induced concrete deterioration generally depend on several factors, including: 1) the inherent reactivity (nature and level of reactivity) of the aggregate material, 2) the pH of the concrete pore fluid which is related to the total alkali content of the concrete mixture, 3) the availability of moisture, 4) the temperature and thermal gradients, and 5) configuration and structural restraint provided to the concrete structure or element.

Premature/unexpected deterioration in concrete structures is often detected during routine site inspections that are generally performed on a regular basis to monitor the overall condition of concrete structures. The visual condition survey is generally accompanied by sampling of a selected number of concrete structures and laboratory testing of the cores collected from them. Laboratory investigations are of critical importance to determine whether or not ASR can be considered a major contributing factor to the deteriorations observed, evaluate the extent of the damage affecting the concrete structures, and determine the potential for future expansion of the concrete. The analysis of the field and laboratory investigations will be critical in the selection of repairs and/or mitigation requirements to be undertaken. This paper reviews the various approaches that have been used to mitigate the effects of ASR in concrete.

2 Improvement of Drainage

Considering the critical influence of moisture on the development of extensive ASR expansion in concrete, it is commonly recommended to critically review the drainage systems serving the affected members. Modifications could be implemented to allow water to drain away from the structure rather than onto or through parts of it (Hobbs 1988). The application of a waterproof membrane (e.g. PVC geomembrane) on the upstream face of concrete dams may provide protection against ingress of water in the concrete (De Beauchamp 1995; Scuero 1995; Matos et al. 1995).

3 Crack Injection

Filling macrocracks or construction joints with cement grout or epoxy resins is commonly done to restore structural continuity or to limit water penetration in AAR affected structures (Matos et al. 1995; Durand 1995, Bérubé et al. 1989; Charlwood and Solymar 1995); it is also commonly performed before applying a waterproof sealing or water repellent agent. In a number of cases, the effectiveness of this approach in ASR-affected structures was limited since cracks reappeared a few months/years after treatment (Bérubé and Fournier 1987; Ishizuka et al. 1989). Injection of modern flexible grouts may prove to be more effective than rigid epoxy resins to prevent leakage through joints or cracks in a concrete member where ASR expansion is still active.

4 Moisture Control - Coatings (Sealers, Membranes)

Numerous studies have shown that ASR typically develops or sustains in concrete elements with internal relative humidity > 80-85% (BCA 1992; Stark 1990). Thin concrete elements are unlikely to be deleteriously affected by ASR when exposed to indoor or outdoor constantly dry conditions (i.e. with no external supply of moisture), or when immersed in fresh or in sea water because of the leaching of alkalis or the dilution of [Na^+,K^+-OH^-] from/in the concrete pore fluid. On the other hand, massive concrete elements incorporating a reactive aggregate are often at risk of AAR, even those kept indoor or in arid desertic conditions, because of the high internal humidity conditions maintained, at least periodically, in such elements (Stark 1990; Stark and Depuy 1987).

The effectiveness of surface treatments against ASR is influenced by the actual effectiveness of the specific product to control moisture exchange between the concrete and the atmosphere; coatings that permit the escape of water vapor are preferable to allow progressive drying of the concrete. Some silanes and siloxanes have shown beneficial effect in controlling moisture content in concrete and the extent of deleterious expansion due to AAR (Bérubé et al. 2002a). Bérubé et al. (2002b) described the application of various types of sealers on highway median barriers affected by ASR (Fig. 1A). In some cases (e.g. some silanes), the treatment had a dramatic beneficial impact not only on the cosmetic appearance of the affected concrete member (Fig. 1B) but also contributed in progressively reducing internal humidity content and expansion of the concrete (Bérubé et al. 2002b). Grabe and Oberholster (2000) reported that a silane treatment on ASR-affected concrete railway sleepers has been effective in reducing the rate of deterioration due to ASR, thus extending their service life (Figs. 1C & 1D).

Putterill and Oberholster (1985) have found that some surface film coatings, such as polyurethane coatings and water repellent agents, e.g. water-based silicates, were ineffective in preventing long-term water penetration. Badly cracked concrete piers supporting the Hanshin Expressway in Japan were repaired at an age of 7 years by first filling the cracks with an epoxy resin injected under pressure and then either coating with an epoxy resin or impregnating with silane followed by a cosmetic coating of a polymer cement paste (Hobbs 1988) (Fig. 2A). This approach did not suppress the expansion of the piers since, after only a few years of further exposure, some crack widening had been observed (Fig. 2B). Ono (1989) also reported limited effectiveness of crack injection followed by surface coatings on concrete structures in Japan.

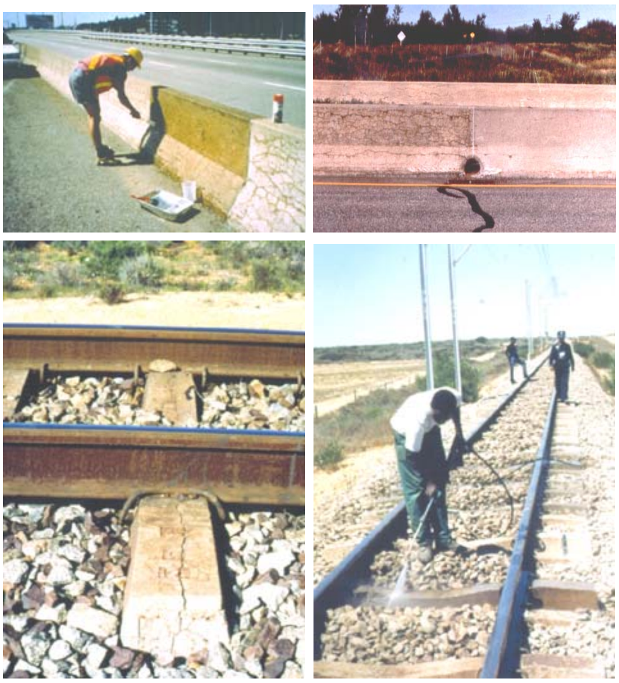

Figure 1 - (A). Application of sealers on highway median barriers affected by ASR. (B). Unsealed/control (left) and sealed (right) of a highway median barrier treated with silane (pictures taken three years after treatment). (C). Condition of concrete sleepers affected by ASR in the Sishen-Saldanha railway line in South Africa. (D). As part of the management programme, a number of cracked concrete sleepers were treated with silane. (Pictures C and D: courtesy of R.E. Oberholster, PPC Technical Services, Cleveland, South Africa).

Impermeable surface coatings/membranes may represent an interesting approach to prevent further deterioration of concrete (e.g. due to frost action) when expansion due to ASR is terminated. Durand (2000) reported the results of monitoring ASR-affected concrete foundations of electric steel towers that had been subjected to various types of repairs, including epoxy injection, impermeable coating, strengthening and encapsulation. The data showed that the foundations to which a bituminous coating had been applied for the buried portions and the exposed parts coated with a flexible polymer membrane continued to expand at a significant rate after the repair work (Fig. 2C & 2D).

In the case of non-structural distress, repair may include removal and replacement of only severely damaged concrete and application of a protective moisture-proof coating or relatively impermeable concrete layer. For structurally adequate pavements affected by AAR, maintenance and rehabilitation measures may include: (1) undersealing where voids exist beneath the slab, (2) joint and crack repair, (3) joint and crack sealing, (4) improvement of drainage, and (5) improvement of load transfer (ACI 1998). Extensive work performed in South Africa has shown that the most cost-effective solution for the rehabilitation of road pavements cracked by ASR was the use of different types of pavement overlays (Van der Walt et al. 1981).

Figure 2 - (A). Reinforced concrete pier of the Hanshin expressway in Kobe (Japan) affected by ASR. Vertical cracks reappearing a few years after the treatment with various types of coating. (B). Beams were also repaired by using either polyurethane resins or epoxy resins; cracks also reappeared shortly after the treatment. (C & D). Massive electric tower foundations affected by ASR. Some of the foundations were treated by applying a bituminous coating on the buried surfaces and a flexible water-resistance polymer membrane on exposed concrete surfaces.

5 Lithium Treatment

Since the pioneering work of McCoy and Caldwell (1951), several researchers have confirmed that lithium-based compounds can reduce significantly expansion due to ASR (Folliard et al. 2003). Laboratory investigations have shown that the effectiveness of lithium to control ASR expansion is mainly a function of the concrete alkali content, and the type and reactivity level of the aggregate. Lithium-based admixtures have been used to (1) control ASR expansion in new concrete incorporating reactive aggregates, and (2) limit the progress of ASR in existing concrete structures. For the latter, lithium salts either spread on the surface of ASR affected concrete pavements or introduced into the concrete by vacuum impregnation, or during the electrochemical chloride removal process, have been used (Folliard et al. 2003; Stokes 1995; Stokes et al. 2003). Although early treatments used lithium hydroxide solution, lithium nitrate solution is now the preferred choice as it is pH neutral, easier to handle, and has better penetration rates.

Figure 3 - (A). Topical application of lithium-based solutions at the surface of a pavement section affected by ASR (B). Condition of not-treated (control) and treated sections (after six topical treatments with lithium nitrate solution) of concrete pavement affected by ASR in Delaware (USA). Spalling of concrete at joints in more frequently observed in the untreated sections (Pictures A & B: courtesy of D.B. Stokes, FMC Corporation – Lithium Division, Charlotte, USA).

5.1 Topical Treatment

Topical application has been the most common method of applying lithium to ASR-affected concrete (primarily pavements and bridge decks) in recent years (Fig. 3A). It is quite clear from past topical applications of lithium that the lingering question is whether or not topical treatment of lithium leads to sufficient penetration to reduce ASR-induced damage. The potential for lithium ingress is significantly influenced by the extent of deterioration of the concrete at the time of treatment. Cracking will clearly facilitate ingress of the solution, but, if the deterioration of the concrete has proceeded to far, it may too late to treat the affected concrete.

Stokes et al. (2003) described the treatment of State Route 1 in Delaware, USA. Approximately 6.4 km of 8-year-old, ASR-affected concrete pavement was treated with six applications of 30%-LiNO$_3$ at a rate of 0.24 L/m^2 over a period of three years (two treatments per annum). Control sections were left untreated at either end of the project. Four years after the first application, one of the control sections was showing severe deterioration in the form of excessive cracking and spalling at the longitudinal and transverse joints. Figure 3B shows photographs of the control and treated sections at this age, and it is evident that the treated sections exhibit less deterioration. One year later, this control section was rehabilitated by grinding the surface layers and placing an asphalt overlay. The Li-concentration profiles measured from cores taken four years after the first application indicate that the depth of penetration is a function of the extent of cracking. In the more heavily cracked areas (crack widths in the region of 1 mm at the surface), the lithium had penetrated to a depth of at least 50 mm.

5.2 Electrochemical Impregnation Method

This technology currently being used in industry involves the application of low voltage DC electric potential to migrate chloride out of salt contaminated concrete structures. By making a few modifications to this system, it can be used to introduce lithium into a structure (Whitmore and Abbott (2000). Various lithium compounds have been used to date as the electrolyte including lithium nitrate, lithium hydroxide and lithium borate. Limited testing of bridge decks treated electrochemically have indicated that a significant quantity of lithium is absorbed from the electrolyte during treatment and that depths of penetration of at least 30 mm are possible (greater depths were not tested). Whitmore and Abbott (2000) described the treatment of five concrete pier footings of a bridge in New Jersey (USA) using an electrochemical system. The treatment involved installation of titanium mesh on the top surface of each footing, and the addition of several anode “reservoirs” and auxiliary cathodes (Fig. 4A) to accelerate migration of the lithium solution. The system ran for four weeks, with an average consumption of 1.6 US gallon (7.9L) of lithium solution per yd3 (M3) of concrete (Vector 2001) (Fig. 4B).

5.3 Vacuum Impregnation

Originally developed in Europe in the early 1970s, the vacuum injection/ impregnation processes have been utilized in North America since the mid 80s for the in-situ restoration of concrete, stone and masonry structures. Under negative pressure, appropriately selected repair products and materials (e.g. lithium-based admixtures) can penetrate into the deteriorated system thus filling cracks, interconnected cracks, voids and even microcracks. It has been reported that the vacuum processes can actually fill cracks as fine as 5 µm using low-viscosity resins (Boyd et al. 2001). Vacuum injection/impregnation has already been used for repairing ASR affected members. For example, in Southern California, the treatment of alkali-silica damaged high line tower pier footings to a depth of ~4.5 m with minimal excavation (<2 m) was reported; core drilling the member revealed interconnected lateral cracking at a depth of ~1.25 m. In October 2003, the Pennsylvania State DOT treated the abutment wall, sidewalk, the parapet and the deck of a structure under the “Evaluation of Lithium Vacuum Impregnation on a Structure” (Marcy Lucas, PENNDOT, personal communication 2003).

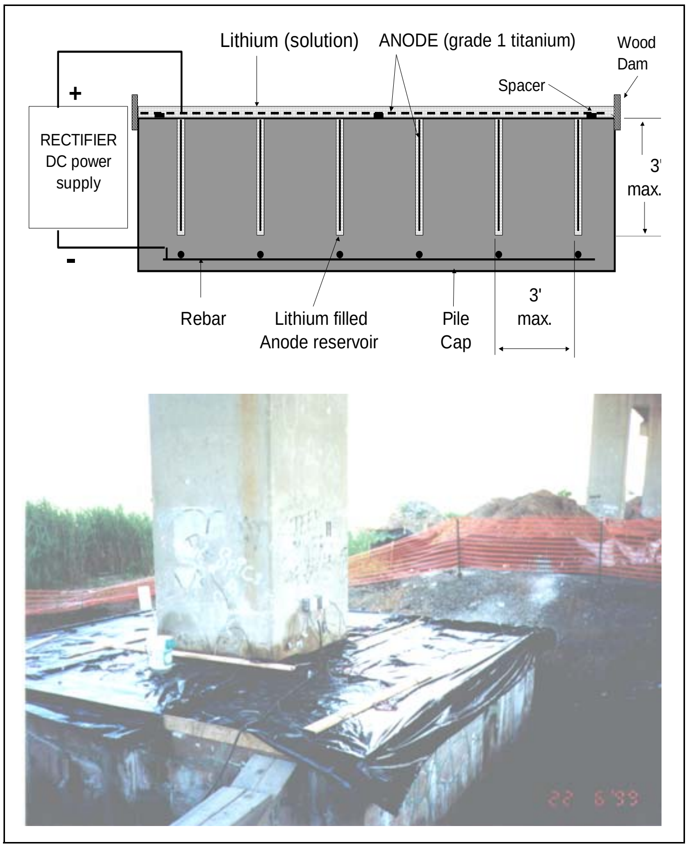

Figure 4 - (A & B). Repair of pier footings of a highway structure suffering from severe cracking and spalling due to ASR using an electrochemical system for lithium impregnation (Pictures A & B: courtesy of D. Whitmore, Vector Construction Group, Winnipeg, Canada).

6 Strengthening

Over the past few decades, a large number of investigations have been carried out to study the effect of ASR on reinforced concrete members (Putterill and Oberholster 1985; Kobayashi 1989; Swamy 1990, 1995; Swamy and Al Asali 1987, 1989; Abe et al. 1989; Inoue et al. 1989; Clayton 1989; Hobbs 1990; ISE 1992; Jones and Clark 1996). Such studies have shown that physical restraint or containment (e.g., encapsulation of the affected member by a surrounding non-reactive concrete, applied stress or reinforcement) can significantly reduce deleterious expansion due to ASR in the direction of restraint.

Post tensioning in one or two dimensions, or by encasement in conventional reinforced concrete, is currently used as a mean to restore the integrity of the structure; however, it should generally be restricted to relatively small masses of structural concrete because of the huge forces that may result from the expansive process due to AAR (Rotter 1995; CSA 2000). Post-tensioned tendons or cables are considered to be an effective solution for thin arch dams (Singhal and Nuss 1991) or structural members of bridge/highway structures; however, they may be less attractive for large concrete structures because of the necessity of periodic distressing (Rotter 1995). Figures 5A to 5D illustrate the repair of a highway structure affected by ASR in South Africa. Cracking due to ASR was observed in the pile caps supporting reinforced concrete columns. The cracked concrete was first removed (Fig. 5B), additional steel reinforcement was added around the pile cap (Fig. 5C) and external strengthening was provided by means of prestressed cables (Fig. 5D). Strengthening by introducing reinforcement with straps, steel plates and tensioning through bolts was also found to be effective in providing containment for the for the top chord and tower top area of the historical Montrose bridge in Scotland (Wood and Angus 1995) (Figs. 5E and 5F).

Figure 5 - (A-D). Highway structure affected by ASR in South Africa. (B). The cracked concrete in the pile caps was first removed. (C). Additional steel reinforcement was added around the pile cap. (D). External strengthening was provided by means of prestressed cables. (E). General view of Montrose bridge (Scotland) (F). The strengthening remedial work consisted in reinforcement by straps, plates and tensioned bolts to provide full containment for the top chord and tower top area. (A to D: courtesy of R.E. Oberholster, PPC Technical Services, Cleveland, South Africa) (E and F: courtesy of J.G.M. Wood, Structural Studies & Design Ltd., Chiddingfold, UK).

Methods to restrain expansion and movement in ASR-affected mass concrete foundations can include rock anchors and/or encapsulation. Bérubé et al. (1989) and Durand (2000) described the repair of a group of electricity tower concrete foundation affected by ASR in Quebec City (Canada). The foundations had suffered from significant swelling and cracking due to ASR (Fig. 6A). The repair program selected consisted in splitting the foundations in two blocks (Fig. 6B), followed by the encapsulation with reinforcing steel and silica-fume concrete (Figs. 6C to 6F). Durand (2000) showed that this type of treatment resulted in significant reduction in the expansion rate of the affected element. Care should be taken in designing the encapsulating element because, if sufficient reinforcement is not provided to control stresses due to AAR expansion, the only beneficial effect of encapsulation may be to limit the ingress of moisture (CSA 2000). In the case of the concrete anchor block for the above electricity towers (Fig. 7A), the repair approach selected was to apply a bituminous coating on the buried surfaces and a flexible water-resistance polymer membrane on the exposed concrete surfaces. External strengthening through the use of steel frames, rods and plates was then implemented (Figs. 7B and 7C) (Bérubé et al. 1989; Durand 2000).

Figure 6 - (A to F). Rapair of a group of electricity tower concrete foundation affected by ASR in Quebec City (Canada). (A). Map-cracking and gel exudation affecting a 29-year-old concrete foundation. (B). Splitting the foundations in two blocks. (C to F). Encapsulation with reinforcing steel and silica-fume concrete.

Strapping or encapsulation of AAR-affected reinforced concrete columns by or with composite materials may be an interesting solution providing sufficient structural strengthening is assured. Carse (1996) described the repair program of a bridge structure affected by ASR in Australia. Vertical cracking has been observed in the pre-stressed octagonal piles supporting the structure about 13 years after commissioning. The repair strategy consisted in monitoring progress of ASR expansion and then repair the piles in which ASR had nearly exhausted itself. Glass-fibre composite repair to 500 above high water level and concrete encasement to bed level was performed (Figs. 7C to 7E). As an alternate method to the glass-fibre composite, wrapping was also carried out with two layers of carbon fibre composite materials (Carse 1996) (Fig. 9F).

Figure 7 (A) - Concrete anchor block for electricity towers affected by ASR (B and C). External strengthening using steel frames, rods and plates. (D to F). Bridge structure affected by ASR in Australia. (D). Glass-fibre composite repair to 500 above high water level and concrete encasement to bed level. (E). View of cofferdam and split aluminium formwork. (F). Wrapping with two layers of carbon fibre composite materials. (Pictures D to F: courtesy of A. Carse, Queensland Transport, Brisbane, Australia).

7 Stress Relief - Slot Cutting

This approach was applied to a number of AAR-affected gravity dams and intakes in order to relieve stress build-up due to AAR (Charlwood and Solymar 1995). This may provide only a temporary solution for concrete structures in which the expansion process due to AAR is not terminated; re-cutting may then be necessary thus increasing the cost of the rehabilitation program.

ASR has been extensively affecting the structures at the Mactaquac Generating Station (Fredericton, Canada). Since the early 1970's. a comprehensive remedial measures and long-term ASR management program has been developed and implemented. As part of the program, diamond wire saw cuts have been used to de-stress and control the expansion in the water retaining structures since 1988 (Thompson et al. 1995) (Fig. 8A to 8C). A 4-year cycle program of slot cutting for the intake structure at Mactaquac Dam, New Brunswick, was proposed because of the continuing growth rate (Fig. 8D). It is important to note, however, that slot-cutting will modify the distribution of internal stresses in the concrete structure, reduce the internal restraint of concrete expansion (Gocevski and Pietruszczak 2000); consequently, the expansion rate is likely to increase after the cutting and before the relief gap is closed (Charlwood and Solymar 1995; Rotter 1995). Additional reinforcement may be necessary to assure stability of concrete elements during and after slot-cutting.

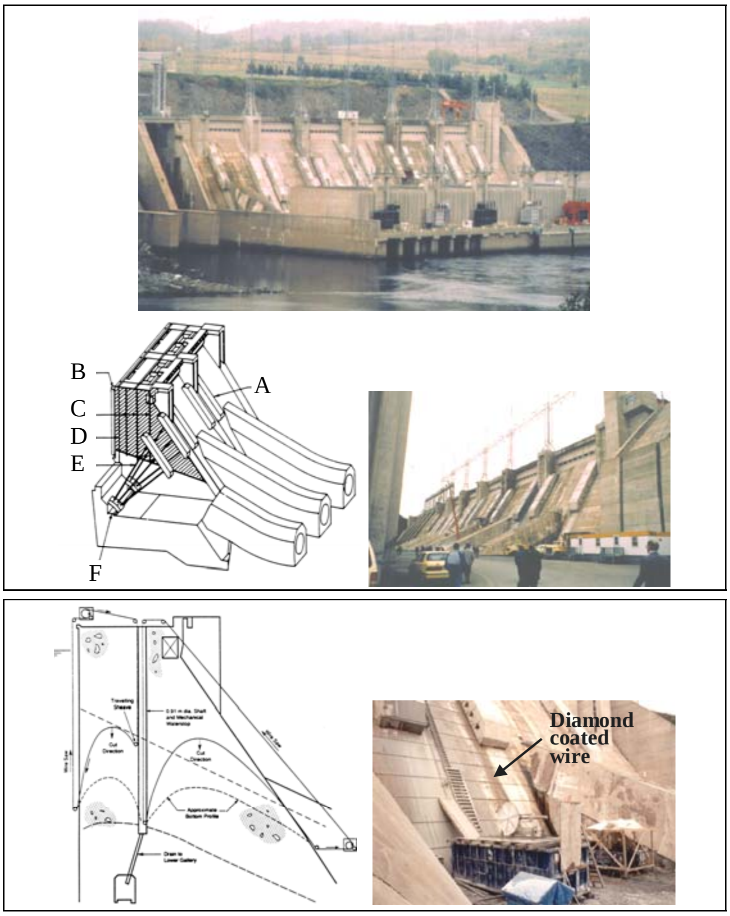

Figure 8 - Mactaquac Generating Station (Fredericton, Canada). (A). Intake structure and powerhouse. (B). In order to assure stability in the intake structure resulting from slot cutting, large capacity (330 t) 19 strand post tensioned tendons were installed from the downstream face of the intake structure to the lower drainage gallery. The legend for the figure is: A-tendon pads, B-blister cofferdam, C-shear keys, D-waterstop, E-tendons, F-drainage gallery (C). Downstream view of the intake structure showing the tendon pads (D). Sketch of the intake structure slot-cutting process. (E). Close view of the set-up for the slot-cutting with diamond-coated wire. (Sketches B & D: Thompson & Steele 1992).

8 Replacement

Even if replacement of the AAR-affected concrete member may represent the safest remedial measure, it is rarely economically acceptable. In most cases, only selected parts of the structures will be replaced, while modifications to the mostly deteriorated or affected parts of the structure can be undertaken to meet acceptable load conditions (e.g. Blight and Ballim 2000). The Laboratoire Central des Ponts et Chaussées recently indicated that, so far, eight concrete structures affected by ASR have been demolished and replaced in France for political, economic and technical reasons. From a strict technical point of view, the structures could have been maintained in service with an appropriate monitoring program to assure public safety (LCPC 2003).

9 Conclusion

A review was made of the most commonly used management actions for concrete structures affected by ASR. Because of the critical importance of moisture on ASR expansion, controlling moisture access to the concrete by improving drainage systems or using surface treatments with products such as silanes/siloxanes will generally remain a manageable and sometimes quite efficient method for relatively small ASR-affected concrete elements. The effectiveness of lithium to control ASR expansion has been recognized for more than 50 years and increasing interest is shown to determine whether it could efficiently slow down the progress of ASR expansion in existing structures. Work is currently in progress to develop efficient methods of treatment that would allow significant penetration of lithium into the ASR-affected concrete. Physical restraint (e.g. anchoring, post-tensioning, encapsulation) and stress relief (e.g. slot cutting) are commonly used to try reducing/controlling the progress/rate of ASR expansion; however, this type of action should be designed with care since it could result in increasing expansion rates in "unrestrained" or "relieved" directions. Demolishing/replacing large ASR-affected concrete structures is rarely done; however, case have been reported where members of such structures being replaced for serviceability and safety reasons.

10 References

[1] Abe, M., Kikuta, S., Masuda, Y. and Tomosawa, F., 1989, "Experimental Study on Mechanical Behavior of Reinforced Concrete Members Affected by Alkali-Aggregate Reaction", Alkali-Aggregate Reaction in Concrete: Proceedings of the 8th International Conference, Kyoto, Japan, 1989, ed. K. Okada, S. Nishibayashi and M. Kawamura, The Society of Materials Science, Japan, pp. 691-696.

[2] ACI Committee 221, 1998, "State-of-the-Art Report on Alkali-Aggregate Reactivity (ACI 221.1R-98)", American Concrete Institute, Farmington Hills, MI, 31p.

[3] BCA (British Cement Association), 1992, The Diagnosis of Alkali-Silica Reaction – Report of a Working Party, 2nd Edition, Slough, UK, SL3 6PL, 44p.

[4] Bérubé, M.A. and Fournier, B., 1987, "Le Barrage Sartigan dans la Beauce (Québec), Canada : un cas-type de détérioration du béton par des réactions alcalis-granulats", Canadian Journal of Civil Engineering, Vol. 16, No. 3, pp. 372-380.

[5] Bérubé, M.A., Chouinard, D., Pigeon, M., Frenette, J., Rivest, M. and Vézina, D., 2002a, "Effectiveness of Sealers in Counteracting Alkali-Silica Reaction in Plain and Air-Entrained laboratory Concretes Exposed to Wetting and Drying, Freezing and Thawing, and Salt Water", Canadian Journal of Civil Engineering, Vol. 29, No. 2, pp. 289-300.

[6] Bérubé, M.A., Chouinard, D., Pigeon, M., Frenette, J., Rivest, M. and Vézina, D., 2002b, "Effectiveness of Sealers in Counteracting Alkali-Silica Reaction in Highway Median Barriers Exposed to

Wetting and Drying, Freezing and Thawing, and Deicing Salts", Canadian Journal of Civil Engineering, Vol. 29, No. 2, pp. 329-337.

[7] Bérubé, M.A., Fournier, B. and Frenette, J., 1989, "Détérioration de fondation de pylônes d'ancrage de lignes de transport d'électricité par des réactions alcalis-granulats, performance mécanique et réparation du béton", Canadian Journal of Civil Engineering, Vol. 16, No. 6, pp. 945-959.

[8] Blight, G.E. and Ballim, Y. 2000. Properties of AAR-Affected Concrete Studied Over 20 Years. Alkali-Aggregate Reaction in Concrete: Proceedings of the 11th International Conference, Quebec City, Canada, 2000, ed. M.A. Bérubé, B. Fournier and B. Durand, Centre de recherche interuniversitaire sur le béton (CRIB), pp. 1109-1118.

[9] Boyd, J.L., Sabnis, G.M. and Boyd, J.A., 2001, "Application of Vacuum Technology to Restore Concrete Structures", The Indian Concrete Journal, January 2001, pp. 35-40.

[10] Carse, A., 1996, "The Asset Management of Alkali-Silica Reaction in a Long Bridge Structure", Alkali-Aggregate Reaction in Concrete: Proceedings of the 10th International Conference, Melbourne, Australia, 1996, ed. A. Shayan, pp. 1025-1032.

[11] Charlwood, R.G. and Solymar, Z.V., 1995, "Long-term Management of AAR-Affected Structures – An International Perspective", AAR in Hydroelectric Plants and Dams: Proceedings of the 2nd International Conference, Chattanooga, USA, 1995, United States Committee on Large Dams, pp. 19-55.

[12] Clayton, N., 1989, "Structural Performance of ASR Affected Concrete", Alkali-Aggregate Reaction in Concrete: Proceedings of the 8th International Conference, Kyoto, Japan, 1989, ed. K. Okada, S. Nishibayashi and M. Kawamura, The Society of Materials Science, Japan, pp. 671-676.

[13} CSA (Canadian Standards Association), 2000, *Guide to the Evaluation and Management of Concrete Structures Affected by Alkali-Aggregate Reaction*, CSA A864-00, Canadian Standards Association, Mississauga, Ontario, Canada, 108p.

[14] De Beauchamp, T., 1995, "The Progress of Remedial Measures at Chambon Dam", AAR in Hydroelectric Plants and Dams: Proceedings of the 2nd International Conference, Chattanooga, USA, 1995, United States Committee on Large Dams, pp. 209-220.

[15] Durand, B., 1995, "Review of Repair Methods Used at Hydro-Quebec to Inhibit AAR in Concrete Structures", AAR in Hydroelectric Plants and Dams: Proceedings of the 2nd International Conference, Chattanooga, USA, 1995, United States Committee on Large Dams, pp. 289-309.

[16] Durand, B., 2000, "Long-term Monitoring Results of Concrete Electrical Tower Foundations Affected by ASR and repaired with Different Products and Repair Methods", Alkali-Aggregate Reaction in Concrete: Proceedings of the 11th International Conference, Quebec City, Canada, 2000, ed. M.A. Bérubé, B. Fournier and B. Durand, Centre de recherche interuniversitaire sur le béton (CRIB), pp. 1049-1058.

[17] Folliard, K.J., Thomas, M.D.A. and Kurtis, K., 2003, "Guidelines for the Use of Lithium to Mitigate or Prevent ASR", Publication No. FHWA-RD-03-047, Federal Highway Administration, Washington D.C., January 2003, 78p.

[18] Fournier, B. and Bérubé, M.A., 2000, "Alkali-Aggregate Reaction in Concrete: a Review of Basic Concepts and Engineering Implications", Canadian Journal of Civil Engineering, Vol. 27, No. 2, pp. 167-191.

[19] Gocevski, V. and Pietruszczak, S., 2000, "Assessment of the Effects of Slot-Cutting in Concrete Dams Affected by Alkali-Aggregate Reaction", Alkali-Aggregate Reaction in Concrete: Proceedings of the 11th International Conference, Quebec City, Canada, 2000, ed. M.A. Bérubé, B. Fournier and B. Durand, Centre de recherche interuniversitaire sur le béton (CRIB), pp. 1303-1312.

[20] Grabe, P.J. and Oberholster R.E., 2000, "Programme for the Treatment and replacement of ASR Affected Concrete Sleepers in the Sishen-Saldanha Railway Line", Alkali-Aggregate Reaction in Concrete: Proceedings of the 11th International Conference, Quebec City, Canada, 2000, ed. M.A. Bérubé, B. Fournier and B. Durand, Centre de recherche interuniversitaire sur le béton (CRIB), pp. 1059-1068.

[21] Hobbs, D.W., 1988, Alkali-Silica Reaction in Concrete, Thomas Telford, London, 183p.

[22] Hobbs, D.W., 1990, "Cracking and Expansion Due to Alkali-Silica Reaction: Its Effect on Concrete", Structural Engineering Review, Vol. 2, pp. 65-79.

[23] Inoue, S., Fujii, M., Kobayashi, K. and Nakano, K., 1989, "Structural Behaviors of Reinforced Concrete Beams Affected by Alkali-Silica Reaction", Alkali-Aggregate Reaction in Concrete: Proceedings of the 8th International Conference, Kyoto, Japan, 1989, ed. K. Okada, S. Nishibayashi and M. Kawamura, The Society of Materials Science, Japan, pp. 727-732.