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Alkali-aggregate reactions in Ontario

Chris Rogers, P.E. Grattan-Bellew, R. Doug Hooton, J. Ryell, and M.D.A. Thomas

Abstract: In Ontario, two types of alkali-aggregate reaction exist. Each type is evaluated using different tests. Over the past few years, new tests have been introduced to replace some existing test methods. The new tests are faster and more reliable. Preventive measures such as the use of low-alkali cement and supplementary cementing materials, while they are effective, have not been extensively used with reactive aggregate in Ontario. Beneficiation or selective extraction is used with some potentially reactive aggregates.

Key words: alkali-aggregate reaction, concrete, cracking, Ontario, structures.

Résumé : En Ontario, deux types de réaction alcali-granulat existent. Chaque type est évalué en utilisant différents tests. Durant les dernières années, de nouveaux tests ont été introduits pour remplacer quelques existantes méthodes de tests. Les nouveaux tests sont plus rapides et plus fiables. Des mesures préventives comme l'utilisation de ciment à faible alcali et des adjuvants, pourtant efficaces, n'ont pas été considérablement utilisés avec des granulats réactifs en Ontario. La bonification ou l'extraction sélective est utilisée avec quelques granulats réactifs potentiels.

Mots clés : réaction alcali-granulat, béton, fissuration, Ontario, structures.

[Traduit par la Rédaction]

Introduction

Certain concrete aggregates react with the alkaline pore solution in concrete, which produces expansion leading to the cracking and deterioration of concrete. These reactions are known as alkali-aggregate reactions (AAR). The reactions found in Ontario can be grouped into two broad types: alkali-carbonate rock reaction and alkali-silica reaction. All natural rocks react to some extent with the alkaline pore solution in concrete, but sometimes the reaction produces deleterious expansion. In all cases of deleterious expansion, the following are required: the presence of a certain amount of reactive material in the aggregates; the presence of a high concentration of hydroxyl ions in the concrete pore solution; and a moist environment. Normally the higher the alkali content of the cement and the higher the cement content of the concrete, the greater the rate of expansion and cracking. The cracking of the concrete creates channels for water movement in the concrete, which may lead to an increase in saturation and reduced freeze-thaw durability and also increased chloride penetration to the reinforcing steel (Fig. 1).

It is possible to use low-alkali cement or other preventive measures, but in Ontario most purchasers and suppliers generally prefer not to adopt these techniques due to the difficulty of inspection to ensure the preventive measures have been taken. Most of the concrete in Ontario is made with non-deleteriously reactive aggregates. It is important that potentially reactive aggregates are recognized and properly investigated prior to construction, since there is no way of preventing the reaction after the concrete has been placed. The current Canadian approach for evaluating aggregate reactivity and determining preventive measures is summarized in Thomas et al. (1997).

Historical perspective on alkali-aggregate reactivity in Ontario

The oldest Canadian concrete structure known to have been affected by alkali-aggregate reactivity (AAR) was the Hurdman Bridge built in Ottawa in 1906 and demolished in 1987. It was not until the 1950s, however, that AAR was first documented in Canada (Swenson 1957). Over the past 40 years, cases of AAR have been found in many parts of Ontario with a variety of rock types (Figs. 2 and 3). The history of AAR in Ontario is unusual because two types of reaction have been found. The first discovered, and the most serious, is known as the alkali-carbonate rock reaction and is confined to Ordovician limestones found in the southern part of the province. The second type and most widespread is the alkali-silica reaction, which is found with a wide variety of silica bearing rocks and minerals throughout Ontario.

Ontario cements

The alkali content of cement is normally expressed as Na_2O equivalent alkalies, which is calculated as follows: $\% \text{K}_2\text{O} \times 0.658 + \% \text{Na}_2\text{O} = \% \text{Na}_2\text{O equivalent} (\text{Na}_2\text{Oe})$. There are very limited data about the alkali contents of On-

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Fig. 1. Cracking of structures caused by alkali-silica reaction in Ontario. (A) Concrete pavement of E.C. Row Expressway, Windsor, 5% chert in fine aggregate after 12 years showing offset of transverse skewed joints due to expansion; (B) Dougall Avenue, Windsor, 5% chert in fine aggregate after 12 years; (C) Lady Evelyn Lake Dam, New Liskeard, argillite and greywacke after 65 years; (D) Regional Road 55 over Hwy. 17, Sudbury, 70% argillite, greywacke, and sandstone after 4 years; (E) Alkali-carbonate rock reaction with dolomitic limestone from Cornwall, after 3 years showing displacement of joint of expansive versus non-expansive concrete indicating 1.2% expansion; (F) Englehart River Bridge, Hwy. 66, near Kirkland Lake, Precambrian chert after 15 years; and (G) Prince Edward Viaduct, Toronto, parapet wall made with granite after 70 years.

tario cements prior to about 1950. Table 1 shows data from Ontario Hydro for cements available in Ontario in 1942. In Ontario, most normal cements have had alkali levels of more than 0.8% Na_2O equivalent at least since the early 1950s until relatively recently. In 1978, the range of alkalis of five Ontario Type-10 cements was about 0.84–1.18% Na_2O

equivalent (Chojnacki 1978) with individual values as high as 1.35%. In 1988, three plants in Ontario, which made high-alkali cement, also made a lower alkali cement of less than 0.70% alkalis, without the up to 5% limestone addition permitted since 1983 by Canadian cement standards, to meet local U.S. highway department specifications. These

Fig. 2. Geographical distribution of potentially alkali-reactive aggregates in Ontario.

Fig. 3. Location of quarries known to contain alkali-carbonate reactive dolomitic limestone.

Table 1. Alkali contents of Canadian cements in 1942 (from Ontario Hydro).

Acid-soluble alkalies	Montreal	Hull	St. Marys	Port Colborne	Belleville	Fort Whyte, Winnipeg	Hull Modified cement
% Na ₂ O	0.40	0.70	0.33	0.09	0.49	0.28	0.49
% K ₂ O	0.87	0.72	0.67	0.75	0.99	0.65	0.53
% Na ₂ O equiv.	0.97	1.17	0.77	0.58	1.14	0.71	0.83
% Na ₂ O equiv. (water-soluble)	0.73	0.64	0.44	0.48	0.98	0.17	0.68

lower alkali cements were usually reserved for the export market to the U.S., and not normally sold in Canada (Rogers 1990). The alkali content of Type-10 cements commonly used in Ontario over the past 20 years is shown in Table 2.

Recently, Ontario cement producers have been taking steps to lower the alkali contents of their normal cements. The reason for this is twofold: a desire to produce higher strength concrete (in general, higher alkali cements usually give lower 28-day compressive strengths than similar concrete made with lower alkali cements) and concern by their customers about alkali-aggregate reactivity. In the past the cement companies regarded the universal adoption of the specification of low-alkali cement to control AAR with concern. There was a natural apprehension that purchasers would begin to specify the universal use of low-alkali cement to reduce the likelihood of alkali-aggregate reactivity as a backup measure even with proven non-reactive aggregates.

History of alkali-aggregate reactivity research programs in Ontario

Alkali-carbonate rock reaction

The first occurrence of this reaction was in Kingston in the mid-1950s. Crushed dolomitic limestone from the local Pittsburg quarry was used in concrete for the Barryfield Barracks. Within two years of construction, much of the concrete had severely cracked. Tony Inderwick, an engineer working for the Department of Defence, experimented with making concrete beams made with various materials and leaving them outside. He was able to show that the coarse aggregate was responsible for the damage (personal communication). Ed Swenson, of the National Research Council, was consulted in 1956, and he started a program of research which was to last over 15 years. In 1957, the Ontario Department of Highways also started investigations of the concrete aggregates in the area in preparation for the construction of pavements and bridges of a new four-lane highway. Ontario Hydro conducted regional studies of the distribution of the reactive rocks within the outcrop area of the dolomitic limestone. This work resulted in a large number of papers and reports (for instance, Swenson and Gillott 1964; Smith 1964, 1974; Dolar-Mantuani 1964). The report of this reaction in concrete attracted worldwide attention because the reactive rock was not identified by the tests used at that time for the well-known alkali-silica reaction, which measured the long-term expansion of mortar bars stored at 38°C made with sand or stone crushed to sand sizes (ASTM C 227). When Swenson crushed the rocks from the Pittsburg

Table 2. Acid-soluble alkali content of Type-10 Portland cements commonly used in Ontario.

Plant location	Na ₂ Oe in 1978	Na ₂ Oe in 1988	Na ₂ Oe in 1998
A, Quebec	?	0.87	0.81
A, Ontario	0.94	0.88	0.59
B, Ontario	1.03	0.98	0.86
C, Ontario	1.10	0.99	0.99
D, Ontario	1.20	0.99	0.94
E, Ontario	0.81	0.43	0.40
F, Ontario	1.03	1.13	0.60
A, Michigan	0.90	?	0.48
A, Manitoba	0.68	0.71	Closed
A, Alberta	?	0.67	0.54
B, Alberta	?	0.77	0.56

Note: From Sault Ste Marie westerly, Michigan and western Canadian cements are commonly used.

quarry to sand size, expansion was insignificant (Swenson 1957). The failure of the standard ASTM C 227 test for alkali-silica reaction to predict expansion of concrete made with aggregates from the Kingston area caused other North American agencies to conduct extensive studies, which were presented at a Symposium in 1964 (Highway Research Board 1964).

The concrete expansion test developed by Swenson and Gillott in the 1950s became the standard Canadian test for alkali-aggregate reaction. This is known colloquially as the concrete prism expansion test and was published by the Canadian Standards Association (CSA 1994a). Originally the test was conducted at 23°C in a moist curing room with an expansion limit of 0.020% after 84 days. This was changed over the years as more knowledge about the relationship with field performance became available, to the current limit of 0.040% after one year when stored at 38°C using a higher alkali loading (5.25 kg/m³ Na₂Oe) in the concrete.

Swenson and Gillott were unable to show conclusively the mechanism of expansion of these reactive rocks but concluded the best working hypothesis was as follows: alkalies from the cement enter the aggregate and react with the dolomite crystals causing them to de-dolomitize with the production of the minerals brucite (Mg(OH)₂) and calcite (CaCO₃)₂. This may be written as follows:

The process of de-dolomitization did not in itself cause the expansion of the aggregate particles but initiated expansion. Expansion was caused by water adsorption on previously dry clay mineral (mainly illite) surfaces near the dolomite crystals, the irreversible swelling accompanying water adsorption was responsible for the aggregate expansion (Gillott and Swenson 1969). They found that they could also produce expansion by inducing microfractures while heating the rock at 490°C for 3 h. It is thought that the one reason for the instability of the dolomites in the Gull River Formation compared with most other dolomites is the presence of iron (Fe) substituting for Mg in the dolomite crystal lattice. The presence of Fe alters the structure giving it a lattice dimension intermediate between that of dolomite and ankerite (iron carbonate). Similar observations have been made with expansive carbonate rocks in Iowa (Wendell Dubberke, Iowa Department of Transportation, personal communication). It should be noted, however, that there are many rocks with disordered dolomite crystal lattices which are not alkali-expansive. It is also noteworthy that the expansion cannot be induced by immersing the rocks in sodium and potassium solutions of neutral pH.

Alkali-silica reaction in northern Ontario

In the 1960s, Ontario Hydro was planning a new dam on the lower Montreal River where it flows into Lake Temiskaming. At about the same time Ontario Hydro investigated reports of distress in the nearby Lady Evelyn Lake control dam, west of Latchford. This dam, built in 1925, controlled the flow of water into the Montreal River and was a conventional stop log control dam with a number of bays. These kinds of dams had been built out of concrete throughout Ontario by logging companies in the early part of the century. In the mid-1960s, concrete expansion and displacement of this structure prevented the proper operation of the stop logs and control of water levels. Ludmila Dolar-Mantuani, the petrographer for Ontario Hydro, was consulted. Dolar-Mantuani (1969) discovered that an alkali-silica reaction had taken place. The coarse aggregate was composed of gravel containing argillite, siltstone, greywacke, and sandstone of Precambrian age. The reaction was unusual because the aggregate when tested in the mortar bar expansion test (ASTM C 227) only caused slow expansion. Deleterious results ($>0.10\%$) were not usually obtained until after one year of testing, which was abnormally long. The rocks could also be made to expand in the rock cylinder expansion test intended for the alkali-carbonate reaction. This pointed to an unusual type of expansion somewhat different from the conventional alkali-silica reaction. Dolar-Mantuani showed that both fly ash and low-alkali cement would be effective in preventing deleterious expansion of new concrete. The Lady Evelyn Lake dam was replaced in 1972 using an aggregate containing the same reactive rock types and a low-alkali cement ($<0.6\%$ Na_2Oe) and after 25 years showed no cracking.

The studies reported by Dolar-Mantuani started a review of other structures in the area, made with similar rock types for signs of alkali-silica reaction. It was found that a number of similar dams in the area between Lake Huron and New Liskeard were affected (Big Eddy, Stobie, Wanapitae, Coni-

ston, Maskinonge, Matabitchuan, Latchford, and dams on the upper French River).

Grattan-Bellew (1978) studied the expansivity of aggregate in the Sudbury area. These rocks were of the same geological age and type as those studied by Dolar-Mantuani (1969). To aid in the studies, a miniature rock prism expansion test was developed. This expansion test, similar to but quicker than the rock cylinder expansion test (ASTM C 586), was used to recognize the most reactive rock types and to aid in their petrographic categorization. It was found that the amount of expansion was related to the amount of microcrystalline silica present in the rock. Further studies in the Sudbury area showed pattern cracking normally became visible about 5–10 years after construction. Significant repair was usually necessary after 25 years, with replacement starting after 40 years (Magni et al. 1986). As a result of these studies, agencies in this area either adopted the use of low-alkali cement or fly ash (Ontario Hydro) or banned the use of aggregates containing more than 15% of the reactive rock types (Ontario Ministry of Transportation).

Ontario Department of Highways review

In 1969, the Ontario Department of Highways started an extensive review of the presence of alkali-aggregate reaction in their bridges. This program was started as a result of the report by Dolar-Mantuani (1969) and also because of extensive damage to bridges found between Sudbury and North Bay. These bridges were about 30 to 35 years old and were in very poor condition. Pattern cracking (a typical symptom of AAR) on bridge surfaces was classed on a scale of 1 to 5. A rating of 1 was given to concrete showing a network of cracks, typically less than 0.5 mm wide and often barely visible; a rating of 5 was given to concrete with a network of wide cracks typically wider than 3 mm. About 1200 bridges were inspected, photographed and classified, with an average age of 18.7 years. Eighty bridges, which were some of those where ASR was strongly suspected, were selected for further study. Cores were taken from these structures and examined under the microscope for signs of ASR such as silica gel in voids, cracks and at aggregate/paste interfaces, reaction rims on coarse aggregate particles, and internal cracking of the concrete. This laboratory study showed that nearly all the suspect structures were affected by alkali-silica reaction (G. Woda, personal communication).

A summary of the results is shown in Fig. 4. This shows that pattern cracking was common in Ontario bridges but showed wide regional variation. The lowest frequency of cracking was in the London area where relatively chert free gravels and sands are used. The Huntsville area showed relatively high frequency of damage, little of it severe, because of the extensive importation of moderately expansive alkali-carbonate reactive rock from the Orillia area (Ryell et al. 1974). Damage in the New Liskeard, Sudbury, and North Bay areas was caused by the presence of the reactive sandstones, argillites, and greywackes. Damage noted in Cochrane and Thunder Bay Districts was predominantly caused by the presence of Palaeozoic chert from the James Bay Lowlands. The proportion of structures affected by alkali-aggregate reaction related cracking were as follows: 4% were severely affected, 12% were significantly affected, and 25% were moderately affected.

Fig. 4. Frequency of pattern cracking (p/c) due to alkali–aggregate reaction in Ontario bridges in 1969–1970 (data from Kenora and Sault Ste Marie was not reported).

Characteristics and distribution of alkali-reactive rocks

Alkali–carbonate rock reaction

Rocks of the Gull River Formation, found in quarries in a belt between Orillia and Kingston and in parts of the Ottawa-St. Lawrence lowlands, are alkali–carbonate reactive (Fig. 3). The Gull River Formation is of Middle Ordovician age. It is a 30–60 m thick sequence of horizontally bedded, thin to medium bedded, microcrystalline and fine crystalline limestone with interbeds of dolostone and dolomitic limestone. The reactive rocks are beds of fine-grained dolomitic limestone with a significant clay mineral content. Under the microscope, the rocks have a unique texture of euhedral dolomite rhombohedra (20–80 μm) floating in a finer-grained matrix of calcite and clay minerals. These rocks are reasonably durable when used in granular base or asphaltic concrete applications but can cause severe expansion and cracking of Portland cement concrete within three years. In a case near Cornwall, concrete sidewalks expanded 1.2% after three years (Rogers 1986). The force of expansion of these rocks in hydroxide solutions has been found to be greater than 14 MPa (Hadley 1961), which is more than sufficient to destroy concrete. The rate and amount of expansion is related to the alkali content of the cement. The higher the alkali content, the greater the expansion (Fig. 5).

The alkali–carbonate reaction only normally occurs with coarse aggregate from quarries. Only certain beds or levels within the quarry may be reactive. A number of different techniques may be used to identify the potential reactivity of these quarried aggregates, of which the simplest is a chemi-

cal test (CSA A23.2-26A). This test measures the relative amount of dolomite by measuring the ratio of calcium to magnesium, and the clay content by measuring the alumina (Al_2O_3) within the rock. This test can be completed in a few days on a stockpile sample. The results are plotted on a graph (Fig. 6), which allows the immediate acceptance of most carbonate aggregates which are normally either relatively pure dolostones or limestones. If an aggregate fails the chemical test, testing using the concrete prism expansion test (CAN3-A23.2-14A) for one year is required. The suspect aggregate is mixed in concrete with a cement content of 420 kg/m^3 and cast into prisms 75 $\times$ 75 $\times$ 285/400 mm. The prisms are measured and stored in a moist environment at 38°C for one year. The maximum permitted expansion is 0.040%.

Other testing techniques may also be used, such as a rock cylinder expansion test (ASTM C 586) developed as a research technique by Hadley (1961). Detailed examination of thin sections under the microscope to look for the characteristic texture of the reactive rocks is also useful, especially when combined with X-ray diffraction. These specialized techniques are usually used in the detailed exploration of quarries or potential quarry sites, and are not used for accepting aggregate stockpiles. Mortar bar expansion tests (either ASTM C 227 or CSA A23.2-25A) are not effective at judging the potential for expansion due to the alkali–carbonate reaction. The expansion measured by these tests with known alkali–carbonate reactive rocks is small, compared to the expansion of concrete, and is probably due to the crushing of the aggregate to sand sizes necessary for the test (Swenson 1957; Grattan-Bellew 1990). It is likely that

Fig. 5. The amount of expansion of alkali-carbonate reactive Pittsburg quarry aggregate depends on the alkali content of the cement.

the expansive pressure exerted by sand size particles is insufficient to cause significant expansion of mortar bars compared to larger particles.

Alkali-silica reaction

Silica is normally a relatively insoluble material; however, solubility is significantly increased in alkaline solutions. Concrete has a pH of 13 or greater. Depending on the activity of the alkali, which is related to the alkali content of the cement, silica from aggregates may be dissolved and form an expansive alkali-silica gel. Subsequent water uptake by the gel will cause swelling of the aggregate particles and paste leading to expansion and cracking of the concrete. Diagnosis of alkali-silica reaction in concrete is normally done under the microscope to look for deposits of gel in cracks and voids with associated cracking. Alkali-silica reaction is generally a slow process and may not be recognized for many years after concrete is placed. The main alkali-silica reactive materials found in Ontario are the silica (SiO₂) minerals chalcedony, and strained and microcrystalline quartz. Cherts, siliceous limestones, argillites, greywackes, siltstones, sandstones, arkoses, quartzwackes, volcanic rocks, quartz schists, and granites from Ontario have all been found to be alkali-silica reactive. Artificial glass, such as waste glass, is also alkali-silica reactive and should be avoided in concrete.

The accelerated mortar bar test (CSA A23.2-25A) is a normal first step for evaluating the potential reactivity of concrete aggregates. Testing of about 500 Ontario aggregates showed that 16% exceeded the CSA-recommended expansion limit of 0.15% indicating potential alkali-silica reactivity. The accelerated mortar bar test (Hooton and Rogers 1989) is a recent replacement in Canadian Standards for the conventional mortar bar test (ASTM C 227) that was in use for over 30 years. In the ASTM C 227 mortar bar test, bars are stored in a moist environment at 38°C for up to a year. The length of time necessary to get results means that the test was impractical to use on most construction jobs. There was also a problem caused by leaching of alkalies out of the bars, depending on the type of storage container that was

used. This has resulted in some highly reactive aggregates giving negative results due to the use of the wrong type of container (Rogers and Hooton 1991). The quick chemical test (ASTM C 289), which measures the amount of silica in solution and also reduction in alkalinity under standard conditions, is difficult and time consuming, and the presence of carbonate minerals in the aggregate can give false results. This test is also not capable of recognising some of the more slowly-reactive rocks (Grattan-Bellew and Litvan 1976).

Palaeozoic rocks

Chert is found in gravel pits (of glacio-fluvial origin) and bedrock quarries throughout most of south-western Ontario and in gravels in much of northern Ontario (Fig. 2). These cherts are of Palaeozoic age and contain silica in three forms: ultrafine microcrystalline quartz (not resolvable under the optical microscope); chalcedony, which is a fibrous form of silica; and as coarse microcrystalline quartz. The first two forms are potentially alkali-silica reactive; the coarse microcrystalline variety seems to be less reactive. It is not possible to determine the proportion of the various varieties in a chert particle without microscopic examination. Chert, in addition to being alkali-silica reactive, may also have very poor resistance to freezing and thawing. Leached, porous cherts are especially susceptible to frost action and commonly cause popouts on concrete surfaces and, when abundant, may cause severe deterioration of concrete.

In northern Ontario between Matheson and Longlac, in the area around Sioux Lookout, and as far west as Ear Falls, many structures, built between the 1920s and early 1950s, have deteriorated and been replaced or repaired because of a combination of alkali-silica reaction and frost action caused by the presence of chert found in the local gravels and sands. The chert came from Palaeozoic sedimentary rocks that outcrop in the James Bay Lowlands. The chert has been transported south by glacial-fluvial action and is typically found in eskers and glacial outwash deposits. In the mid-1950s, the detrimental nature of chert became recognized, and thereafter chert-free aggregate was used in most new structures. There has, as a result, been a considerable improvement in durability and a reduction in maintenance and repair costs of the newer structures. A notable exception was the construction in 1991 of new bridges taking Hwy. 11 over the Kapuskasing River. The contractor submitted chert-free aggregate for approval of his concrete mixture design, but thereafter substituted a local chert-rich gravel. The bridges showed popouts on the concrete surface after one winter and are expected to have a reduced life.

On the north shore of Lake Superior between Nipigon and White River, some of the concrete structures on Hwy. 17, built in the 1950s, show cracking caused by alkali-silica reaction. The reactive aggregate was small amounts of chert (less than 5%) found in many of the local sands. A CNR bridge near Pass Lake, east of Thunder Bay, was also found to be affected by alkali-silica reaction because of the use of a cherty sand probably imported from the Nipigon area for repairs conducted in the early 1950s.

In the Windsor and Sarnia area, several concrete structures and a pavement, built in the early 1970s, are deteriorating because of an alkali-silica reaction. The reactive component was about 5% leached chert present in sands im-

Fig. 6. Plot of CaO/MgO and alumina for known alkali-carbonate expansive and non-expansive carbonate rocks from Ontario.

ported from the Yipsilanti area of Michigan. A number of other sands found in southeastern Michigan have also been found to be alkali-silica reactive.

In southwestern Ontario, cherts are found in sands and gravels and in some quarries. These cherts are of Silurian age and may constitute over 60% of the volume of material in some bedrock sections, and over 20% of the gravels in some areas. When tested in the quick chemical test (ASTM C 289) they are classed as potentially reactive. These cherts are not composed of pure silica but usually contain calcite and dolomite. Some varieties have had the carbonate minerals removed by leaching resulting in a low density, porous structure. These leached cherts are damaged by freezing and thawing and often cause popouts on concrete surfaces and where abundant can cause serious damage in concrete exposed to frost action (Ingham and Dunikowska-Koniuszy 1965). Testing in mortar bar tests and concrete prisms has shown that generally these cherts present little risk of deleterious alkali-silica reaction when present in significant amounts. This is confirmed by observation of structural performance, where few cases of damage have been noted. This lack of damage is probably because the amount present is above the pessimum proportion where maximum damage can occur.

Siliceous limestones from the Bobcaygeon Formation of Middle Ordovician age are alkali-silica reactive. These rocks immediately overlie the potentially alkali-carbonate reactive Gull River Formation. These rocks outcrop in the same area, in a belt between Orillia and Kingston and in the lowlands between the Ottawa and St. Lawrence rivers. In the Ottawa area both alkali-silica and alkali-carbonate beds may sometimes be found in the same quarry. Not all beds are reactive. The reactive beds are characterized by the pres-

ence of small amounts of visible black chert (3% or less), microscopic chalcedony, and a silica content of between about 5% and 10%. About 23 structures on Highway 417 east of Limoges have been built with these limestones. Structures in the Arnprior and Pembroke areas are also affected. Those parts of the structures exposed to direct moisture usually show characteristic pattern cracking within 10 years. Post-tensioned, voided bridge decks and support columns show characteristic linear cracking after about 15 years. The Saunders Dam at Cornwall was built with similar rock and after 30 years has proven to be deleteriously alkali-silica reactive (Grattan-Bellew 1994). It is possible that in some cases the aggregates themselves may contribute alkalis to the reaction. It seems likely that the clay minerals in these impure limestones may undergo cation exchange with calcium hydroxide from the cement paste to contribute potassium and sodium, which in turn may increase the hydroxyl concentration of the concrete. These reactive rocks are similar to those found in Québec, where they are found in the lowlands between Montreal and Québec City and have given much trouble in concrete due to alkali-silica reaction (Fournier and Bérubé 1989).

At least four quarries in the Ottawa – St. Lawrence lowlands have been found to contain these reactive rocks. In most of these quarries, non-reactive concrete aggregate can be supplied by selective quarrying of non-reactive benches or areas within the quarry. In these operations, great care and conscientious testing is required to ensure that concrete stone does not become contaminated with reactive rock.

Cases of deleterious reaction have not yet been proven from quarries, which contain Bobcaygeon Formation limestone, in the Orillia to Kingston area. However, a structure in Lindsay built in 1954 was found to be alkali-silica reactive

in the mid-1980s. The reactive coarse aggregate was a quarried limestone of the Bobcaygeon Formation. The source of the aggregate has not been found. Some gravels, found between the outcrop area and the shore of Lake Ontario in the Peterborough and Port Hope areas, do seem to be slowly reactive. Many structures in this area show both characteristic surface cracking and microscopic evidence of alkali-silica reaction. The reactive aggregates are gravels composed of mixtures of alkali-carbonate reactive dolomitic limestones and alkali-silica reactive siliceous limestones. It seems likely that both reactions occur at the same time. The limited testing that has been done indicates that these aggregates meet the existing specification requirements but nevertheless may cause long-term expansion of concrete.

The Potsdam and Nepean sandstones have been found to be alkali-silica reactive in southwestern Québec (Berard and Lapierre 1977). These sandstones outcrop in the Kingston area and in the Ottawa-St. Lawrence Lowlands. These sandstones are the basal Palaeozoic sediments in these areas and are overlain by younger sedimentary rocks of Ordovician age. These rocks have not been quarried for concrete aggregate production in Ontario, and no structures have been found to be deleteriously affected. An old bridge on Hwy. 2 west of Kingston contained a small amount of this sandstone and showed characteristic reaction rims, but the quantity of sandstone was too small to have caused distress to the concrete.

Precambrian rocks

The Canadian shield contains large amounts of potentially alkali-silica reactive rocks. The very oldest rocks have been extensively metamorphosed and seem to be less susceptible to alkali-silica reaction.

The Englehart River Bridge on Highway 66, west of Kirkland Lake, was built in 1969 using coarse aggregate crushed from waste rock from the nearby Adams Iron Mine. The aggregate contained cherty iron formation of Precambrian age known as taconite. The chert was composed of a mosaic of microcrystalline quartz with abundant fluid inclusions. It is possible that salts enclosed within the fluid inclusions have aggravated the reaction. The structure shows extensive cracking caused by alkali-silica reaction. This is the only known case of deleterious alkali-silica reaction with Precambrian chert. Precambrian cherts are found throughout Ontario and especially in the Thunder Bay area where the well-known "Gunflint" chert is found.

The metamorphosed sedimentary rocks of the Huronian Supergroup (argillites, siltstones, greywackes, and sandstone/arkose), which are about 2.3 billion years old, are alkali-silica reactive (Dolar-Mantuani 1969). These rocks outcrop in an area from Desbarats, on the north shore of Lake Huron, through Sudbury to New Liskeard. These rocks are found in gravel deposits in the outcrop area and may also be found in small amounts in gravels in southwestern Ontario.

Field surveys of highway structures in the Sudbury area (Magni et al. 1986) have shown that at least 26 structures were affected by this reaction with rocks of the Huronian Supergroup. The coarse aggregate was from local gravel deposits containing about 65–90% of the reactive rock types. Many older structures have been replaced as a result of dete-

rioration due to this alkali-silica reaction. Many of the others require or will require extensive repairs. Many dams in this area are also affected by this reaction and have required repairs or replacement. The old concrete pavement of Hwy. 17, east of Coniston, placed in 1938, shows extensive damage due to alkali-silica reaction. This pavement is largely buried today, but an example showing typical damage caused by alkali-silica reaction can be seen 1 km east of Wahnapiatae on the north side of the existing highway. In the Sudbury area, most of the commercial gravel sources contain excessive amounts of the reactive rock types; as a result to obtain concrete aggregate, quarries in non-reactive rock have been developed or non-reactive aggregate has been imported from outside the immediate area (Ontario Geological Survey 1987).

In the New Liskeard area, the content of Huronian Supergroup reactive rock types in the gravels is lower (40–55%), and there is a higher proportion of argillite and greywacke compared to sandstone/arkose than found in the Sudbury area. Also in this area, the local sands contain trace amounts (<1%) of alkali-silica reactive Palaeozoic chert. At least six highway structures in this area have shown cracking and associated deterioration due to alkali-silica reaction.

These reactive rocks of the Huronian Supergroup are not easily recognized by the conventional tests for alkali-silica reaction. Tests such as the mortar bar expansion test (ASTM C 227), quick chemical test (ASTM C 289), or the concrete prism expansion test at low cement contents (310 kg/m³) do not show these rocks to be reactive. In order to induce expansion in laboratory tests, it was found that abnormally high amounts of alkali had to be added to the cement (Rogers 1990). Because of the failure of the concrete expansion test to recognize these reactive aggregates, petrographic examination was used as an interim measure in the 1980s and 1990s to classify potentially reactive aggregates in this region. Field investigations had shown that, if the quantity of potentially reactive rock types (argillite, siltstone, greywacke, sandstone/arkose) was more than about 30% of the coarse aggregate, structures usually showed cracking within about 15 years and sometimes within 4 years. As a result, if the amount of reactive rock types was less than 15%, the aggregate was used in concrete without further testing. Aggregates which contained greater than 15% reactive rock were not used (Magni et al. 1986).

Greywackes and argillites older than the Huronian Supergroup sequence are found over much of northern Ontario. These older rocks do not seem to be deleteriously reactive based on their field performance. One bridge in the Thunder Bay area was found to contain an alkali-silica reactive greywacke, but the quantity was insufficient to have caused distress. The reason for the lack of significant expansivity with these rocks is not known but may be related to the higher degree of metamorphism and alteration to which they have been subjected. It is postulated that the quartz has been recrystallized to a more stable form in these older rocks. Alternatively, it is possible that the cement supplied in those northern and northwestern parts of the province where these rocks are found is of relatively low-alkali content and this has been insufficient to cause deleterious expansion. This is an area for future research.

Two bridges in the city of Toronto have shown an alkali-silica reaction with two different quarried granites. Red-coloured granites were used in exposed aggregate surfaces on the parapets of the Prince Edward Viaduct and Rosedale Ravine Bridge built between 1916 and 1918. After 70 years, the concrete showed characteristic pattern cracking, closing of expansion joints, and bending of some elements. Drilling had been done in the past to re-open expansion joints but continued expansion had closed the joints again. Another bridge, built in 1926 using a similar parapet design and dolomitic marble as the coarse aggregate, is undamaged and in excellent condition. Examination of concrete cores from the parapets containing the granite showed that the pattern cracks penetrated the concrete about 50 mm. Below this, the concrete was extensively microfractured and contained alkali-silica gel lining the microfracture surfaces and filling air voids. Some of the granite particles showed dark rims on their outer edge in contact with the mortar. The source of the granites used in the concrete could not be found. The degree of optical strain of the quartz and the partly granulated texture with areas of microcrystalline quartz indicate the granites are petrographically similar to granites of Grenville age from Eastern Ontario. The parapets were replaced in the late 1980s with precast concrete elements made with a crushed granite of Grenville age from Washago, Ontario, using low-alkali cement (about 0.45% Na_2O equivalent).

Petrographic examination of concrete from older bridges and dams in the country east of Georgian Bay, south of the Ottawa River, and as far east as Kingston has shown dark clarified rims on the periphery of some granite and granite gneiss coarse aggregate particles of Grenville age. This is normally evidence of a reaction between the aggregate and the cement. In most cases, the quantity of reactive granite and gneiss in the concrete was small and had not caused distress. When the quantity has been greater, as in the Otto-Holden Dam at Mattawa on the Ottawa river, distress has been noted. Generally, the reaction of granites with cement alkalis is slow and hard to reproduce in the laboratory. Granites of Grenville age meet all the existing testing criteria for alkali-silica reactivity. Grenville age granites should probably be used with preventive measures, such as low-alkali cement, as a precaution when they make up a significant proportion of the aggregate. Older granites found in northern Ontario do not contain excessively strained and granulated quartz and are not judged to be reactive. This conclusion is supported by the general lack of deleterious reactivity in structures in which they are used.

In the Wawa area, the local gravels contain about 45% volcanics and greywacke and were judged to be potentially reactive in the accelerated mortar bar test (Grattan-Bellew 1990). Field performance is lacking because the cement used in this area is normally imported from the United States and typically has an alkali content less than 0.70%. In the construction of the Magpie River hydroelectric scheme, 50% blast-furnace slag cement was used as a precautionary measure with a cement containing about 0.70% alkalis (Donnelly 1990). A survey in 1997 showed no evidence of AAR damage in the slag concrete, while in a nearby bridge built with the same aggregate and 0.7% alkali cement, cracking due to AAR was present.

Fig. 7. Plot of concrete expansion against concrete alkali content for three deleteriously alkali-reactive aggregates from Ontario.

The Frederickhouse River Dam near Iroquois Falls was constructed in 1938 with stone quarried from the site. The aggregate was a rhyolite porphyry, which is a fine-grained quartz-rich volcanic rock. The structure now shows signs of expansion and cracking and has required cutting of stress relief slots in the deck slabs (Bérubé et al. 1992). To the east of Lake Nipigon, in the Beardmore area, quartz mica schist has been found to be alkali-silica reactive in laboratory tests but the rock has not been used in concrete. It is likely that there are many potentially alkali-silica reactive rocks in Ontario, but they have not been recognized because of the low level of construction activity and testing in many areas of the north.

Concrete expansion testing

A characteristic of testing of Ontario reactive aggregates has been the need to use sufficient amounts of cement and alkali to detect deleterious expansion with a specific aggregate. Figure 7 shows the expansion of concrete made with three different Ontario aggregates. In Fig. 7, "Pittsburg" denotes an alkali-carbonate reactive dolomitic limestone from Kingston, Ontario. It can be seen that a threshold level of about 2.0 kg/m³ of alkali expressed as sodium oxide equivalent in concrete is required to cause significant expansion. This amount is calculated by multiplying the cement content in kg/m³ by the alkali content of the cement in per cent. In the case of the Spratt aggregate over 3.0 kg/m³ of alkali is required to cause expansion. The Spratt aggregate is a reactive siliceous limestone of the Bobcaygeon Formation from the Ottawa area. The Sudbury aggregate requires at least 5 kg/m³ to give expansion in laboratory tests. This aggregate is a gravel from Sudbury, Ontario and contains alkali-silica reactive argillites, greywackes, and sandstones of the Precambrian Huronian Supergroup. In the 1970s and 1980s, concrete testing was conducted (Hooton 1990) using the then current CSA standard, which had been developed to recognize the alkali-carbonate reactive aggregates represented by the Pittsburg aggregate. It was soon recognized that many aggregates known to be deleterious in the field could not be induced to expand in laboratory concrete expansion tests. This started investigations of ways of chang-

Fig. 8. Plot of expansion of concrete mixtures made with alkali-silica reactive siliceous limestone aggregate and high-alkali cement with fly ashes of various composition.

ing the concrete test to correct this deficiency. These studies resulted in the following changes: increasing the temperature of testing from 23°C to 38°C, increasing the cement content from 310 to 420 kg/m³, increasing the alkali content of the cement used to 1.25% Na₂O_{eq}, by the addition of NaOH in solution to the concrete mixing water. It was also found that the conditions of storage could cause leaching of alkalis out of the concrete prisms, which would slow down or stop the expansion (Rogers and Hooton 1991). As a result of this work in Ontario and elsewhere, changes were made to the Canadian standard test to ensure that false results would rarely occur in the future.

Preventive measures

Low-alkali cement and supplementary cementing materials

Low-alkali cement is defined by ASTM as cement with an alkali content of less than 0.60% Na₂O equivalent. The specification of low-alkali cement, while it is usually effective, is unusual in Ontario. In northern Ontario, the Ministry of Transportation used low-alkali cement (<0.60% Na₂O equivalent) in four northern Ontario bridges in 1970, but has seldom specified it since. A notable exception was the use in 1990–1992 of lower-alkali cements (<0.70% Na₂O equivalent) for concrete paving jobs on Hwy. 115 with a slightly reactive gravel aggregate near Peterborough. Ontario Hydro used low-alkali cement to reconstruct the Lady Evelyn Lake Dam in 1972. In the mid-1980s, Canadian railway companies started to specify low-alkali cement for all concrete, irrespective of the nature of the aggregate. The reason for this was the deterioration of prestressed concrete railroad ties due to alkali–aggregate reactivity (Rogers and Tharmabala 1990) and the difficulty of testing concrete aggregate supplies throughout Canada, often at short notice. It should be noted that low-alkali cement is not effective at controlling expansion due to the alkali–carbonate rock reaction (Swenson and Gillott 1964; Rogers and Hooton 1992).

Reducing cement contents and, hence, concrete alkali levels is often not practical because of the severe Canadian climate, which generally requires low water/cement, air-entrained concrete for all exposed work. In practical terms, minimum cement contents of 325–450 kg/m³ are required if durability is to be ensured.

Both blast-furnace slag cement and fly ash are effective at preventing excessive expansion of concrete made alkali-silica with reactive aggregate and high-alkali cement. Figure 8 shows that the amount of fly ash necessary to prevent expansion depends on the chemistry of the fly ash. The most effective control being obtained with low calcium content ashes. Figures 9 and 10 show that increased control of deleterious expansion is obtained with increasing amounts of either slag or fly ash.

The use of blast-furnace slag as a supplementary cementing material has generally not been adopted to control alkali-silica reaction, despite its apparent effectiveness at high levels of substitution (>50%). A notable exception was the use of 50% ground granulated blast-furnace slag cement on a recent hydroelectric development in northern Ontario (Donnelly 1990). These structures have performed well after 10 years. Figure 9 shows that as the proportion of slag substitution for high-alkali cement (1.25% Na₂O equivalent) increases, expansion is reduced. One problem with the use of slag as a preventive measure is the need to use quite high proportions, which may lead to other concerns. In laboratory freeze-thaw scaling tests where de-icer salts are used, concretes made with large amounts of blast-furnace slag cement, or fly ash, have been found to be more sensitive to surface de-icer salt scaling. This has also been confirmed in laboratory salt-scaling tests (ASTM C 672) and, in field performance studies which have shown that with 50% substitution of blast-furnace slag cement, scaling loss from the surface is observed (Afrani and Rogers 1994). For this reason, the Ontario Ministry of Transportation conservatively only permits a maximum of 25% blast-furnace slag cement substitution. In addition, the use of large amounts of supplementary cementing materials in cold weather may result in a slower rate of strength gain leading to practical problems of construction scheduling. The harsh Canadian winter climate provides practical problems with use of high replacements amounts of supplementary cementing materials to control alkali–aggregate reactivity.

It should be noted that blast-furnace slag cement is not suitable for controlling expansion of concrete affected by the alkali–carbonate rock reaction. Slag has been found to apparently increase expansion of these aggregates compared with high-alkali cement (Rogers and Hooton 1992; Thomas and Innis 1998). The reason is unknown but may be due to an as yet not understood reaction.

Fly ash is used in Ontario, but rarely for the purpose of controlling AAR. A notable exception was the successful use of 20% and 30% fly ash with high-alkali cement (1.08% Na₂O equivalent) by Ontario Hydro in the Lower Notch Dam in 1971 to prevent an alkali-silica reaction with an argillite (Sturup et al. 1983; Hooton 1990; Thomas 1996). The contractor was given the option of either using low-alkali cement or fly ash with the quarried aggregate at Lower Notch. This case is probably unique in North Amer-

Fig. 9. Plot of expansion of concrete made with various alkali-silica reactive coarse aggregates and various amounts of blast-furnace slag cement substituting for high-alkali Portland cement.

ica. It is the only known instance of the use of a known alkali-reactive aggregate in a large dam where construction was permitted with high-alkali cement, the only precaution being the use of an effective fly ash. This dam has performed well for 30 years.

Today it is recognised that the costs of repair and maintenance of large hydroelectric structures affected by alkali-aggregate reactions are huge. The risk of AAR in such structures compared to incremental extra costs of taking preventive action dictates a "belt and suspender approach" to concrete mixture designs by using two effective precautionary measures, for instance, the use of fly ash or slag with low-alkali cement, or low-alkali-silica fume blended cement.

Aggregate beneficiation and selection

A commonly used measure to prevent AAR is the beneficiation or the selective quarrying of aggregate. Ingham and Dunikowska-Koniuszy (1965) found that the highest proportion of chert in gravel deposits in southwestern Ontario was normally about 20 to 10 mm in size, with lesser amounts in larger and smaller sizes. This is due to the size of the parent chert nodules in bedrock and also due to breakdown of the often frost sensitive chert in the glacio-fluvial environment. This phenomenon has been used to produce acceptable concrete aggregates from chert-rich gravels, by selectively crushing coarse cobbles and boulders which normally contain much less chert. Another technique used to remove relatively low density shale and chert is heavy media separation. Plants near Chatham and Woodstock operated in the 1980s. Gravel jigs have also been used in the past to remove shale and chert from gravel, but with limited success (Ingham 1965). For instance, concrete coarse aggregate made from gravels of the Port Elgin area for the Bruce Generating Stations in the 1970s was beneficiated by jigging but the need for constant attention to the operation of the jigs made the operation marginally economic.

In horizontally bedded, carbonate rock quarries known to contain alkali-carbonate reactive beds or alkali-silica reac-

Fig. 10. Plot showing that the amount of fly ash necessary to prevent deleterious expansion with Spratt siliceous limestone alkali-silica reactive coarse aggregate depends on fly ash composition.

tive siliceous limestone, reserving a specific level or bench of non-reactive rock for use in concrete is a common practice (Ryell et al. 1974). The underlying or overlying beds may be alkali-reactive, but careful, conscientious extraction and stockpiling can ensure an adequate supply of non-reactive rock.

Aggregate specifications used by the Ministry of Transportation

In 1986, the Ministry of Transportation introduced lists of pre-approved concrete aggregates into their contract documents. The reason was twofold: (i) testing of suspect alkali-reactive aggregate took so long that there was never time for aggregate intended to be used in pavement or bridge construction to be tested before it had been used; (ii) the test methods available at that time were not reliable at recognizing all varieties of reactive aggregate. It was decided to require a history of satisfactory long-term field performance before aggregates were listed. New sources would only be accepted after extensive laboratory testing. Contractors were required to supply concrete aggregates from sources shown on the lists. In 1987, there were a total of 193 sources of approved concrete aggregate, of which 82 supplied both coarse and fine aggregates. There were a few sources which had supplied concrete aggregate in the past that were not incorporated in the new lists. These were mainly sources in the Sudbury area where it was impossible to supply a non-expansive aggregate. In other sources, it was usually possible to change the location and method of extraction or beneficiate the material to provide an acceptable aggregate.

In 1997, the Ministry of Transportation of Ontario (MTO) introduced new concrete aggregate specifications into their contracts, which incorporated the latest recommendations of CSA A23 (1994). In 1997, concrete aggregate suppliers were asked to do their own testing to demonstrate that their aggregates met the requirements. Previously, this testing had been done by MTO. The change to supplier demonstration

of compliance with specifications resulted in a reduction from 403 sources to 234 sources throughout Ontario.

Management of structures affected by alkali–aggregate reactivity

Generally, it has been found that alkali-reactive bridge structures do not need exceptional repair techniques or efforts. This is not always the case with large or massive concrete structures. In massive concrete structures, it may be necessary to cut relief slots to accommodate expansion and associated stresses, which can cause severe damage to other parts of the structure. Fortunately the need for this kind of rehabilitation has been rare in Ontario. The normal practice of the Ministry of Transportation has been to carry out routine repair as required to ensure structural integrity and to control the rate of deterioration caused by other mechanisms such as corrosion of reinforcing steel. Generally, bridges affected by ASR in Ontario have given a useful life of 40 or more years. Maintenance costs are usually higher than those of unaffected structures up to an age of 40 years; thereafter the cost of future repairs may become so great that it is more cost effective to replace the structure. Small water level control dams seem to also last about 40 years, but thereafter costs of repair become significant. Good examples being the restoration of the Big Eddy Dam, west of Sudbury (Gore and Bickley 1987) and the Coniston Dam east of Sudbury (Read and Thomas 1995). A complication with repair of older dams is their general lack of adequate seismic capacity, most of them having been designed without thought to this problem. This may lead to greater costs than would often be anticipated.

Occasionally it has been found useful, in the case of bridges of doubtful structural capacity, to conduct full-scale load testing using loaded trucks to measure structural capacity. These tests have shown that even with structures that appear to be in terrible condition, there is seldom cause for concern. Ontario bridges have usually been found to have wide margins of safety even when they appear to be in terminal condition.

In a survey of 215 structures affected by AAR in the Port Hope area carried out in the late 1980s, it was found that those parts of the structure which first showed cracking due to AAR were the wingwalls, barrier walls, and hand rail posts which are most directly exposed to precipitation and splashing. This damage was usually apparent within 20 years of construction. By the time the structures were 30 to 40 years old, many other parts were cracked, such elements as retaining walls, abutments, and edge beams showing damage. Some elements rarely showed cracking even when the remainder of the structure showed obvious signs of AAR-related cracking. Thin bridge decks rarely show cracking or serious damage, probably because they often are protected from moisture ingress by waterproofing membranes and because they are kept relatively dry by evaporation from the soffit. The reduced level of saturation probably slows the progress of AAR compared with other concrete bridge elements. In contrast, thick post-tensioned bridge decks affected by AAR usually show longitudinal cracks on the

soffit and this cracking will ultimately affect their service life.

Concrete made with the most expansive alkali–carbonate rock (ACR) dolomitic limestones can give field expansions of up to 1.2% in three years. In these cases, which are rare, exceptional measures must be taken. For instance, in the Cornwall area (Rogers 1986) it was found useful to cut stress relief slots through concrete curb, gutter, and sidewalk and replace the space with asphaltic concrete. This prevented further explosive damage but only gave a few more years of service. Most concrete damaged by ACR in the Cornwall area had to be replaced within 10 years. Fortunately, no major bridges were constructed with this aggregate. A small county bridge east of Lancaster has had steel beams supported on piles placed under the deck as a fail safe measure.

Concrete pavements in Ontario have generally not been seriously affected by AAR. In some cases, slight AAR may be beneficial. Most high traffic volume concrete pavements have been repaired and overlaid with asphalt after about 20 years. In eastern Ontario, the oldest exposed concrete pavements were two in which there was accidental slight expansion caused by ASR with quarried alkali–silica reactive limestones of the Bobcaygeon Formation. The slight expansion counteracted the natural shrinkage of the pavement and enhanced load transfer at transverse joints, reducing faulting, leading to a better than average ride up to an age of about 25 years. The closed joints also prevent the infiltration of debris, which can result in spalling. If the expansion due to AAR becomes too great, there will be reduced life of the pavement. Damage such as a high frequency of blow ups and associated stress-induced disintegration at the joints are the most obvious problems. Normally excessive expansion due to ASR will usually be seen as parallel longitudinal cracks on the surface of pavements rather than random cracks commonly seen when there is no constraint. Of the over 100 major concrete paving contracts in Ontario since the late 1950s, only two cases of damaging ASR are known, both in southwestern Ontario with chert in the aggregate.

Conclusions

In Ontario over the past 45 years, with few exceptions, the main strategy employed by owners of the concrete infrastructure, specifying agencies, and the engineering community, to avoid the deleterious expansion and cracking due to alkali–aggregate reactions, has been to identify and reject expansive aggregates.

This strategy to a large extent is the logical outcome of the continued program of research and development, laboratory testing of aggregate sources, and field investigation of concrete performance carried out by government agencies and the universities. Such organizations have devoted considerable resources to the study of alkali–aggregate reactions in Ontario and the current state of the art reflects this effort. In a general sense the locations and geological type of reactive aggregates have been well documented and such information is readily available to users of concrete.

A number of factors have contributed to the development and adoption of this “no reactive aggregate” policy. These include the availability in most parts of Ontario of proven

non-reactive aggregates at reasonable cost and the relatively low cost of the concrete aggregates expressed as a fraction of the total cost of the concrete. The relative ineffectiveness of low-alkali cement and supplementary cementing materials for the highly expansive alkali-carbonate rock reaction in eastern Ontario supported the view that the only practical policy was to avoid the use of such materials. The high total cost of rehabilitation of seriously deteriorated highway structure or replacing a structure 20 to 30 years before its anticipated normal service life does not encourage risk taking when selecting a source of concrete aggregate.

In southern Ontario, which represents by far the largest market for concrete in the province, the fact that quarried dolostone sources of the Niagara Escarpment and the surrounding glacial gravel sources are not reactive has tended to support the conservative policy of avoiding the use of reactive aggregates. Only on a few remote dam sites where the cost of the concrete aggregate is likely an important factor in the economy of the structure have alternatives such as the use of low-alkali cement been used.

Studies in Ontario and other parts of Canada have demonstrated that preventive measures to avoid excessive or deleterious expansion of the concrete can be taken that will allow the use of alkali-silica reactive aggregates in many conditions. In the most challenging environments for structures with a long required service life, such preventive measures include restrictions on the alkali content of the concrete and the addition of supplementary cementing materials for highly reactive aggregates. It is anticipated that the CSA Standards A 23.1 and A 23.2 to be published in the first year of the 21st century will document acceptable procedures for the preventive measures discussed above. The pace of scientific discovery makes it almost foolish to try and predict what advances will be made in the concrete industry over the next generation to avoid performance problems with reactive aggregates. The search for a discriminating accelerated test that will identify the degree of reactivity of a specific aggregate will continue, and the emergence of a more environmentally aware society and restrictions on the mining of aggregates will encourage the use of reactive aggregates with appropriate preventive measures.

The commercial ready-mix concrete industry will continue to be the major supplier of concrete to construction projects and as technology develops a much wider range of materials, products and admixtures will be available to meet the performance requirements of the project. Suppliers quality control procedures and owners quality assurance will need substantial changes in concept and implementation to take full advantage of the emerging technologies.

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