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Saunders Generating Station

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Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station

by P. E. Grattan-Bellew

Concrete cracking, characteristic of alkali-aggregate reaction, was observed in Saunders Generating Station. This investigation was designed to confirm that alkali-aggregate reaction was the primary cause of the observed concrete deterioration, evaluate the extent of concrete deterioration, determine the remaining expansion potential of the concrete, and decide whether sufficient alkali remained in the concrete to sustain the reaction. The extent of the concrete deterioration was investigated by comparing the damage rating index (DI) of cores taken from various parts of the structure. The damage rating index is determined by measuring the number of defects observed on polished cores, under a stereobinocular microscope. Silica gel, a characteristic alkali-silica reaction product, was observed in concrete from various parts of the generating station, confirming that alkali-silica reaction had occurred. The expansion potential of the concrete was evaluated by monitoring the expansion of cores stored under various accelerating conditions. The expansivity of the aggregate in the concrete was confirmed by extracting aggregate from cores and testing it in the Canadian Standard concrete prism test. The aggregate was found to be marginally reactive. The concrete cores showed almost the same expansion as the prisms made with the aggregate reclaimed from concrete cores from the structure. The measured alkali contents of the concrete in cores were found to be higher than the original values; this is thought to be due to alkali derived from the aggregates. Experiments showed that a considerable amount of the alkalies in the aggregate could be extracted by cation exchange in pastes of calcium hydroxide. This supports the hypothesis that excess alkalies found in the concrete are derived from impure limestone aggregates.

Keywords: alkali content; **alkali-silica reactions**; concretes; dams; expansion; mortars (material); prisms.

Saunders Generating Station (G.S.), situated on the St. Lawrence River, just west of the city of Cornwall, Ontario, Canada, was constructed between 1955 and 1959. The aggregate used was extracted from a nearby quarry operated by Ontario Hydro. In 1980, the potential alkali reactivity of the aggregate, taken from the original stockpile in 1955, was reevaluated, using the version of the concrete prism test A23.2-14A current at that time.[1] The result of this test indicated that the aggregate showed no potential for alkali-aggregate reaction, and it was concluded that alkali-aggregate reaction (ASR) was unlikely to occur at Saunders G.S.[2]

Recently, cracking frequently associated with ASR was observed in the walls of the scroll case, in various parts of the generating station (Fig. 1). The type of map-pattern cracking observed is frequently associated with concrete affected by alkali-aggregate reaction. A field evaluation of the structure also pointed to alkali-aggregate reaction as being the most likely cause of the distress experienced in operation of the generating station.[3]

The aims of this investigation were as follows:

1. Determine whether observed cracking was due to alkali-silica reaction (ASR) or alkali-carbonate reaction (ACR).

2. Estimate the future expansion potential of the concrete.

3. Determine if there is still sufficient alkali present in the concrete to sustain the reaction.

4. Attempt to explain the occurrence of alkali-aggregate reaction and decide if this is the cause of deterioration in concrete containing aggregates that had been evaluated as innocuous.

RESEARCH SIGNIFICANCE

Operational problems caused by expansion due to alkali-silica reaction (ASR) are becoming an increasing problem in older dams and other large concrete structures exposed to moist environments. In many instances, alkali-silica reaction appears to continue, more or less indefinitely, and the extent of damage therefore increases with the age of the affected structure. Repair work should not be undertaken until the cause of deterioration has been confirmed, and until it has been determined whether expansion is ongoing, as this can have a significant effect on durability of the repair. The purpose of this paper is to outline the laboratory procedures followed to confirm that ASR was, in fact, the primary cause of deterioration observed in the structure, and to predict the future course of the reaction.

Paddy Grattan-Bellew is a senior research scientist at the Institute for Research in Construction, National Research Council, Canada, specializing in concrete durability and building materials. His main research interest is the effects of alkali-aggregate reaction on durability and serviceability of concrete structures. He is a member of ACI Committee 221, Aggregates, and the author of numerous papers and one text-book on alkali-aggregate reactions.

GEOLOGY AND ALKALI-AGGREGATE REACTIVITY IN THE CORNWALL AREA

Cornwall is located in the Ottawa-St. Lawrence lowlands. The quarry from which the aggregate was obtained is in Ordovician limestone of the upper and lower members of the Gull River formation.

Alkali-silica reactive limestone is encountered in several quarries in Eastern Ontario, the most notable being the Spratt Quarry in Ottawa.[4] Severe cracking due to alkali-carbonate reactivity was observed in a sidewalk at Cornwall City Hall. Aggregate for the sidewalk came from a nearby quarry. It is evident that limestone from the region of Cornwall could exhibit either alkali-carbonate or alkali-silica reactivity.

EXPERIMENTAL PROCEDURE
Petrographic evaluation of concrete from Saunders G.S.

Concrete samples were selected from diamond drill cores taken as part of the field investigation and instrumentation of the structure. The cores were sawed lengthwise, and one surface of each was polished for examination under a stereobinocular microscope. Thin sections were made from the other half of the cores.

The damage index (DI) of the concrete in the cores was determined by measuring the number of each type of defect in every square of a 1.5-cm (0.6-in.) grid, using a mechanical stage under a stereobinocular microscope at a magnification of 16X. The defects included: cracks, with and without gel, in aggregate particles and in the paste; reaction rims and debonding around reacted aggregate particles; and the presence of gel in air voids. A minimum area of 180 cm^{-2} (28 in.^{2}) was evaluated for each core.

The sum of each type of defect was multiplied by a factor designed to relate the observed defect to its probable contribution to the deterioration of the concrete (Table 1). Finally, the sum of each type of defect was normalized for 100 cm^{-2} (15.5 in.^{2}). The sum of the factored totals of each type of defect gives the damage rating index (DI) of the core. The DI gives a measure of the amount of deterioration due, primarily to alkali-aggregate reaction, but also to factors such as cracks from other causes.

The presence of gel in fine cracks can readily be confirmed by examination of cores coated with uranyl acetate in UV light.[5] In a few instances, the presence of gel was confirmed by drilling 2-cm- (0.79-in.)-diameter cores from the polished surfaces, and examining them under a scanning electron microscope (SEM) equipped with an electron microprobe that permitted elemental analysis of the material under observation.

Petrographic examination of thin sections was used to determine the mineralogical compositions of the fine and coarse aggregates, identify the fossils, and record evidence

Fig. 1—Photograph of map-pattern cracking of retaining wall due to alkali-silica reaction at Canadian end of Saunders G.S.

Table 1—Factors applied to total number of each defect type*

Feature measured	Factor
Coarse aggregate with cracks	× 0.25
Coarse aggregate with cracks and gel	× 2
Coarse aggregate debonded	× 3
Reaction rims around aggregate	× 0.5
Cement paste with cracks	× 2
Cement paste with cracks and gel	× 4
Air voids lined with gel	× 0.5

*Measured on polished surface of concrete core, to modify raw numbers to take into account probable impact of these defects on condition of concrete, and to obtain damage rating index DI.

of ASR in the form of cracks and gel in the aggregates and paste.

Expansion potential of concrete

The residual expansion potential of the concrete in Saunders G.S. was determined by measuring length change of cores 45 mm (1.77 in.) in diameter by 250 mm (10 in.) long, stored under various accelerating conditions. Three cores were used in each test. Cores were stored at 100 percent humidity at 38 C (100 F) to accelerate the reaction and at 12 C (53.6 F) to simulate the expansion expected in the structure. Cores were also stored in 1 M NaOH at 23, 38, and 80 C (73, 100, and 176 F) to determine the ultimate expansion potential of the concrete at various temperatures.

Potential expansivity of aggregate from concrete in Saunders G.S.

Potential expansivity of aggregate extracted from cores from various drill holes in the upper part of the structure was determined and compared to the expansivity of aggregate

Table 2—Chemical analysis of reclaimed, coarse, and fine aggregate from original 1955 stockpile

Element	Reclaimed aggregate, kg/m³	¼-in. 1955 stockpile, kg/m³	1955 stockpile fine aggregate, kg/m³	Average analysis, kg/m³
SiO_2	10.460	2.71	2.57	—
Al_2O_3	2.680	0.81	0.91	—
Fe_2O_3	1.210	0.45	0.45	—
CaO	43.250	52.06	51.40	—
MgO	2.200	0.90	0.80	—
Na_2O	0.240	0.05	0.06	0.120
K_2O	0.920	0.24	0.24	0.470
Na_2O equivalent	0.845	0.21	0.22	0.425

1 kg/m³ = 1.686 lb/yd³.

from the 1955 stockpile, evaluated previously.[2] The aggregate was extracted from the concrete by soaking it overnight in water, followed by immersing in liquid nitrogen and then thawing in a microwave oven. The aggregate was readily released from the paste after this treatment. Final cleaning was accomplished by soaking it briefly in dilute HCl.

Potential alkali-reactivity of reclaimed aggregate, and that from the 1955 stockpile, was evaluated in the proposed 1994 version of the CSA concrete prism test. In this test, the cement content was increased from 310 kg/m³ (523 lb/ft³) specified in the 1990 standard to 420 kg (707 lb).[6] The alkali content of the concrete was 5.25 kg/m³ (8.85 lb/yd³). In the concrete prisms made with coarse aggregate, reclaimed from the cores, a nonreactive local sand was used as fine aggregate to isolate contributions of the fine and coarse aggregate to the expansion. In the prisms made with coarse aggregate from the 1955 stockpile, manufactured sand from a stockpile, also acquired in 1955, was used as fine aggregate.

Potential reactivity of fine aggregate was evaluated in the proposed accelerated mortar bar test, ASTM P 214.[7] The fine aggregate used in the structure consisted either of manufactured limestone sand, alone, or blended with a natural quartz sand. For the laboratory investigation, aggregates reclaimed from the cores taken from within the structure and from the slab on the deck of the power house were used as fine aggregate. Fine aggregate from the original 1955 stockpile was also evaluated.

Measurement of alkali content of concrete
The alkali contents of the concrete cores were determined by pulverizing a few hundred grams of concrete core and reducing them progressively to 10 g (0.35 oz) of <75 μm material, which was boiled in deionized water for 10 min, soaked in water overnight at room temperature, and filtered. The filtrate made up to 1 liter and the amounts of sodium and potassium in the solution were determined by atomic absorption spectroscopy.

Determination of potential alkali contribution of

limestone aggregate to pore solution in concrete

The limestone contained up to 18 percent acid-insoluble residue, consisting mainly of illite with some quartz and feldspar. Chemical analyses of the limestone (Table 2) show that it has an average Na_2O content of 0.12 percent and an average K_2O content of 0.47 percent, although all of this would not necessarily be extractable.

Details of the extraction process used are given elsewhere.[8] The percentages of Na_2O, K_2O, and calculated Na_2O equivalent extracted from the crushed limestone were determined (Table 2). The reclaimed aggregate is that extracted from concrete cores from the upper part of the structure. The other two aggregates were taken from the original 1955 stockpile.

RESULTS
Evidence of ASR in polished concrete cores
The damage ratings of cores from Saunders G.S. are summarized in Fig. 2; for comparison purposes, four reference samples from other Ontario Hydro dams, and one from Beauharnois Dam, are also included.[9] The nonreactive reference with a DI of 51 is from Lower Notch Dam, which was built with reactive aggregate and a high-alkali cement with a 30 percent replacement by fly ash. No deterioration was observed after 30 years. Cores from the two other dams, Coniston and McVittie, both show considerable evidence of deterioration. A wall at the National Research Council in Ottawa, built with a nonreactive granitic gravel that showed no sign of cracking after 40 years, had a damage rating of 35. Cracking of aggregate particles and a trace of gel are usually observed in most concrete, and are not necessarily evidence of significant deterioration. Damage ratings in the range of 20 to 50 are therefore not necessarily indicative of significant deterioration of the concrete.

The DI for cores from Saunders G.S. varies considerably (Fig. 2). This is not too surprising in a large structure built over a period of 4 years, as the aggregate and cement would have varied during the course of construction. Similar variation was also observed in the cores from the McVittie Dam (Fig. 2). Moisture content of the concrete in the structure may also vary; for example, it is probably drier under the floor (Core #3 from under floor) of the generating station than deeper in the structure (Core ITEW6 44').

The presence of gel lining cracks, in the aggregate, in the paste, and in air voids [Fig. 3(a) and 3(b)] indicates that an alkali-silica reaction has occurred. The very low DI of 10 for Core #5 from ITWW2 at 64 ft (19.5 m) taken from the lower part of the structure may be due to the use of aggregate from the upper, and less reactive, lift of the quarry. Aggregate from near the bottom of the quarry would have been used in the upper parts of the structure, such as the concrete slab for the rails on the roof of the power house, with a DI of 80.

The four cores No. #1 through 4, from the S3 gallery, located on the downstream side of the generating station, show widely varying damage ratings (Fig. 2). All the cores were taken from the wall separating the gallery from the scroll case. Core #1 was taken from a dry area of the wall showing only a few fine cracks. The other cores were taken from wet areas showing cracking. It is uncertain whether the differ-
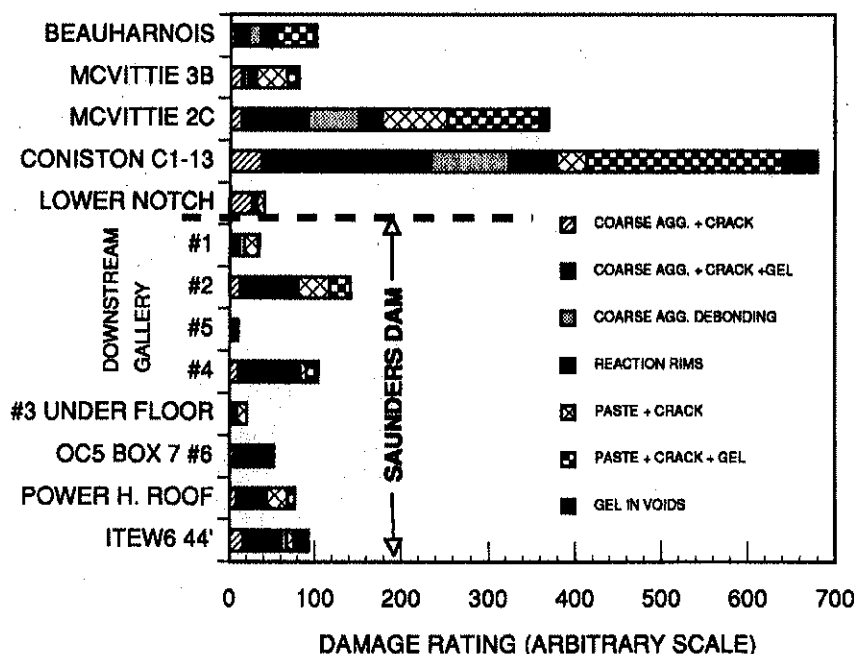
Fig. 2—Comparison of damage ratings of cores from various parts of Saunders G.S., other Ontario Hydro Dams, and Beauharnois Dam. Concrete in Lower Notch Dam was made with reactive aggregate (high-alkali cement with 30 percent replacement of cement by fly ash)

ences in the damage indexes for the four cores are due entirely to differences in the moisture content of the concrete, or are reflections of variations in the reactivity of the aggregate, or both.

The reproducibility of the method for determining the damage rating was investigated by taking two cores from a section of a slab, under the rails on the roof of the power station that showed extensive map-pattern cracking [Fig. 3(c)]. The damage indexes of Cores #1 and 2 are 80 and 72, respectively (Fig. 4). The difference in the indexes of the two cores is 5 percent, which is not significant, as it was shown in previous unpublished experiments that at the 95 percent confidence level, the coefficient of variation between five individual measurements, by one operator, averaged 20 percent. It was concluded that the differences in DI between the cores from the structure are real, and reflect differing degrees of reaction in different parts of the structure.

Results of examination of thin sections

Examination of thin sections from cores taken from various parts of Saunders G.S. showed that there was abundant evidence of alkali-silica reaction in the form of gel filling air voids and cracks. These observations confirm that ASR had occurred in the concrete. In one crack in the aggregate, two generations of gel were found, indicating that ASR had continued for some time (Fig. 5).

Expansion of concrete cores stored under accelerating conditions

The mean expansions of pairs of cores stored at 100 percent humidity at 12 and 38 C (53.6 and 100 F) are shown in Fig. 6. If the current rates of expansion, determined according to the method of Grattan-Bellew, are projected for 10 years, expansions of about 0.2 and 0.37 percent would be expected for the cores stored at 12 and 38 C (53.6 and 100 F),

respectively.[10] In practice, it is unlikely that these rates of expansion would be maintained.

Expansions of concrete prisms stored at 38 C and 100 percent relative humidity

Expansions of concrete prisms made with reclaimed aggregates and aggregates from the 1955 stockpile are shown in Fig. 7(a). At 600 days, the prisms containing aggregate from the cores expanded by 0.043 percent. The expansion appears to have leveled off by 200 days, possibly due to leaching of alkalies.[11] The reclaimed aggregate is classed as potentially reactive, as the expansion exceeds the 0.04 percent limit. Prisms containing aggregates from the 1955 stockpile show just under 0.02 percent expansion after 600 days. These prisms showed no expansion for the first 50 days, but thereafter, the trend of the expansion curve is similar to that of the prisms containing aggregate extracted from the cores. This suggests that, although this aggregate is less reactive than that recovered from the cores, it shows some sensitivity toward the alkali content of the pore solution of the concrete.

The projected expansions of the prisms containing aggregate from the cores at 10 and 30 years, calculated from the current rates of expansion, are 0.125 and 0.214 percent, respectively.[10] However, in practice, these rates might not be maintained in a structure.

The expansions of concrete prisms, made with aggregates from the 1955 stockpile, containing 310 kg and 420 kg/m^3 (523 lb and 707 lb/yd^3) of cement are shown in Fig. 7(b). For the first 90 days, expansions of the prisms containing 420 kg (707 lb/yd^3) were lower than those containing 310 kg (523 lb/yd^3) of cement, but by 200 days they exhibited double the expansion found with the 310 kg (523 lb/yd^3) mix. This confirms that, although the aggregate would normally be classi-

Fig. 3(a)—Optical micrograph of gel filling cracks (indicated by arrows) in limestone aggregate particles and paste; scale divisions in 0.5 mm. (0.02 in.)
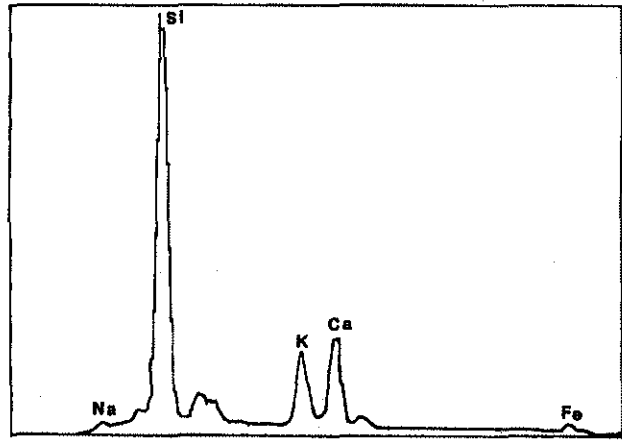

Fig. 3(b)—Electron probe spectrum from silica gel showing the presence of calcium, potassium, sodium, and silica
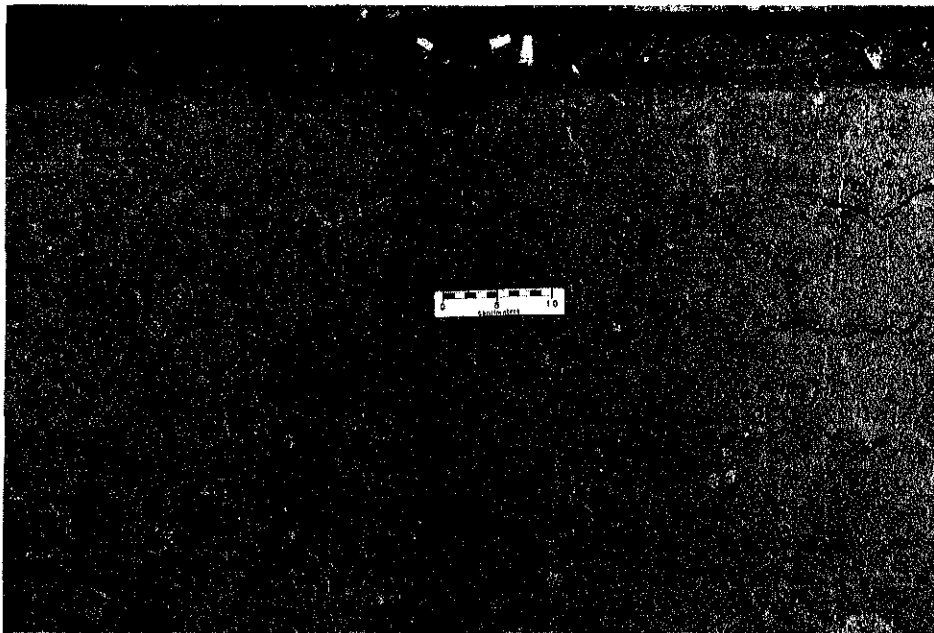

Fig. 3(c)—Map-cracking in concrete slab supporting rails for gantry on power house deck. One rail visible at top of photograph. Scale bar is 10 cm (3.9 in.) long
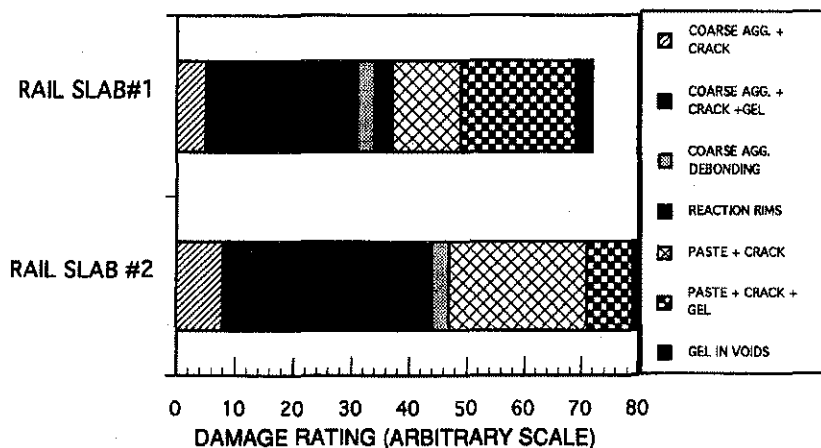

Fig. 4—Damage ratings of two cores taken from slab supporting rails on deck roof [Fig. 3(c)]
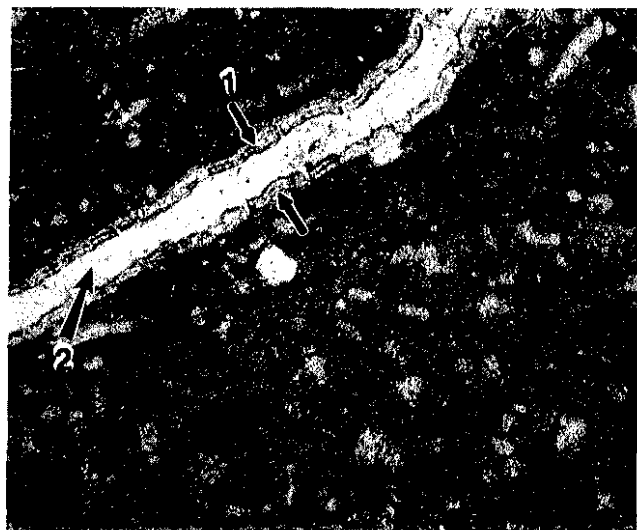
Fig. 5—Optical micrograph of thin section of concrete of two generations of gel, 1 and 2 (indicated by arrows), filling crack in cement paste. Original gel, which appears to have desiccated and broken up, lines crack walls. Subsequently, additional gel filled central part of crack. Field of view is 0.75 mm (0.03 in.) wide

Fig. 7(a)—Expansions of concrete prisms made with aggregate reclaimed from cores from the structure and 1955 stockpile. Both concretes contain 420 kg/m³ (708 lb/yd³) of cement
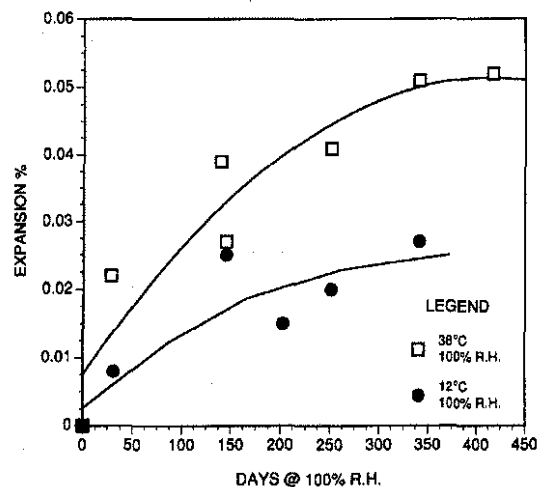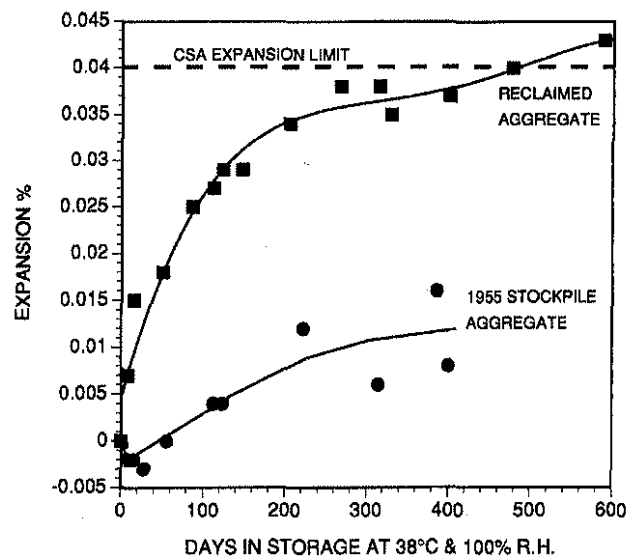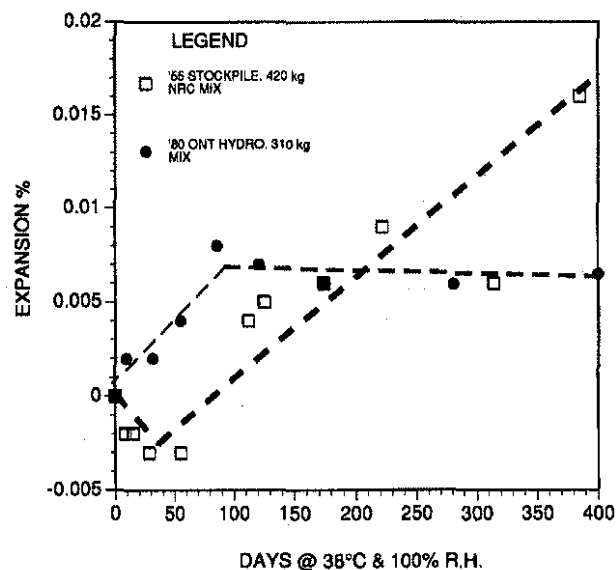

Fig. 6—Expansions of 7-cm-diameter concrete cores stored at 100 percent humidity at 12 and 38 C (53.6 and 100 F)

fied as nonreactive, it showed some susceptibility to the alkali-content of the concrete.

Mortar Bar Accelerated Test (ASTM P 214)

Results of the accelerated mortar bar test on the three aggregates are shown in Fig. 8. The mortar bars containing reclaimed aggregate expanded by only 0.06 percent at 14 days, while those containing aggregate extracted from cores from the slab supporting the rails expanded by 0.096 percent. The mortar bars made with manufactured sand from the 1955 stockpile expanded by only 0.023 percent. Guidelines given in ASTM P 214 suggest that expansions greater than 0.1 percent at 14 days may be indicative of potentially deleterious expansion in concrete. These tests indicate that the aggregate from within the structure and manufactured sand are innoc-

Fig. 7(b)—Comparison of expansions of concrete prisms made with 1955 stockpile aggregate containing 310 kg/m³ (523 lb/yd³) of cement (Ontario Hydro 1980 test) and current test using 420 kg/m³ (708 lb/yd³) of cement

uous. The aggregate from the concrete slab from the deck of the power house was marginally expansive. However, it must be recalled that the aggregate had already been in the concrete, reacting for over 30 years, when these tests were conducted. Results indicate that the fine aggregate may also have contributed to expansivity of the concrete.

Alkali contents of cores taken from Saunders G.S.

Water-soluble alkali contents of 15 cores from various parts of the structure were determined (Table 3). Values obtained ranged from 2.69 to 5.29 kg/m³ (4.5 to 8.9 lb/yd³) of concrete, with a mean value of 4.05 kg/m³ (6.83 lb/yd³). As-
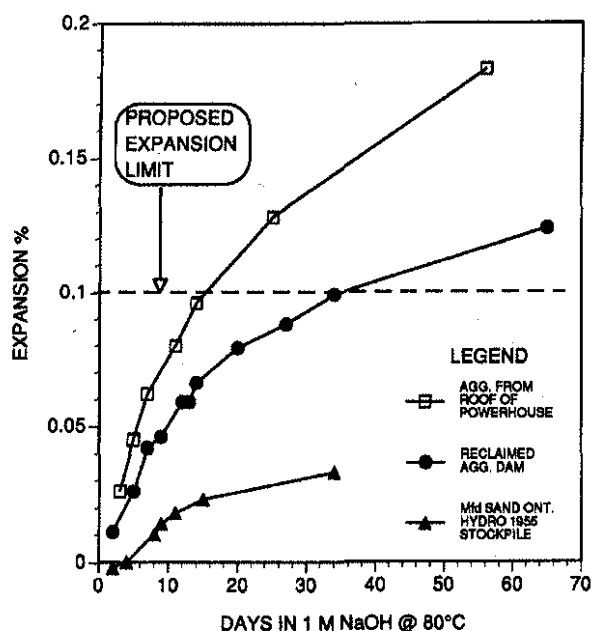
Fig. 8—Expansions of mortar bars in accelerated test at 80 C (176 F) containing fine aggregates extracted from concrete cores taken from structure and from manufactured sand from 1955 stockpile

Table 3—Alkali contents of selected cores from Saunders G.S.

Core location	Alkali content of concrete Na_2O equivalent, m^3
OC4 Box 1, 6 to 7 ft	3.60
ITWW2 Box 4	3.70
ITWW2, 0 in. (under floor)	3.40
PLDT, above rock	3.22
PLDT, 13 in. to 2 ft (top of slab)	2.76
ITWP5, 44 ft 3 in. to 45 ft (bottom of hole)	4.97
ITWP5, 3 to 9 in.	4.32
ITWP5, 19 ft 4 in. to 19 ft 10 in.	3.08
ITEW6, 74 to 85 ft	5.12
ITEW6, 115 ft 4 in. to 116 ft	4.55
ITEW6, 8 to 16.5 ft	5.29
Gallery S3 (dry wall)	4.43
Gallery S3 (wet wall)	5.06
Gallery S3 (wet wall with cracks)	4.33
Roof of power house at G4 (betweeen rails)	2.69
Average of 15 cores with standard deviation	4.05 ± 0.8

suming that the alkali content of the cement was 1 percent Na_2O equivalent and that the average cement content of the concrete was 260 kg/m³(438 lb/yd³), the average alkali content of the concrete would be 2.6 kg/m³ (4.38 lb/yd³) of Na_2O equivalent. The alkali content of the concrete slab under the rails on the roof of the power house was 2.69 kg/m³ (4.5 lb/yd³), similar to the estimated alkali content of the concrete. The 1-ft-thick concrete slab under the rails was isolated from the deck by an asphaltic membrane, and hence migration of alkali from the concrete in the bulk of the structure to the rail slab was prevented. The alkali content of the rail slab may therefore not have changed significantly since construction.

The test method for determining the alkali content of the concrete was evaluated by measuring that of two cores from a precast concrete beam. The total alkali content of the concrete determined from an analysis of the cement and from the mix design was 3.9 kg/m³ (6.6 lb/yd³). The mean of the two determinations was 3.75 kg/m³ (6.32 lb/yd³). This is in reasonable agreement with the calculated value when allowance is made for the determined alkali content as the water-soluble alkali, which would probably be 10 to 15 percent less than the total alkali. There are three hypotheses that could account for the enhanced alkali content of the concrete:

1. Localized alkali concentration by migration within the structure.
2. Addition of alkali from an external source.
3. Addition of alkali from the aggregate.

If concentration of alkali by migration had occurred, there should have been areas in the structure where the alkali level was high and other areas where it was low. This may have occurred, locally, for instance, in the walls of the galleries, but it would not account for the high alkali concentrations in the concrete from deep within the structure.

As no evidence was found to support Hypothesis 1 or 2, it was concluded that limestone aggregate was the most probable source of the alkali. The contribution of alkalis to concrete by aggregates is well documented; however, it has not previously been demonstrated for limestones.[12]

Alkali extraction from limestone aggregate mixed in paste of calcium hydroxide

The limestone reclaimed from concrete cores from the structure was characterized by a high acid-insoluble content, varying from 8 to 18 percent. The insoluble fraction was composed mostly of clay minerals, dominantly illite with some finely divided feldspar and quartz. Illite contains weakly bonded sodium and potassium ions in interlayer positions readily extracted by cation exchange with calcium in the pore solution of the concrete.[13,14] Details of the procedure for extraction of alkali from the aggregate in a calcium hydroxide paste are reported elsewhere.[8] The total amount of alkali, expressed as Na_2O equivalent extracted after 1 day, was 0.16 percent by weight of the rock, but after 93 days only another 0.08 percent was extracted. In these experiments, alkali was extracted from finely pulverized limestone, but in the concrete the surface area of the aggregate, particularly the coarse aggregate, would be much lower, and hence the rate of extraction of alkalies would be lower. However, as limestone was also used as the fine aggregate, the alkali contribution from this source could still be significant.

The following first-order calculations are used to illustrate the possible influence of alkalies extracted from the aggregate on the alkali content of the concrete. For simplicity, only the Na_2O equivalent, subsequently referred to as the alkali, is used in this example. The Na_2O equivalent alkali content of the limestone is 0.85 percent by weight of the rock (Table 1). The maximum amount of alkali extracted from the limestone calcium hydroxide paste is 0.24 percent out of a total of 0.85 percent, i.e., 28 percent of the alkali was extracted. Assuming that after 30 years in the concrete, 25 percent of this amount, i.e., 7 percent, would have gone into the concrete pore solution in the dam, an amount of 0.06 percent

Na$_2$O equivalent is calculated. The mix design of the concrete is: 2000 kg (3371 lb/yd^3) of aggregates, 250 kg (421 lb/yd^3) of cement, and 163 kg/m^3 (275 lb/yd^3) of water. The amount of alkali extracted would be 2000 × 0.06 percent = 1.2 kg/m^3 (2.02 lb/yd^3) of alkali in concrete. If this is added, the estimated original alkali content of 2.6 kg (4.4 lb), a value of 3.8 kg/m^3 (6.4 lb/yd^3), is obtained. This is within the range of values measured in the cores (Table 3). These results suggest that the hypothesis of excess alkali found in the concrete cores derived from the limestone aggregate is plausible. The result of increasing the alkali content from about 2.6 to about 4 kg/m^3 (4.4 to 6.7 lb/yd^3) would be to increase the expansivity of a marginally reactive aggregate to a level where it could cause damage to the concrete.

REACTIVE SILICA IN LIMESTONE AGGREGATE

Examination of thin sections of concrete, and of the insoluble residue in the SEM, showed the presence of three types of quartz grains in the limestone aggregate: rounded detrital quartz grains (300 μm) deposited in the sediment during its formation; small, euhedral quartz grains (30 to 50 μm) of secondary origin; and veinlets of chert consisting of microcrystalline quartz with a grain size in the order of a few micrometers.

The chert (microcrystalline quartz) particles were almost certainly reactive. Observation of insoluble residues in the SEM indicates that there is less reactive silica, and more clay minerals, in the limestone from Saunders G.S. than in the well-documented Spratt limestone. Limestone from Saunders should therefore be less reactive than that from Spratt. This was confirmed by the concrete prism test on aggregate reclaimed from Saunders G.S. [Fig. 7(a)], which showed an expansion of just under 0.04 percent at 1 year, compared to an expansion of over 0.1 percent for Spratt aggregate.

DISCUSSION AND CONCLUSIONS

The occurrence of ASR in concrete from Saunders G.S. was confirmed by the presence of reaction products in cracks and voids in the concrete. The reactivity of the aggregate in the concrete was confirmed by results of concrete prism tests conducted on aggregate reclaimed from cores, and by the expansion of concrete cores stored under various conditions.

Results of the accelerated mortar bar test ASTM P 214 indicate that, at most, the fine aggregates are only marginally expansive. However, the fine aggregate may, nonetheless, have contributed to overall expansion of the concrete. There is, however, considerable evidence that expansion and damage to concrete due to ASR under laboratory conditions underestimate the amount of expansion and damage observed in the field.[15] The damage rating of 2-year-old concrete prisms made with reclaimed aggregate from Saunders G.S., in which expansion had essentially stopped, was compared to that of cores from the structure showing high and low damage ratings in Fig. 9. Expansion, and hence the damage index of concrete prisms, generally tapers off after about 1.5 years, whereas in structures, deterioration often continues more or less indefinitely. This probably accounts for the lower damage rating of the concrete prisms shown in Fig. 9.

Results of tests on concrete prisms containing aggregates from the 1955 stockpile with 310 and 420 kg/m^3 (523 and
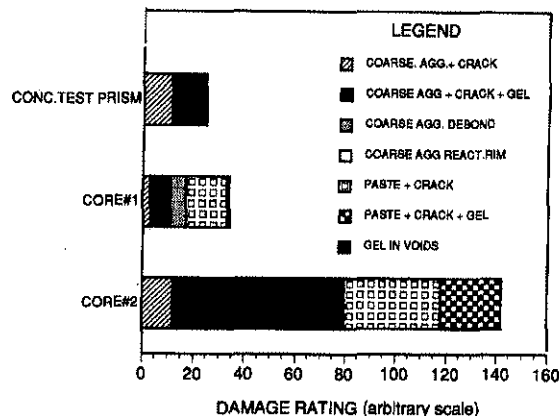

Fig. 9—Comparison of damage ratings of two cores taken from Saunders G.S. with damage rating of 2-year-old concrete prism made with aggregate reclaimed from cores taken from structure

707 lb/yd^3) of cement show that slightly higher expansion is observed in concrete with this marginally expansive aggregate at the higher cement content, corresponding to an alkali content of 5.25 kg/m^3 (8.65 lb/yd^3) NaO$_2$ equivalent. This explains the low expansion obtained by Ontario Research Division using concrete made with aggregate from the 1955 stockpile with a cement content of 310 kg/m^3 (523 lb/yd^3). These results indicate that there is a threshold alkali content below which little or no expansion is observed under laboratory conditions. The threshold alkali level for this aggregate in concrete prism tests is not known, but may be in the range of 3.5 and 4 kg/m^3 (5.9 and 6.7 lb/yd^3). However, in the structure, excessive expansion and cracking occurred in the concrete slab on the deck of the power house, in which the measured alkali content was only 2.69 kg/m^3 (4.5 lb/yd^3). The mean alkali content measured from 15 cores from various parts of the structure was 4.05 kg/m^3 (6.83 lb/yd^3), but some values were over 5 kg/m^3 (8.4 lb/yd^3). It is probable that, at present, there is sufficient alkali in the concrete to sustain the reaction.

The initial alkali content of the concrete contributed by the cement is unlikely to have been more than 2.6 kg/m^3 (4.4 lb/yd^3). Additional alkali found in the concrete was almost certainly derived from illite and water-soluble alkalies in the limestone coarse and fine aggregate. No measurements of the alkali content of the concrete were made between 1955 and 1991, so it is not possible to determine when it would have been high enough to sustain ASR. In other structures made with concrete containing reactive siliceous limestone aggregate, cracking due to ASR was not usually observed before 5 or 6 years, and it is possible that it might take the same time for sufficient alkali to be extracted from the aggregate to promote the reaction in Saunders G.S. It is therefore probable that little expansion would have been observed within the first 10 years of operation of Saunders G.S. These findings are consistent with the observation that problems related to ovalling of the turbine throat rings and generator stators were first observed in 1972, some 14 years after the generating station went into operation.

The wide variation in surface cracking and damage ratings of cores from different parts of Saunders G.S. is difficult to

explain. It may in part be due to the drying out of thinner concrete elements such as the floor slab, where Core #3 was taken, but it may also reflect variations in the reactivity of the aggregate in different parts of the structure. Areas in the concrete with lower moisture levels may show correspondingly lower damage rating indexes. The high damage rating of Core #2 taken from deep in the mass concrete of Hole ITWW2 indicates that alkali reaction occurred throughout the generating station and not just near the surface.

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