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AN ASSESSMENT OF THE EFFECTIVENESS OF BLAST-FURNACE SLAG IN COUNTERACTING THE EFFECTS OF ALKALI-SILICA REACTION

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ABSTRACT

In 1988 and 1989, a series of hydraulic structures were built in Northern Ontario, Canada using an aggregate that was judged to be likely reactive. As a mitigative measure, it was decided to use 50% replacement of Portland cement by ground-granulated, blast-furnace slag. Some 10 years after construction, the structures remain in excellent condition with no evidence of freeze-thaw deterioration or alkali-aggregate reactivity.

This paper outlines the studies conducted and the performance of 50% slag replacement of cement at the Magpie River project in comparison to the performance of a bridge constructed at the same time, but using a conventional Portland cement mix design.

Keywords: Alkali-silica reaction, blast-furnace slag, field performance, preventative measures

INTRODUCTION

In 1988, Great Lakes Power Limited (GLP) undertook the construction of the Magpie River Development, located in northwestern Ontario near the town of Wawa. The project involves three separate single-unit powerhouses and intake structures, and a spillway for a total concrete requirement in the order of 25 000 m^3.

At the time of construction, the results of petrographic analyses, standard alkali-aggregate reaction (AAR) test methods, accelerated mortar bar tests and a review of existing structures in the region indicated that the aggregates available in the Wawa area were at least marginally susceptible to alkali-silica reaction (ASR). As the use of an alternative source of aggregates was not economically feasible, extensive testing was performed to establish a means of counteracting the effects of this mechanism of expansion. On the basis of these tests, the use of ground-granulated, blast-furnace, slag substitution for 50% by mass of the Portland cement was found to be the best means of ensuring the long-term durability of the concrete structures.

INVESTIGATIONS TO ESTABLISH THE POTENTIAL FOR AAR IN THE WAWA AREA

In 1979, the Ministry of Transportation of Ontario (MTO) performed testing of potential aggregate sources in the Wawa area. At that time, the quality of the aggregate in the only commercial quarry in the Wawa region (locally known as Harry Millar's Pit) was deemed to be acceptable, in terms of Los Angeles Abrasion, sulphate soundness, and other physical properties. The potential for AAR was not specifically addressed during the 1979 survey; however, petrographic analysis did indicate significant percentages of graywacke (17.8%), volcanics (30.8%), and also traces of chert in coarse samples, which all have been noted to be reactive under certain circumstances.

Therefore, site investigations for the Magpie River Development undertaken in the mid-1980s included an examination of existing concrete structures in the Wawa and surrounding areas to assess potential for AAR problems. The results of these investigations indicated the existence of map cracking in two older, large diameter culverts located along the Algoma Central Railway line.

On the basis of the results of these initial investigations, it was concluded that there was at least some risk that the aggregates available from Millar's Pit would be susceptible to the effects of alkali reactivity. For this reason, testing, specifically designed to assess the potential reactivity of the Millar's Pit aggregates, was performed in the laboratories of the National Research Council (Institute for Research in Construction) (Gratten-Bellew 1987, 1988). As listed below, the tests involved the normal Canadian Standards Association (CSA) standard AAR tests as well as, what was at the time, an experimental accelerated mortar bar test.

- thin section examination of the coarse fraction
- the ASTM C289 chemical test on the sand fraction
- petrographic examination of coarse and fine fractions
- the ASTM C227 mortar bar test
- concrete prism test CSA A23-2-14A-M77 (accelerated version at 38 °C but with 310-kg/m^3 cement content)
- accelerated mortar bar test (now CSA A23.2-25A or ASTM C1260).

The results of these tests indicated that the sand fraction of the materials contained in Millar's Pit was composed primarily of nonreactive, crystalline quartz (SiO_2). In addition, the results of the chemical test (ASTM C289) and mortar bar tests (C227) were well below recommended limits. Therefore, it was concluded that this fraction of the materials from the Millar's Pit was nonreactive.

On the other hand, petrographic and thin section analysis of the coarse fraction of gravels contained in Millar's Pit indicated that altered volcanic rocks containing a high percentage of microcrystalline quartz comprised about 67% of the material. The presence of these materials suggested the possibility of a slow, late-expanding form of ASR. Therefore, additional tests were undertaken to assess the potential for AAR.

As shown in Fig. 1, the results of concrete prism expansion tests (CSA A23.2-14A-M77) indicated that the total expansion fell within the CSA limits. However, at the time of tender, the concrete prism testing had only been performed for a limited period (200 days). Therefore, additional testing was considered necessary to evaluate the potential for a slow, late-expanding alkali-silica form of reaction which had been known to affect numerous structures in Northern Ontario (Dolar-Mantuani 1969). It is noted that higher expansions would have been obtained with the current version of the concrete prism test that uses 420-kg/m^3 cement with the alkali loading raised to 5.25 kg/m^3 (CSA A23.2-14A-94). For example, with the current test, the Sudbury aggregate would give 0.185% to 0.201% expansion at 2 years (Thomas and Innis 1999).

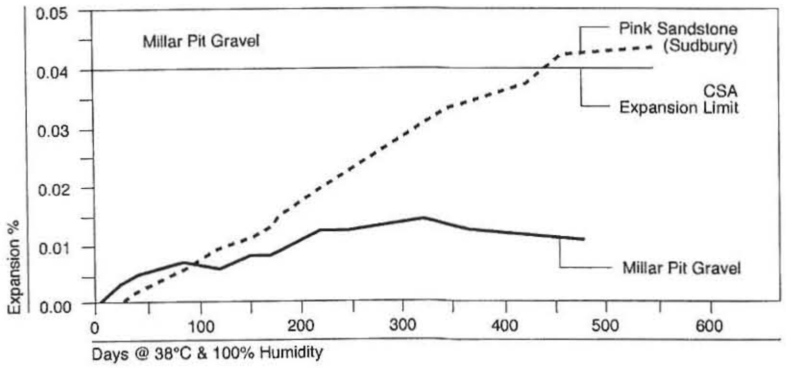

Fig. 1: Results of concrete prism testing on Millar's Pit aggregates

As there was insufficient time to permit standard CSA testing to be performed prior to the award of contract, a (what was at that time) experimental accelerated mortar bar test was used to provide a rapid indication of whether or not there may be an AAR problem associated with the Millar's Pit aggregates. As shown in Fig. 2, the results of accelerated mortar bar tests (ASTM C1260) indicated that the aggregates might be at least marginally reactive (14-day expansion approximately 0.18%).

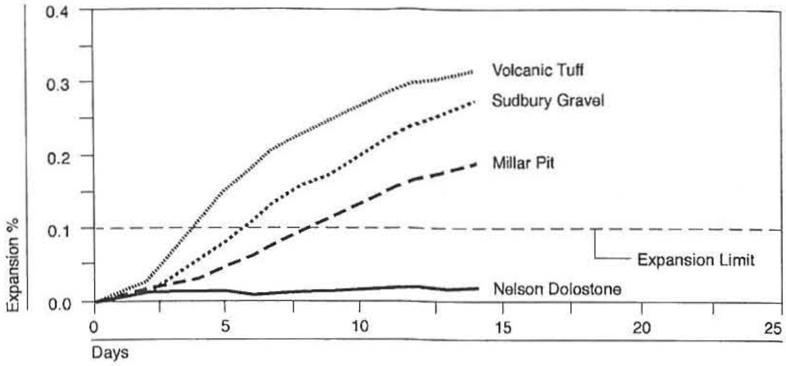

Fig. 2: Results of accelerated mortar bar testing performed on Millar's Pit Aggregates

On the basis of these considerations, it was concluded that the aggregates in the Wawa region should be considered as potentially deleteriously reactive. Therefore, a cost-effective means of mitigating the reaction was required.

THE USE OF GROUND, WATER-GRANULATED, BLAST-FURNACE SLAG TO COUNTERACT AAR

As the cost of importing suitable, nonreactive aggregates was prohibitive, alternative measures to counteract the deleterious long-term effects of the slow/late-expanding ASR were examined. As reported by Donnelly (1990), after a review of a number of alternative mitigative measures, the partial replacement of normal Portland cement with ground, water-granulated, blast-furnace slag was determined to be the best available method for counteracting potential ASR problems.

The effectiveness of slag in preventing expansion due to AAR has been the subject of a number of papers published in various countries. Most of the literature suggests that up to a 50% replacement of normal Portland cement is required to counteract the effects of ASR depending on the reactivity of the aggregate (Oberholster and Davies 1986, Duchesne and Berube 1994, Thomas and Innis 1998). This requirement was confirmed by ASTM C1260 accelerated mortar bar tests performed on Millar's Pit aggregates (Fig. 3), where 50% slag mixture did not exceed 0.10% even after 49 days. Since then, ASTM C1260 test results have been found to correlate well with longer term concrete prism test results for evaluation of slags and other supplementary cementing materials (Berube and Duchesne 1992, Thomas and Innis 1998, 1999).

CONSTRUCTION

Materials

Construction activities were undertaken in 1988 and 1989. The cement was supplied by Lafarge Canada Limited, from the Alpena, Michigan plant. Slag was supplied by the Reiss Lime Company of Canada Limited and originated from the Algoma blast-furnaces at Sault Ste. Marie,

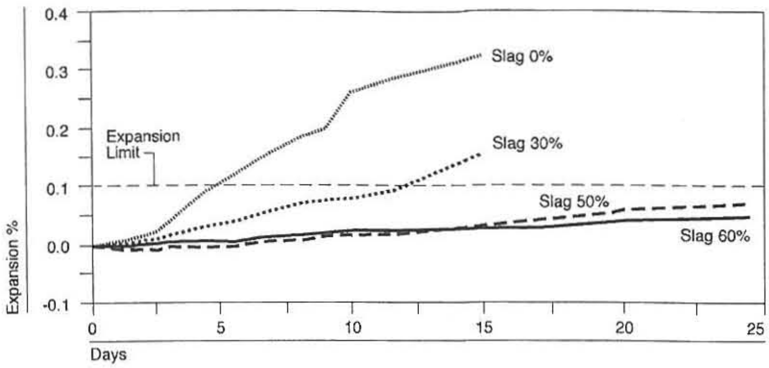

Fig. 3: Results of accelerated mortar bar tests performed on samples prepared with various slag replacement levels

Ontario. Chemical characteristics are listed in Table 1. Both the fine and coarse aggregates for the project were obtained from the local commercial gravel pit in the Wawa area known as Harry Millar's Pit. Admixtures consisted of a water-reducing agent, Grace WRDA-82, and an air-entraining agent, Grace DAREX AER.

Concrete Mix Designs

A concern regarding the use of 50% slag was the impact that it might have on the construction schedule. While having a beneficial effect on heat of hydration in the mass concrete pours, slag cement concrete is known to have slower initial strength gain, potentially delaying form-stripping, and adversely affecting the construction schedule. To counteract this concern, studies were undertaken to determine the mixtures that would be necessary to permit formwork-stripping within an acceptable (i.e., 24 hour) period of time.

Typically, compressive strength results for slag cement with replacement levels of 50% and higher are at least as good or better than normal Portland cement at 28 days. However, at early ages (1 to 2 days), an almost linear relationship between the percentage loss in early compressive strength and the percentage of slag used was found (Donnelly 1990). For this reason, literature studies, and testing of large-scale concrete specimens, up to 1 m^3 in size, were undertaken to establish the minimum strength required to permit forms to be stripped. On the basis of these tests, it was concluded that a form-stripping strength of 3.8 MPa was required, which resulted in the need to use relatively high cementitious contents which resulted in 28-day strengths in excess of what was required. A variety of mixes were established with varying total cementitious contents, and associated 1-day compressive strengths (Table 2). This allowed the amount of cementitious materials used to be managed on a pour-by-pour basis, with rich mixes only employed where early formwork-stripping was necessary. This technique worked well during construction, reducing costs with no recorded instances of any formwork-stripping delays. In general, the measured 1-day compressive strengths were somewhat higher than expected, with mixes having cementitious contents as low as 290 kg/m^3 typically providing adequate compressive strengths to permit formwork-stripping after 2 days.

TABLE 1: Typical Chemical Properties of Cement and Slag Used at the Magpie River Development

Chemical Properties	Portland Cement	Slag
Loss on ignition	1.20%	-
SO_3	2.47%	0.4%
CaO	64.70%	32.5%
MgO	1.99%	16.0%
SiO_2	21.50%	38.0%
Al_2O_3	5.01%	8.5%
Fe_2O_3	2.61%	0.3%
S	-	1.2%
K_2O	-	0.6%
Insoluble residue/other	0.29%	1.5%
Total alkali, Na_2O_{eq}	0.60%	0.61%

TABLE 2: Summary of Major Concrete Mixes Used at the Magpie River Development

Mix	No. 11	No. 16	No. 23[1]	No. 27
% of Total Concrete Placed	56%	21%	12%	3%
Portland (kg/m^3)	145	180	155	185
Slag (kg/m^3)	145	180	155	185
Water (kg/m^3)	145	150	155	155
40-mm stone (kg/m^3)	570	580	-	-
20-mm stone (kg/m^3)	570	580	1000	1040
Sand (kg/m^3)	770	700	845	740
Air	5%	5%	6%	6%
WRDA 82 (ml/100 kg)	280	280	280	280
w/cm	0.50	0.42	0.50	0.42
Slump (mm)	110-115	85-90	95-105	85-90
Approx 1-day compressive strength (MPa)	2.1	3.8	2.1	3.4

[1] Pump mix.

PERFORMANCE

Ten years after construction, all of the concrete at the Magpie River Development remains in excellent condition. Despite severe winter conditions, with temperatures often falling below -40 °C, there has been no significant evidence of freeze-thaw deterioration and no evidence of AAR (Fig. 4) in any of the concrete structures.

Although 10 years is insufficient to positively judge AAR performance, in 1998 it was observed that a bridge constructed by the MTO in the Wawa area in 1988 has cracked extensively and exhibited signs of AAR (Fig. 5). This structure was built using the same aggregates and cement as was used for the Magpie River project. In addition, as summarized in Table 3, the mix design was very similar to the Magpie River rich mix (#16 in Table 2), with the exception that no slag was used. For this reason, a program of sampling and testing of the Magpie River structures and the Wawa bridge was initiated.

Fig. 4: Steephill Falls spillway (condition of spillway upstream pier, 10 years after construction)

Fig. 5: Map cracking on Magpie River bridge

TABLE 3: Comparison of Mix Designs

	MTO Bridge Mix	Magpie River Development Form-Stripping Mix #16
Coarse aggregate (kg/m^3)	1083	1060
Fine aggregate (kg/m^3)	715	700
Cement (kg/m^3)	390	360[1]
Water (kg/m^3)	160	150
Admixtures	WRDA 82, DAREX	WRDA 82, DAREX

[1] Cementitious content: cement + slag.

Field Sampling

In 1997, four 100-mm diameter cores were taken from selected areas of the Magpie River Development powerhouse and spillway structures in order to assess the effectiveness of the use of slag in counteracting the suspected ASR. Each core was drilled to a minimum depth of 18 in. For comparison purposes, one core was also obtained from the MTO bridge structure which did appear to be exhibiting signs of cracking due to ASR. After drilling, the 100-mm diameter core samples were wrapped in plastic and waxed to avoid moisture loss.

Cores were obtained from the following locations:

Core #	Location	Orientation
1	Center of upstream pier on spillway	vertical
2	Secondary concrete at spillway gate guide	vertical
3	Upstream parapet wall of spillway bridge	horizontal
4	Upstream wall in powerhouse sump	horizontal
5	Magpie River highway bridge, left abutment	horizontal

Laboratory Evaluation

In the laboratory, the cores were quartered, with one quarter used to obtain a polished section and a thin section from both the surface and at 75-mm depth. In addition, one quarter was tested by means of uranyl acetate staining. The remaining two quarters were saved for future testing. In Table 4, the results of thin section analysis indicated no evidence of ASR-related gel or cracking in any of the cores taken from the dam structures. On the other hand, as shown in Fig. 6, the highway bridge core showed cracking and ASR gel. The uranyl acetate tests also showed that AAR was only evident in the core taken from the highway bridge.

TABLE 4: Results of Thin Section Analysis

Core No.	Remarks
1	From the massive upstream pier of the spillway indicated good quality concrete and showed no evidence of ASR.
2	From the secondary concrete behind the vertical steel spillway gate guide showed a significant number of number of bleed channels, 50 to 100 µm wide and numerous partially of unhydrated cement grains which is not unusual for secondary pours where placement conditions are usually less than ideal. However, the concrete showed no evidence of AAR.
3	From the spillway bridge parapet wall was found to contain excessive entrained air and to have a surface mortar repair but no evidence of ASR.
4	From the powerhouse sump wall showed good quality concrete with no signs of ASR or other damage.
5	Highway bridge. In this section at 75-mm depth, many air voids were lined with ASR gel and there was some microfracturing. A few air voids were infilled with ettringite (inside the gel lining), which is not unusual in concrete exposed to freezing and thawing in Northern Ontario. The aggregates were highly altered volcanics (diabase, fieldspars, biotite) and with 1% to 2% Paleozoic chert particles. The thin section from the surface of this core did not exhibit significant evidence of ASR gel. However, the polished section exhibited some reaction rims on the volcanic rock particles as well as a socket where a chert particle had partially dissolved leaving ASR and ASR gel in adjacent air voids. It was concluded that in the Magpie River bridge, the most significant source of reactive aggregate was the small amount of Paleozoic chert.

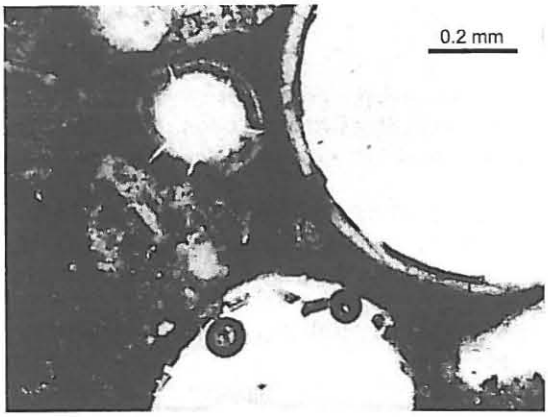

Fig. 6: Thin section analysis of core samples taken from the Wawa highway bridge

CONCLUSIONS

The use of 50% ground, water-granulated, slag cement proved to be a cost-effective method of counteracting the effects of the slow/late-expanding alkali-silica type of reaction. During construction, the slag concrete was found to provide a consistent, workable mix and, through good site management on a pour-by-pour basis, it was found delays associated with formwork-stripping could be avoided without any significant cost penalty. The performance of the concrete some 10 years after construction has been excellent. The slag concrete has proven to be dense and durable with no significant signs of freeze-thaw deterioration despite being subjected to severe northern Canadian winters.

Based on the results of petrographic examinations of cores taken from the structures, the use of 50% slag cement has been effective to date in preventing deleterious effects of ASR at the Magpie River Development. While a 10-yr evaluation period is not sufficient to be conclusive, confirming evidence of the effectiveness of this measure is the fact that a highway bridge of similar age and constructed with the same materials did exhibit map cracking due to ASR. Given these promising preliminary results, monitoring of the Magpie River structures for signs of AAR will continue.

The results of this study would also suggest that the accelerated mortar bar test was successful in identifying a marginally reactive aggregate which the older CSA concrete prism test indicated was nonreactive.

REFERENCES

Berube, M.A. and Duchesne, J. 1992. "Evaluation of Testing Methods for Assessing the Effectiveness of Mineral Admixtures in Suppressing Expansion due to Alkali-Aggregate Reaction". *Proceedings, Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-132, Vol. 1, pp. 549-575.

Dolar-Mantuani, L. 1969. "Alkali-silica reactive rocks in the Canadian shield", *Highway Research Board Record No. 268*, pp. 99-117.

Donnelly, C.R. 1990. "The Use of Slag Cement to Counteract Alkali-Aggregate Reactivity at the Magpie River Development". *Proceedings of the Canadian Geotechnical Conference*, Quebec City.

Duchesne, J. and Berube, M.A. 1994. "The effectiveness of supplementary cementing materials in suppressing expansion due to ASR: Another look at the reaction mechanisms: Part 1: Concrete expansion and portlandite depletion". *Cement and Concrete Research*, Vol. 24, No. 1, pp. 73-82.

Grattan-Bellew, P.E. 1987. "Potential Alkali-Aggregate Reactivity of Gravel from Millar Pit, Wawa, Ontario", *Client Report.*

Grattan-Bellew, P.E. 1988. "Effect of Slag Replacement of Expansivity or Mortar Bars Containing Aggregate from Millar's Pit, Magpie River Development", *Client Report.*

Oberholster, R.E. and Davies, G. 1986. "An accelerated method for testing the potential alkali reactivity of siliceous aggregates", *Cement and Concrete Research*, Vol. 16, pp. 181-189.

Thomas, M.D.A. and Innis, F.A. 1998. "Effect of slag on expansion due to alkali-aggregate reaction in concrete", *ACI Materials Journal*, Vol. 95, No. 6, pp. 716-724.

Thomas, M.D.A. and Innis, F.A. 1999. "Use of the accelerated mortar bar test for evaluating the efficiency of mineral admixtures for controlling expansion due to alkali-silica reaction", *Cement, Concrete, and Aggregates*, Vol. 21, No. 2, pp. 157-164.