Use of the damage rating index (dri) to evaluate level of deterioration due to alkali-silica reaction in 34-year old concrete from the Sudbury area

Carole Anne MacDonald, Soils and Aggregates Section, Materials Engineering and Research Office, Ministry of Transportation, Downsview, ON, Canada, caroleanne.macdonald@ontario.ca

Matthew Piersanti, Alliance Verdi Civil Inc., Ontario, Canada

Medhat Shehata, Faculty of Engineering and Architectural Science, Ryerson University, Toronto, Ontario, Canada, mshehata@ryerson.ca

Joel Magnan, Soils and Aggregates Section, Materials Engineering and Research Office, Ministry of Transportation, Downsview, ON, Canada, Joel.Magnan@ontario.ca

INTRODUCTION

In 2012 and 2013, major rehabilitation of 4 to 6 bridges immediately west of Sudbury, ON, Canada took place. Much of the concrete had reached the end of its service life, in large part due to deterioration caused by alkali-silica reaction (ASR). The bridges were constructed between 1979 and 1980 using coarse and fine aggregates derived from local gravel deposits (Sudbury Gravel) that are now well known to cause ASR. No supplementary cementing materials or other mitigative measures were used in the concrete for these bridges. Materials acquired from these 32 to 34-year-old structures continues to provide a unique opportunity for research in several areas [1-2].

This study will focus on application of the damage rating index (DRI) to concrete cores obtained from the barrier walls of 2 of these structures that visually show different levels of deterioration. DRI was also performed on cores subjected to accelerated testing methods to help assess potential for residual expansion of the same elements. Additionally, this study looks at how two different petrographic preparation techniques and how a modification of the current DRI method used affects results. DRI was also attempted on cylinders of concrete made using reclaimed crushed concrete (RCC) aggregate produced from the same barrier walls. However, it was found that application of DRI on concretes containing recycled materials may require further modifications of the method for it to be an effective tool.

ASR in the Sudbury Region

Alkali-silica reactivity (ASR) was first identified in the Sault Ste. Marie – Sudbury – New Liskeard areas as early as 1969 [3, 4]. Cause for the ASR was found to be reactive rock types present in the local gravel deposits including: argillite, greywacke, quartz wacke, and quartz sandstone to arkose. These reactive rock types are primarily derived from the Proterozoic bedrock formations of the Huronian Supergroup that underlie many of the surficial gravel deposits in the region. Work by Dolar-Mantuani 1969 [4] and Gratten-Bellew 1978 [5] studied and described these rock types in detail, as well as their performance in field concretes and test methods available at the time. Further field surveys and investigations by Magni et. al [6] were later completed as restrictions were placed on use of these aggregates in concrete in the mid-1980's by MTO. In 1986, due to its demonstrated deleterious levels of ASR in field performance and its unique reaction characteristics, MTO established a 100 t stockpile of Sudbury Gravel coarse aggregate. The Sudbury Gravel continues to be one of three alkali-aggregate reaction (AAR) reference materials available from MTO to develop new test methods, mitigation strategies and for test method control and calibration [7].

MATERIALS AND EXPERIMENTAL DETAILS

Materials

Materials acquired in 2012 and 2013 include portions of an abutment from one of the main highway bridges as well as sections of barrier walls from two on/off ramp bridges over a railway line. The two ramp bridges had visibly different levels of deterioration due to differences in traffic levels, exposure to moisture and de-icing salts, and relative amounts of frost (Figures 1 and 2). In addition to full sections of barrier walls and abutment pieces, several tons of crushed concrete demolition waste (RCC) were shipped to an MTO site in the Toronto area for further study.

Figure 1: Highly deteriorated barrier walls from the East-North Ramp Bridge, April 2013.

Figure 2: Low deteriorated barrier walls from the North-West Ramp Bridge, June 2013.

Experimental Program Highlights

Instrumentation was placed into four sections of the high and low deteriorated barrier walls stored at the MTO site to measure expansion during additional long-term field exposure [1-2]. Numerous cores were also taken from both high and low deteriorated walls for further testing including DRI, RCC experiments, and measurement of residual expansion under similar conditions to the 1-year duration 38 °C concrete prism test (CPT), i.e. the cores were implanted with measuring pins and stored upright in buckets lined with cloth and raised above water. The buckets were placed in a room maintained at 38 °C and readings were taken as per CSA A23.2-14A [8]. RCC aggregate produced from high and low deterioration cores was also used as part of the program to make new concrete [1-2]. Cylinders of these RCC mixes were also provided for DRI testing.

DAMAGE RATING INDEX

Overview

DRI is a semi-quantitative petrographic method used to provide information regarding the degree of damage sustained by a sample of concrete due to AAR. The method reports a numerical index that is referred to as a "Damage Rating Index" or DRI. The purpose for completing DRI on these cores was to: 1) quantify the degree of damage and range in DRIs for concrete that has reached the end of its service life; 2) compare DRIs of cores subjected to 1-year of testing at 38 °C and > 95% relative humidity; and

3) compare results from the DRI analyses to expansion measurements obtained during the experimental testing program; and 4) examine how two different petrographic preparation techniques and a modification to the DRI method used can affect results.

DRI Procedure – this study

Procedure and practice used in this study is similar to that of Gratten-Bellew and Mitchell 2006 [9], except UV light was not used for the analysis. Damage features and weighting factors employed are also modified from Grattan-Bellew and Mitchell 2006 [9] (Table 1).

Table 1. Petrographic features and weighting factors used in the DRI for this study

Petrographic Features		Feature Code	Weighting Factors
Cracks in coarse aggregate particle	Closed (without ASR gel)	CrCA	0.75
	Opened or in a fine network (without ASR gel)	OCrCA	4
	Cracks with ASR gel	Cr+GCA	2
Cracks in the cement paste	Without ASR gel	CrCP	2
	With ASR gel	Cr+GCP	4
Debonded coarse aggregate		DCA	3
Reaction rim on coarse aggregate		RRCA	0.5
Reaction products in voids of the cement paste		GAV	0.5

Sample Preparation and Modifications to the DRI Method Used

Each of the concrete cores and cylinders were saw cut longitudinally into slabs and plane surfaces polished using a combination of coarse loose abrasive (60-70 grit), followed by progressively finer stages of grinding/polishing using diamond impregnated resin polishing disks. Water was used as a lubricant and rinsing agent in all cases. This preparation method is referred to as 'normal' in Table 2. Additionally, two cores, one from a high deterioration area and one from a low deterioration area were impregnated with yellow fluorescent dyed epoxy to determine how this preparation step may affect DRI results (Table 2).

Typically, only coarse aggregate particles at least 5mm and larger (longest direction) are counted during the DRI procedure (Method 1, Tables 2 and 3). Although, some researchers have chosen to also include portions of the fine aggregate sized 2 mm and larger (longest direction) in the counts [10] (Method 2, Tables 2 and 3). To test how this variation on the method can affect results with this type of concrete, DRIs were performed on the cores using both variants.

Table 2. Summary of cores tested and results. F.E. = Fluorescent Epoxy.

Core ID	Barrier Wall Condition	Petrographic preparation method	DRI Method 1	DRI Method 2
H4	High deterioration	Normal preparation	705	946
HAF		F. E. impregnation	668	985
L3	Low deterioration	Normal preparation	513	703
L1F		F. E. impregnation	573	854

Table 3. Summary of DRI results for cores tested for 1 year at 38 °C and >95% R.H.

Core ID	Barrier wall condition	Treatment	Preparation Method	DRI Method 1	DRI Method 2
High B	High deterioration	1-year at 38 °C and >95% R.H.	Normal	1018	1000
Low C	Low deterioration	1-year at 38 °C and >95% R.H.	Normal	808	885

RESULTS

Results of the DRI analyses are summarized in Tables 2 and 3. DRIs performed by method 1 ranged from 668 to 705 and 946 to 985 by method 2 in the high deteriorated cores. DRIs on the low deteriorated cores ranged from 513 to 573 by method 1 and 703 to 854 by method 2. Fluorescent epoxy impregnation of the cores did not seem to appreciably alter final DRI results, however it did noticeably change the relative proportions of some of the petrographic features counted (Figure 3). In particular, the number of features counted containing ASR gel was notably less in the impregnated cores as compared with the non-impregnated that were only subject to normal preparation procedures (Figure 3). A likely explanation is that the strong colouration of the yellow dyed epoxy in normal plane light may have overwhelmed and visually obscured the ASR gel in some locations where it was present, particularly in the case of cracks in the cement paste.

Table 4. Summary of expansion results and change in DRI for high and low deterioration cores subjected to 1 year of testing at 38°C and >95% R.H.

Core Sets Tested	Treatment	Expansion	Δ DRI
High deterioration cores, N = 3	1-year at 38 °C and >95% R.H.	0.05%	313
Low deterioration cores, N = 3	1-year at 38 °C and >95% R.H.	0.10%	295

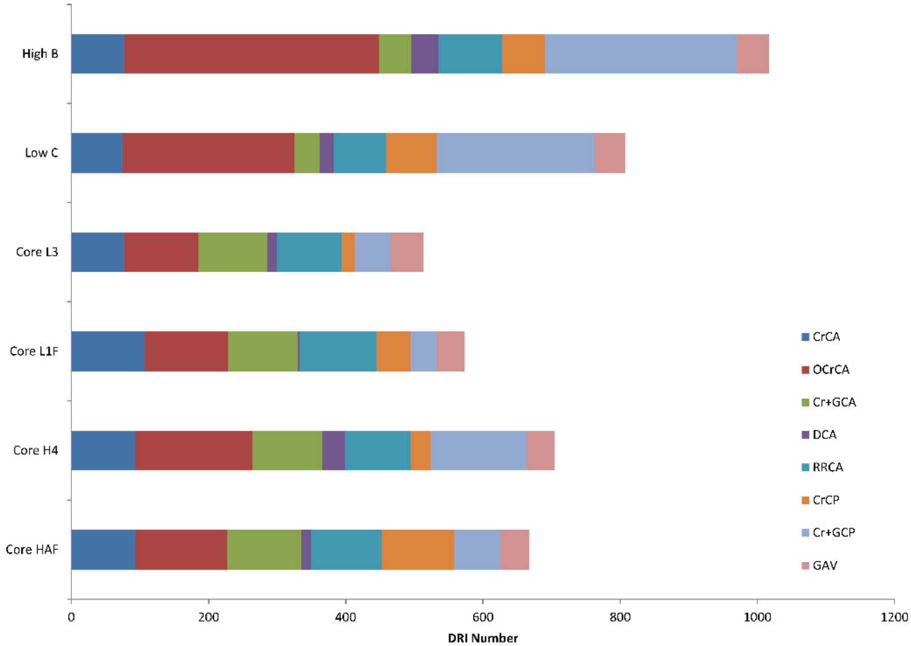

Figure 3: Chart of DRIs for each of the cores examined by Method 1 showing the relative contribution to the DRI that the individual defect types or petrographic damage features provide.

High and low deterioration cores subjected to 1-year of testing at 38 °C and >95 R.H. showed nearly identical increases to their DRIs of 313 and 295 respectively as compared with similarly prepared cores that were not subjected to the same test conditions (Table 4). Although the relative change in DRIs during the 1-year test period was nearly the same, the recorded expansions were quite different. Expansion of the low deterioration cores (~0.10%) was nearly double that of the high deterioration cores (~0.05%) (Table 4). Based on the measured differences in expansion, one might conclude that this is a symptom of a slowing rate of reaction, and/or that the alkalis and available silica are depleting in the highly deteriorated concrete. However, closer examination of Figure 3 that shows the relative contribution of different features to the DRI, reveals a marked increase in those features that are most indicative of severe deterioration of concrete due to ASR, e.g., CrCP, Cr+GCP, OCrCA and DCA. Comparison of the detailed DRI results for cores High B and Low C show that core High B appears to have relatively more features counted in several of the categories, mainly open cracks in the coarse aggregate and cracks in the cement paste containing ASR gel (Figure 3). Comparison of the graph bars for cores H4 and High B and cores L3 and Low C both show large increases in the number of open cracks in the coarse aggregate and cracks in the cement paste containing ASR gel over the 1-year test period.

DISCUSSION

The high DRIs reported for both the low and high deterioration cores correlate well with the type and frequency of damage features present in the concrete that are directly attributable to ASR (Figure 3). In particular the abundance of CrCP and Cr+GCP indicates a high level of damage. The relatively high abundance of OCrCA is exclusively due to ASR as the cracks occur mostly within the reactive rock types and often have traces of ASR gel visible within the cracks. These reactive rock types (argillite, greywacke, arkose-arenite) do not normally have these visible open cracks prior to incorporation in concrete. Figure 3 also shows how different parts of a structure or different structures built with the same materials and that are of the same age can exhibit different levels of damage. The different levels of damage in this case is directly related to the different exposure conditions as the bridge with the high deterioration walls was known to have a higher traffic volume with relatively more exposure to moisture and deicing salts.

There is no reported absolute scale or ranges of DRIs in the literature that is correlated to specific degrees of damage and/or expansions due to AAR. Most practitioners using the DRI refrain from providing absolute ranges for DRI because of the many different versions of the method in the literature, as weighting factors and features considered may be modified for specific cases and/or deterioration mechanisms, and because of the wide variation in the DRIs of concrete containing different types of aggregates. Petrographers may change and adapt the type(s) of features counted and/or adjust weighting factors to account for the materials used or to better highlight and pinpoint damage due to different deterioration mechanisms, or to potentially filter out innocuous features or filter damage due to a mechanism that one is not concerned with. The method has also been used for mixed deterioration mechanisms including combinations of damage features due to ASR, DEF, frost damage, etc.

For comparison purposes, DRI results on 14-year old concrete judged to show minor to no symptoms of ASR at the time of examination ranged from 59 to 109. The concrete was from the same general geographic area as the Sudbury concrete, was constructed with similar mix proportions but was found to contain only 15-30% of the reactive aggregate lithologies indicated in this study. The Sudbury concretes examined in this study tended to have approximately ≥80% reactive lithologies present in the coarse aggregate.

DRIs have also been reported on non-reactive lab concretes by Gratten-Bellew 2012 [11]. A DRI of 45 was reported for 3-month old lab concrete that was made with a non-reactive limestone. It should be noted that Gratten-Bellew [11] adjusted the weighting factor for cracks in the coarse aggregate from 0.75 to 0.25 in this case to account for pre-existing cracks known to occur in the coarse aggregate. It is interesting to note that if the weighting factor of 0.75 had been applied, the DRI of the same concrete would have been 150.

CONCLUSIONS

- DRIs reported for both the high and low deterioration cores are reflective of a very high degree of ASR. This concrete was removed from service in large part due to the deterioration observed in the field.
- DRI was effective at distinguishing between the visibly high and low deteriorated barrier walls.
- In general, DRI Method 1 was found to be more effective at distinguishing between concretes of visibly high and low deterioration in the field. With increasing DRIs, Method 2 appears to be less sensitive.
- DRIs performed on cores with fluorescent epoxy impregnation had similar DRIs to the non-impregnated cores.
- As expected, high and low deteriorated cores that were subjected to 38°C and ≥95% RH for 1 year showed increases to the DRIs. Increase to the DRI was similar for both cores tested.
- Expansions recorded after the 1-year test period do not correlate with the DRI results. It is likely that newly-formed ASR gel dissipates within pre-existing cracks without causing much expansion in the case of the high deterioration cores.

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