A COMPARISON OF DAMAGE RATING INDEX WITH LONG-TERM EXPANSION OF CONCRETE PRISMS DUE TO ALKALI-SILICA REACTION

P.A. Dunbar, P.K. Mukherjee
Ontario Hydro Technologies, 800 Kipling Avenue
Toronto, Ontario, Canada, M8Z 5S4

R. Bleszynski & M.D.A. Thomas
University of Toronto, Department of Civil Engineering
35 St. George St., Toronto, Ontario, Canada M5S 1A4

ABSTRACT

A damage rating system for quantifying the amount of distress in concrete structures due to alkali-silica reaction (ASR) was recently developed by the Institute for Research in Construction-National Research Council of Canada (IRC-NRC). The system involves identifying and counting the number of features characteristic of damage due to ASR in a prepared concrete sample. Such features are given a weighting factor to calculate the damage rating index (DRI). This system was applied to a number of test prisms especially made for the evaluation of alkali-aggregate reactivity (AAR) in concrete. The expansions of the prisms were measured periodically for up to 15 years under 23°C and 38°C laboratory conditions following appropriate CSA/ASTM/Ontario Hydro test procedures. A comparison of expansion against DRI demonstrated that no single correlation exists suggesting that the weighting factors used to calculate the DRI require review for evaluation of AAR in general. A multivariable statistical analysis was also conducted on these data in an attempt to determine whether a relationship exists between the linear expansion and the observed features of ASR. The statistical analysis indicates that a larger pool of data is required.
Keywords: alkali-aggregate reactivity (AAR), alkali-silica reaction (ASR), concrete distress, damage rating, damage rating index (DRI), expansion, statistical analysis

INTRODUCTION

In several regions of Canada, concrete deterioration due to alkali-aggregate reactivity (AAR), especially alkali-silica reaction (ASR) and less importantly alkali-carbonate reaction (ACR), has been diagnosed (Rogers & Worton, 1985; Grattan-Bellew, 1995a, 1995b; Thomas et al., 1992). Damage due to AAR has resulted in costly repair programs and, in some cases, structures have needed to be replaced.

To conduct a study of how to relate concrete deterioration to actual concrete expansion accompanying AAR, it is first necessary to select a damage rating system which takes into account all features which characterize damage due to AAR. A system must be chosen that assigns a damage rating index (DRI) to the concrete for the purpose of comparison. Several damage rating systems have been proposed such as the stiffness damage test by Crisp, Waldron & Wood (1993) and the thin section crack inventory method by Sims, Hunt & Miglio (1992) but there is no universally accepted method. The damage rating system chosen for this study is the one recently developed by Grattan-Bellew (1995a) at the Institute for Research in Construction-National Research Council of Canada (IRC-NRC) to evaluate distress in concrete structures. The method was designed for evaluating the condition of concrete damaged primarily by ASR.

Damage ratings were conducted on concrete prisms that had been monitored for long-term expansion to determine if a relationship existed between the DRI and expansion due to AAR. To date, no studies have been attempted to correlate the DRI to concrete expansion data.

Research significance

The damage rating system is a novel approach to quantifying deterioration of concrete due to AAR. However, the technique is still under development. This paper discusses the results of a preliminary evaluation of the technique to compare DRI to concrete expansion data. The current method of evaluating the potential expansiveness of aggregate-cement combinations due to AAR is by monitoring expansion of concrete prisms under laboratory condition for a period of one year. This method provides an indirect measure of the potential for AAR in concrete without quantifying nor describing the damage due to alkali-silica gel formation and concrete expansion. Finally, a multivariable statistical analysis was conducted on a limited data set in an attempt to revise the weighting factors and determine whether a statistical relationship existed between the linear expansion and the observed features of ASR.

The damage rating index

Damage ratings were performed on concrete prism according to the method described by Grattan-Bellew (1995a). Each feature characteristic of ASR (Table 1) was counted and the results were normalized for an area of 100 cm^2, multiplied by a weighting factor and summed to give the DRI. For this study, the gel fluorescence test (Natasaiyer & Hover, 1988) was employed prior to counting the features of ASR and was found to be effective in reducing the possibility of missing gel deposits during the damage rating analyses.

Table 1 Features and weighting factors assigned to characteristics of ASR

Feature measured	Feature description	Weighting factor
A	Coarse aggregates with cracks	0.25
B	Coarse aggregates with cracks and gel	2.00
C	Coarse aggregates debonded	3.00
D	Reaction rims around aggregates	0.50
E	Cement paste with cracks	2.00
F	Cement paste with cracks and gel	4.00
G	Air voids lined or filled with gel	0.50

gel refers to alkali–silica gel

Concrete prism specimens

Damage ratings were performed on 21 concrete prisms, ranging in age from 2 to 15 years, and were previously cast and tested according to CSA/ASTM/Ontario Hydro test procedures. Eleven prisms underwent accelerated expansion testing at 38°C only (Table 2), two prisms were tested at 23°C only (Table 3), and four prism sets (two prisms per set) were tested at both 38°C and 23°C (Table 4). The expansion and DRI results for each prism is recorded on Tables 2 to 4, inclusive. Prisms were cast from fourteen different coarse aggregate sources which have been classified into seven distinct types (Table 5).

The influence of fine aggregate on ASR is negligible in this study as known non-reactive aggregate was used to cast the prisms. The alkali content of the cements used was most commonly 1.17% (Na_2O equivalent) and, through the addition of NaOH during concrete mixing, was as high as 2.0%.

Table 2 Percent expansion and DRI results for concrete prisms stored at 38 °C and 100% rh

Sample number	Cement alk"%" content	Age (years)	Maximum "%" expansion	DRI
1	1.04	11	0.070	40
2	1.04	11	0.058	30
3	1.17	11	0.061	60
4	1.17	10	0.085	100
5	1.17	9	0.02	60
6	1.17	9	0.07	30
7	1.17	5	0.011	20
8	1.17	4	0.078	50
9	1.17	4	0.181	160
10	1.17	4	0.086	20
11	1.25	2	0.162	300

Table 3 Percent expansion and DRI results for concrete prisms stored at 23°C and 100% rh

Sample number	Cement alk"%" content	Age (years)	Maximum "%" expansion	DRI
12	2.00	15	0.029	120
13	2.00	15	0.063	60

Table 4 Percent expansion and DRI results for concrete prisms stored at 38 °C and 23 °C (*) and 100% rh

Sample number	Cement alk"%" content	Age (years)	Maximum "%" expansion	DRI
14−1	1.04	13	0.069	10
*14−2	1.04	13	0.027	40
15−1	1.04	13	0.018	30
*15−2	1.04	13	0.016	30
16−1	1.17	9	0.021	20
*16−2	1.17	9	0.015	20
17−1	1.17	9	0.085	100
*17−2	1.17	9	0.022	100

Alk= alkali content of cement (Na2O equivalent)

Table 5 Coarse aggregates used to cast prisms to test for potential AAR

Sample number(s)	Coarse aggregate source
3,4,5,11	limestone
15−1,15−2	40% limestone, 60% silicates
16−1,16−2	dolomite
8,9,10	greywacke
1,2,6	intermediate (intrusive?) gneiss
7	granitic gneiss
17−1,17−2	sandstone
12,13	slag from Canadian nickel producer
14−1,14−2	high density (magnetite−hematite blend)

Damage rating results

A plot of percent expansion against DRI for all prisms demonstrated the following results (Figure 1):

- There is no apparent correlation between expansion and DRI.
- All prisms with a DRI of less than or equal to 120 expanded less than 0.09%.
- Prisms having expansions greater than 0.09% have DRI's greater than or equal to 160.
- 67% of the prisms with greater than 0.04% expansion, a threshold value where cracking is usually first visible, showed evidence of cracking.

A comparative plot of all prisms tested at 23°C and 38°C at 100% relative humidity shows no correlation for either temperature (Figure 2). Overall, the samples tested at 38°C show a wider scatter of data and have larger expansions than the prisms tested at 23°C. Higher expansions would be expected for concrete prisms tested in an accelerated environment.

A comparative plot of identical concrete prisms, described in Table 4, of the same mixture compositions and age and tested under different temperature conditions (Figure 3) show that samples tested at 38°C expanded more than samples tested at 23°C. The DRI for samples tested at 38°C are identical to those at 23°C except for sample 14 (-1,-2), containing high density coarse aggregate, which has a lower DRI of 10 for the prism tested at 38°C as compared to the DRI of 40 at 23°C. Both samples 14 and 17(-1,-2) have a large spread in their expansions at different temperatures although the damage rating does not differ significantly.

A plot of expansion against DRI for concrete prisms cast using different coarse aggregate sources is shown on Figure 4. The classification of the coarse aggregate sources used in each mix design is given in Table 5. A correlation may exist between percent expansion and DRI for prisms cast with intermediate gneiss and granite gneiss aggregates (see Trend 1, Figure 4). Furthermore, a correlation may exist for prisms cast with coarse carbonate aggregates (see Trend 2, Figure 4) and for those prisms cast with greywacke aggregates, see Trend 3, Figure 4. All data points for the remaining aggregate sources are scattered with insufficient data to establish possible correlations.

Figure 1 Plot of percent expansion versus DRI for all prisms. Concrete begins to crack between 0.04 to 0.06% expansion.

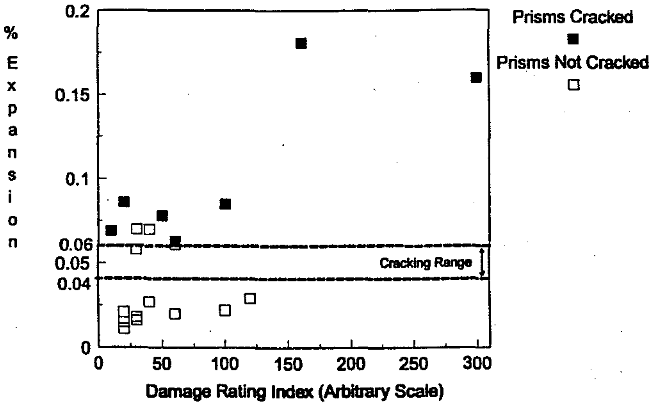


Figure 2 Plot of percent expansion versus DRI for prisms tested at 23 °C and 38 °C and 100% rh

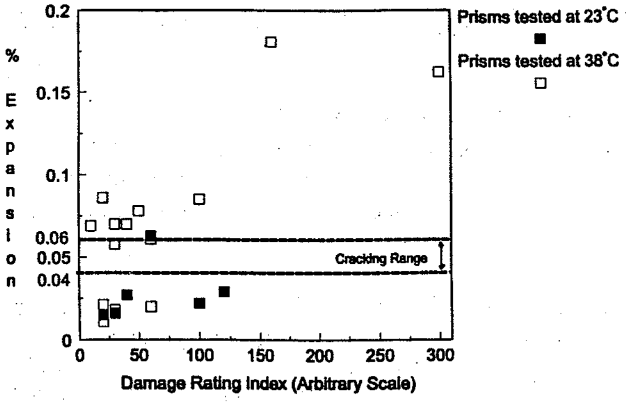


Figure 3 Plot of percent expansion versus DRI for identical prisms tested at 23 °C and 38 °C and 100% rh

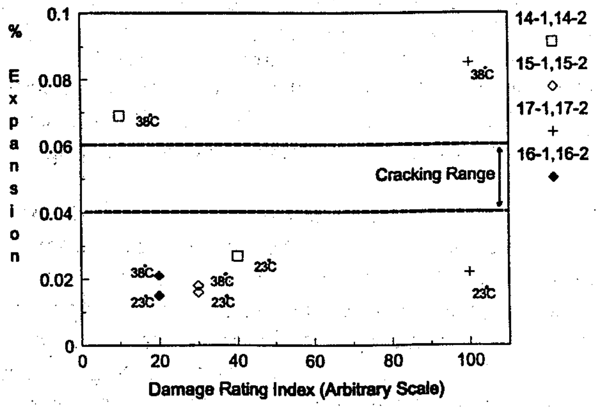
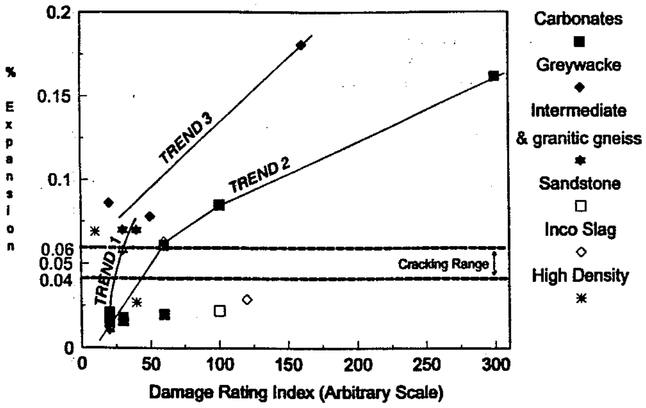


Figure 4 Plot of percent expansion versus DRI for prisms caste with different coarse aggregates. Lines have been drawn to illustrate possible trends



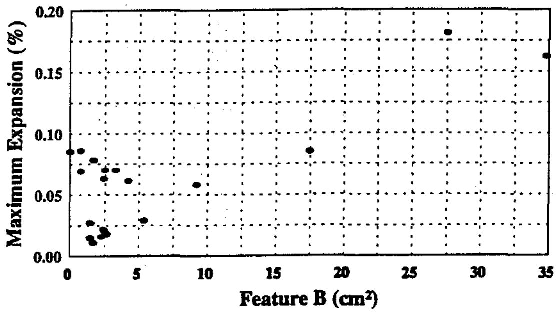
Statistical analysis of data

A multivarible statistical analysis was conducted on the data set in an attempt to determine the influence of weighting factors and determine whether a relationship existed between the linear expansion and the observed features of ASR, features A through G (Table 1). This analysis met with limited success. However, an inspection of the raw data, where each feature was plotted against maximum prism expansion, demonstrated that coarse aggregates with cracks (feature A) and coarse aggregates with cracks and alkali-silica gel (feature B) showed the best trend with maximum expansion (Figure 5). The plots for the other features showed no significant trends in the data nor contributed any valuable information concerning their effect on maximum expansion. Feature B was found to increase linearly with maximum expansion and was tested in the regression modelling procedure. Based on the limited data set, the regression equation that best modeled the maximum expansion of concrete suffering solely from ASR was:

$$\text{maximum expansion} = 0.0039 * \mathbf{B} + 0.0358$$

where **B** is the number of cracks in the coarse aggregate containing alkali-silica gel counted and normalized to 100 cm^2. However, this model should be used with caution as the representativeness and the accuracy of the model are suspect due to the small and biased data set.

Figure 5 Feature B (coarse aggregates with cracks and gel) versus maximum expansion



DISCUSSION

There are two distinct populations of data on a plot of expansion versus DRI; those prisms with a DRI of less than or equal to 120 with less than 0.09% expansion and prisms with DRI's and expansions exceeding these values. An upper limit of 0.09% expansion is very high for this study since concrete usually begins to crack between 0.04 to 0.06% expansion but this limit is the best that can be achieved using the available data. The statistical analysis confirms the conclusion that a larger sample size including more specimens with high expansion values is necessary for future studies.

The fact that no correlation exists between expansion and DRI may be attributed to either one or both of the following explanations: A - the weighting factors used in the summation of the DRI may require adjustments; B - no single relationship exits between petrographic features and expansion for all aggregate types. Of all seven features characteristic of ASR used to calculate the DRI, the number of cracks in aggregates most affect the overall calculation for DRI. Even though the aggregate cracking is assigned the lowest weighting factor (X0.25) it can often be difficult to discern the source of the cracking and thus concrete damage due to ASR can be overestimated. For example, all too often cracks within the aggregate predate concrete manufacturing and were derived from a combination of cracking due to ancient tectonic forces in the bedrock, from freeze-thaw action and quarrying operations. The weighting factor of X0.5 assigned to alkali-silica gel either lining air voids or completely infilling voids may be too high and thus overestimate the DRI. The question remains as to how much damage to the concrete is truly being contributed by alkali-silica gel formation in air voids if the cement paste surrounding these voids is not cracked due to gel formation and expansion. Therefore, the weighting factors may require adjustments. The possibility that no single relationship exits between petrographic features and expansion for all aggregate types is shown to some extent on Figure 4 where there appears to be a correlation between expansion and DRI for prisms cast with either intermediate and granitic gneiss, carbonate or greywacke coarse aggregates; different trends for different rock types. Although insufficient data exists to reinforce these trends at this time, the trends indicate that ASR will be manifested in different ways within different types of aggregates. For example, for a given level of expansion one might expect to observe less obvious signs of gel formation in a dense aggregate with well dispersed and finely disseminated reactive microcrystalline quartz, which is often the case in greywacke, than in an aggregate with the large chunks of reactive silica mineral phases such as chert. Research has shown that different trends exist for different aggregate types when expansion is plotted against a range of microcrystalline quartz percentage found within a population of a particular aggregate type (Grattan-Bellew, 1992). Different levels of alkali-silica gel production for a specific aggregate type will result in differing levels of damage and expansion to a concrete specimen thus producing the trends observed above.

Although not presented here, it is our experience that this damage rating system has demonstrated itself to be an excellent tool in evaluating the distribution of damage due to ASR in a single concrete structure.

CONCLUSIONS AND RECOMMENDATIONS

The data presented and evaluated in this report is limited. Therefore, additional damage ratings on concrete prisms are necessary to compile a larger database for comparative analysis. Concrete prism with a DRI rating of less than 120 may have experienced less than 0.09% expansion. These results can only be applied to unrestrained concrete specimens that have not been subjected to freeze-thaw damage, chemical attack, or any other mechanism of concrete deterioration typical of outdoor exposure conditions. There appears to be a limited but different correlation between expansion and DRI for prisms cast with either intermediate and granitic gneiss, carbonate or greywacke coarse aggregates indicating that any relationship between petrographic features of ASR and expansion may be aggregate dependent.

In order to facilitate further development of the damage rating system this technique should be applied to a limited number of field concrete specimens and reviewed for its applicability under field conditions. The weighting factors should be re-evaluated taking into consideration the following: the physical damage to the concrete, other than by AAR; the origin of cracks in the aggregates; if air voids filled or lined with alkali-silica gel contribute significantly to concrete deterioration; and if cracking occurring in aggregates that do not propagate into the surrounding cement paste should be ignored during the damage rating analyses.

Further studies should be initiated to determine how DRI varies with concrete expansion, aggregate type, restraint, stiffness and age of concrete. Included in these studies should be specimens cast with supplementary cementing materials, used to retard AAR.

ACKNOWLEDGEMENTS

Funding was provided by Ontario Hydro Technologies and a NSERC grant at the University of Toronto. We would like to thank Dr. Grattan-Bellew for his guidance in using the damage rating technique.

REFERENCES

Crisp, T.M., Waldron, P., & Wood, J.G.M. 1993, 'Development of non-destructive test to quantify damage in deteriorated concrete', Magazine of Concrete Research, Vol. 45, 247-256.

Grattan-Bellew, P.E. 1995a, 'Alkali-silica reaction in concrete from Saunders generating station', ACI Materials Journal, Vol. 92, No. 2, March-April, 126-134.

Grattan-Bellew, P.E. 1995b, 'Overview of AAR in Canada', CANMET/ACI International Workshop on Alkali-Aggregate Reactions in Concrete, in proceedings, 65-82.

Grattan-Bellew, P.E. 1992, 'Microcrystalline quartz, undulatory extinction & the alkali-silica reaction', Proceedings of the 9th International Conference on Alkali-Aggregate Reaction in Concrete, London, England, Vol. 1, 383-394.

Natesaiyer, K., & Hover, K.C. 1988, 'Insitu identification of ASR products in concrete', Cement and Concrete Research, Vol. 18, 455-463.

Sims, I., Hunt, B., & Miglio, B. 1992, 'Quantifying microscopical examinations of concrete for alkali-aggregate reactions (AAR) and other durability aspects', American Concrete Institute, SP 131-14, 267-287.

Rogers, C.A. & Worton, S. 1985, 'Alkali-Aggregate Reactions in Canada, a Bibliography', Ontario Ministry of Transportation, Report No. EM-73.

Thomas, M.D.A., Mukherjee, P.K., McColm, E.J., & Everitt, M.F. 1992, 'Case histories of AAR in hydraulic structures in the UK and Canada', Proceedings of International Conference on Concrete Alkali-Aggregate Reactions in Hydroelectric Plants and Dams, CEA in association with CANCOLD, Fredericton, New Brunswick, September-October, Technical Paper No. 11.