THOROUGH CHARACTERIZATION OF CONCRETE DAMAGE CAUSED BY AAR THROUGH THE USE OF A MULTI-LEVEL APPROACH

Leandro Sanchez[1*], Benoit Fournier[2], Marc Jolin[2], Josée Bastien[2], Denis Mitchell[3], Martin Noel[1]

[1]University of Ottawa, Ottawa, ON, CANADA

[2]Université Laval, Québec, QC, CANADA

[3]McGill University, Montréal, QC, CANADA

Abstract

Over the last few years, comprehensive management programs for the diagnosis and prognosis of AAR in aging concrete structures were developed in North America, based on a series of laboratory test procedures. Although promising, these lab-procedures presented several parameters whose impacts were not completely understood, which significantly reduced their applicability for the appraisal of deteriorated concrete structures in service. In this context, it has been suggested that two lab-procedures, namely the *Stiffness Damage Test (SDT)* and the *Damage Rating Index (DRI)* could reliably assess the condition of concrete affected by AAR. However, the full multi-level characterization of AAR damage through the coupling of the prior tools has never been treated so far. This paper presents the overall assessment of 35 MPa concrete specimens incorporating a wide range of reactive aggregate types/natures, and presenting different AAR distress degrees (i.e. expansion levels from 0.05 to 0.30%).

Keywords: damage assessment, stiffness damage test (SDT), damage rating index (DRI), multi-level approach

1 INTRODUCTION

Alkali-aggregate reaction (AAR), a chemical reaction between certain mineral phases from the aggregates and the alkali hydroxides from the concrete pore solution, is one of the most harmful distress mechanisms affecting the durability of concrete infrastructures worldwide [1]. Bérubé et al. [2] and Fournier et al. [3] recently developed comprehensive management programs for the diagnosis and prognosis of AAR in aging concrete structures based on a series of laboratory test procedures. Although promising, these lab-procedures still present several parameters whose impacts are not completely understood, which significantly reduces their applicability for the appraisal of concrete structures/structural elements in service. Sanchez et al. [4, 5] showed that both the *Stiffness Damage Test (SDT)* and the *Damage Rating Index (DRI)*, mechanical and microscopic tools respectively, can reliably assess the damage degree of AAR affected concretes by the adjustment of some of their input and output parameters. However, an overall distress evaluation, which would encompass the full characterization of the damaged concrete through a multi-level approach (i.e. microscopic features vs. mechanical behaviour), has rarely been performed so far and very few data are available.

2 TOOLS FOR ASSESSING CONCRETE DAMAGED BY ASR

"Damage" is defined in this work as the harmful consequences (measurable ones) of various types of mechanisms (e.g. loadings, shrinkage, creep, AAR, DEF, freezing and thawing, etc.) on the mechanical properties, physical integrity and durability of a concrete element/material. Therefore, in practical terms, the word damage is considered here as being part of: 1) the stiffness reduction of the concrete; 2) the mechanical properties reductions of the material and; 3) the physical integrity/durability loss (related to the net cracking extent) of the concrete.

It has been found that AAR strongly influences some of the mechanical properties of the affected concrete material. This influence depends on several factors such as the cement type, the reactive (or non-reactive) aggregates types/natures, the material's strength as well as AAR type, kinetics and amplitude. Moreover, as stated by [6], both AAR kinetics and distress (in terms of cracks' evolution) change as a function of the aggregate's types/natures.

* Correspondence to: Leandro.sanchez@uottawa.ca

Therefore, the development and use of laboratory/field procedures to evaluate AAR damage degree in concrete (diagnosis) and also its development over time, thus enabling the prediction of further damage in the affected material (prognosis), would be extremely interesting, mainly for the selection of effective methods for repairing/reinforcing distressed concrete structures/structural members. Over the years, several microscopic and mechanical tools were developed and used for assessing damage in concrete due to AAR, and among them, the procedures described in the following sections were found to be the most suitable.

2.1 Stiffness Damage Test (SDT)

In the early 1990's, Crisp and co-workers proposed to use the *Stiffness Damage Test (SDT)* to quantify the degree of distress in concrete due to ASR [7, 8]. The test method was actually developed by Walsh [9] who observed a good correlation between the crack density and the cycles of loading/unloading (stress/strain relationship) of rock specimens. Crouch [10], following those results, proposed a new test procedure (Stiffness Damage Test - SDT) based on cyclic compression loading of concrete specimens (cylinders or cores).

Sanchez et al. [4, 5] actually pursued the work of Smaoui and co-workers [11, 12], by applying the SDT procedure to specimens cast from concrete mixtures of various mix designs (25, 35 and 45 MPa) and incorporating a variety of reactive aggregates (coarse vs. fine), as well as on concrete cores extracted from an extremely damaged concrete overpass in Quebec City (Canada). The goal of those studies was to verify the influence of the test loading level and several input parameters (such as concrete environment, humidity, specimen size, etc.) on the output test analyses. Likewise, an evaluation of the output test responses as a function of the expansion levels of the affected specimens was performed. Based on an extensive investigation program and the statistical analysis of the test results, the authors presented the following main conclusions: 1) the SDT should be carried out by applying a percentage of the concrete strength instead of using a fixed load (as originally proposed by [7, 8, 11, 12]); 2) the use of 40% of the design concrete strength seems to be the best approach for distinguishing damaged concrete specimens with regard to their expansion levels; 3) the use of applied loads up to 40% of the design concrete strength enables the use of the same specimen for supplementary analyses, such as compressive or tensile strength, since the test seems to keep its "non-destructive" character up to that point; 4) the output parameters such as the hysteresis area (HA) and the plastic deformation (PD) over the five cycles, as well as the modulus of elasticity (ME) (as an average value of the second and third cycles), were chosen as the most diagnostic output results of the test; 5) the input parameters such as the concrete's cure history (i.e. the specimen moisture condition), the sample's geometry and size, the sample's location within the structural member (zone and direction), as well as the selection of the sample's strength level for stiffness damage testing, seems to strongly influence the output analyses of the SDT and; 6) the use of indices (*Stiffness Damage Index* - SDI and *Plastic Deformation Index* - PDI) instead of absolute HA or PD values, which take into account the ratio of "dissipated energy/total energy" implemented in the system, better represents the real "damage" of the affected materials; actually, this approach decreases the impact of a poor selection of maximum loading level for stiffness damage testing and provides an easier understanding of AAR evolution as a function of its expansion [4, 5].

2.2 Damage Rating Index (DRI)

The *Damage Rating Index* (DRI) is a semi-quantitative microscopic analysis performed with the use of a stereomicroscope (about 15-16x magnification) where damage features associated with AAR are counted through a 1 cm^2 grid drawn on the surface of a polished concrete section [13]. The number of counts corresponding to each type of petrographic features is then multiplied by weighing factors, whose purpose is to balance their relative importance towards the mechanism of distress considered (for instance ASR) [14-16].

Sanchez [5, 17] used the DRI, applying the new version proposed by [13], to evaluate AAR distress coming from different reactive aggregate types and concrete strengths. The concrete specimens assessed by the authors presented different expansion levels (from 0.05% up to 0.30%) and the compressive strength of the concretes ranged from 25 MPa to 45 MPa. The main results found were the following:

- The DRI semi-quantitative output final value effectively distinguished well the different expansion levels in ASR affected concretes incorporating either reactive sands or reactive coarse aggregates. However, to be an effective and practical semi-quantitative tool, the analyses should be performed on the aggregate particles down to 1 mm in size, instead of 2 mm as proposed by [13]. Moreover, all the DRI semi-quantitative data correlated well with the expansion level of the affected specimens;

- DRI semi-quantitative numbers were quite similar between the 25 and 35 MPa mixes at each expansion level. However, in the 45 MPa concretes, the behaviour was found to be slightly different as greater and similar numbers were found for low and moderate expansion levels (i.e. 0.05% and 0.12%, respectively), while the presence of gel was found to be greater at all expansion levels studied [17]. Also, cracking in the cement paste (and sometimes in the aggregate particles) was significantly more difficult to identify in the 45 MPa polished sections than in the 25 and 35 MPa concretes, at least at the magnification used for the DRI procedure (≈15-16x); this was particularly true for the polished sections incorporating the reactive sands [5, 17];
- Considering the DRI results, an "envelope of damage results" (i.e. results found within well-defined boundaries/limits) was found towards the expansion level of the affected samples. Exceptions were however noted for concretes incorporating the alkali-carbonate reactive Kingston limestone and the Potsdam orthoquartzite, which presented much more and much less damage, respectively, than the average range of the other mixes.
- The analysis of all data from petrographic features counting allows a better understanding of the damage mechanism in the ASR-affected specimens than just relying on the absolute DRI numbers. For instance, the number of opened cracks in the aggregate particles and their extension into the cement paste, with and without gel, was found to increase with increasing expansion, thus confirming those features as diagnostic of the progress of ASR in the test specimens examined, Similarly, the crack density (CD - counts/cm^2), increases with increasing expansion in the AAR affected specimens for all the concrete mixtures studied. Moreover, as for the DRI number, an "envelope of crack density results" is observed towards the expansion level of the affected samples [5, 17].

3 SCOPE OF THE WORK

As indicated in the previous sections, AAR affects the various mechanical properties of concrete differently (i.e. stress/strain behaviour, the modulus of elasticity, tensile and compressive strengths, etc.), which may impact on the performance of structures/structural members in service. Moreover, according to several research studies, the use of different reactive aggregate types and natures could also produce different "alkali-aggregate reaction patterns" in the affected materials, such as reaction kinetics, distress features and crack's evolution against expansion, etc., which could require different remedial actions/solutions. This paper presents the overall evaluation of AAR damage evolution as a function of its expansion level. The analyses were performed through the use of 35 MPa concrete specimens cast in the laboratory, incorporating a wide range of reactive aggregate types (i.e. fine vs. coarse aggregate) and natures (lithotypes). At specific expansion levels, the microscopic and mechanical tools described in Section 2 were carried out in order to evaluate the material changes as a function of AAR progress. Finally, quantitative charts/tables for the condition assessment of AAR in aging concrete structures are proposed.

4 MATERIALS AND METHODS

4.1 Materials and mixture proportions

Twelve 35 MPa concrete mixtures incorporating ten different reactive aggregate types/natures were selected for this study. The coarse aggregates ranged from 5 to 20 mm in size. Non-reactive fine (Lav) and coarse (HP or Dia) aggregates were used in combination with the reactive aggregate materials for concrete manufacturing. Table 1 provides information on the different aggregates used in this study. All 12 concrete mixtures were designed to present the same amount of cement paste and aggregates in volume, thus allowing to compare similar systems with different aggregates and strengths. Table 2 gives an example of the concrete mix design used in this study (Tx + HP)

4.2 Materials and mix designs

A minimum of 35 cylinders, 100 by 200 mm in size, were cast from each of the twelve concrete mixtures manufactured in the laboratory. After 24 hours in their moulds, the specimens were demolded and then placed for 24h in the moist curing room. Small holes, 5 mm in diameter by 15 mm long, were then drilled at both ends of each test cylinders and stainless steel gauge studs were glued in place, with a fast-setting cement slurry, for longitudinal expansion measurements. The cylinders were left to harden for 48 h prior to performing the "0" length reading, after what they were placed in sealed plastic buckets (22 liters) lined with damp cloth (4 cylinders per bucket). All buckets were then stored at 38°C and 100% R.H. and the test cylinders were monitored for length changes regularly until they reached the expansion levels chosen for this research, i.e. 0.05 ± 0.01%, 0.12 ± 0.01%, 0.20 ± 0.01% and 0.30 ± 0.01%. As per ASTM C 1293, the buckets were cooled to 23 °C for 16 ± 4 h prior to periodic axial expansion measurements. When the above expansion levels were reached, the specimens were wrapped in plastic film and stored at 12°C until testing (because of testing capacity issues).

Prior to mechanical testing, both ends of each cylinder were carefully mechanically ground to avoid any interference from the stainless steel gauge studs used for expansion measurements. Also, even though the specimens were wrapped in plastic film and storage at 12°C, they were placed in the moist curing room for 48 hours, protected from running water, before testing, in order to allow appropriate saturation of the test specimens, following the procedure proposed for concrete cores extracted from real concrete structures (A23.2-14C). Length and mass readings performed on a number of test specimens showed that the 12°C storage did not have any adverse effect on the test specimens [4].

After the storage period, the concrete cylinders meant for microscopic analyses were first cut in two axially and then one of the flat surfaces thus obtained was polished. A portable hand-polishing device, which uses diamond-impregnated rubber disks (no. 50 (coarse), 100, 400, 800, 1500 à 3000 (very fine)), was found most suitable as it does not use loose abrasive powders that can fill up cracks/voids in the concrete and quality polishing is obtained with minimal water supply.

4.3 Methods for assessment and analysis

General

Table 3 presents the testing matrix developed for this study. The investigation program carried out on concrete cylinders of various expansion levels includes mechanical testing (SDT, elastic modulus and compressive strength evaluation) and semi-quantitative petrographic analysis (DRI).

Stiffness damage test (SDT)

For each concrete mixture and at each expansion level chosen (0.00% (control); 0.05%; 0.12%; 0.20% and 0.30%), three cylinders (two in the control's case) were subjected to five cycles of loading/unloading at a controlled loading rate of 0.10 MPa/s. The SDT was performed at a loading level corresponding to 40% of the 28-day concrete strength [4,5]. In the case of the control specimens, the SDT was carried out on two cylinders cast and maintained at 12°C for a 47-day period, as described below. All of the results presented hereafter are the average values obtained on three (or two) specimens at each expansion level tested.

Damage Rating Index (DRI)

A semi-quantitative petrographic analysis, using the DRI, was performed on one specimen from each concrete mixture at the various expansion levels studied (Table 3), according to the method described by Sanchez [5,17]. Actually, the counts of cracks in the aggregate particles were determined on particles down to 1 mm in size, so that the distress coming from reactive sands might be well assessed. The DRI final number presented hereafter is the value normalized to 100 cm^2 obtained over polished concrete specimens at each expansion level.

Compressive strength test

Compressive strength was measured in two ways. First, tests were carried out on sets of two cylinders to determine the 28, 90 and 180-day strength of each concrete mixture. For this first procedure, since some of the specimens contained highly-reactive aggregates, the Standard ASTM C 39 procedure could not be followed due to the development of AAR. Therefore, the samples were wrapped and placed at 12°C for a 47, 150 and 300-day period, which represents, respectively, the same 28, 90 and 180-day period according to the maturity concept presented by ASTM C 1074. The "equivalent" 28-day compressive strengths obtained from this procedure were actually used to determine the loading level (40%) to be used for the SDT.

Second, compressive strength tests were performed on two of the three cylinders of each concrete mixture and at each expansion level, at the completion of the SDT, with the aim of verifying the compressive strength reductions of the material as ASR develops. This procedure was adopted and considered valid after the results obtained by Sanchez et al. [4] confirmed the largely non-destructive character of the SDT.

5 RESULTS

5.1 Stiffness damage test (SDT)

As previously mentioned, Sanchez et al. [4] showed that the SDT needs to be carried out at 40% of the design (28-day) concrete strength to obtain diagnostic responses over the test. However, in most cases, when condition assessments are carried out on aging concrete structures, the 28-day strength of the concrete(s) used is unknown. Thus, [5, 18] suggested that the most suitable approach regarding practical purposes would be to first determine the compressive strength on cores extracted from zones that are not/less damaged in the structural element under investigation, and then the SDT might be carried out at 40% of that value. However, it has been found that this approach disables the use of both absolute HA and PD values as by [4], because depending on the loading level chosen for testing, a huge variability in the test responses can be obtained, thus leading to a misinterpretation of the damage degree in the concrete under investigation [5,18]. Based on that, Sanchez [5,18] proposed to use the following two indices instead of absolute HA and PD values: SDI and PDI. The first index represents the dissipated energy (over the five compression cycles)/the total energy implemented in the system (area under the stress/strain curve), while the second corresponds to the plastic deformation (over the five compression cycles)/total deformation in the system.

Figure 1A shows that a concave trend of the SDI against the expansion level is obtained for the 35 MPa concrete specimens affected by ASR, with values ranging from about 0.08 for sound concretes up to 0.35 for 0.30% of expansion. Similar trends were obtained for the PDI, with values ranging from about 0.05 to 0.30 for 0.30% of expansion (Figure 1B).

5.2 Damage rating index (DRI)

Figure 2 gives a plot of the DRI numbers as a function of the expansion levels of the concrete specimens. A full description of the development of microscopic AAR features of deterioration against the expansion level of the affected concrete specimens, both in a qualitative and a semi-quantitative way is given in [5,17]. The DRI was found to increase linearly and quite similarly with increasing expansion for the 35 MPa mixtures investigated, with the exception of the concrete mixtures incorporating the King alkali-carbonate reactive aggregate and Pots siliceous sandstone. The latter presented respectively much more and much less damage, as a function of expansion, than the average range of the other mixes.

5.3 Mechanical properties

Modulus of elasticity (ME)

Figure 3A presents the ME reduction, as a function of expansion, for the 35 MPa concretes investigated. Globally, for low expansion levels (i.e. 0.05%), a fairly wide range in ME losses (i.e. from 5% up to about 30%) was obtained between the different aggregate combinations tested. For higher expansion levels ($\geq$ 0.20%), the ME reductions ranged from 40% up to $\approx$ 65%. Moreover, even though the levels of modulus of elasticity losses varied from one aggregate to another, similar "reduction trends" were generally observed as a function of the expansion level of the various AAR-affected specimens.

Compressive strength test (CS)

Figure 3B illustrates the compressive strength reductions for the 35 MPa concrete mixtures investigated. In general, CS was found to decrease in a somewhat modest way with increasing expansion. Despite some variations from one reactive aggregate combination to another, similar trends in CS reductions were obtained for the various mixtures investigated, with maximum CS losses reaching about 10% at 0.05% expansion, 10 to 20% at 0.12% expansion and 20 to 30% at expansions $\geq$ 0.20%.

6 DISCUSSION

6.1 Multi-level approach

Understanding and measuring AAR distress in concrete as a function of increasing expansion

Sanchez et al. [5] proposed the use of an "extended" DRI determination on concrete affected by AAR, i.e. by also using complementary observations such as the measurements of the cracks lengths, widths, density and a complete analysis of the counts of distress features, for reliably assessing the development and progress of distress in concrete due to AAR. Sanchez et al. [5,17] thus suggested that the development of ASR cracking within concrete incorporating "quartz-bearing" reactive aggregates (e.g. greywacke, siliceous limestone, gneiss, schist, argillite, etc.) can likely be explained by the following two-step process: a), the formation of "new" cracks within the reactive aggregate particles in the early stages of the chemical reaction (including ASR "activation" of (pre-existing) closed cracks formed through aggregate processing operations), and b), the extension of the above cracks into the cement paste to form a cracking network with increasing expansion. Following the minimum energy law, it would indeed be easier for the expanding system to propagate the cracks produced through step (a) described above, instead of creating a significant number of new cracks. In other words, new cracks will always be generated as the alkali reaction keeps developing, but the amount of "new" cracks will be overcome by the increase in length and width of the cracks already formed, thus making the counts of distress features to keep increasing, but at a lower rate, with increasing expansion in the system.

This proposed mechanism is supported by the analysis of the *Stiffness Damage Index (SDI)* and *Plastic deformation Index (PDI)* indices described in Section 5.1. (Figures 1A & 1B), where SDI generally displays a "concave" increasing trend with increasing expansion. This suggests, as confirmed by petrographic analysis, that a fair amount of "new" ASR cracking is formed at low/moderate levels of expansion (e.g. 0.05 – 0.12%), mostly inside the aggregate particles, thus resulting in significant energy spent in the system (i.e. resulting in steadily increasing SDI and PDI values) to close those cracks under compressive load. As the expansion progresses (0.20% or greater), the development of new cracks within the aggregate particles stabilizes or increases at a lower rate, while existing cracks extend into the cement paste to form a network of cracks that connect progressively to each other. Moreover, these cracks also increase in length and width and become filled in by significant amounts of ASR products with progressive expansion. This phenomenon would result in the increasing trend found for the SDI & PDI parameters at the early stage of expansion, which will slow down and progressively level off as the presence of ASR gel makes the cracks more difficult to close at higher expansion levels.

Understanding how the development of AAR features of deterioration influence the mechanical properties of concretes

The extensive testing carried out in this study allowed to observe, despite some variability related to the materials characteristics, a strong correlation between the development of microscopic features of deterioration (visible on polished concrete sections at 15-16x magnification under the stereomicroscope – as by Sanchez [5]) and changes in the mechanical properties of the concrete specimens as a function of expansion due to ASR; one uses the term "ASR" here instead of AAR since the concrete mixture incorporating King limestone (which is known to develop ACR) presented different distress responses towards the expansion levels.

The next few subsections present a global analysis of test data obtained in this study on concretes incorporating a range of alkali-reactive quartz-bearing rocks (category 2 of reactive rock types according to the Appendix B of CSA A23.1-2009):

<u>Negligible damage (< 0.03% expansion)</u>

The "control" concrete specimens that were examined in this study showed "negligible" to very low levels of expansion, i.e. ranging from 0.00% up to about 0.03%. The petrographic examination of such concrete specimens identified the presence, as the main features of "deterioration", of *closed cracks within the aggregate particles*, likely originating from aggregate processing operations, as well as initiation of some ASR-related cracking. Very limited (traces), localized microcracks were observed in the cement paste, mostly unrelated to aggregate's cracking and possibly resulting from various phenomena such as shrinkage, improper/excessive consolidation, etc. Overall, those specimens had DRIs ranging from 100 to 155. The SDI obtained from those specimens ranged from 0.06 to 0.16.

<u>Marginal expansion (e.g. 0.03 – 0.05%)</u>

In the initial phases of "significant" ASR development, which correspond to the marginal/low expansion levels (between 0.03% and about 0.05%) or the *inception period* mentioned by some authors, the major distress features correspond to the development of opened cracks due to ASR within some of the reactive aggregate particles, thus resulting in a strong increase of both the SDI parameter and the DRI number. This distress feature, which has in good part developed from pre-existing closed cracks, likely results in a significant drop in the "stiffness" of the reactive aggregate particles and, moreover, of the stiffness of the concrete material as a whole. This phenomenon is likely responsible for the rapid and significant drop in modulus of elasticity (reaching up to about 40%, depending on the reactive rock type) of the ASR-affected concretes observed at low expansion levels. It is important to mention that no significant microcracking, was observed in the cement paste of the various concrete specimens examined at that level of expansion (i.e. at the magnification used for DRI);

however, it is likely that cracking has developed at the submicroscopic level in the immediate vicinity of some reacting aggregate particles, thus contributing to the drop in ME observed already at low expansion levels. On the other hand, the development of such cracking within the aggregate particles does not seem to affect significantly the compressive strength of the concretes (-10 to 15%, depending on the reactive rock type), which failure mode is more progressive by nature.

Moderate expansion (e.g. about 0.10 – 0.12%)

When the expansion progresses to moderate levels, the number/proportion of *opened cracks within the aggregate particles with and without reaction products*, keeps increasing and some "new cracks" are generated; however, the main feature characterizing this second stage of the ASR reaction is that some of the above cracks actually extend into the cement paste, affecting both the bulk cement paste in the close vicinity of the aggregate particles and some areas of the interfacial transition zone (ITZ). This results in significant increase in the SDI (about 0.15-0.31) and DRI (about 330 – 500) values, which likely explains why the affected material's "stiffness" keeps dropping but at a slightly lower rate (20 to 50% reduction in modulus of elasticity depending on the reactive rock type), as the stiffness' loss relies rather on the stiffness of the aggregates, as mentioned earlier. In terms of compressive strength loss, moderate reductions are found at this stage (0 to 20% depending on the reactive rock type), as some cracks reach the cement paste, likely damaging the bulk paste itself and the ITZ. Therefore, when concretes in that condition are loaded in compression, some ASR cracks near the ITZ could be used as "fast tracks" to initiate and propagate fracture, since they are less stiff locations/features than the ITZ.

High expansion (e.g. about 0.20%)

For high expansion levels (about 0.20%), the generation of "new" cracks within the aggregate particles and the cement paste seems to be overcome by an increase in length and width of the existing ones. Also, at this stage, the vast majority of the cracks generated within the aggregate particles have already reached the cement paste, and they start linking into cracks elsewhere larger network, which makes the DRI values to increase (500-765). The modulus of elasticity of the majority of the affected concrete mixtures keeps dropping, reaching 35 to about 60% reductions depending on the reactive rock type; however, the reductions rate slowed down significantly and even levelled off for some concretes between 0.12 and 0.20%. This suggests that the extension into a cracking network within the concrete matrix does not necessarily result in an increase stiffness loss rate. This is also highlighted by stabilized SDI values (0.19-0.32), perhaps partly due to the increasing presence of ASR products in the cracks. On the other hand, a continuing/progressive loss in compressive strength, now ranging from 10 to 35%, is observed at this expansion stage in the affected concretes. As the mechanism of fracture in compression is more ductile than the mechanism in tension, the development of cracking networks due to ASR creates instability in the system, thus resulting in progressive losses in compressive strength. This assumption agrees with the work of Kubo and Nakata [19], where important compressive strength losses were found only for concretes damaged due to ASR at expansion levels ≥ 0.30%.

Very high expansion (e.g. ≈ 0.30%; this is the maximum expansion level investigated in this study)

At this expansion level, extensive cracking is found into the cement paste with cracks largely connecting reactive aggregate particles with one another. Consequently, DRI values kept increasing up at this level, mainly from the spreading of cracking into the cement paste and the aggregate particles. Losses in modulus of elasticity has largely levelled off, reaching values of about 80%. Otherwise, compressive strength losses continue to progress with reductions of 35% or greater being observed. Therefore, from this expansion level, ASR cannot be considered just a serviceability/durability related problem since the loss in the mechanical properties of the affected materials reach important values.

7 CONCLUSIONS

As part of this study, the reliability of various tools for the damage assessment in concretes incorporating various types of alkali-reactive aggregates was investigated. Ideally, such tools should take into account the progress of the physical effect of this deleterious mechanism on the concrete material's properties through the quantification of damage features, such as cracking at the micro and macro levels, with the resulting impact these features may have on either the stiffness or the mechanical properties of the materials affected. The extensive testing carried out in this study on 35 MPa concretes incorporating various aggregate types (i.e. fine vs. coarse aggregates) and natures (i.e. ≠ lithotypes) showed that the *Damage Rating Index (DRI)* and the *Stiffness Damage Test (SDT)* can indeed reliably provide the condition assessment of aging concrete affected by AAR through a selected number of critical output parameters. Moreover, the multi-level assessment coming out of the link between microscopic and mechanical tools can thus facilitate the understanding of the global ASR distress process.

Figures 1 to 3 show strong correlations between ASR expansion and the mechanical and microstructural data (multi-level assessment) obtained for all the concrete mixtures (i.e. ≠ aggregate types/natures) investigated in this study. Similar "damage patterns", which are represented by the presence of "strong data envelopes", were indeed found in each of the parameters studied (e.g. SDI, PDI, DRI number, ME or CS). Exceptions are found for two mixtures discussed previously: King + Lav and Pots + Lav. The identification of cracks in the Pots reactive aggregate particles was particularly a challenge considering the petrographic characteristics of that medium-grained siliceous sandstone, which might have distorted the results achieved in the DRI. In the case of the reactive King aggregate, which is susceptible to alkali-carbonate reaction (ACR) in concrete, largely different microscopic features of deterioration characterized by large amounts of cracking within the cement paste and somewhat limited cracking in the aggregate particles were obtained, resulting in greater DRI values against increasing expansion than typical alkali-silica reactive aggregates. This reaction still needs to be further studied in terms of either chemical or distress development.

8 REFERENCES

[1] Fournier, B, Bérubé, MA (2000) : Alkali–aggregate reaction in concrete: a review of basic concepts and engineering implications. Canadian Journal of Civil Engineering, 27 (2): 167-191.

[2] Bérubé, MA, Smaoui, N, Bissonnette, B, Fournier, B (2005) : Outil d'évaluation et de gestion des ouvrages d'art affectés de réactions alcalis-silice (RAS). Études et Recherches en Transport, Ministère des Transports du Québec, Septembre, 140 p.

[3] Fournier, B, Bérubé, MA, Folliard, K, Thomas, M (2010): Report on the diagnosis, prognosis, and mitigation of alkali-silica reaction (ASR) in transportation structures. US Department of Transportation, Federal Highway Administration, Publication FHWA-HIF-09-004.

[4] Sanchez. LFM, Fournier. B, Jolin, M, Bastien, J (2014) : Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to ASR: test loading and output responses for concretes incorporating fine or coarse reactive aggregates. Cement and Concrete Research, (56): 213-229.

[5] Sanchez, LFM (2014): Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction, PhD thesis, Department of Geology and Geological Engineering, Université Laval, Québec.

[6] Giaccio G, Zerbino, R, Ponce, JM, Batic, R (2008): Mechanical behaviour of concretes damage due to ASR. Cement and Concrete Research. (38): 993-1004.

[7] Crisp, TM, Waldron, P, Wood, JGM (1989): Development of a non destructive test to quantity damage in deteriorated concrete. Magazine of Concrete Research, 45 (165): 247-256.

[8] Crisp, TM, Wood, JGM, Norris, P (1993): Towards Quantification of Microstructural Damage in AAR Deteriorated Concrete. International Conference on Recent Developments on the Fracture of Concrete and Rock. September.

[9] Walsh, JB(1965): The effects of cracks on the uniaxial elastic compression of rocks.. Journal of Geophysical Research, (70): 339-411.

[10] Crouch, RS (1987): Specification for the determination of stiffness damage parameters from the low cyclic uniaxial compression of plain concrete cores. Revision A. Mott. Hay & Anderson. Special services division. Internal technical note.

[11] Smaoui, N, Bérubé, MA, Fournier, B, Bissonnette, B, Durand, B (2004) : Evaluation of the Expansion Attained to Date by Concrete Affected by ASR – Part I : Experimental Study. Canadian Journal of Civil Engineering, (31): 826-845.

[12] Smaoui, N, Fournier, B, Bérubé, MA, Bissonnette, B, Durand, B.(2004): Evaluation of the Expansion Attained to Date by Concrete Affected by ASR - Part II : Application to Non-reinforced Concrete Specimens Exposed Outside. Canadian Journal of Civil Engineering, (31): 997-1011.

[13] Villeneuve, V, Fournier, B (2012): Determination of the damage in concrete affected by ASR – the damage rating index (DRI). In: Drimalas, T, Ideker, JH, Fournier, B (editors): Proceedings of the 14th International Conference on Alkali–Aggregate Reaction in Concrete, May 20–25th 2012, Austin (Texas), 2012.

[14] Shrimer, FH (2006): Development of the Damage Rating Index Method as a tool in the assessment of alkali-aggregate reaction in concrete: a critical review. In: Fournier, B (editor):

Proc. Marc-André Bérubé symposium on AAR in concrete, CANMET/ACI Advances in concrete technology seminar, Montréal, Canada, 391-411.
[15] Grattan-Bellew, PE, Danay, A, (1992) : Comparison of laboratory and field evaluation of AAR in large dams. Proc. of the International Conference on Concrete AAR in Hydroelectric Plants and Dams, Canadian Electrical Association & Canadian National Committee of the Int. Commission on Large Dams.
[16] Thomas, MDA., Folliard, KJ, Fournier, B, Rivard, P, Drimalas, T (2013): Methods for evaluating and treating ASR-affected structures: results of field application and demonstration projects. Volume II: Details of field applications and analysis. Report FHWA-HIF-14-003, FHWA, U.S. Dept of Transportation (FHWA), November 2013, 342p.
[17] Sanchez, LFM., Fournier, B, Jolin M, Duchesne, J (2015): Reliable quantification of AAR damage through assessment of the damage rating index (DRI). Cement and Concrete Research, (67): 74-92.
[18] Sanchez, LFM., Fournier, B, Jolin M, Bastien, J (2015): Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to ASR: input parameters and variability of the test responses. Construction and Building Materials (77): 20-32.
[19] Kubo, Y, Nakata, M (2012): Effect of reactive aggregate on mechanical properties of concrete affected by alkali-silica reaction. In: Drimalas, T, Ideker, JH, Fournier, B (editors): Proceedings of the 14th International Conference on Alkali–Aggregate Reaction in Concrete, May 20–25th 2012, Austin (Texas), USA.

TABLE 1: Aggregates used in the study.

Aggregate		Reactivity	Location	Rock Type	Specific gravity	Absorption (%)
Coarse	NM	R	New Mexico (USA)	Polymictic Gravel (mixed volcanics, quartzite, chert)	2.53	1.59
	QC	R	Quebec (CAN)	Siliceous and argillaceous limestone	2.50	1.16
	Wyo	R	Wyoming (USA)	Granite, amphibolite, mixed volcanics	2.64	0.87
	Conr	R	Halifax (CAN)	Metagreywacke, shale, siltstone	2.72	0.37
	King	R (ACR)	Kingston (CAN)	Dolomitic argillaceous limestone	2.69	0.55
	Virg	R	Virginia (USA)	Metagranite	2.78	0.45
	Rec	R	Recife (Brazil)	Granite, gneiss, mylonite	2.64	0.59
	Pots	R	Montreal (CAN)	Siliceous sandstone (orthoquartzite)	2.57	1.15
	Dia	NR	Quebec (CAN)	Diabase (plutonic rock)	3.00	0.51
	HP	NR	Newfoundland (Canada)	High-purity fine-grained limestone	2.68	0.44
Fine	Tx	R	Corpus Christie (USA)	Polymictic sand (granitic, mixed volcanics, quartzite, chert, quartz)	2.60	0.55
	Wt	R	Texas (USA)	Polymictic sand (chert, quartz, feldspar)	2.60	0.40
	Lav	NR	Quebec (CAN)	Natural derived from granite	2.71	0.54

TABLE 2: example of Concrete mixture cast in this study, i.e. using the same quantity (in volume) of aggregates and paste.

Type of concrete	Concrete Mix designs: Ingredients and strengths		35 MPa [1]	
			kg/m³	L/m³
Equivalent volumes (paste and aggregates) (Base series)	Tx + HP	Cement	370	118
		Water	174	174
		Air	-	20
		Sand	790	304
		Coarse aggregate	1029	384

[1] The contents are slightly different (in mass) for mixes using different aggregates – according to their specific gravity.

TABLE 3: Testing matrix.

Mix design tested	Tests methods	Number of samples for each expansion level				
		0.00% (control)	0.05%	0.12%	0.20%	0.30%
25, 35 and 45MPa	Stiffness Damage Test/compressive strength	2	3	3	3	3
	Damage Rating Index	1	1	1	1	1
	Tensile strength test (gas pressure tension test)	2	2	2	2	2
	28, 90 and 180-day compressive strength (ASTM C1074) [1]	6	--	--	--	--
Minimum number of specimens tested for each concrete mixture = 35						

[1]See section 5.3.3

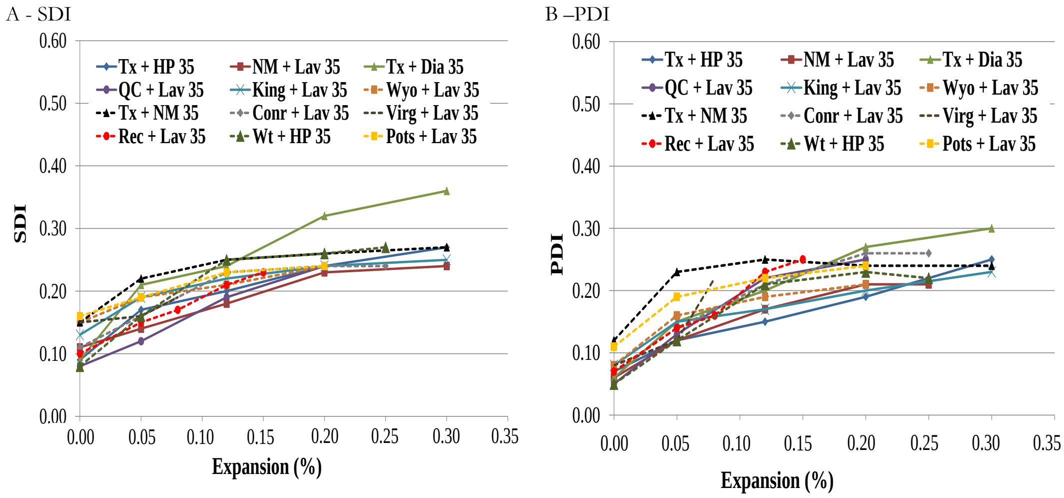

FIGURE 1: SDT parameters (SDI and PDI) as a function of ASR expansion for 35 MPa concretes incorporating a variety of reactive aggregates.

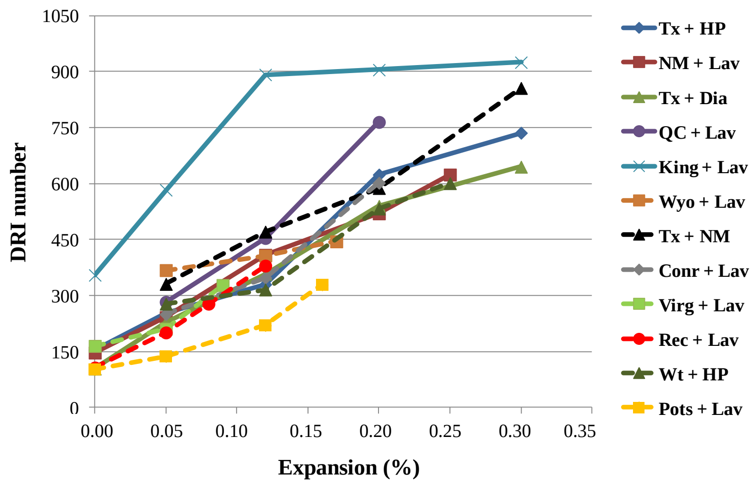

FIGURE 2: DRI numbers as a function of ASR expansion for 35 MPa concretes incorporating a variety of reactive aggregates.

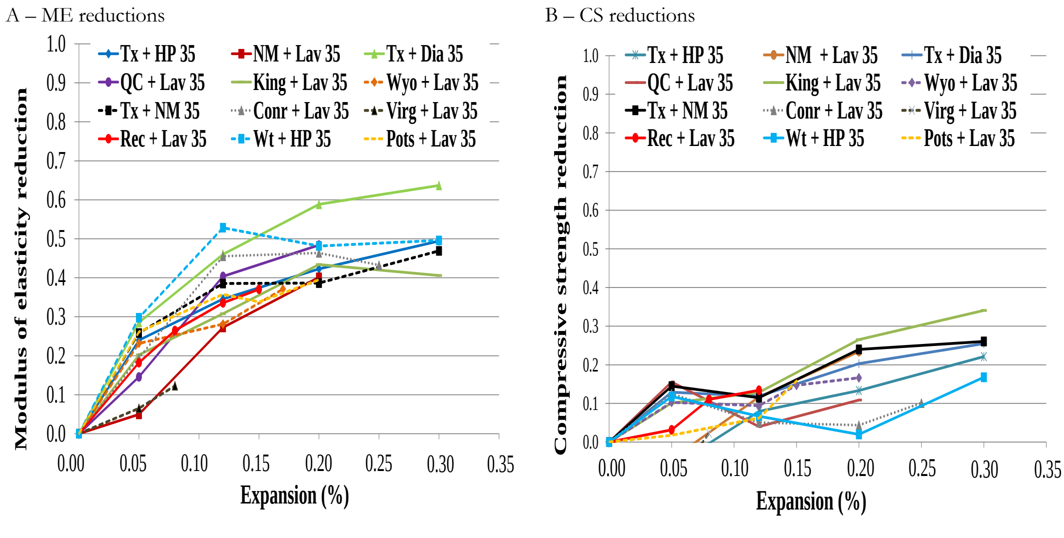

FIGURE 3: Reductions in the modulus of elasticity (ME) (A) and compressive strength (CS) (B) as a function of ASR expansion, for 35 MPa concretes incorporating a variety of reactive aggregates.