THE USE OF THE DAMAGE RATING INDEX (DRI) FOR THE CONDITION ASSESSMENT OF AGING DISTRESSED CONCRETE

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Abstract

This paper presents the results of the condition assessment of twenty concrete mixtures incorporating ten different reactive aggregates through the *Damage Rating Index (DRI)*, a microscopic and semi-quantitative petrographic tool, with the aim of verifying AAR distress development as a function of the specimen's expansion. The DRI was found to provide a reliable assessment of the degree of damage in the concretes samples incorporating reactive fine or coarse aggregates. An envelope of DRI damage assessments values against the expansion level of the affected materials is proposed. Moreover, the evaluation of a damaged aging concrete structures showed that the DRI is a powerful tool to provide the condition assessment of AAR-distressed concrete infrastructure conditions.

Keywords: alkali-aggregate reaction, crack detection, degradation, damage rating index, durability

1 ASSESSMENT OF AAR DAMAGE BY DRI

1.1 Introduction

Over the past decades, engineers and researchers have tried to develop tools and procedures to assess the current condition (diagnosis) and the potential for further expansion/distress (prognosis) of concrete damaged due to alkali-aggregate reaction (AAR), essential steps for selecting efficient methods to treat (protect, repair and/or reinforce) a structural concrete element suffering from AAR. In this context, Grattan-Bellew and co-workers [1-3] proposed the *Damage Rating Index* method (DRI), a semi-quantitative petrographic method that is increasingly being used in North America [4-6], as well as other petrographic methods [7, 8], for assessing damage in concrete.

1.2 General comments on the DRI

The DRI is a microscopic analysis performed with the use of a stereomicroscope (15-16x magnification) where damage features generally associated with alkali-silica reaction (ASR) are counted through a 1 cm^2 grid (i.e. 10 x 10 mm units) drawn on the surface of a polished concrete section. 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, for instance ASR. The factors used in the method were chosen on a logical basis, but relatively arbitrarily; they were recently modified in order to reduce the variability obtained by different petrographers performing the test [9]. Ideally, a surface of at least 200 cm^2 should be used for DRI analysis, and it may be greater in the case of mass concrete incorporating larger size aggregate particles. However, for comparative purposes, the final DRI value is normalized to a 100 cm^2 area [3].

The main goal of the DRI is not to "replace" the conventional petrographic procedures of concrete, such as ASTM C 856, which may require special techniques or tools (e.g. scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDXA), X-Ray diffraction (XRD), etc.) to assess the cause of concrete distress. The DRI is rather a complementary petrographic tool aiming at quantifying the "damage degree" between different elements of a structure or as a function of time within a specific concrete member. It is also important to mention that even though the DRI has been used by several researchers, there is currently not a standard test procedure. Furthermore, although the differences between highly and mildly distressed concrete specimens are generally clear under the microscope [10, 11], there is currently no classification to separate low, moderate or high damage levels in the DRI.

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2 SCOPE AND OBJECTIVES OF WORK

Sanchez [12, 13] used the DRI for assessing the progress of damage in concrete mixtures incorporating an alkali-silica reactive fine aggregate from Texas and a reactive coarse aggregate from New Mexico. However, according to the information available in the literature, the use of different reactive aggregate types in concrete can generate different reaction kinetics and physical features of deterioration as a function of expansion. Therefore, a study incorporating a wider range of reactive aggregates was carried out to further understand the mechanisms of damage generation in concrete due to AAR, and to confirm the efficiency of the DRI as a tool to quantify this damage. Moreover, comparisons between the results found in the laboratory and in concrete cores extracted from ASR-affected structures are needed in order to verify the DRI efficiency in providing the condition assessment of aging infrastructure.

3 MATERIALS AND METHODS

3.1 Materials and mixture proportions

Twenty concrete mixtures of different strengths (i.e. 25, 35 and 45 MPa) and incorporating ten different aggregate types with a proven reactive history in field structures were made in 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, including the lithological composition of the aggregates. In the case of the polymictic gravels, the reactive rock types are highlighted in bold. The reactive material in the aggregates selected corresponds to micro-to cryptocrystalline quartz. In the case of the Postdam aggregate, the epitaxial siliceous cement surrounding the well-rounded quartz grains of the sandstone was found to be the reactive component. All of the 20 concrete mixtures were designed to contain the same volume of paste and aggregates, i.e. from one mix to another, regardless of the mixture strength, so one could compare similar systems. Tables 2 and 3 illustrate the concrete mix-designs used for the 25, 35 and 45 MPa mixtures.

3.2 Testing concrete in the laboratory

Concrete cylinders, 100 by 200 mm in size, were cast from each of the twenty 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 cut in two axially and then one of the flat surfaces 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.

3.3 Methods for assessment and analysis

The Damage Rating Index was determined according to the procedure proposed by Villeneuve & Fournier [9]. The original DRI proposed by Grattan-Bellew and co-workers [1-3] was developed to evaluate damage in concrete induced by coarse reactive aggregates. In this study, concrete specimens were made with coarse and fine reactive aggregates. Thus, crack counts were acquired on particles ranging from 1 to 20 mm in size. Particle lithologies and their internal (mineral) grain sizes varied substantially from one aggregate type to another, which could potentially affect cracking behaviour and consequently DRI data. Moreover, since it has been found that the coefficient of variation (in percent; defined as the difference between the two specimens divided by their average) found for concrete cast in the laboratory and presenting the same mix-design was fairly low as by [12, 13] (within ±10%), DRI assessments were carried out on one single polished section of 100 cm² only.

4 RESULTS

Figure 1 illustrates the DRI numbers obtained for all concrete mixes as a function of ASR expansion. A good correlation is observed between the semi-quantitative DRI numbers and the expansions attained in the various test specimens cast from the 25 to 45 MPa concretes. Fairly linear correlations were indeed generally observed in the case of the 25 and 35 MPa mixtures. A slightly different behaviour was however noticed at low expansion levels for the 45 MPa concrete mixtures where almost no difference was found between the DRI numbers obtained for expansion levels of 0.05% and 0.12%. This suggests that a significant degree of damage, actually higher than that obtained for the 25 and 35 MPa concretes, has developed due to ASR at relatively low expansion (i.e. 0.05%) in the 45 MPa concretes. The above level of deterioration, however, remains stable up to 0.12% for 45 MPa mixtures, while increasing almost similarly to the other mixtures after about 0.12% expansion levels.

Overall, the greater the level of AAR distress/progress, the greater is the DRI number obtained in the concrete specimen. Moreover, even though the results varied according to the aggregate types and natures, very similar trends were observed from one aggregate to another, which indicates that the global distress behaviour measured by the DRI could be considered the same. Different mechanisms of damage development were however obtained for King + Lav and Pot + Lav concretes. In the King + Lav case, several cracks were identified in the cement paste already for low and moderate expansion levels (0.05% - 0.12%), which resulted in significantly higher DRI results outside of the envelope obtained for ASR aggregates. This so called alkali-carbonate reaction (ACR), which still causes many conflicts and debates in the scientific community [14], showed in this work to be completely different from the other common ASR mechanisms in terms of development of distress features at each expansion levels analysed. Otherwise, an opposite behaviour was obtained in the case of the Pots + Lav concrete. It was indeed extremely difficult to identify cracks both in the aggregate particles and in the cement paste of those ASR-affected specimens. Therefore, the total counts of petrographic features of deterioration were much lower than those found for the other concrete mixtures at similar expansion levels, which explains the significantly lower DRI values thus obtained (i.e. under the envelope). Interestingly, despite lower values, the progress of DRI values as a function of expansion remained similar to that obtained with the other alkali-silica reactive aggregates (curve somewhat parallel to the envelope).

Finally, the following DRI ranges were obtained for the various ASR aggregates studied (excluding King aggregate):

- *Control specimens*: DRI values between about 100 and 165;
- *Expansion of 0.05%:* DRI values between 200 and 350;
- *Expansion of 0.12%:* DRI values between 300 and 500;
- *Expansion of 0.20%:* DRI values between 500 and 700;
- *Expansion of 0.30%:* DRI values between 600 and 850.

4.1 Cracking features/characteristics for ASR

Figure 2 illustrates the typical crack features identified in most of the concretes incorporating the different ASR aggregate types used in this work. Actually, these features of "damage" were already identified by Bérard and Roux [15]. Disregarding the aggregate lithotypes and for the vast majority of the concrete mixtures evaluated in this work, the following two different ASR distress features were observed within the reactive aggregate particles:

- Peripheral or "onion skin" cracks (Figure 2A), likely due to diffuse reactions leading to swelling of the bulk reactive aggregate particle and;
- Internal or "sharp" cracks (Figure 2B), caused very likely by internal reactions leading to cracks formation within the aggregate particle, filled or not with gel.

5 DISCUSSION

5.1 AAR damage vs. DRI measurements: what are we really measuring?

First of all, to evaluate the DRI as a tool to quantify damage in concrete due to AAR, it might be interesting to first define the word *damage*. In a generic way, damage can be defined as the harmful consequences (measurable ones) of various types of mechanisms (e.g. loadings, shrinkage, creep, ASR, DEF, freezing and thawing, etc.) on the mechanical properties, physical integrity and durability of a concrete element/material. Thus, in practical terms, damage can be considered as: 1) the stiffness reduction of the concrete material, which is measured by the modulus of elasticity (ME); 2) the mechanical properties reductions (i.e. tensile and compressive strength) of the concrete material and; 3) the physical integrity loss of the affected material, which is directly linked to its durability related issues. Therefore, this study is intended to evaluate the reliability of the DRI to act as a tool for specifically assessing the "physical integrity loss" (i.e. extent of internal cracking or crack density) in concrete due to AAR.

In the previous sections, a correlation has been established between the internal cracking development due to AAR (DRI number) and the expansion induced in various AAR-affected concrete specimens. Although not a direct/full indicator of damage, expansion was selected here as the basis for comparing the development of physical distress in the above concretes through the use of the DRI.

The results presented so far suggest that the DRI, through the last version proposed by [8], can reliably assess the development of "distress" (i.e. internal cracking) in various types of concrete (i.e. 25, 35 and 45 MPa, coarse and fine reactive aggregates, ≠ lithotypes) as a function of AAR increasing expansion. In addition, the data suggest that the weighing factors proposed by [9], in addition to contributing at reducing variability between operators, actually contribute at reliably assessing the progress of the harmful chemical reaction as a function of expansion due to AAR. However, since a grid composed of 1 cm^2 squares is drawn on the polished concrete specimens in order to enable the distress features counting for DRI assessment, this survey takes into consideration not only the counts of cracks, but also indirectly their length, as the same cracks present in adjacent squares would be counted twice or several times instead of once depending on their extent. Therefore, the DRI measurement of the concrete's "damage degree" (or reaction progression) may represent, in certain cases and especially for higher AAR expansions, both the number of cracks and the ***importance*** of those cracks, represented by either the crack's lengths or the weighing factors proposed for the method.

On the other hand, although the DRI analysis through the use of square grids could reliably state the damage degree of a concrete sample, this procedure provides limited information towards the understanding on how AAR develops itself as a function of concrete expansion. This can be rather assessed through the analysis of the damage development within individual aggregates particles. For instance, Figure 3A compares the counts of closed cracks (CCA) and opened cracks (OCA) in reactive sand particles divided by the total number of sand particles analysed in 25 MPa concrete specimens of different expansion levels. On the other hand, Figure 3B compares the counts of opened cracks (OCA) in reactive coarse aggregate particles divided by the total number of coarse aggregate particles analysed in 25 and 35 MPa concrete specimens of different expansion levels. The above data suggest that the development of cracking within reactive aggregate particles is actually not linear as a function of concrete expansion, the relationship showing a concave shape, close to a logarithmic function. These results agree with the data obtained by [16], who moreover found that the distress vs. expansion relationship depends on the reactive aggregate particle size. This phenomenon can likely be explained by the following two-step process: a), the formation of new cracks in the early stages of the chemical reaction, and b), since all mechanisms are governed by the minimum energy law, once the cracks formed in the early stages of the reaction reach a given critical length and width, it is then easier for the expanding system to propagate those cracks instead of creating new ones. In other words, new cracks will always be generated as the alkali reaction progresses, but the amount of "new" cracks will be overcome by the increase in length and width of the cracks already formed. On the other hand, the behaviour of the CCA towards expansion in the affected concrete was quite different (Figure 3A). The proportion of closed cracks within fine reactive aggregate particles was found to decrease with increasing expansion up to 0.12%, which suggests that some of those cracks are "taken over" by the alkali-reaction. This trend keeps progressing up to the point when new closed cracks form within the reactive particles, which possibly demonstrates the action of the overall pressure generated by ASR within the concrete matrix.

5.2 Models of damage generation due to AAR

Based on the analysis of the qualitative descriptions and DRI numbers presented before, the following qualitative damage model of ASR development against expansion in concretes incorporating alkali-reactive quartz-bearing rocks (category 2 of reactive rock types according to the Appendix B of CSA A23.1-2009) [17] is proposed (Figure 4). Note that the expansion levels mentioned in the various steps of the proposed model are not absolute values but rather used as indicative only. Also, it is good to mention that King + Lav mix, which presented a completely different distress pattern, is not covered in this model and will be discussed separately afterwards.

- At low expansion levels (i.e. around 0.05%), Type A cracks and Type B cracks can be found in the aggregate particles. Type A cracks are *sharp cracks* that could correspond to closed cracks produced through aggregate processing operations or weathering, or more porous zones in the aggregate particles. Such zones would facilitate the penetration of the highly alkaline pore solution, and thus a faster reaction process happens compared to other areas of the bulk aggregate particle. This crack type is often formed according to the aggregate's characteristics, being generated either in the bulk aggregate volume or in the aggregate's periphery, as illustrated by Figure 2 and 4. In addition, in sedimentary or metamorphic rocks, cracks of the A Type could form preferentially along the bedding or metamorphic layering through aggregate processing operations. On the other hand, Type B cracks or *onion skin* cracks could be formed in the aggregate particles that do not present a pre-existing closed cracked/porous zone. The pore solution penetration is thus quite homogeneous and the crack's feature would be almost parallel (peripheral) to the aggregate's boundary. At this level, both crack types are found inside the aggregate particles and it is unlikely to find cracks in the cement paste extending from aggregate's cracking. Moreover, it is quite unusual to notice the presence of gel at this expansion level (at least at the magnification used for DRI observations - ≈ 16x);

- At moderate expansion levels (from 0.10 - 0.12%), the cracks described above start growing and some Type A cracks start reaching and extending, but to a limited extent, into the cement paste. However, the type B cracks continue their development inside the aggregate's boundary. At this expansion level, the presence of ASR gel is noticed (mainly in the opened cracks in the aggregate particles);
- At high expansion level (e.g. 0.20%), Type A cracks typically extend into the cement paste and can actually reach the cement paste on both sides of the aggregate particle. Type B cracks are likely to have enveloped more than a half of the aggregate particles at this point. In addition, the presence of ASR gel is generally found in both the aggregate particles and the cement paste of affected specimens, and its amount depends on the aggregate's nature and concrete characteristics.
- At very high expansion levels (e.g. ≥ 0.30%), type A cracks link to other cracks formed at other location in the concrete, either due to ASR within adjacent reactive aggregate particle or non-reactive aggregate particles or the cement paste resulting from ASR pressure developing within the concrete matrix, as described in the previous sections. A more or less extensive network of cracking will then link several aggregate particles to each other. On the other hand, type B cracks can extend into the cement paste at some locations. These cracks either extend into the interfacial transition zone (ITZ), which may cause the debonding of the aggregate particle, or into the bulk cement paste to link to the cracking network. Moreover, the amount of ASR gel found in either the cement paste or the aggregate particles is greater than that observed at the 0.20% expansion level.

It is important to mention that both Type A and B cracks will not necessarily be present simultaneously in all reactive aggregate particles, and that a particular crack type may be forming preferentially in some rock types, depending on their nature. Crushed aggregates may be more prone to the formation of Type A cracks considering the processing operations that can induce additional internal cracking prior to their use in concrete. The presence of layering in sedimentary/metamorphic rocks may also significantly control cracking shape in the aggregate particles. In the case of gravel aggregates, both types of cracking could be observed depending on the extent of the processing operations and of the rock composition/properties. In the NM gravel, Type B cracks typically form in the highly reactive rhyolitic aggregate particles.

In the specific case of the King + Lav aggregate combination, where a somewhat different chemical reaction is involved (i.e. so called *alkali-carbonate reaction* – ACR), the distress pattern was indeed largely different. In the early stages of the chemical reaction and for low expansion levels (i.e. 0.05%), some closed cracks along with minor opened cracking in the aggregate particles were observed. However, significant cracking without gel is already present in the cement paste, mainly at the Interfacial transition zone (ITZ). For moderate expansion levels (i.e. 0.12%), the network of cracking keep increasing in the cement paste up to a point where a very important crack density is observed in the concrete specimens. Likewise, few opened cracks are also generated in the aggregate particles. For higher expansion levels (i.e. 0.20% or more), the features already found for 0.12% level keep progressing, increasing their lengths and widths and some debonding of the aggregate particles is seen.

5.3 Practical use of the DRI for assessing damage in concrete cores extracted from concrete structures

In recent years, the DRI has been used for assessing concrete damage in cores extracted from aging concrete infrastructure [11, 18]. However, there is no much data correlating results obtained in the laboratory with those obtained from concrete cores. Likewise, the qualitative model presented before has never been applied to assess the extent of ASR distress in "real concrete" elements. Therefore, this evaluation is required prior to the practical DRI application for engineering purposes.

Furthermore, understanding sample size and representativeness is of key importance for the correct interpretation of DRI data on (damaged) field concrete. For reasons of practicality, the maximum dimensions of cores extracted from a field structure are limited, as is the total number of cores for financial (as well as concrete-structural) reasons. Meanwhile, statistically reliable assessment of bulk aggregate demands examination of a minimum number of particles, primarily defined by the abundance in vol. % relative to bulk of the (reactive) species of interest. The number of aggregate particles comprised in a prepared concrete specimen surface is inversely related to particle size and interspacing. Thus, the DRI data obtained on sample material with limited representativeness must be critically considered, cautiously interpreted, and conservatively extrapolated.

In order to verify, compare and validate the DRI as a reliable and efficient tool for the condition assessment of aging concrete, analyzes were carried out on concrete cores extracted from the foundation blocks of an ASR-affected overpass (Robert-Bourassa/Charest), located in Quebec City, Canada [19]. The structure was built in 1966 using a dark-grey, fine-grained Ordovician limestone that was later recognized as alkali-silica reactive. Technical reports stated that the concrete of the foundation blocks was designed to reach 24 MPa at 28 days. Several cores, 100mm in diameter, were extracted, adjacent to each other to reduce variability, from both the exposed (end portions) and protected portions (i.e. under the bridge deck) of the foundation blocks supporting the Y-shaped columns of the structure. Likewise, analyzes were performed on the cores as a function of their depths from the surface. Once extracted, the specimens were stored in the laboratory, prepared (i.e. cut axially and polished) and thus the DRI was determined. Figure 5 illustrates the results obtained.

The DRI charts confirmed that the cores extracted from exposed zones presented greater degree of damage than that obtained for the cores extracted from non-exposed zones. Moreover, the "surface" cores (50-250 mm) of both zones (exposed and non-exposed) showed greater damage than the "internal" specimens (250-450mm). In both cases (i.e. exposed or not), it is very interesting to note that higher numbers of *Opened Cracks in the aggregate particles (OCA)* as well as *Cracks in the Cement Paste (without (CCP) and with (CCPG) gel)* are generally observed in the surface portions of the cores compared to the internal portion of the specimens. The above features are definitely indicative of the extent of ASR in the core specimens. Briefly, the results found can be summarized as hereafter:

- 1075 - exposed and surface;
- 975 - exposed and core/internal specimens;
- 800 - non-exposed and surface;
- 700 - non-exposed and core/internal specimens.

If one compares the "field" results with those obtained in the laboratory, first of all one notices that they are quite comparable (since the order of magnitude obtained was quite similar), which seems to demonstrate that the DRI numbers found in laboratory specimens could be used as guidelines for values obtained in field concrete, despite the differences normally expected for field concrete (e.g. greater variability, ≠ curing and environmental conditions, ≠ load, stress field and restrains conditions, etc.). Moreover, going through Figure 4 and using the laboratory assumed values to find the probable expansions attained in the field, the following degrees would be the following: a) ≈ 0.45 for exposed and surface cores; b) 0.40 for exposed and internal cores; c) 0.35 for non-exposed and surface cores and; d) 0.30 for non-exposed and internal cores. The above results are considered quite consistent and logic since the cores extracted from the foundation blocks presented very important signs of distress (greater than the 0.30% specimens cast in laboratory) and also crack features/patterns that resembled those found for 0.30% expansion specimens, according to the qualitative model (Figure 4). These results demonstrate that although different, damage in field concrete behaves similarly to damage in concrete cast in the laboratory.

6 CONCLUSIONS

The main objective of this study was to assess the condition, as a function of expansion, of different types of concretes (25 to 45 MPa) incorporating a wide range of reactive aggregate types, using a semi-quantitative petrographic method, the *Damage Rating Index* (DRI). The method was then applied to concrete cores extracted from an ASR-affected overpass to evaluate its efficacy in determining the condition of the above structure. Such investigations were also used to better understand AAR-related damage generation and development as a function of expansion in the concrete specimens. The main conclusions from the above investigations are as follows:

- The DRI number can provide a reliable assessment of the degree of expansion in AAR-affected specimens when the deleterious reaction comes either from a reactive sand or a reactive coarse aggregate. However, the use of the DRI number only do not give further information about the exact nature/cause of the specimen's damage;

- A similar progress in DRI values, as a function of expansion, was observed for concretes of different strengths or incorporating different reactive rock/aggregates types, which allowed obtaining an envelope of DRI results against the expansion level of the concrete specimens. However, exceptions could be seen for an alkali-carbonate reactive rock (King) and a siliceous sandstone (Pots), which displayed somewhat different reaction mechanisms or kinetics than that observed for most other reactive quartz-bearing rocks investigated;
- For the aggregates investigated, no significant differences in the development of petrographic features of deterioration were observed between 25 and 35 MPa concretes at similar expansion levels. However, the cracking pattern was more difficult to identify and also seemed slightly different for the 45 MPa mixtures, especially in the early stages of the chemical reaction where damage degrees higher than that observed in the 25 and 35 MPa concretes were obtained. Moreover, the presence of gel was found to be greater for 45 MPa concrete mixtures for all expansion levels;
- For all alkali-silica reactive aggregates investigated, the counts of opened cracks in the aggregate particles, as well as cracks in the cement paste, with and without gel, increased with increasing expansion in the test specimens. They were found to be indicative petrographic features of the development of AAR in the concrete specimens. Opened cracks are likely to develop inside the reactive aggregate particles in the early stages as a result of the chemical reaction process and initiating from closed cracks induced through aggregate processing operations. With the progress of ASR, the number and importance (i.e. length and width) of those opened cracks increase and cracks formed inside the aggregate particles extend into the cement paste for higher expansion levels (≈0.12%). Exceptions were seen for the mixture King + Lav where a largely different damage pattern was found for all the expansion levels studied (this aggregate is supposed to generate alkali-carbonate reaction – ACR);
- A model for the development of ASR damage in concrete as a function of expansion in concrete was defined, mainly based on two cracking types commonly found in the concrete specimens. *Sharp* (Type A) and/or *Onion skin* (Type B) cracks were found to form in the aggregates particles in the early stages of the reaction, then extending into the cement paste with increasing expansion to eventually connect reactive aggregate particles in an extensive cracking network. Type A and Type B cracks are not necessarily present at the same time in the affected aggregate particles. Their presence will be a function of rock type characteristics;
- A different pattern of damage generation is observed with the alkali-carbonate reactive aggregate King. In this case, extensive cracking in the cement paste develops in the early stages of the reaction/expansion process, with cracking also developing, but to a lesser extent, within the aggregate particle;
- The petrographic investigations carried out in this study suggest that the development of cracking within individual alkali-silica reactive aggregate particles do not follow a linear pattern as a function of expansion in concrete. It is proposed that a significant number of new cracks will form in the early stages of the chemical reaction until some of them reach given critical length and width. Following the minimum energy law, it will then be easier for the expanding system to propagate those "critical" cracks instead of creating new ones. Thus, the rate of crack generation within the aggregate particles will start slowing down until very large expansion levels are reached;
- Analyses of field concrete cores extracted from an ASR-affect overpass showed that the DRI is a promising tool for providing the condition assessment of aging concrete. Moreover, the DRI numbers found for laboratory specimens were found to be useful guidelines to be used in the analysis of field concrete.
- Finally, a comparative analysis of the impact of ASR on the mechanical properties of concrete, as a function of expansion, and the development of petrographic features obtained through the DRI is in progress to confirm the reliability of the latter as a global damage assessment tool for ASR-affected concrete structures. In addition, the use of the tool for assessing different distress mechanisms such as freezing and thawing, delayed ettringite formation, etc. would be an asset in order to provide a global applicability for the tool.

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TABLE 1: Aggregates used in the study.

Aggregate		Reactivity	Location	Lithological composition [2]	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/**gneiss**, amphibolite, **mixed volcanics**	2.64	0.87
	Conr	R	Halifax (CAN)	**Metagreywacke**, shale, siltstone, **argillite**	2.72	0.37
	King[1]	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 (CAN)	High-purity fine-grained limestone	2.68	0.44
Fine	Tx	R	Corpus Christi (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

[1] Material subject to alkali-carbonate reaction (ACR).
[2] In the case of the polymictic gravels, the reactive rock types are highlighted in bold.

TABLE 2: Concrete mixtures using the same volume of aggregates and paste (base series)

Mixtures	Materials	Quantities in mix, kg/m³		
		25 MPa	35 MPa	45 MPa
	Cement	314	370	424
	Water	192	174	157
Tx + HP	Sand	790		
	Stone	1029		
Tx + Dia	Sand	896		
	Stone	1029		
NM + Lav	Sand	714		
	Stone	1073		
QC + Lav	Sand	705		
	Stone	1068		

TABLE 3: Concrete mixtures using similar volumes of aggregates and paste (complementary series).

Materials	Quantities in the mix, kg/m³ (35 MPa)							
	Lav + Wyo	Lav + Pots	Lav + Conr	Lav + King	Lav + Virg	Lav + Rec	Wt + HP	Tx + NM
Sand	770	737	807	794	829	773	790	719
Stone	1065	1068	1060	1062	1061	1062	1029	1040
Cement	370							
Water	174							

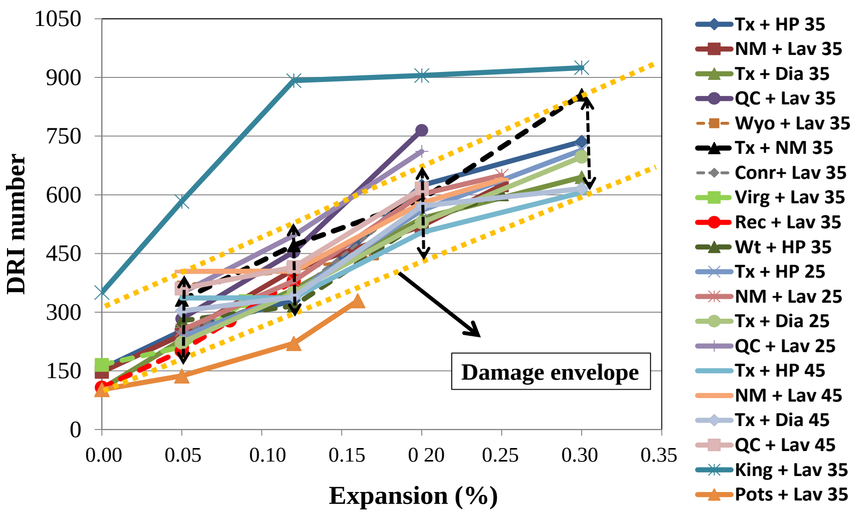

FIGURE 1: DRI numbers as a function of AAR expansion for all concrete mixes. The results are given of r 25, 35 and 45 MPa concrete mixtures.

A - Wyo + Lav, 35 MPa (0.17%) – sharp crack type B - Wyo + Lav, 35 MPa (0.17%) – onion skin crack type

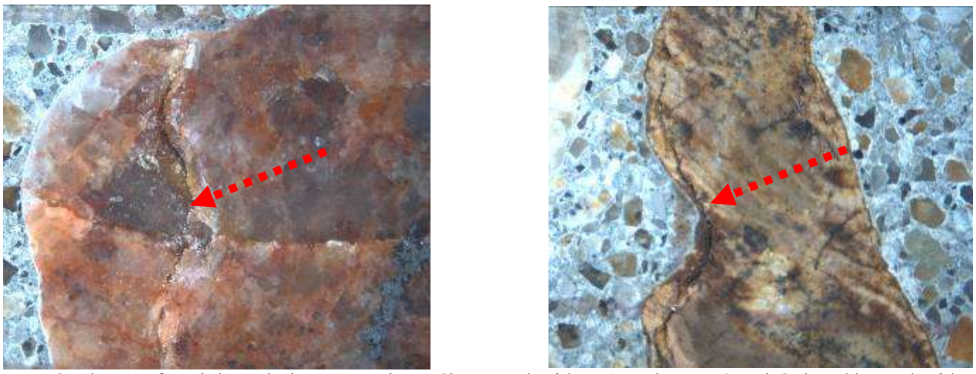

FIGURE 2: Crack types found through the DRI analyzes: Sharp cracks (Type A – Figure 2 a) and Onion skin cracks (Type B – Figure 2B).

A – Tx + HP 25 MPa mixture

B – NM + Lav, 25 and 35 MPa mixtures

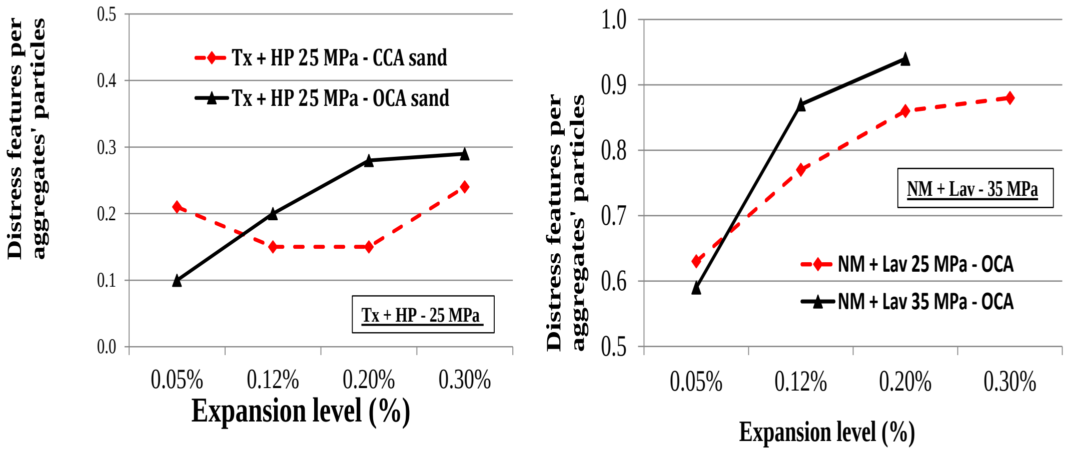

FIGURE 3: Evolution of the proportion of AAR-generated cracks (without or with reaction products) within each individual reactive aggregate particles as a function of the concrete expansion. (CCA: closed cracks in the aggregate particle; OCA: opened crack in the aggregate particle).

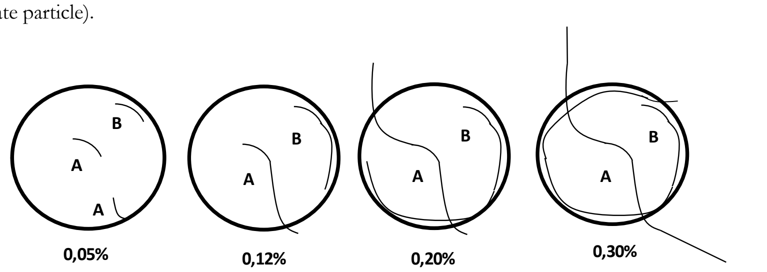

FIGURE 4: Qualitative microscopic AAR damage model vs. levels of expansion between 0.05 and 0.30%. Type A corresponds to sharp cracks, while Type B corresponds to onion skin cracks.

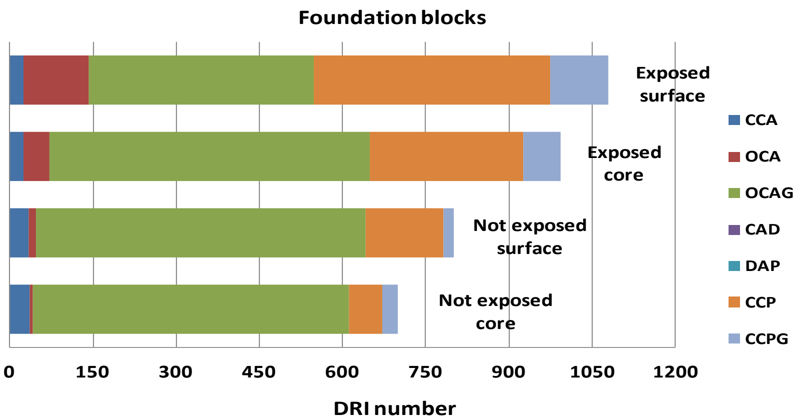

FIGURE 5: DRI charts for the cores extracted from Robert/Bourassa overpass.