Microscopic assessment of alkali-silica reaction (ASR) affected recycled concrete aggregate (RCA) mixtures derived from construction and demolition waste (CDW)

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Abstract

Construction and demolition waste (CDW) is significantly increasing over the last decades worldwide. A wide number of research has been conducted on the treatment and reuse of CDW in new concrete. The latter is expected to decrease the carbon footprint of concrete construction towards a greener future of civil engineering activities. Yet, CDW may present low inner quality, pre-existing damage or critical conditions, for example whether an alkali-aggregate reaction (ASR) reactive aggregate has been used in the CDW material. Therefore, several questions arise on whether there is a potential of further ASR-induced expansion and deterioration of ASR-affected recycled concrete aggregate (RCA) derived from CDW. This work aims assess ASR affected RCA concrete retrieved from distinct member of a demolished overpass (RBC) after nearly 60 years of service. Results suggest that the overall performance of ASR-affected RCA concrete is different from conventional affected concrete and depends on the amount, features and source of RCA material.

Keywords: *alkali- aggregate reaction (AAR); construction and demolition waste (CDW); damage rating index (DRI); expansion; recycled concrete aggregates (RCA)*

1. INTRODUCTION

Concrete is indeed the most important construction material used around the globe. Yet, it has a quite negative impact towards sustainability; according to the IPCC (Intergovernmental Panel on Climate Change), the production of every ton of cement releases around 650 kg of CO_2[1]. Portland cement (PC), likely the most important concrete ingredient, is considered to be the major responsible for the carbon footprint of the material. The global PC production in 2013 was 4.2 billion tons, which yielded 5.2 billion tons of CO_2 [2]; PC production currently accounts for 8% of the global CO_2 emissions [3]

There are numerous ways to increase sustainability and thus decrease carbon footprint of concrete construction. Amongst those, the use of recycled concrete aggregates (RCA) derived from construction and demolition waste (CDW) has been receiving increased attention [4]–[6]. Yet, RCA derived from CDW may present low inner quality, pre-existing damage or critical conditions, for example whether an alkali- reactive aggregate has been used in the CDW. Therefore, several questions arise on whether there is a potential of further ASR-induced expansion and deterioration of a mixture made of an ASR-affected RCA [7].

2. RECYCLED CONCRETE AGGREGATES (RCA)

RCA may be obtained mainly from two distinct sources: CDW and returned concrete. RCA from CDW is a product manufactured by removing, crushing, and processing existing concrete structures, while RCA from returned concrete is obtained by crushing the leftover concrete that was brought back and discharged at the concrete plant. The intrinsic difference between RCA and natural aggregates (NA) is the fact that RCA is a two-phase material comprised of the original virgin aggregate (OVA) embedded into residual mortar (RM) or residual paste content (RP) in the case of coarse or fine recycled concrete aggregates, respectively [9], [10].

The amount of RM varies according to the processing procedure performed for transforming concrete debris into aggregates and the type and quality of the OVA (i.e. lithotype, texture, shape, etc.) and RM (i.e. mechanical properties, porosity, etc.) [9], [10]. RCA concrete presents a significantly different microstructure when compared to conventional concrete (CC), which may directly affect the performance of the recycled material at both the fresh and hardened states [9], [10]. RCA particles are commonly more porous, rougher and more angular than the corresponding NAs due to the presence of the attached mortar within the particle's composition [9], [10]. Thus, RCAs are characterized by considerably higher water absorption and lower specific gravity when compared to NAs [9], [10]. Consequently, the properties of the RCAs are directly related to the amount and features of the mortar or cement paste adhered to the particles [9], [10].

3. ASR IN CONVENTIONAL AND RECYCLED CONCRETE

Alkali-silica reaction (ASR), a chemical reaction between some unstable mineral phases from the aggregates used in concrete and the alkali hydroxides from the concrete pore solution, is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide [8]. ASR generates a product that swells in the presence of water, causing volumetric expansion and leading to severe damage of the affected material such as micro/macro cracking, loss of mechanical properties and stiffness [9]. It is well known that the mechanical properties of ASR affected concrete are significantly reduced; despite elastic modulus and tensile strength that significantly drop at early stages of the reaction, compressive strength can also drop at high and very high expansion levels [8].

Conventional concrete (CC) consists of three main components: cement paste, aggregates and the interfacial transition zone (ITZ). ITZ is usually the weakest region in CC due to its higher porosity than the other two components [10]. Conversely, RCA concrete presents a complete different microstructure when compared to CC, incorporating multiple ITZs (between OVA and RM and between RCA and new cement paste) [10]. Therefore, one might expect ASR-induced expansion and damage to be different in recycled concrete made of RCA.

Understanding the potential of further deterioration of ASR-affected RCA concrete requires a comprehensive investigation on the "secondary" induced expansion along with an in-depth study on the distress propagation within the recycled material; for instance, would a new crack be generated from an originated crack from the RCA or a new crack due to the chemical exchange between the new cement paste and the OVA? Current research on ASR-affected RCA concrete verified that ASR may keep being produced under conditions enabling its development. Moreover, RCA affected mixtures were seen to require more mitigation procedures to lessen this "secondary expansion" due to ASR [11]–[13]. Yet, very few is known on the generation and propagation of cracks along with their influence on the mechanical properties of affected recycle concrete mixtures.

4. ROBERT-BOURASSA/CHAREST BRIDGE

Robert-Bourassa/Charest (RBC) overpass was a highway bridge structure (Quebec, Canada) that was built in 1966 using an alkali-silica reactive coarse limestone aggregate. RBC was made of a deck resting on reinforced concrete Y-shaped columns, themselves supported by massive concrete foundations (Fig. 4.1). No specific information is available on the concrete mix-designs; however, technical reports indicate that the 28-day concrete design strengths were 24 MPa for the foundation blocks and 28 MPa for the columns and decks. Over the last 3 decades, many signs of distress were developed on the various members of the structure. This included extensive steel corrosion and concrete delamination/spalling at the level of the deck; map cracking, scaling, disaggregation and pop-outs affecting the massive concrete foundations due to ASR and freeze–thaw (FT) cycles; and concrete spalling and steel corrosion on the columns and foundations exposed to salt-water spray from traffic on the Robert-Bourassa highway [17].

One of the central concerns regarding RBC structural long-term performance was related to the distress degree of its Y-shaped columns and thus in 2000, a number of rehabilitation techniques including surface treatments (i.e. rigid coatings, silane/siloxane based products) and structural confinement (i.e. GFRP wrapping systems) were adopted to suppress further ASR induced expansion and damage. In 2010/2011, RBC overpass was demolished, yet several concrete members (i.e. bridge deck, columns and foundation blocks) instead of being discarded were selected and processed (i.e. crushed, sieved and cleaned) to produce RCA [14].

Figure 4.1: RBC overpass after nearly 50 years in service [15].

5. SCOPE OF THE WORK

This work appraises the potential of further damage of recycled concrete made of ASR affected CDW materials. Demolished concrete from distinct RBC members (i.e. bridge deck, columns and foundation blocks) was processed to produce RCA. Then, concrete specimens proportioned as per ASTM C1293 (i.e. CPT mixtures) were manufactured in the laboratory incorporating distinct amounts of RCA (i.e. 50% and 100%) and stored in conditions (38°C and 100% RH) enabling further ASR development. A "secondary" expansion level (i.e., 0.12%) was selected for further microscopic analysis through the damage rating index (DRI) method, so that a better understanding on the overall ASR-induced development and propagation in RCA concrete might be achieved.

6. MATERIALS AND METHODS

6.1 Materials and mix proportions

Six RCA concrete mixtures displaying the same mechanical properties (i.e. 35 MPa compressive strength) and incorporating three different RCA sources (i.e. Columns – DCO; Bridge deck – DTA, and foundation blocks - DCU) were manufactured in this study as per ASTM C1293. The RCA ranged from 5 to 20 mm in size. The concrete mixtures manufactured presented either 50% or 100% of RCA. The mixes incorporating only 50% of RCA also embodied a coarse non-reactive high purity limestone (HP). A non-reactive natural sand was used for all mixtures. A conventional Portland cement (CSA Type GU, ASTM type 1) containing high alkali content (0.88% Na_2Oe) was used in all mixtures. Reagent grade NaOH was selected to raise the total alkali content of the mixtures to 1.25% Na2Oe by cement mass, for accelerating ASR-induced expansion process. The amount RM was disregarded in this study since one would like to appraise the potential of ASR further development at the "worst case scenario"; hence a direct replacement method (DRM) was adopted.

6.2 Production of test specimens

A total of three cylinders, 100 by 200 mm in size, were cast from each RCA mixture manufactured in the laboratory. After 24 hours in their mould, the specimens were demoulded and placed for over 24 hours in the moist curing room. Small holes, 5 mm in diameter by 15 mm long, were then drilled in both ends of each cylinder 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 hours prior to performing the "0" length reading; afterwards, they were placed in sealed plastic buckets lined with damp cloth. All buckets were then stored at 38℃ and 100% relative humidity and the test cylinders monitored for length changes regularly until they reached the expansion level selected for further analysis: 0.12 ± 0.01%. Once the test specimens reached the above expansion level, they were wrapped in plastic film and stored at 12°C to stop further ASR development until tests were conducted.

6.3 Methods for assessing damage

Before further analysis, the specimens were unwrapped and expansion readings were taken to confirm that no outstanding expansion (and or shrinkage) took place during the storage period. Then, the specimens were cut in two, axially, and one of the flat surfaces was polished using a standard polishing device which uses diamond-impregnated rubber disks (No 50 [coarse], 100, 400, 800, 1500, 3000 [very fine]); this device was found most suitable for the work, as it does not loose abrasive powders that can fill up cracks or voids in concrete, and high quality polishing is obtained with minimal water supply so that AAR-gel leaching is avoided. Afterwards, the DRI was performed as per Sanchez et al. [18].

The Damage Rating Index (DRI) is a microscopic analysis proposed by Grattan-Bellew and Danay whose main purpose is to appraise internal damage in affected concrete. The DRI is performed on polished concrete sections with the use of a stereomicroscope (with magnification approximately 15 to 16x) where damage features associated with a damage mechanism (i.e. ASR in this case) are counted through a 1 cm² grid drawn on the surface of a polished concrete section [16]. The damage features are then multiplied by weighing factors whose purpose is to balance their relative importance. At the end of the analysis, a DRI number is calculated; the higher the number, the higher AAR-induced damage [18]. Ideally, a surface of at least 200 cm² should be evaluated; however for comparative purposes, the final DRI value is normalized to a 100 cm² area. Over time, researchers from Laval University improved the procedure so that it might better represent "damage" in its broader sense, while reducing its subjectivity and variability amongst operators [19]. Recently, Sanchez et al. performed the DRI on concrete samples presenting a wide range of strengths and fabricated with numerous coarse and fine aggregates [20]. This work confirmed the relationship between AAR-induced expansion levels and DRI numbers. Therefore, the DRI was considered to be a very effective method for assessing AAR affected concrete [20].

7. RESULTS

7.1 AAR Kinetics

Figure 7.1 presents the average expansion (i.e. average of three concrete specimens) vs. time from all RCA mixtures manufactured in the laboratory. As one may notice, ASR kinetics and induced development are quite different depending upon the RCA source (DCO, DTA or DRU) and amount (50% and 100%) used. Results suggest that ASR development is faster in mixtures incorporating 100% of RCA material, as expected. Values of 0.12% expansion have been achieved by these mixtures within 200 days. Conversely, ASR kinetics seems much slower for mixtures containing 50% of reactive RCA material, except for the mix incorporating RCA – DCO material. Expansion levels of 0.12% were reached at 200, 241 and 373 days for DCO 50, DTA 50, and DCU 50 mixtures, respectively.

7.2 Damage appraisal

In this section, damage has been evaluated in two distinct ways for comparison purposes. First, just prior to demolition, cores from the foundation blocks, columns and bridge deck were extracted from RBC, evaluated through the DRI as per [21], and illustrated in Figure 7.2 (the DRI numbers presented herein are the average of 2 cores per member; i.e. 200 cm^2 appraised). Afterwards, RCA has been produced from the distinct RBC members and used as coarse aggregates to manufacture six new recycled and "reactive" concrete mixtures. The damage assessment of specimens from these mixtures upon reaching further 0.12% expansion is illustrated in Figure 7.3.

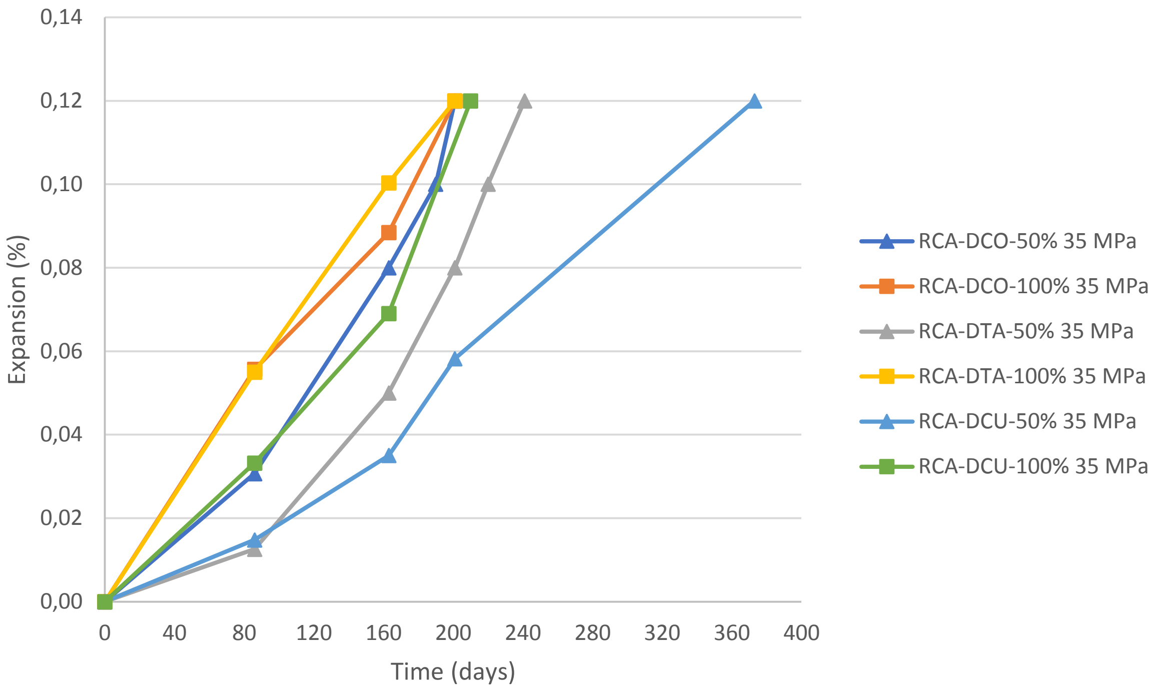


Figure 7.1: Expansion vs. time for all RCA mixtures manufactured in the laboratory.

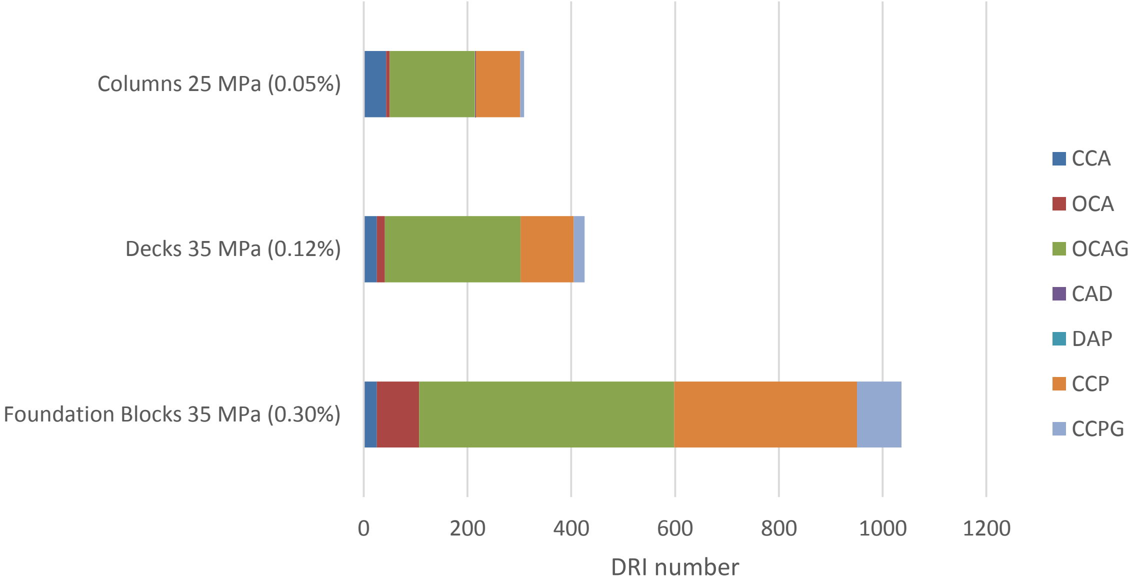


Figure 7.2: DRI charts for concrete cores extracted from the distinct RBC members.

Analyzing Figure 7.2 results, one verifies that the foundation block displays the highest distress and DRI number (over 1000) followed by the bridge deck (over 400) and the bridge column (300). These numbers would represent 0.30%, 0.12% and 0.05% expansion attained to date for these members as per [17].

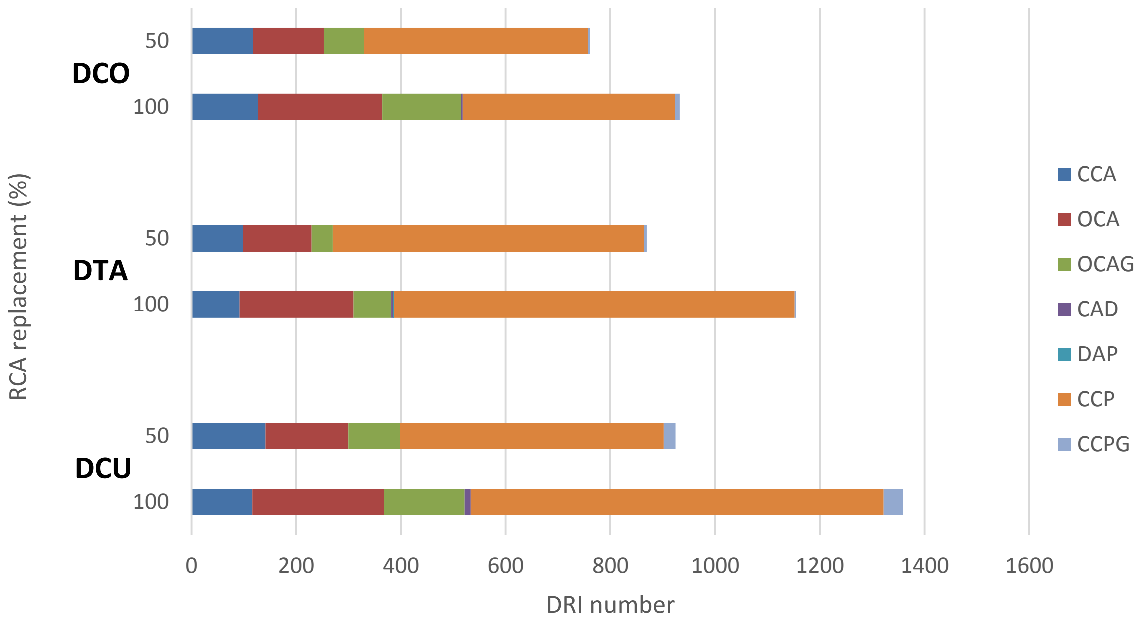


Figure 7.3: DRI charts for RCA concrete with different replacement % in 0.12% of expansion

Analyzing Figure 7.3 one notices that the DRI numbers of RCA concrete specimens incorporating 100% RCA particles is greater than specimens just presenting 50% of RCA material. Furthermore, RCA DCU specimens yielded the highest amount of damage (foundation block; 1350 and 950) followed by DTA (bridge deck; 1150 and 850) and then DCO (bridge column; 900 and 880) specimens, respectively for 100 and 50% of RCA.

Overall, all cores extracted from RBC and RCA specimens manufactured in the laboratory clearly indicate the present of ASR-induced damage since important amounts of open cracks within the aggregate particles (with and without gel – OCA and OCAG - red and green charts) along with cracks in the cement paste (with and without gel – CCP and CCP – orange and light blue charts) are observed in all of them. Yet, it seems that a much higher presence of ASR gel is found in specimens directly retrieved from RBC members. Moreover, higher amounts of cracks within the cement paste, with or without gel (CCP and CCPG; orange and light blue) are observed in recycled concrete samples when compared to RBC cores. The latter might be related to the intrinsic and distinct microstructure of the RCA particle.

To complement the above study and complete the information gathered so far, supplementary petrographic analyses were conducted according to the DRI extended version as per [6].

- Assessment of damage features in %, without considering the weighing factors (Figure 7.4) as well as maximum length and width of the open cracks (Figure 7.5) for each test specimen;
- Assessment of the crack density (i.e. total number of open cracks per area examined) for each test specimen (Figure 7.6).

Figure 7.4 presents the relative proportion of the distinct crack types observed on the RCA specimens (i.e. closed cracks within the aggregates – CCA, open cracks within the aggregates with or without gel (OCA + OCAG) and cracks in the cement paste (CCP + CCPG). It is possible to notice that between 50 and 60% of the petrographic distress features are composed of CCA, which is not necessarily an ASR-related feature and could have been generated while the crushing process of the aggregates or due to their weathering. However, about 10 to 25% of damage is observed within the aggregate particles (respectively for 50% and 100% of RCA) while about 20 to 30% is found in the cement paste. All the above indicate indeed a clear ASR development on these samples as per [19, 21].

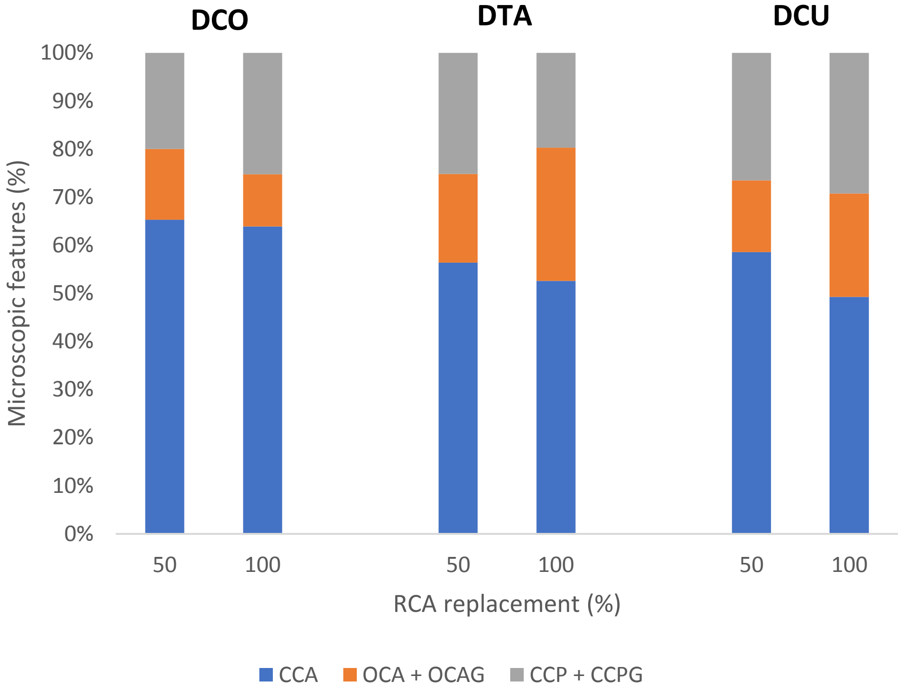
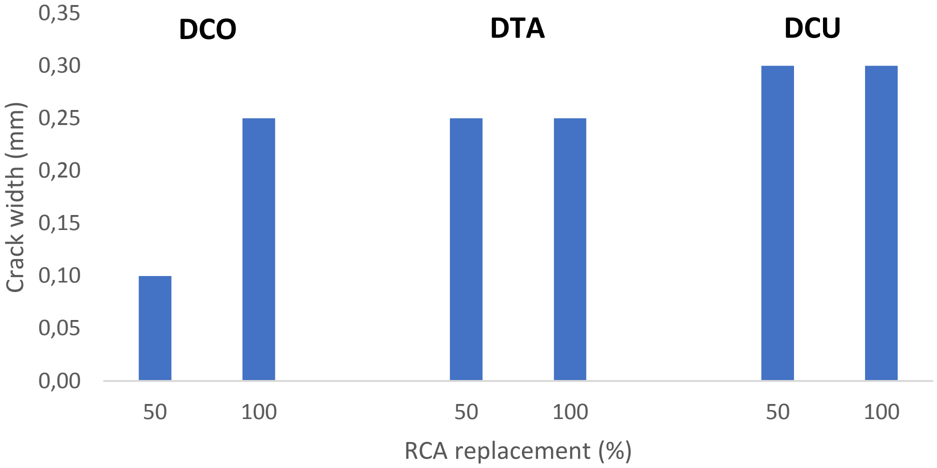


Figure 7.4: Microscopic features of deterioration (in %, without using the DRI weighing factors) normalized for 100 cm2 surface area.

Figure 7.5 illustrates the maximum crack lengths and widths observed on ASR-affected RCA concrete specimens made of RCA from the distinct RBC members. DCU specimens presented both, the highest crack lengths and widths (i.e. 25 mm and 0.30 mm), respectively for 100% RCA replacement. DTA and DCO specimens showed lower and quite close results, yielding cracks lengths and widths of about 16 mm and 0.25 mm, respectively. The above results followed the same trend when the use of 50% RCA material, yet, the values obtained of both lengths and widths were either similar or lower.

Figure 7.6 gives a plot of the crack density results (i.e. number of open cracks within the aggregates and cement paste, with and without reaction products over the examined area) of the all recycled concrete specimens. Evaluating the results, one notices that the crack density, as for the DRI number and cracks length/width, is higher for recycled samples incorporating 100% DCU material (i.e. ≈ 5 counts/cm^2), followed by 100% DTA samples (i.e. ≈ 4.2 counts/cm^2) and 100% DCO specimens (i.e. ≈ 3.5 counts/cm^2). This trend is maintained for 50% RCA replacement, but much lower values were obtained (i.e. ≈ 3.2, 3.0 and 2.6 counts/cm^2, for DCU, DTA and DCO, respectively).



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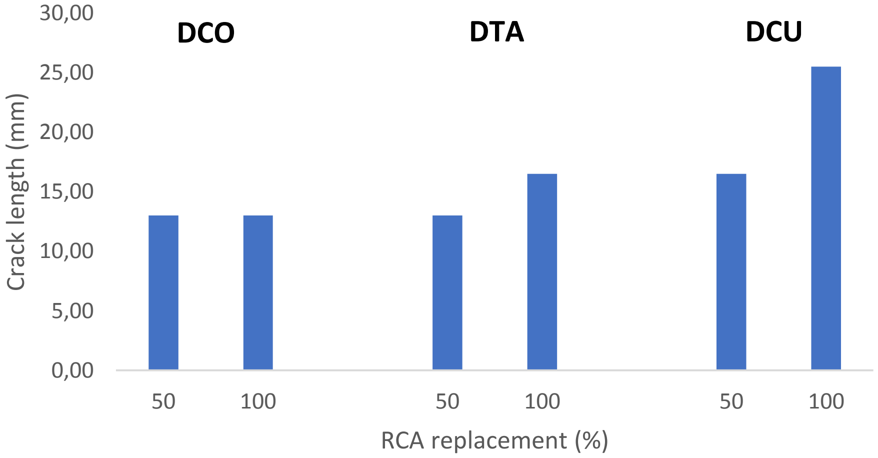


B)

Figure 7.5: Maximum length (A) and width (B) of cracking for ASR-affected recycled concrete with different replacement % RCA.

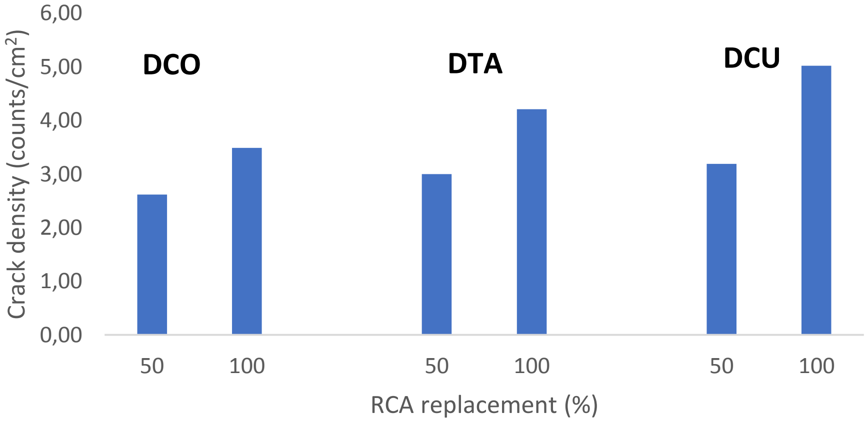


Figure 7.6: Crack density (sum of opened cracks in aggregate particles and cracks in cement paste, with and without reaction products - counts/cm2) for all RCA mixtures manufactured in the laboratory.

8. DISCUSSION

8.1 Effect of the RCA type/source on the development of ASR development

The DRI results illustrated in Figures 7.1 and 7.3 indicate that ASR-induced expansion and damage are directly related to the RCA source used in the recycled concrete. The latter seems to indicate that the expansion attained to date of the affected concrete (i.e. prior crushing) and the potential for further distress (i.e. available reactive silica) may govern the “secondary” ASR development.

In this work, a very reactive siliceous limestone from Quebec (Canada) was selected for use in the concrete mixtures used to build RCB overpass. This aggregate generates about 0.20-0.25% expansion while tested in the concrete prism test (CPT) as per ASTM C1293 [11]. Microscopic assessment of RBC members after nearly 60 years of service indicate that about 0.30%, 0.12% and 0.05% of expansion had been achieved for the foundation blocks (DCU), bridge deck (DTA) and columns (DCO), respectively (Figure 7.2). While DCU has yielded higher expansion than forecasted in the CPT (i.e. 0.20%), the other two members were expected to still present “significantly” amount of unreacted material.

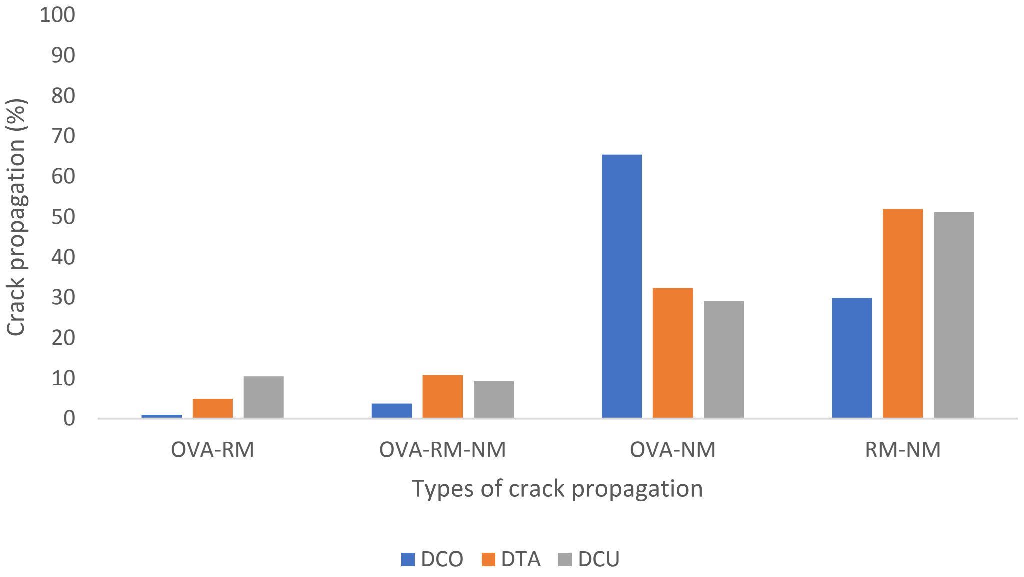
Figure 7.1 somewhat indicates the above discussion, since faster ASR kinetics was found for 100% RCA concrete made of DTA and DCO materials. The latter is even more evident for 50% RCA replacement where DCO presented the fastest kinetics, followed by DTA and DCU, which inversely agrees with the expansion and damage attained to date by these members (Figure 7.2). Yet, all the above RCA sources were still able to provide the recycled mixtures with “secondary” 0.12% expansion and the damage obtained at this stage was quite different from both the conventional cores previously appraised and from each other (i.e. as per the RCA amount and type). Further explanations are still needed in this regard.

8.2 Crack propagation of ASR-affected RCA concrete

To better understand the damage development of ASR-affected RCA concrete from distinct sources, it is important to investigate how ASR-induced cracks propagate in the recycled system. As verified in the DRI analysis (Figure 7.3), new cracks are indeed generated through the “secondary” ASR development, since higher DRI values were obtained for the recycled mixtures when compared to RBC cores. Furthermore, it has been identified four distinct types of “crack propagation” in RCA concrete: 1) cracks generated in the OVA that extend to the RM; 2) cracks generated in the OVA that extend directly to the new matrix - NM; 3) cracks generated in the OVA that extend to the NM through the RM; 4) cracks generated in the RM that extend directly to the NM.

Figure 8.1 illustrates the percentages of the aforementioned four types of crack propagation for all RCA mixtures evaluated in this study. Analyzing the plot one sees that the two main types of cracks propagation found are from the OVA to the NM and from the RM to the NM. There is very few cracks being generated/propagated in the OVA and running out to the RM or RM and then NM. Furthermore, interestingly, the OVA-NM type of cracks were more prone to happen in the DCO, followed by DTA and DCU. The latter seems to emphasize that since a greater amount of silica was still available in this RCA material, further cracks tend to be developed within the reactive aggregate (i.e. OVA) using new alkalis from the recycled system (i.e. NM). Conversely, no clear trend was observed in the RM-NM type of crack propagation, although it seems that DTA and DCU materials present higher amounts of this damage feature when compared to DCO. The latter suggests that since DTA and especially DCU had experienced much higher “previous” expansion levels than DCO, ASR-induced cracks are expected to be longer and as per [21] at this stage of the reaction, being already extended to the RM of the RCA. Hence, upon further and “secondary” expansion, these cracks tend to propagate directly from the RM to the NM. Figure 8.2 demonstrates typical distress features identified in the ASR-affected RCA concrete mixtures.

The aforementioned discussion seems to indicate that the overall damage (or DRI numbers) observed in ASR-affected RCA concrete will be greater after “secondary” expansion, yet will not increase linearly nor proportionally to the “first” ASR-induced expansion since some pre-existing cracks developed within the first expansion will be reused as fast-tracks while the “secondary” induced deterioration; this makes the DRI number to increase as a function of expansion but in a slower fashion in RCA concrete when compared to conventional ASR affected mixtures and suggest that the overall performance of ASR-affected RCA is different than conventional concrete and directly dependent on the RCA source, features and amount.



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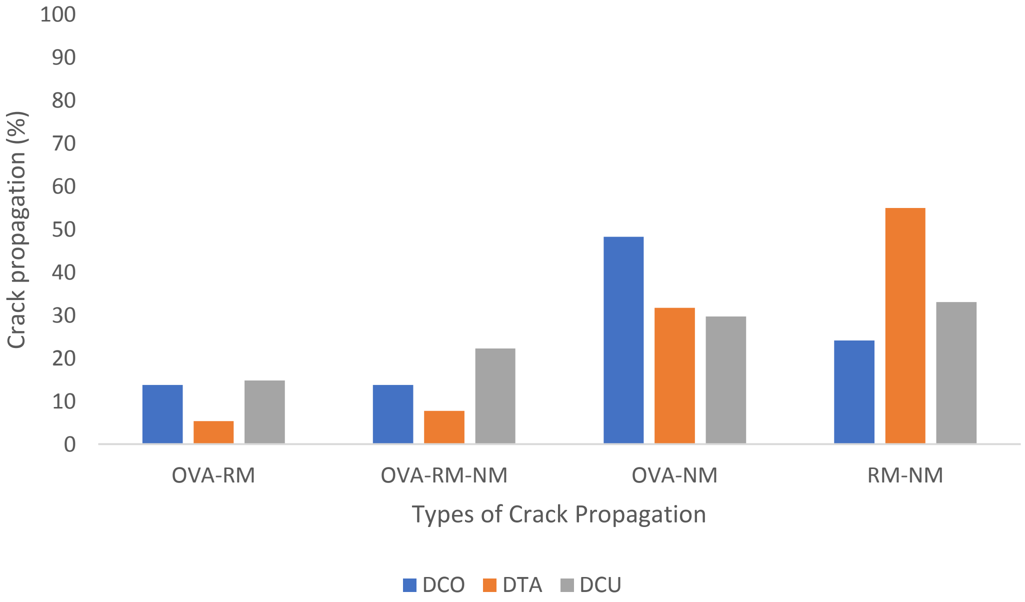
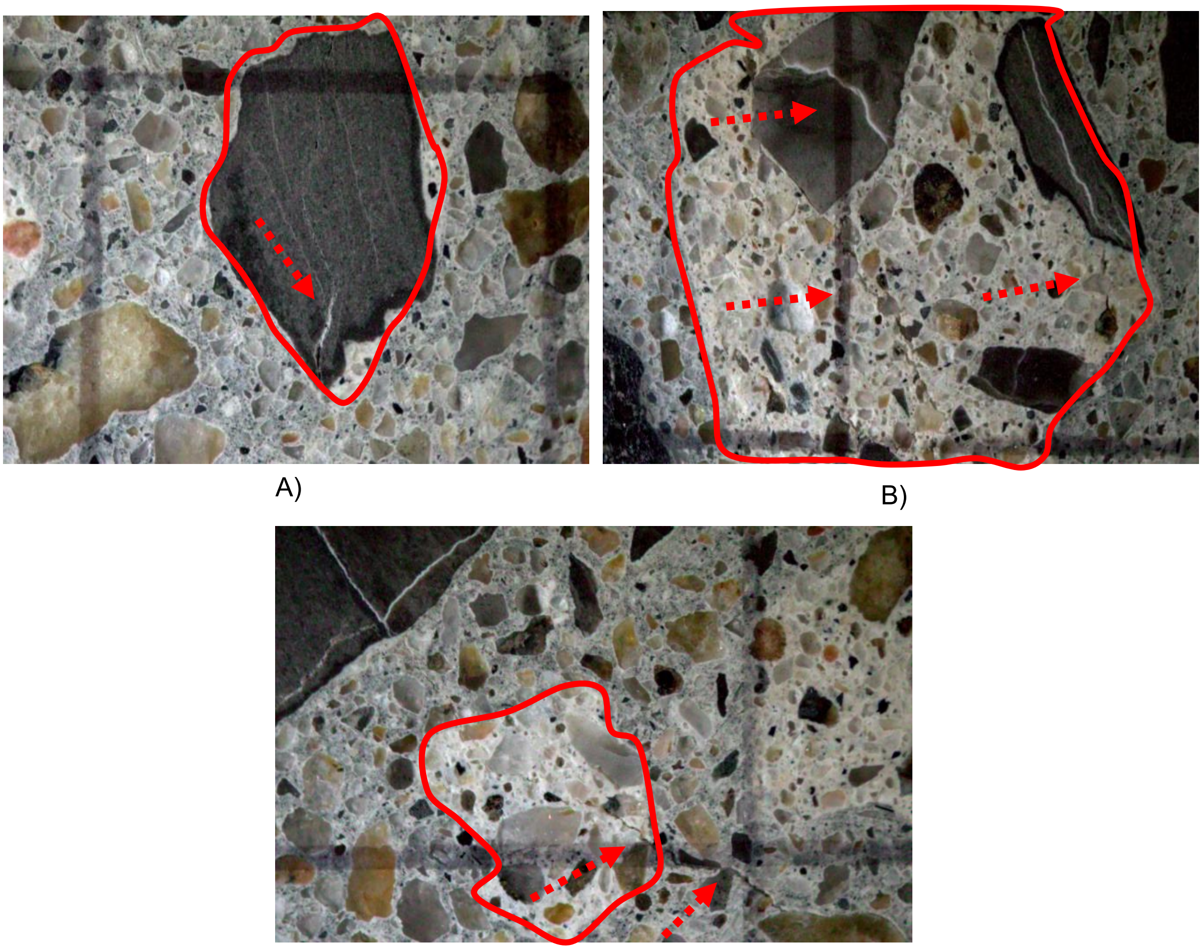


B)

Figure 8.1: Crack propagation for the RCA mixtures A) 50% of replacement B) 100% of replacement



A)

B)

C)

Figure 8.2: Typical cracking features identified in the concretes A) Open crack in the OVA with gel, B) Open crack with gel in the OVA that extend to the RM and NM, and C) Crack propagating from the RM to the NM.

9. CONCLUSION

The main objective of this study was to assess condition of ASR-affected RCA as a function of the source and amount. The main findings of the current research are presented hereafter:

- Kinetics of ASR-affected RCA concrete depends upon the RCA source (i.e. the higher the previous expansion, the slower the “secondary” ASR kinetics) and amount (the higher the RCA amount, the faster the ASR kinetics);
- ASR-induced “secondary” damage is not linear nor proportional to the first induced deterioration. The latter is likely due to the increase of pre-existing cracks within the RCA while the development of secondary expansion;
- The results gathered in this work seem to indicate that the overall performance of ASR-affected RCA concrete depends on the amount, features and source of RCA material.

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