

Assessing Condition on Alkali-Silica Reaction (ASR) Affected Recycled Concrete

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Abstract

Many highway and hydraulic structures in North America have been reported to be affected by alkali aggregate reaction (ASR). It is anticipated that most of these structures will be demolished as they approach the end of their service lives. Recycling demolished concrete as aggregates in new concrete is an option that not only reduces the amount of construction demolition waste (CDW) disposed in landfills but also lessens the consumption of non-renewable resources such as natural aggregates. However, the use of recycled concrete aggregate (RCA) in new concrete requires detailed research to make sure that the durability of the recycled material is not compromised, especially if the RCA had been previously affected by ASR. In this research project, coarse recycled concrete aggregate (RCA) is reclaimed and processed from distinct members (i.e. foundation blocks, bridge deck and columns) of an ASR-affected overpass after nearly 50 years of service. RCA concrete mixtures incorporating 50 and 100% replacement are manufactured and stored in conditions enabling further ASR development. Mechanical (i.e. Stiffness Damage Test - SDT) and microscopic (Damage Rating Index - DRI) analyses are performed at a fixed “secondary” induced expansion of 0.12%. Results show that the overall performance of the ASR-affected recycled mixtures depends upon the “past” condition of the RCA particles. Moreover, the DRI was able to capture the “past” and “secondary” induced expansion and damage of affected RCA while the SDT only detected the “secondary” distress development. Lastly, an adapted version of the DRI was proposed to further evaluate the overall damage of recycled concrete along with properly displaying “past” and “secondary” induced distress.

Keywords: Alkali-silica reaction (ASR); recycled concrete aggregates (RCA); construction and demolition waste (CDW); damage rating index (DRI); expansion; damage.

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List of Symbols/Abbreviations

AAR	Alkali Aggregate Reaction
ACI	American Concrete Institute
AMBT	Accelerated Mortar Bar Test
ASR	Alkali-Silica Reaction
CC	Conventional Concrete
CDW	Construction Demolition Waste
CO ₂	Carbon Dioxide
CP	Cement Paste
CPT	Concrete Prism Test
CRCA	Coarse Recycled Concrete Aggregates
CSH	Calcium Silicate Hydrate
DEF	Delayed Ettringite Formation
DRI	Damage Rating Index
DRM	Direct Replacement Methods
E	Modulus of Elasticity
EDXA	Energy Dispersive X-Ray Analysis
EMV	Equivalent Mortar Volume Method
EV	Equivalent Volume
FT	Freeze-Thaw Cycled
FHWA	Federal Highway Administration
FP	Fresh Paste
FRC	Fine Recycled Concrete Aggregates
GFRP	Glass Fiber Reinforced Polymer
ITZ	Interfacial Transition Zones
LA	Los Angeles
NA	Natural Aggregates
NLI	Non-Linearity Index

OVA	Original Virgin Aggregates
PDI	Plastic Deformation Index
PPMs	Particle Packing Models
PSD	Particle Size Distribution
RBC	Robert-Bourassa/Charest
RCA	Recycled Concrete Aggregates
RCP	Residual Cement Paste
RM	Residual Mortar
RP	Residual Paste
SCMs	Supplementary Cementing Materials
SEM	Scanning Electron Microscopy
SDI	Stiffness Damage Index
SDT	Stiffness Damage Test
SSD	Saturated Surface Dry
TM	Total Mortar
w/c	Water to Cement Ratio
XRD	X-Ray Diffraction

Chapter One: Introduction

1.1. Synopsis

Demolition of aging structures and their substitution by new ones, is a frequent phenomenon nowadays around the world. About 570 million tones of construction and demolition waste (CDW) are generated in the USA per year, which is more than twice the amount of generated municipal solid waste (EPA, 2017). Demolition represents more than 90 percent of total CDW debris generation (EPA, 2017). The most common method of managing this material has been through its disposal in landfills. Therefore, huge deposits of CDW have been created, consequently becoming a serious problem for the society in general. On the other hand, production and utilization of concrete is rapidly mounting, which results in increased consumption of natural aggregates. Over 1.5 billion tons of crushed stone are produced in the United States in 2019, an increase of 8% compared with that of 2018 (USGS, 2019). This situation leads to a question about the preservation of natural aggregates sources.

Recently, effective use of recycled concrete aggregates (RCA) in cement and concrete industry have attracted a lot of attention from both environmental and natural resources perspectives. It has been found that the use of RCA derived from CDW in concrete may reduce the aforementioned environmental issues along with decreasing the carbon footprint of new construction. Numerous countries have incorporated some recycling plans with varied success; the recycling rate of CDW reached up to 98% in Japan, 30% in Europe, 57% in Australia, and 68% in the United States (Fiore *et al.*, 2018).

A wide number of researchers (Evangelista and de Brito, 2007; Poon and Kou, 2010; Xiao *et al.*, 2012; Beltrán *et al.*, 2014) have studied the applicability of RCA in structural concrete; generally promising mechanical properties including compressive, tensile, split strength and elastic modulus could be achieved while the use of mix-design techniques that account for the inner characteristics of the RCA material (e.g. amount of residual mortar adhered to the aggregate particles). However, various other studies also showed that recycled concrete may exhibit poorer durability performance compared to conventional concrete with respect to impermeability, chloride resistance, carbonation resistance, frost resistance and alkali-aggregate reaction (AAR) (Etxeberria

and Vázquez, 2010; Delobel *et al.*, 2016; Johnson and Shehata, 2016). Data suggests that the durability of RCA concrete was mainly determined by the amount and quality of residual mortar (RM) attached to RCA particles (Guo *et al.*, 2018). High RCA content and higher amount of RM can result in higher porosity and water absorption, leading to poorer durability performance (Peng *et al.*, 2020). Furthermore, it was also verified that using supplementary cementing materials (SCMs) such as fly ash and or slag, and CO₂ treatment (i.e. RCA carbonation) could significantly improve the pore structure of RCA, therefore producing a more durable RCA concrete (Peng *et al.*, 2020).

Numerous highway and hydraulic structures in Canada and North America have been reported to be affected by AAR. In Ontario, as early as the beginning of the 1980s, it was reported that more than 130 highway structures were affected by AAR (Rogers *et al.*, 1987). It is anticipated that most of these structures will be demolished as they approach the end of their service lives. Although recycling AAR-affected concrete may be a viable option from environmental and economic standpoints, there is still a lack of research that clarifies potential issues (i.e. secondary induced expansion and damage) associated with the use of AAR-affected RCA into new concrete.

1.2. Research objectives

The main objectives of the current research are: (1) to determine the potential of a “secondary” induced expansion and damage of recycled concrete incorporating AAR-affected RCA at distinct distress degrees, and reclaimed from a highly affected overpass after nearly 50 years of service (RBC overpass, Quebec City, Canada), and (2) to evaluate the similarities and discrepancies in terms of damage process (i.e. cracks generation and propagation as a function of induced expansion) of AAR-affected recycled concrete when compared to distressed conventional concrete.

In this research program, RCA derived from the demolition and processing of distinct Robert-Bourassa/Charest (RBC) members (i.e. foundation blocks, bridge deck and columns) was used to manufacture six recycled concrete mixtures in the laboratory through a direct replacement technique (by mass), incorporating either 50 or 100% RCA replacement. A number of 100 by 200 mm cylinders were moulded from each of the six recycled mixtures and then stored in conditions enabling AAR development. Expansion measurements were conducted over time and once a “secondary” level of expansion of 0.12% was reached, mechanical (i.e. SDT) and microscopic (i.e.

DRI) test procedures were carried out to appraise the distress degree and features of AAR-affected recycled mixes. Finally, discussion on the results was performed and considerations for future research in the area were proposed.

1.3. Thesis organization

This thesis is divided into four chapters. Chapter 1 demonstrates the research context and concerns related to the use of AAR-affected CDW in new construction. Furthermore, Chapter 1 displays the research objectives and an overview of the thesis organization.

Chapter 2 provides a detailed literature review on previous studies of RCA concrete, along with testing protocols that will be employed in the current research such as the *Stiffness Damage Test (SDT)* and *Damage Rating Index (DRI)* to assess condition of AAR-affected concrete.

Chapter 3 consists of a journal paper which focuses on the microscopic and mechanical characterization of AAR-affected recycled concrete mixtures.

Chapter 4 brings forward the conclusion obtained throughout this project and proposes suggestions for future research in the area.

It is worth noting that some data gathering (i.e. RCA processing, mix-proportioning of recycled mixtures and monitoring of recycled specimens over time) of the research has been conducted by Dr. Sanchez in his post-doctoral activities. All test procedures and data analysis (i.e. mechanical - SDT and microscopic - DRI) was performed by me with assistance of Andisheh Zahedi (PhD candidate). Furthermore, the scientific manuscript provided in Chapter 3 is my own contribution, co-supervised by Dr. Sanchez and Andisheh Zahedi.

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Chapter Two: Background and literature review

2.1. Overview of RCA

RCA may be produced from (a) the leftover concrete material that returns to the plant, the so-called returned concrete, and (b) demolished concrete structures, the so-called construction and demolition waste - CDW (Rao *et al.*, 2007). Whereas in the former case, the aggregate can be considered relatively clean, with only residual mortar (or cement paste, depending on recycled coarse and or fine aggregates) adhering to it, in the latter case the aggregate could be contaminated with salts, bricks and tiles, sand and dust, timber, plastics, carboard and paper, and metals (Nagataki *et al.*, 2004). As for natural aggregates (NA), the quality and properties of RCA such as particle size distribution (PSD), specific gravity and absorption, frost resistance, etc., needs to be assessed before usage.

RCA is two-phase material comprised of original virgin aggregates (OVA) and residual mortar (RM) attached to the OVA particles (Figure 2.1). Generally, OVA accounts for 65 to 70% by volume of RCA and the rest is RM (Zhang *et al.*, 2015a). The RM is normally more porous than OVA (Khalaf and DeVenny, 2004; Debieb and Kenai, 2008; Quan, 2011), which can lead to high water absorption and considerably affect the fresh and hardened state properties of RCA concrete as summarized in Table 2.1.

Table 2.1: Effect of RCA on the hardened properties of concrete in comparison to OVA concrete (Safiuddin et al., 2013).

Properties	Range of changes
Dry density	5–15% less
Compressive strength	0–30% less
Splitting tensile strength	0–10% less
Flexural strength	0–10% less
Bond strength	9–19% less
Modulus of elasticity	10–45% less
Porosity	10–30% more
Permeability	0–500% more
Water absorption	0–40% more
Chloride penetration	0–30% more
Drying shrinkage	20–50% more
Creep	30–60% more
Thermal expansion	10–30% more

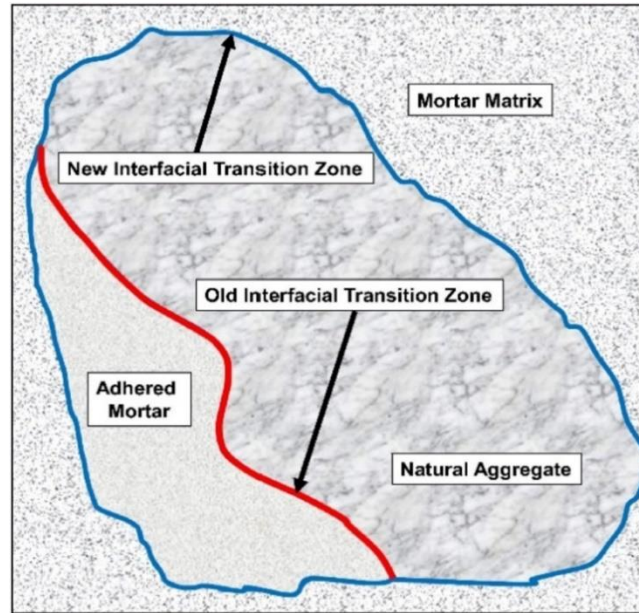


Figure 2.1: Schematic diagram of recycled concrete aggregate (Jayasuriya et al., 2018).

2.2. Properties of RCA

A deep comprehension on the RCA properties and its differences when compared to NA materials may be beneficial to understand the fresh and hardened state properties of recycled concrete mixtures. Amongst the main RCA properties of interest, one may cite density, porosity, and water absorption; shape and size distribution; and Los Angeles abrasion resistance.

2.2.1. Density, porosity, and water absorption

RM adhered to RCA particles is the main factor impacting on the materials density, porosity, and water absorption. The density of RCA is generally lower than NA, since RM is a less dense/more porous material than original virgin aggregates (OVA) (McNeil and Kang, 2013). The variation in density of RCA materials depends on the nature of the aggregate (i.e. lithotype) in question. A study by Thomas et al. (2013) showed that the relative density of RCA (in the saturated surface dry - SSD condition) is approximately 9 to 11% lower than its respective NA. Zhou et al. (2017) reported bulk densities of 1270 and 1435 kg/m³ for RCA and NA respectively, which indicates approximately a 12% difference between them.

Porosity and water absorption are also related aggregate features, and are heavily influenced by the amount and inner quality of the RM. Generally, NA has much lower water absorption and

porosity than RCA. The latter is inversely proportional to the amount of RM attached to the particles. Zhou et al. (2017) found water absorption values from 0.05 to 1.51% for NA and 3.16 to 3.54% for RCA incorporating the same NA in SSD condition. Other studies have also highlighted absorption differences between RCA and NA, where RCA values ranged from 0.50 to 14.75% and NA results varied from 0.34 to 3.00% (ACPA, 2009; Verian, 2012).

2.2.2. Shape and size distribution

RCA tends to be very rough in texture and angular in shape due to the crushing process and the presence of RM. It has been now generally accepted that, either fine or coarse, RCA should be obtained by a series of crushing processes with subsequent removal of impurities (Rao *et al.*, 2007). Normally, a series of 2 successive crushers (i.e. primary and secondary) are required, with oversize particles being returned to the respective crushers to achieve desirable particle size distribution (PSD). Primary crushing usually reduces RCA particles to about 50 mm, while second crushing is used to further reduce the particle size down to 5-20 mm (Ahimoghadam, 2018).

2.2.3. Los Angeles abrasion test

Los Angeles (LA) abrasion test is a procedure that measures the aggregate's toughness. The outcomes of this method often correlate quite well with durability and long-term responses of granular materials (McNeil and Kang, 2013). The LA results is a measurement of the amount of material's loss due to crushing/abrasion mechanisms. Normally, RCA yields higher LA values than NA due to the presence of RM attached to the particles. Various studies show LA values ranging from 20 to 43% loss for RCA materials while values of 15 to 28% may be found for natural aggregates with the same nature (Liu *et al.*, 2011; Verian *et al.*, 2013; Wen *et al.*, 2014; Kurda *et al.*, 2017).

2.3. Properties of RCA concrete

Since RCA displays distinct properties than NA, it is normal to think that RCA concrete mixtures may also behave differently than conventional concrete. This section describes these distinctions in behaviour.

2.3.1. Fresh state performance

Concrete made with RCA presents often lower consistency (i.e. slump test value) than conventional concrete for the same water to cement (w/c) ratio (Liu and Chen, 2008; Smith, 2009; Lotfi *et al.*, 2014). The increase in consistency (and decrease of slump value) of RCA mixtures is attributed to the higher absorption capacity of RCA, along with its rougher surface and more irregular shape (Kurda *et al.*, 2017a). In order to achieve similar consistency values than conventional concrete, recycled concrete mixtures require approximately 5 to 15% of additional mixing water when the RCA is used in either oven-dry or air-dry conditions (Verian, 2012). Thus, increasing the “apparent” water to cement ratio of concrete when RCA is incorporated in the mixture is a common practice (Kurda *et al.*, 2017a). In some cases, this practice can be avoided and thus similar consistency values to conventional concrete may be gathered whether the RCA is used in a (or close to) SSD condition prior to mixing (Brand *et al.*, 2015). The use of admixtures (e.g. water reducers), and supplementary cementitious materials (e.g. fly ash, slag, etc.), or a combination of both, may improve the overall fresh state behaviour of concrete containing RCA and is a common practice used to lessen the amount of water in the mix (Kou *et al.*, 2011; Kurda *et al.*, 2017a).

2.3.2. Compressive strength

The compressive strength of RCA concrete is usually lower than that of conventional concrete. The latter is attributed to the different microstructure of the recycled mixture; i.e. presence of multiple interfacial transition zones (ITZ) in the matrix. The ITZ represents the bond between aggregates and cement paste and is normally the weakest location within the bulk material (Tam *et al.*, 2005; Tam and Tam, 2008; Kong *et al.*, 2010; Kou *et al.*, 2011; Lotfi *et al.*, 2014). In concrete made of NA, the ITZ occurs between the aggregates and the matrix itself (i.e. mortar) while in concrete containing RCA, two types of ITZ take place: between the OVA and RM, and between the RM and new mortar (NM) (Etxeberria *et al.*, 2007; Tam *et al.*, 2005; Kong *et al.*, 2010; Kou *et al.*, 2011; Zhang *et al.*, 2017). Furthermore, lower compressive strength results are often obtained in recycled mixtures by the fact that higher amounts of water are used to lessen the material’s consistency in the fresh state; it has also been found that the water absorption by RCA particles, besides being higher than NA, takes more time to be completed. The latter might increase

the w/c ratio in the system and thus decrease the mechanical properties of the recycled material (Kurda *et al.*, 2017a; Kurda *et al.*, 2018).

Although a wide number of research projects have reported a reduction in strength in RCA concrete, it should be noted that the extent of reduction is related to several parameters such as the mix-proportioning method (i.e. direct replacement vs advanced techniques), replacement ratio, w/c ratio and the moisture condition of the RCA (Sagoe-Crentsil *et al.*, 2001; Ajdukiewicz and Kliszczewicz, 2002). For example, Silva *et al.* (2014) performed statistical analysis on the collected data from literature and reported that compressive strength tends to decrease as the replacement ratio of RCA increases. On the other hand, lowering w/c ratio improves the compressive strength of both concrete containing RCA and NA (Gesoglu *et al.*, 2015). By comparing studies from Gesoglu *et al.* (2015) (w/c ratio 0.3 and 0.43) and Beltrán *et al.* (2014) (w/c ratio 0.5 and 0.6), the incorporation of RCA in concrete mixtures has a higher influence in lowering the compressive strength of concrete made with high w/c ratio as compared to concrete with low w/c ratio (Verian *et al.*, 2018). Apart from the w/c ratio, the moisture condition of the RCA also appears to affect the compressive strength of recycled mixtures. Depending on the moisture level, the compressive strength can be reduced down to 30% or increase up to 20% for 100% RCA replacement (Figure 2.2).

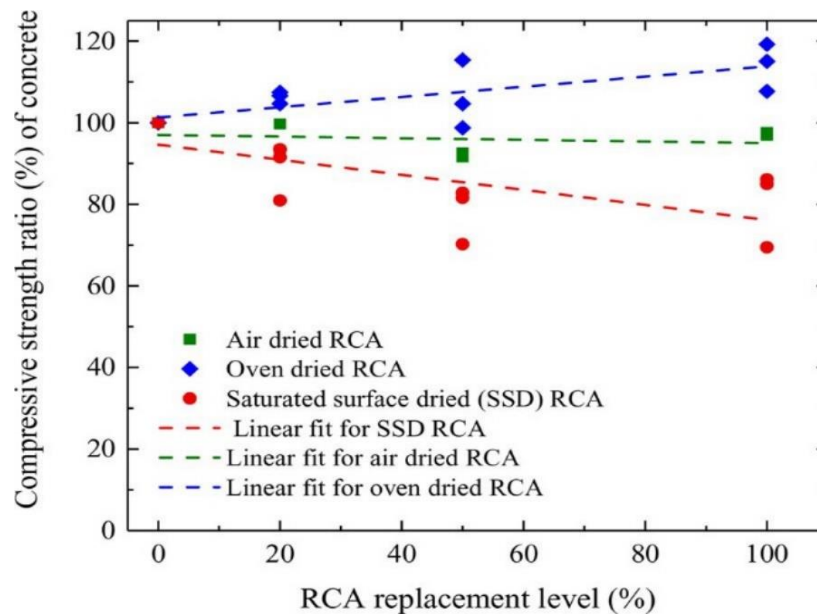


Figure 2.2: Compressive strength variation of concrete with RCA replacement levels for different initial moisture conditions (Verian *et al.*, 2018).

2.3.3. Flexural and tensile strength

A study by Kou et al. (2011) has indicated that the flexural strength of RCA concrete is about 10% lower than that of conventional concrete. The decrease of flexural strength on RCA concrete was noticeable especially when saturated RCA were used in the mixture (Kou *et al.*, 2011). However, studies by Beltrán et al. (2014) have indicated that RCA does not have a significant effect on the flexural strength of concrete. Beltrán et al. (2014) compensated the potential reduction of flexural strength by increasing the amount of cement (up to 45 kg/100% of RCA replacement level) as the amount of RCA increased. At the same time, Beltrán et al. (2014) also increased the amount of water along with the cement in order to keep the w/c ratio at 0.5 and 0.6. On the other hand, Verian et al. (2018) showed that reduction of tensile strength on RCA concrete is up to 10% when only coarse NA were replaced by coarse RCA. In case of both coarse and fine NA replacement by RCA, the tensile strength was further reduced by 10 to 20% (FHWA, 2018).

2.3.4. Modulus of elasticity

Several studies have indicated that concrete containing RCA has a lower modulus of elasticity (E) than conventional concrete, and the reduction is proportional to the increased of RCA used in the mixture (Gomez Soberon, 2002; Xiao *et al.*, 2005; Etxeberria *et al.*, 2007; Kou *et al.*, 2007; Verian, 2012). This loss is associated with the lower E of RCA when compared to NA, specifically due to the presence of RM (Silva *et al.*, 2016a).

Numerous research projects suggested that the modulus of elasticity of concrete made of coarse RCA is from 10 to 33% lower than the modulus of conventional concrete (Hansen, 1986; ACI Committee 555, 2001; FHWA, 2007;). A study by Xiao et al. (2005) indicates that when all the coarse NA is replaced by RCA, the E of concrete reduces by around 45%. Verian et al (2018) compiled the variation of E with respect to the coarse RCA replacement from several researcher projects (Figure 2.3). From the plot, it can be observed that the elastic modulus of RCA concrete can be reduced by up to 20% for 100% replacement of RCA. Yet, it should be noted that most of literature on RCA adopts direct replacement methods (DRM) to mix-proportion RCA concrete. It has been found that DRM are not effective to provide recycled concrete mixtures with suitable properties in the hardened state, such as compressive strength and modulus of elasticity. However, advanced mix-design techniques such as the *Equivalent Mortar Volume (EMV)* method, the

Equivalent Volume (EV) method or even the use of particle packing models (PPMs) were seen to be able to proportion RCA concrete with equivalent mechanical properties than companion conventional concrete (Fathifazl *et al.*, 2009; Hayles *et al.*, 2018).

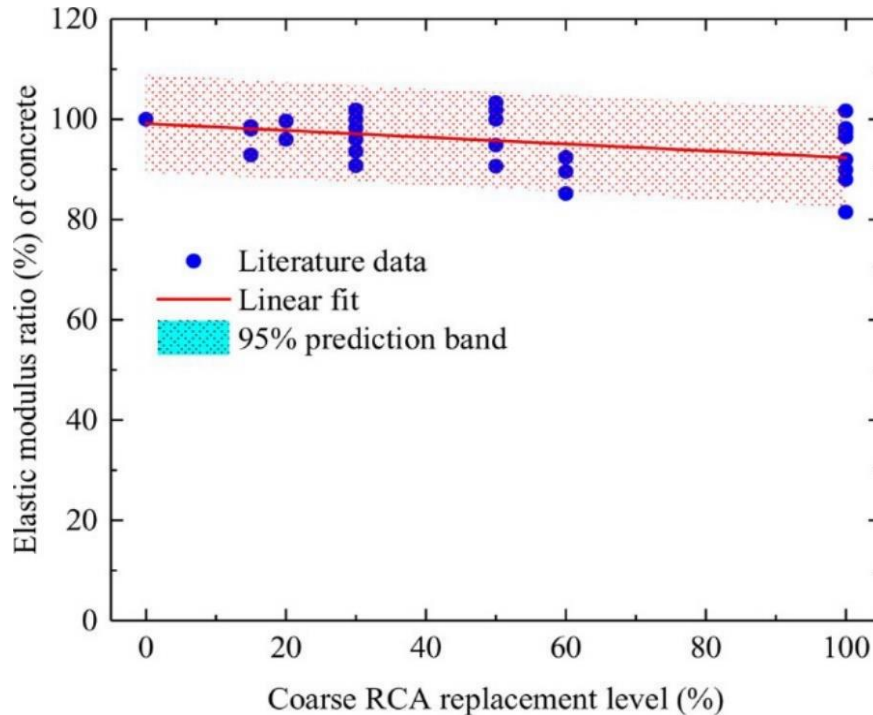


Figure 2.3: Modulus elasticity values of different concrete made with different level of coarse RCA as replacement for coarse NA (Verian *et al.*, 2018).

2.3.5. Creep and shrinkage

The use of RCA in concrete induces high shrinkage due to the large absorption of these aggregates. Some studies show that in RCA concrete at the age of 150 days, shrinkage could be from 0.055% to 0.080%, whereas the comparable value for conventional concrete is only about 0.030% (Verian, 2012; Beltrán *et al.*, 2014). Generally, creep in RCA concrete is found to be proportional to the amount of RCA in the mix; the higher the RCA replacement, the higher the potential creep (Tam and Tam, 2008).

Kou and Poon (2012) reported that creep strain in RCA concrete reached more than 600 μm as compared to less than 500 μm of conventional concrete. According to the authors, this phenomenon was related to the higher amount of paste in RCA concrete (ACI Committee 555, 2001). It is worth noting that the latter is only valid for RCA proportioned with DRM techniques.

2.4. Advanced mix-design techniques to proportion RCA

It has been found that the use of RCA concrete designed through conventional techniques such as DRM often leads to inferior performance in fresh and hardened states as well as in durability-related properties (Ahimoghadam *et al.*, 2019). Conversely, recent mix-proportioning approaches have demonstrated that RCA mixtures with at least similar (if not superior) performance than conventional concrete might be achieved regardless of whether differences in the microstructure of the recycled material were accounted for (Ahimoghadam *et al.*, 2019).

2.4.1. Equivalent mortar volume method (EMV)

The EMV method is based upon and presents the same total mortar (TM) as a control conventional concrete. Thus, corrections to the TM of the RCA mix are made as a function of the RM of the RCA and the TM of the conventional concrete (Ahimoghadam *et al.*, 2019). In this method, the RM is treated within the RCA particle as part of the TM content of the RCA concrete, which means that the TM volume of the RCA concrete is the summation of its residual and fresh mortar volumes (Fathifazl *et al.*, 2009). The use of the EMV method has been shown to produce recycled mixtures with suitable hardened state properties; yet compared to conventional concrete mixtures, the overall fresh state properties (i.e., consistency and rheological behavior) of recycled EMV mix-designed concrete is negatively affected, especially because of the lower amount of fresh mortar available and high amount of coarse aggregates in the recycled mixtures (Ahimoghadam *et al.*, 2019).

2.4.2. Equivalent volume method

The EV method is based on a similar concept to EMV (i.e., accounting for the RM of the RCA), but displays a different assumption: the RCA mix is based on a companion conventional concrete control mix having the same amount (in volume) of cement paste and aggregate as opposed to having the same amount of coarse aggregates and mortar, such as in the EMV method (Ahimoghadam *et al.*, 2019). The EV method treats the RM in the RCA as a combination of residual paste (RP) and residual fine aggregate. Therefore, the total cement paste (CP) of a given RCA mixture is then considered as the summation of its RP and fresh paste (FP) volumes (Ahimoghadam *et al.*, 2019). The EV approach seems to be very promising and has demonstrated

great potential, partially solving some of the fresh state and cement efficiency issues found in the EMV method while keeping the same benefits of the EMV in the hardened state (Ahimoghadam *et al.*, 2019).

2.5. ASR-affected RCA concrete

Alkali-aggregate reaction (AAR), particularly alkali-silica reaction (ASR), is one of the main causes of deterioration of concrete infrastructure worldwide. ASR is a chemical reaction that occurs between the alkali hydroxides (Na, K – OH) in the concrete pore solution and certain siliceous mineral phases of aggregates used to make concrete (Fournier and Bérubé, 2000).

Reclaiming construction and demolition waste (CDW) to manufacture RCA for use in new concrete is a sustainable option that not only reduces the amount of CDW disposed in landfills but also lessens the consumption of non-renewable resources, such as natural aggregates. However, the use of RCA in new concrete requires detailed assessment on the properties and inner quality of the reclaimed material, especially whether the RCA is originated from a structure affected by ASR. It has been reported that the use of ASR-affected RCA in new concrete could result in significant induced “secondary” expansion, comparable to the initial expansion in the conventional concrete (Shehata *et al.*, 2010). Similar observation was also reported by Li and Gress (2006). Other researchers (Grattan-Bellew, 1995; Mulhopadhyay, 2013) further pointed out that RCA produced from ASR-affected concrete might even lead to higher expansion than that of a companion conventional concrete due to the higher exposure of reactive phases from the aggregates after crushing. Conversely, other studies demonstrated that ASR “secondary” induced expansion rate in RCA concrete is lower than in companion conventional concrete (Shehata *et al.*, 2010). Moreover, the higher porosity of RCA may also provide supplementary space to accommodate ASR products, thus resulting in slow “secondary” induced expansion (Delobel *et al.*, 2016).

In principle, the extent of ASR in RCA concrete seems to be mainly controlled by the remaining reactive phases from the aggregates. Thus, if the reactive aggregate phases have been largely consumed in the original conventional concrete, ASR potential may be quite limited in the recycled mixture (Shehata *et al.*, 2010; Rajabipour *et al.*, 2015; Johnson and Shehata, 2016). Figure 2.4 shows that ASR performance of RCA concrete is closely related to RCA’s nature. ASR expansion

of RCA and conventional concrete made from four types of aggregates (Johnson and Shehata, 2016) shows that the RCA mixtures exhibit lower ASR expansion than the companion conventional concrete. Moreover, the higher the aggregate reactivity, the higher the “secondary” induced expansion observed on the RCA mixtures. For instance, Alberta and Springhill aggregates are highly reactive, therefore ASR potential of their corresponding RCAs is higher in comparison to recycled mixtures made of Bernier or Potsdam at similar replacement ratios.

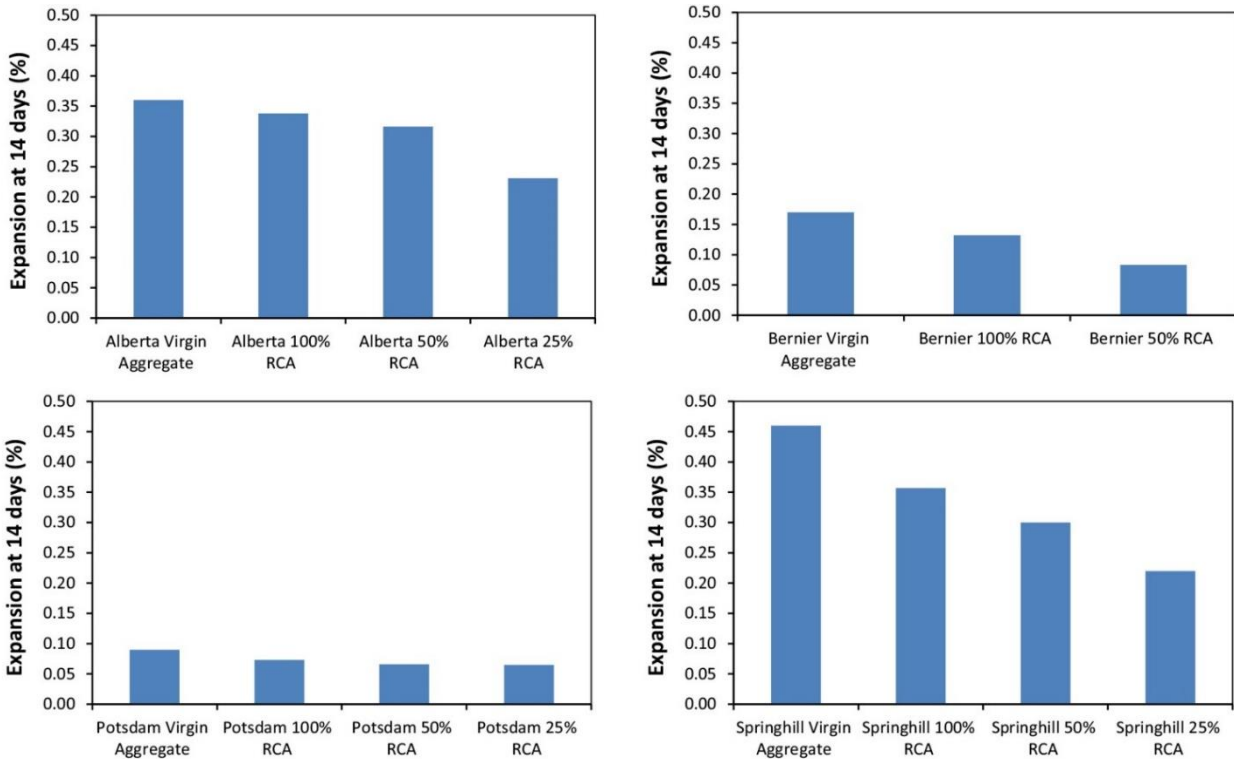


Figure 2.4: Expansion of original virgin aggregate with various sources and RCA generated from concrete containing the same aggregate (Johnson and Shehata, 2016).

2.6. Factors influencing on ASR-affected RCA concrete

2.6.1. Reactivity of the aggregate and past expansion from reclaimed concrete

The alkali reactivity of siliceous aggregates is determined by their nature (i.e. mineralogy); i.e. the presence of siliceous mineral phases with some microstructural disorder (Poole, 1998). Among reactive components, amorphous silica (such as opal and volcanic glass) is typically the most reactive, followed by metastable silica and its crystalline forms containing significant defects/deformations (Poole, 1998).

In the case of ASR-affected RCA, the situation is slightly different. Not only the reactivity of the original virgin aggregate (OVA) matters (McCarthy *et al.*, 2015a), but also the past expansion reached by the concrete reclaimed and processed to produce RCA (Beauchemin *et al.*, 2018). Therefore, both the aforementioned conditions should be evaluated for assessing and forecasting ASR performance of the concrete containing reactive RCA.

It has been reported that RCA concrete may exhibit an important “secondary” induced expansion when the OVA displays high reactivity degrees (McCarthy *et al.*, 2015a). Yet, if most of the siliceous mineral phases had been depleted during the first induced expansion in the conventional concrete, RCA derived from this material (even with high reactivity) might have a much inferior potential for further reaction and thus expansion (Stark, 1996). Figure 2.5 (Adams *et al.*, 2013) gives a plot of the “secondary” induced expansion of mortar bars made of RCA, displaying distinct reactivity degrees (Sp > Al > Be > Po) through the accelerated mortar bar test (AMBT). Higher expansion levels were obtained at 14 days for mortar bar mixtures containing higher reactivity aggregates, except for mortar bars made of Al aggregate. Yet, it has been verified that the structure from which Al had been reclaimed presented a much higher deterioration degree than all the others; hence its past expansion had been likely higher and thus lower amounts of reactive mineral phases were available for the “second” chemical reaction.

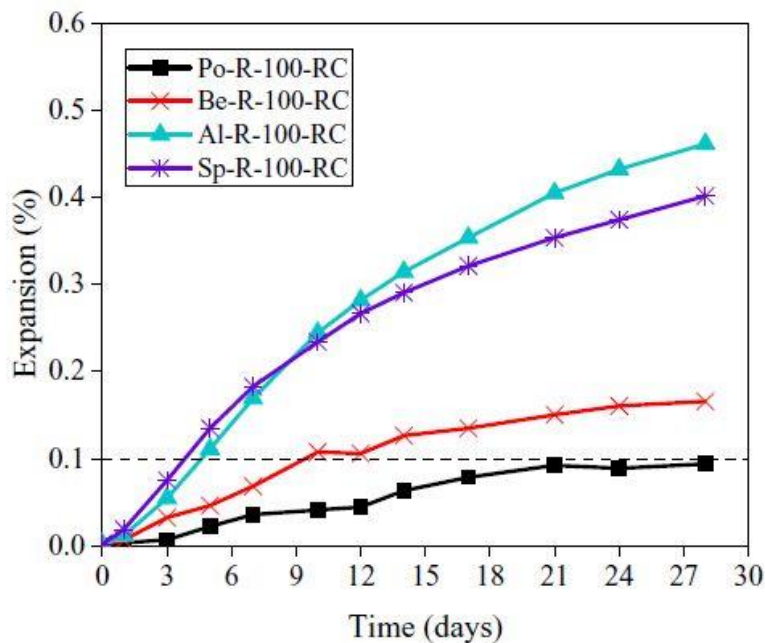


Figure 2.5: Effect of reactivity of OVA on the expansion of RCA (Adams *et al.*, 2013).

2.6.2. Residual mortar

The influence of RM on ASR-induced “secondary” expansion of RCA concrete is complicated to be appraised, since it depends on the reactivity degree of the OVA and alkali content of the RM. According to Shehata et al. (2010), RCA originated from ASR-affected companion concrete containing high amounts of RM exhibited lower expansion than RCA with lower RM contents. Therefore, once the reactive siliceous phases within the OVA had been largely consumed, the alkalis from both RM and new cement paste seemed to not be sufficient to trigger a significant “secondary” expansion.

2.6.3. Crushing stages

It has been reported that RCA crushing stages might also significantly affect the “secondary” induced expansion of RCA concrete. Figure 2.6 clearly illustrates that RCA subjected to secondary crushing stages displays a much higher expansion at 14-day in the accelerated mortar bar test (AMBT) than RCA processed through a single (i.e. primary) crushing stage (Shehata *et al.*, 2010). This could be attributed to the fact that secondary crushing stages normally reduce the amount of RM attached to the RCA particles; thus, higher OVA (i.e. reactive phases) is found in the particle.

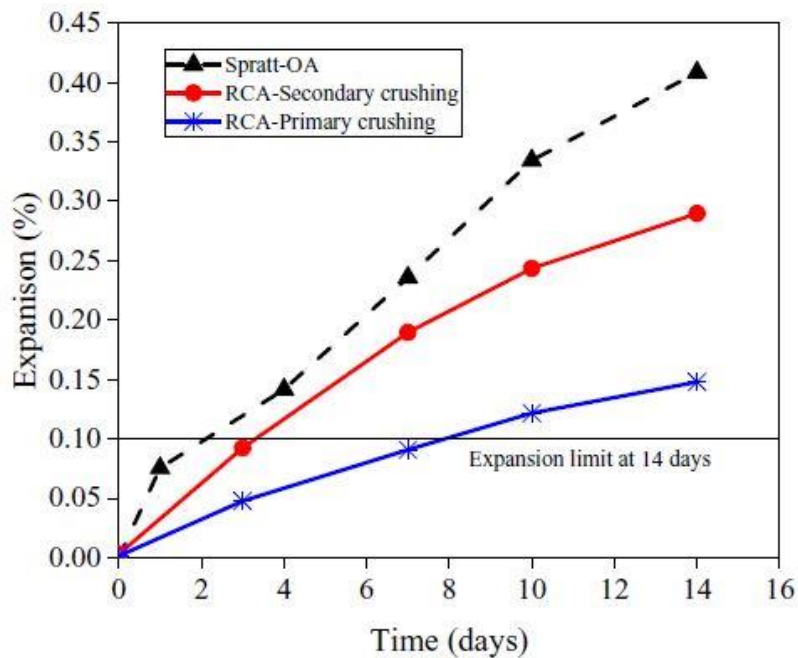


Figure 2.6: AAR expansion of RCA with different crushing stages (Shehata et al., 2010).

2.6.4. RCA and alkali content

It has been reported that the higher the RCA replacement, the higher the “secondary” induced expansion of the affected recycled concrete. The latter is indeed only valid for reactive RCA (Beauchemin *et al.*, 2018). Ideker *et al.* (2013) explored the effect of different RCA replacement ratios on ASR in recycled concrete; it was demonstrated that higher RCA replacement ratios would result in larger expansion levels. The latter was more obvious according to the reactivity of the OVA; the higher the reactivity, the higher the ultimate expansion for greater replacement ratios.

The alkali content of the RM has also been found as an important variable controlling “secondary” expansion in RCA concrete. According to Johnson and Shehata (2016), the induced expansion of concrete specimens made of unwashed RCA was higher than those washed prior to use (Figure 2.7). The latter has been attributed to alkalis leaching from the RM. Similar decrease of ASR induced expansion was also reported by Shehata *et al.* (2010) for concrete with RCA washed over 18 hours. However, only slightly lower expansion levels were observed, since the “new” alkalis from Portland cement could offset the loss of alkalis from the RM (McCarthy *et al.*, 2015a). Hence, it has been observed that the alkali content of the new cement paste was a more important factor than the RM features themselves.

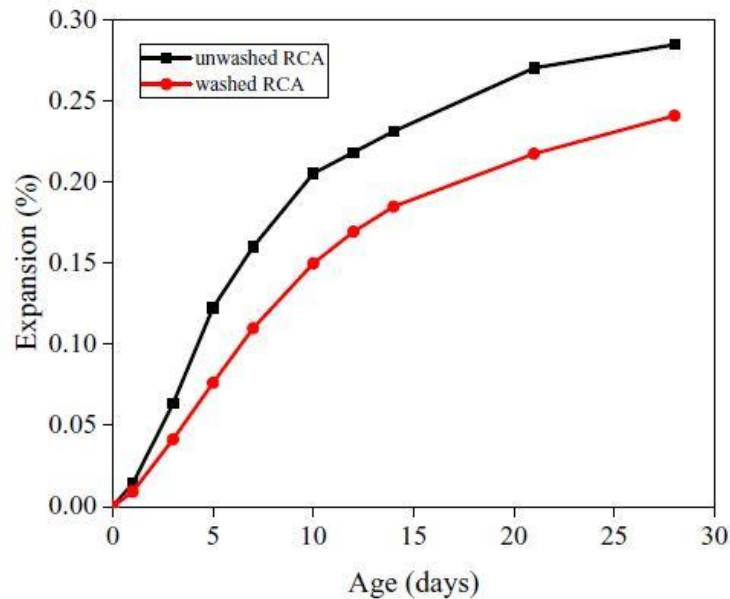


Figure 2.7: Effect of washing on the expansion of RCA mortar bars (Johnson and Shehata, 2016).

2.6.5. Saturation of RCA

Due to high water absorption of RCA, the effective w/c ratio of recycled concrete mixtures could be significantly changed. The latter may not only modify the fresh and hardened states properties of recycled concrete, but also its ASR-induced expansion behaviour. It has been reported that RCA concrete manufactured with dry RCA particles (oven-dry or air-dry) might yield higher expansion levels than those pre-saturated with water (Delobel *et al.*, 2016). The same trend (presented in Figure 2.8) has also been reported by Beauchemin *et al.* (2018). The latter is likely due to the fact that water absorption is a time-dependent phenomenon, and since it might take an important amount of time to be completed (especially in aggregates presenting high absorption capacities such as RCA), a non-negligible amount of supplementary water added to saturate the aggregates could be used in the hydration process of Portland cement; this would increase the w/c ratio and thus raise the porosity of the matrix while lessening the mechanical properties of the recycled material. High porous matrices are deemed to facilitate the alkali-silica exchange and thus enable greater induced expansion and deterioration.

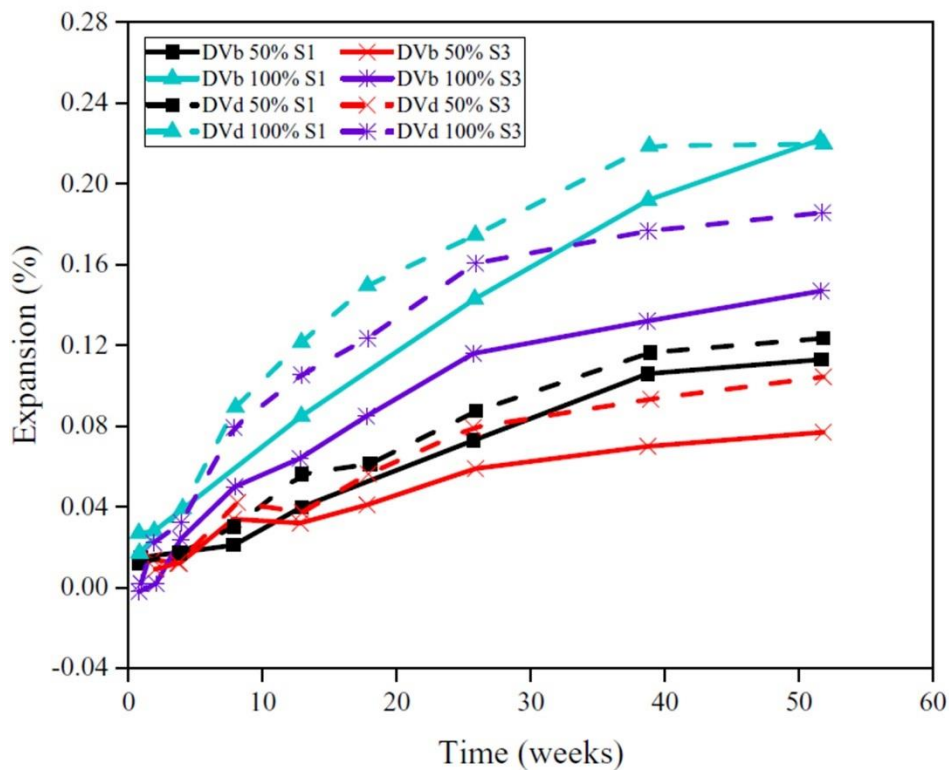


Figure 2.8: AAR expansion of dry and water-saturated RCA with different concrete (Beauchemin *et al.*, 2018).

2.7. Tools for assessing damage in ASR-affected concrete

It has been suggested that the *Stiffness Damage Test (SDT)* and the *Damage Rating Index (DRI)*, mechanical and microscopic tools respectively, can reliably assess the condition of concrete affected by ASR (Sanchez et al., 2017).

2.7.1. Stiffness damage test (SDT)

The SDT has been proposed as a tool to quantify the degree of physical damage in concrete affected by AAR (Chrisp *et al.*, 1993). The test method was first developed by Walsh for rock specimens and then Crouch adapted the procedure for concrete (Walsh, 1965; Crouch, 1987). The method is based on five loading-unloading cycles (in compression) of concrete specimens, and was initially carried out using a fixed load of 5.5 MPa, at a loading rate of 0.10 MPa/s.

Sanchez et al. (2014, 2015, 2016) performed a comprehensive research (i.e. using a wide variety of concrete strengths and reactive aggregate types) on the use of SDT for assessing damage in concrete affected by AAR. Further details on the procedure developments and specific/practical considerations on its application as a diagnostic tool can be found in Sanchez et al. (2014, 2015, 2016). Briefly, after careful evaluation of the test outcomes, it was verified that the SDT needs to be performed at 40% of the material's compressive strength. Moreover, the method was found quite promising for appraising AAR damage in concrete, especially when indices are used as output parameters of the test, namely Stiffness Damage Index (SDI) and Plastic Deformation Index (PDI), which represent respectively the ratio of dissipated energy/plastic deformation to the total energy/deformation implemented over the five loading cycles in the system. Finally, following the works by Chrisp and co-workers (Chrisp *et al.*, 1993; Smaoui *et al.*, 2004), it has been confirmed that the Non-Linearity Index (NLI) is also an interesting outcome to be considered, especially while studying AAR inner cracks orientation.

2.7.2. Damage rating index (DRI)

The DRI was proposed by Grattan-Bellew and coworkers to appraise the microscopic damage features of concrete affected by AAR (Grattan-Bellew and Danay, 1992; Dunbar and Grattan-Bellew, 1995; Grattan-Bellew and Mitchell, 2006). The DRI is a microscopic analysis performed with the use of a stereomicroscope (15-16x magnification) where damage features generally

associated with AAR are counted through a 1 cm² 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 feature is then multiplied by a weighing factor, whose purpose is to balance their relative importance towards the mechanism of distress under analysis (i.e. ASR). The factors used in the method were selected on a logical basis, but relatively arbitrarily; they were recently modified in order to reduce the variability between the petrographers performing the test (Villeneuve and Fournier, 2012). Ideally, a surface of at least 200 cm² should be used for DRI analysis, yet 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 cm² area (Grattan-Bellew and Mitchell, 2006).

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) to assess the cause of concrete distress. The DRI is a complementary petrographic tool targeting at quantifying the “damage degree” between different elements of a structure or as a function of time within a specific concrete member. Examples of the petrographic features of deterioration and the weighing factors used for DRI number calculations are given in Figure 2.9 and Table 2.2 (Villeneuve, 2011).

Sanchez et al. (2015, 2016), used the DRI, applying the new version proposed by Villeneuve (2011), to evaluate AAR distress coming from a number of reactive aggregate types/natures (coarse vs. fine), different concrete strengths (25-45 MPa) and expansion levels (0.05% to 0.30%). The authors found that the DRI is a very suitable tool to detect AAR damage/progress in concrete whatever the aggregate type and concrete strength used, especially when the aggregate particles are analyzed down to 1mm, instead of 2 mm as proposed by Villeneuve and Fournier (2012). Furthermore, Sanchez et al. (2015), described the development of ASR distress in concrete incorporating “quartz-bearing” reactive aggregates (e.g. greywacke, siliceous limestone, gneiss, schist, argillite, etc.) as a two-step process: a), the formation of cracking 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 (i.e. connecting reactive

aggregate particles with one another) with increasing expansion. Following the minimum energy law, it is easier for the expanding system to propagate the cracks produced through step (a) described above, instead of creating a significant number of new cracks. 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. The above mechanism is described by the qualitative damage model proposed by Sanchez et al. (2015) and presented in Fig. 2.10.

Table 2.2: Latest weighing factors proposed by Villeneuve (2011).

Petrographic features	Abbreviation	Weighing factor
Cracks in coarse aggregate	CCA	0.25
Opened cracks in coarse aggregates	OCA	2
Crack with reaction product in coarse aggregate	OCAG	2
Coarse aggregate debonded	CAD	3
Disaggregate/corroded aggregate particle	DAP	2
Cracks in cement paste	CCP	3
Cracks with reaction product in cement paste	CCPG	3

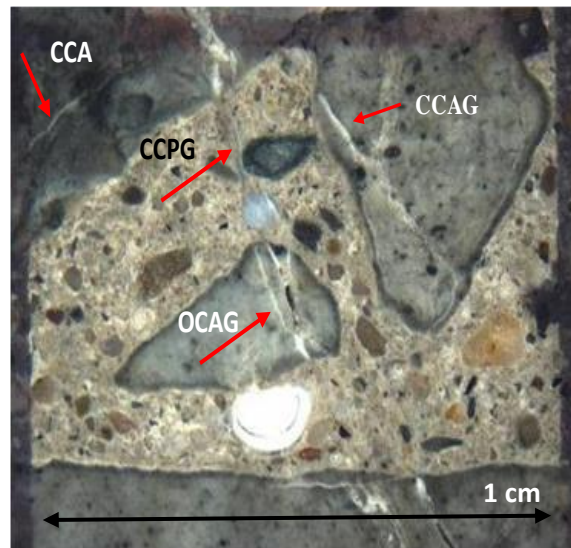


Figure 2.9: Petrographic features to be noted in the DRI analysis (Villeneuve, 2011).

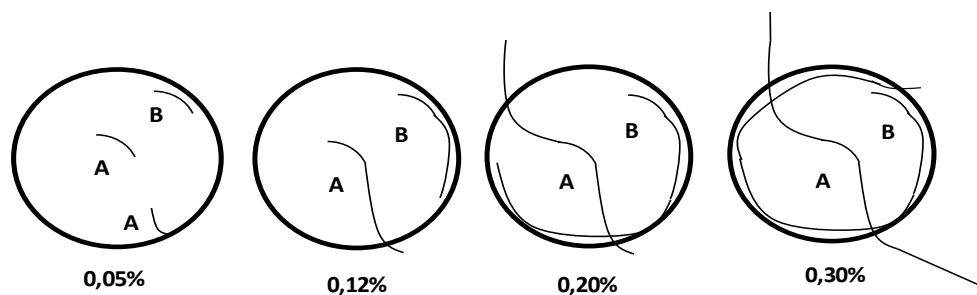


Figure 2.10: Qualitative microscopic ASR damage model vs expansion level (Sanchez et al., 2015).

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Chapter Three: Overall assessment of Alkali-Silica Reaction (ASR) affected Recycled Concrete Aggregate (RCA) mixtures derived from Construction and Demolition Waste (CDW)

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3.1. Abstract

A wide number of research has been conducted on the treatment and reuse of construction and demolition waste (CDW) in new concrete. Yet, CDW may present low inner quality, pre-existing damage or critical conditions, which raises concerns about its use. In this work, coarse recycled concrete aggregate (RCA) is reclaimed and processed from distinct members (i.e. foundation blocks, bridge deck and columns) of an alkali-silica reaction (ASR) affected overpass after nearly 50 years of service. RCA concrete mixtures incorporating 50 and 100% replacement (in mass) are manufactured and stored in conditions enabling further ASR development. Mechanical (i.e. Stiffness Damage Test - SDT) and microscopic (Damage Rating Index - DRI) analyses are conducted at a fixed “secondary” induced expansion of 0.12%. Results demonstrate that the overall damage of the ASR-affected recycled mixtures depends upon the “past” condition of the RCA material. Furthermore, the DRI was able to capture the “past” and “secondary” induced expansion and damage of affected RCA concrete while the SDT simply detected the “secondary” distress development. Finally, an adapted version of the DRI was proposed to better evaluate the overall damage of recycled concrete along with properly displaying “past” and “secondary” induced distress.

Keywords: Alkali-silica reaction (ASR), recycled concrete aggregates (RCA), construction and demolition waste (CDW), damage rating index (DRI), expansion, damage.

3.2. Introduction

Concrete is the most common construction material used around the globe. Yet, it has a somewhat negative impact towards sustainability. Portland cement (PC), likely the most important concrete ingredient, is considered to be the major responsible for its carbon footprint, since according to the *World Business Council for Sustainable Development (WBCSD)*, the production of every ton of PC releases 650 kgs of CO₂ (WBCSD, 2016). The global PC production in 2013 was 4.2 billion tons, which yielded 5.2 billion tons of CO₂ (Van Oss, 2013); PC production currently accounts for about 7% of the global CO₂ emissions (Kumar, 2001; Damineli *et al.*, 2010).

There are numerous ways to increase sustainability and thus decrease carbon footprint of concrete construction. Amongst those, the use of recycled concrete aggregates (RCA) has been receiving increased attention over the last few decades (ACI Committee 555, 2001; Dean *et al.*, 2008; Abbas *et al.*, 2009). RCA may be obtained primarily from two distinct sources: construction and demolition waste (CDW) and returned concrete. RCA derived from CDW is a product manufactured by deconstructing and processing (i.e. crushing, sieving and cleaning) existing concrete structures, while RCA reclaimed from returned concrete is obtained by processing the leftover material that is brought back and discharged at the concrete plant.

Although CDW-RCA is considered an effective strategy to lessen concrete's carbon footprint, it may display low inner quality, pre-existing damage and or critical conditions that can strongly impact the short and long-term performance of recycled mixtures; for instance, if the coarse or fine RCA derived from CDW is an ASR (i.e. alkali-silica reaction) reactive aggregate and thus bears some past deterioration while presenting potential for further expansion and distress. Yet, the potential of a "secondary" induced expansion (especially for CDW-RCA, since the material spent several decades in service before being reclaimed), along with its likely distinction from the traditional physicochemical mechanism in conventional concrete are still not fully understood and require further investigation (Sims and Poole, 2017; Shehata *et al.*, 2010).

3.3. 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 (Fournier and Bérubé, 2000). ASR generates a product (the so-called ASR gel) 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 (Sanchez *et al.*, 2017).

The development of ASR distress in conventional concrete (CC) incorporating “quartz-bearing” natural reactive aggregates (e.g. greywacke, siliceous limestone, gneiss, schist, argillite, etc.) has been reported by Sanchez *et al.* (2015) as a two-step process: a) cracking formation within the reactive aggregate particles in the early stages of the chemical reaction (including ASR “activation” of pre-existing cracks formed through the aggregates processing operations), and b) the extension of the aforementioned cracks into the cement paste which generates an important cracking network (i.e. connecting reactive aggregate particles with one another) with increasing expansion. The latter causes important mechanical properties reductions; despite elastic modulus and tensile strength that are significantly reduced at early stages, compressive strength decreases at high and very high expansion levels as per Sanchez *et al.* (2015).

RCA displays an important intrinsic difference from natural aggregates (NA), which is the fact that RCA is a two-phase material comprised of original virgin aggregate (OVA) adhered to residual mortar (RM) or residual cement paste (RCP) in the case of coarse (CRCA) or fine (FRCA) recycled concrete aggregates, respectively (Shi *et al.*, 2016; De Souza *et al.*, 2019; Ahimoghadam *et al.*, 2020). The amount of RM (or RCP) varies according to the processing technique (converting concrete debris into aggregates) along with the type and quality of the OVA (i.e. lithotype, texture, shape, etc.) and RM (i.e. mechanical properties, porosity, etc.) (Shi *et al.*, 2016; De Souza *et al.*, 2019; Ahimoghadam *et al.*, 2020). Therefore, RCA concrete displays a completely different microstructure and incorporates multiple ITZs (e.g. between OVA and RM and between RCA and new cement paste) (Shi *et al.*, 2016; De Souza *et al.*, 2019; Ahimoghadam *et al.*, 2020). Hence, one might expect ASR-induced expansion and damage to be different in ASR reactive RCA concrete.

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 developed from a pre-existing (ASR-generated) crack within the RCA particle or from a new one due to the chemical exchange between the new cement paste and the reactive OVA? Recent research in the field verified that ASR keeps being produced in CDW-RCA concrete under conditions enabling its development (i.e. high moisture and temperature) (Shehata *et al.*, 2010; Johnson and Shehata, 2016). Moreover, RCA affected mixtures were seen to require higher amounts of preventive measures (e.g. supplementary cementing materials) to lessen their “secondary ASR-induced expansion” (Li and Gress, 2006). Yet, very few is known on cracks generation and propagation of ASR-reactive RCA concrete along with their influence on the mechanical properties of the affected recycle mixture.

3.4. Robert-Bourassa/Charest bridge

The Robert-Bourassa/Charest (RBC) overpass was a highway bridge structure that was built in 1966 in Quebec City (Canada), using an ASR reactive coarse aggregate (reactive siliceous limestone). RBC was made of a deck sitting on reinforced Y-shaped concrete columns, themselves supported by foundation blocks (Figure 3.1). No specific information is available on the concrete mix-designs adopted; yet, technical reports indicate that the targeted 28-day compressive strengths were 24 and 28 MPa for the foundation blocks and columns/decks, respectively. Over the last 3 decades, a wide range of deterioration signs, including ASR, were developed on the structure members as per Sanchez *et al.* (2020).

In 2000, a number of rehabilitation techniques including surface treatments (i.e. rigid coatings, silane/siloxane-based products) and structural confinement (i.e. glass fiber reinforced polymer - GFRP wrapping systems) were adopted to suppress further ASR-induced expansion and damage. In 2010/2011, RBC overpass was considered structurally obsolete and deconstructed; yet, a number of cores were extracted from the distinct structural members prior to its deconstruction. All data from the comprehensive condition assessment of RBC members is found in Sanchez *et al.* (2020). Furthermore, instead of being discarded, RBC members (i.e. bridge deck, columns and foundation blocks) were reclaimed and processed (i.e. crushed, sieved and cleaned) to produce coarse RCA and thus further investigate the potential of “secondary” ASR-induced expansion and associated deterioration features (Sanchez *et al.*, 2020).



Figure 3.1: RBC overpass after nearly 50 years in service (Sanchez et al., 2020).

3.5. Scope of the work

The previous sections clearly emphasized the need to further understand the potential “secondary” ASR-induced expansion and damage development in recycled concrete mixtures. Therefore, this work presents an overall assessment of recycled concrete mixtures made of RCA reclaimed from the RBC overpass deconstruction.

RBC members (i.e. bridge deck, columns and foundation blocks) were deconstructed and processed (crushed, sieved and cleaned) so that coarse RCA might be obtained. It is worth noting that the distinct RBC structural members presented different damage degrees by the time of the deconstruction as per the condition assessment performed by Sanchez et al. (2020) on cores retrieved from each of them (i.e. higher damage degree and thus past expansion were found on foundation blocks, followed by the bridge deck and then bridge columns). Then, concrete specimens proportioned as per ASTM C1293 (i.e. concrete prism test - CPT mixtures) were manufactured in the laboratory incorporating distinct amounts of RCA (i.e. 50% and 100%, in mass) and stored in conditions enabling further ASR development (i.e. 38°C and 100% RH). Monitoring was conducted over time until the recycled concrete specimens reached a “secondary” expansion level of 0.12% (regardless of their past expansion and damage). The multi-level protocol as per Sanchez et al. (2017) was implemented so that an overall evaluation of induced distress on ASR-affected RCA specimens might be performed. Comparisons amongst the distinct mixes along with affected companion conventional concrete are then conducted.

3.6. Materials and methods

3.6.1. Materials and mix proportions

Six RCA concrete mixtures displaying the same mechanical properties (i.e. 35 MPa) and incorporating three different RCA sources (i.e. Columns – CO; Bridge deck – BD, and foundation blocks - FB) were manufactured in this study as per ASTM C 1293. The coarse RCA particles ranged from 5 to 20 mm in size. The concrete mixtures manufactured incorporated either 50% or 100% of RCA. The mixes presenting only 50% of RCA also embodied a non-reactive coarse aggregate (i.e. high purity limestone - HP). Moreover, a non-reactive natural sand was selected for use in all mixtures. A conventional Portland cement (CSA GU type, ASTM type 1) containing high alkali content (0.88% Na₂O_e) was used in this research. Reagent grade NaOH was selected to raise the total alkali content of the mixtures to 1.25% Na₂O_e by cement mass, for accelerating the ASR-induced expansion process. The detailed RCA concrete mixture proportions can be found in Appendix A. The amount of RM was disregarded in this study, since it has been found more appropriate to initially appraise the potential of ASR further development with the most conventionally used proportioning technique in the literature and in practice: the direct replacement method (DRM), in mass. In the DRM, the NA particles are simply replaced by RCA particles in the mix. Therefore, this method provides the final recycled mixture with a higher amount of cement paste (and thus alkalis) and lower amount of coarse original virgin aggregates (OVA) than a companion conventional mix.

3.6.2. Production of test specimens

A total of six cylinders, 100 by 200 mm in size, were manufactured from each RCA mixture fabricated 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 °C and 100% relative humidity and the specimens monitored for length changes regularly. Once the cylinders reached the expansion level selected for further analysis: $0.12 \pm 0.01\%$, they were wrapped in a

plastic film and stored at 12°C to stop further ASR development until microscopic and mechanical tests were conducted.

3.6.3. Testing procedures for assessing damage

Damage Rating Index (DRI)

The Damage Rating Index (DRI) is a microscopic analysis proposed by Grattan-Bellew and Danay (1992), whose main purpose is to appraise inner damage in affected concrete. The DRI is performed on polished concrete sections with the use of a stereomicroscope (15 to 16x magnification) where damage features associated with a given distress mechanism (i.e. ASR in this case) are counted through 1 cm² grids drawn on the surface of the polished sections (Sanchez *et al.*, 2015, 2016). 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 DRI number, the higher the overall inner damage (Sanchez *et al.*, 2015, 2016). 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 such as Villeneuve and Fournier (2012) and Sanchez *et al.* (2015, 2016) have improved the DRI procedure so that it might better represent “damage” in its broader sense, while reducing its subjectivity and variability amongst operators. Sanchez *et al.* (2015, 2016) performed the DRI on concrete samples presenting a wide range of strengths and fabricated with numerous coarse and fine reactive aggregates. These have demonstrated the suitability of the DRI to appraise ASR-induced expansion and damage in concrete. Furthermore, the DRI has been applied to other distress mechanisms such as delayed ettringite formation (DEF) and freeze-thaw cycles (FT) combined or not with ASR, and showed quite promising results (Sanchez *et al.*, 2018).

Prior to the DRI analyses, the specimens were unwrapped, and expansion readings were taken to confirm that no outstanding expansion (and or shrinkage) took place during the storage period at 12°C. 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 lose abrasive powders that can fill up cracks or voids in concrete, and high quality polishing is

obtained with minimal water supply so that ASR-gel leaching is avoided. The DRI was performed as per Sanchez et al. (2015, 2016).

Stiffness Damage Test (SDT)

The SDT was first developed by Walsh (1965) for assessing rock specimens, being afterwards somewhat modified and adapted for concrete by Crouch (1987). The test procedure is quite simple and is based on five compressive loading/unloading cycles that initially were performed with fixed loads of either 5.5 (Chrisp and co-workers) or 10 MPa (Smaoui and co-workers) at a loading rate of 0.10 MPa/s (Chrisp *et al.*, 1993; Smaoui *et al.*, 2004). The first outcomes adopted for the test were the modulus of elasticity, dissipated energy (hysteresis area) and plastic deformation of the first and/or over the five cycles as by (Chrisp *et al.*, 1993; Smaoui *et al.*, 2004).

Sanchez et al. (2014, 2015, 2016) performed a comprehensive research (i.e. using a wide variety of concrete strengths and reactive aggregate types) on the use of SDT for assessing damage in concrete affected by ASR. Further details on the procedure developments and specific/practical considerations on its application as a diagnostic tool can be found in Sanchez et al. (2014, 2015, 2016). Briefly, after careful evaluation of the test outcomes, it was verified that the SDT needs to be conducted at 40% of the material's compressive strength. Moreover, the method was found to be quite promising for appraising ASR damage in concrete, especially when indices are used as output parameters of the test, namely *Stiffness Damage Index (SDI)* and *Plastic Deformation Index (PDI)*, which represent respectively the ratio of dissipated energy/plastic deformation to the total energy/deformation implemented over the five loading cycles in the system. Finally, following the works by Chrisp and co-workers (Chrisp *et al.*, 1993; Smaoui *et al.*, 2004), it has been confirmed that the *Non-Linearity Index (NLI)* is also an interesting outcome to be considered, especially while studying AAR inner cracks orientation.

As per the DRI analysis, the specimens ready for testing were removed from the 12°C, and expansion readings were taken to confirm that no outstanding expansion (and or shrinkage) took place during the storage period. Then, the stainless-steel gauge studs were removed from the samples and their ends ground to achieve flat surfaces. Finally, the specimens were conditioned in the moist curing chamber (i.e. 100% R.H.) over 48h as per Sanchez et al. (2015), and stiffness damage tested according to Sanchez et al. (2014, 2015, 2016).

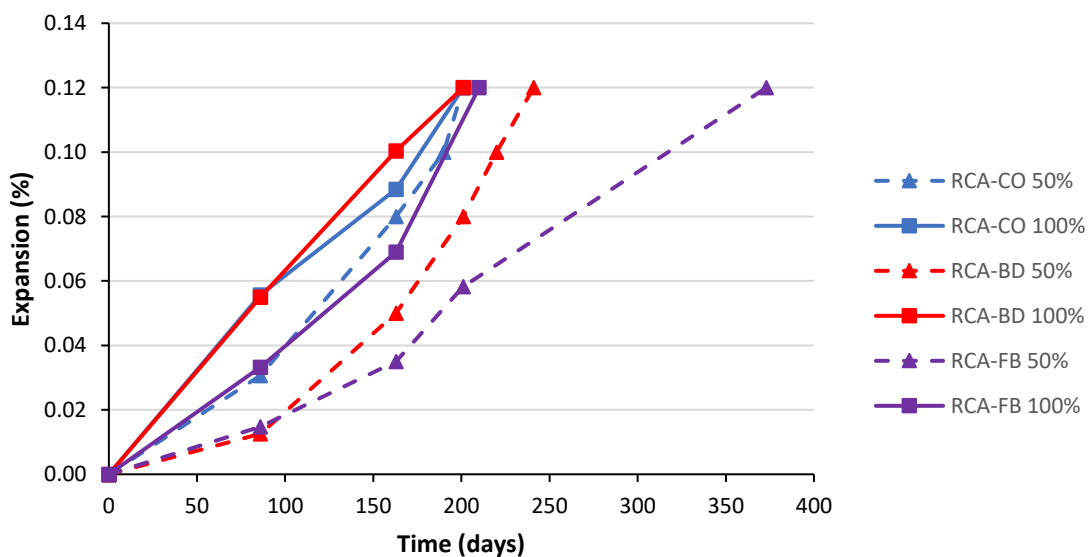
3.7. Results

3.7.1. ASR kinetics

Figure 3.2A presents the average expansion (i.e. average of six concrete specimens, presenting standard deviations of about 0.02% for all testing ages) over time from all RCA mixtures manufactured in the laboratory, while Figure 3.2B illustrates the average mass gain over time for the same recycled mixtures (presenting standard deviations of about 0.10% for all testing ages). As one may notice, ASR kinetics and induced development changes according to the RCA source (i.e. CO, BD or FB) and amount used (i.e. 50% or 100%). ASR development is generally faster in mixtures incorporating 100% of RCA material, as expected. Expansion levels of 0.12% have been reached by these mixtures within 200 days. Conversely, ASR kinetics seems slower for mixtures containing 50% of reactive RCA material, except for the mix incorporating RCA – CO material. Values of 0.12% expansion were reached at 200, 241 and 373 days for CO 50, BD 50, and FB 50 mixtures, respectively.

The mass gain over time followed the same trend as the expansion kinetics (i.e. higher mass gain is verified for mixtures incorporating 100% RCA replacement). The mass gain of the recycled mixtures ranged from 0.5 to 0.8% at 0.12% expansion. Mixtures incorporating 100% RCA varied from 0.6 to 0.8% gain whereas mixes with 50% RCA ranged from 0.5 to 0.6% mass gain.

A



B

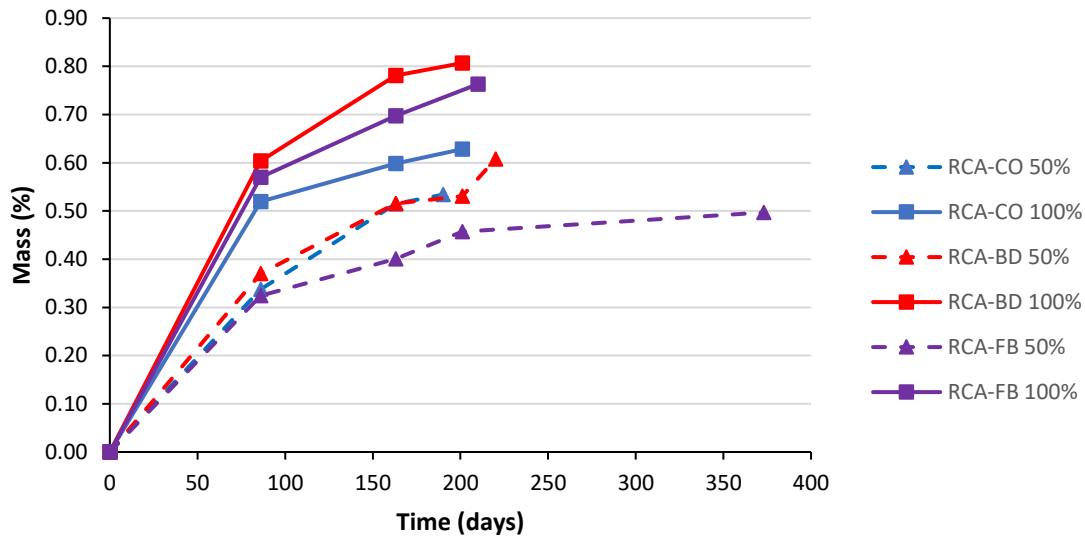


Figure 3.2: A) Expansion vs. time, and B) Mass gain vs time; for all RCA mixtures manufactured in the laboratory.

3.7.2. Microscopic damage appraisal

The “secondary” induced expansion and damage caused by ASR has been microscopically appraised through the use of the *Damage Rating Index (DRI)*. The analyses conducted in this section display two distinct, yet related objectives.

First, RBC structural members (bridge deck, columns and foundation blocks) were cored prior to the deconstruction in 2010/2011 and thus samples were selected from all members to evaluate their current damage degree (see section 3.4). The complete description of the results obtained from this comprehensive condition assessment may be found in Sanchez et al. (2020). Figure 3.3 displays the DRI charts obtained from the three RBC structural members (the DRI numbers presented herein are the average of two 100 cm² cores per structural member; i.e. 200 cm² evaluated per member). Analyzing the data, one verifies that the most important microscopic damage feature obtained for all members is the *open crack in the aggregates with gel* (OCAG – green chart). The latter is indeed an indication of the presence of ASR in all members. Moreover, an important number of *cracks in the cement paste* (with and without gel - CCPG and CCP - light blue and orange, respectively) were observed, especially for the foundation block specimens, which

confirms ASR at an advanced stage. The DRI numbers gathered were 300, over 400 and over a 1000 for the columns, deck and foundation blocks, respectively.

The second analysis was performed on recycled concrete mixtures manufactured using coarse RCA derived from the distinct RBC members (Figure 3.4) and subjected to a “secondary” induced expansion of 0.12%. Evaluating Figure 3.4, it is noticed that the DRI numbers obtained from RCA concrete specimens incorporating 100% RCA particles are greater than specimens only incorporating 50% of RCA material. Furthermore, specimens presenting RCA from the foundation blocks yielded the highest damage degree (RCA-FB - 1350 and 950) followed by the bridge deck (i.e. RCA-BD - 1150 and 850) and then the columns (i.e. RCA-CO - 900 and 880) specimens, respectively for 100 and 50% of RCA. The variation between presented DRI results (average of two tested specimens) and each individual tested specimen is less than 4%. Figure 3.4 data also emphasizes the presence of ASR since important amounts of *open cracks within the aggregate particles* (with and without gel – OCAG and OCA – green and red charts) along with *cracks in the cement paste* (with and without gel – CCPG and CCP – light blue and orange charts) are observed in all of them. Yet, it seems that a much higher presence of ASR gel (OCAG – green chart) is found in specimens directly retrieved from RBC members. Moreover, higher amounts of cracks within the cement paste, especially without gel (CCP – orange chart) is observed in recycled concrete samples when compared to RBC cores. The latter might be related to the intrinsic and distinct microstructure of the RCA concrete.

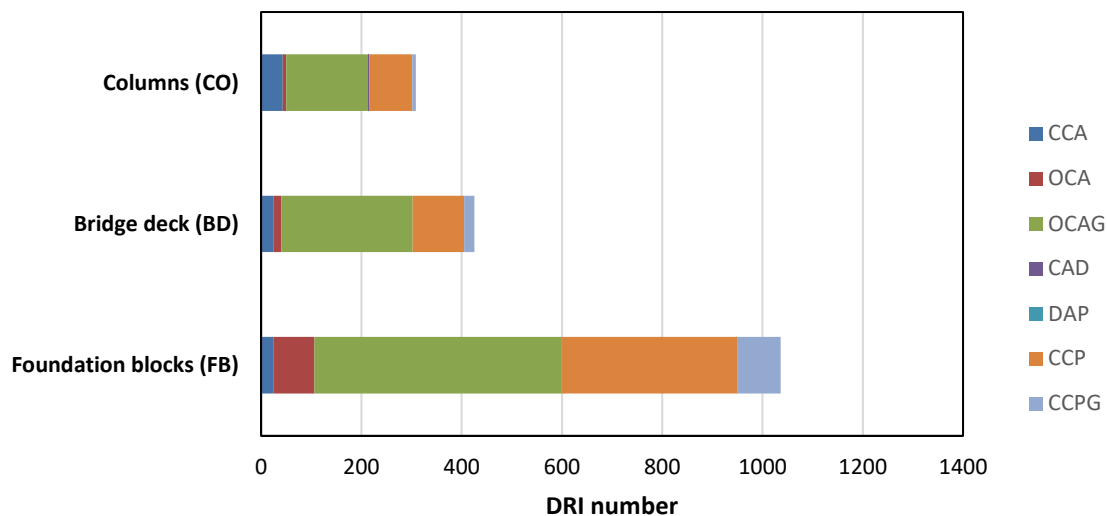


Figure 3.3: DRI charts from cores retrieved from the RBC members (Sanchez *et al.*, 2019).

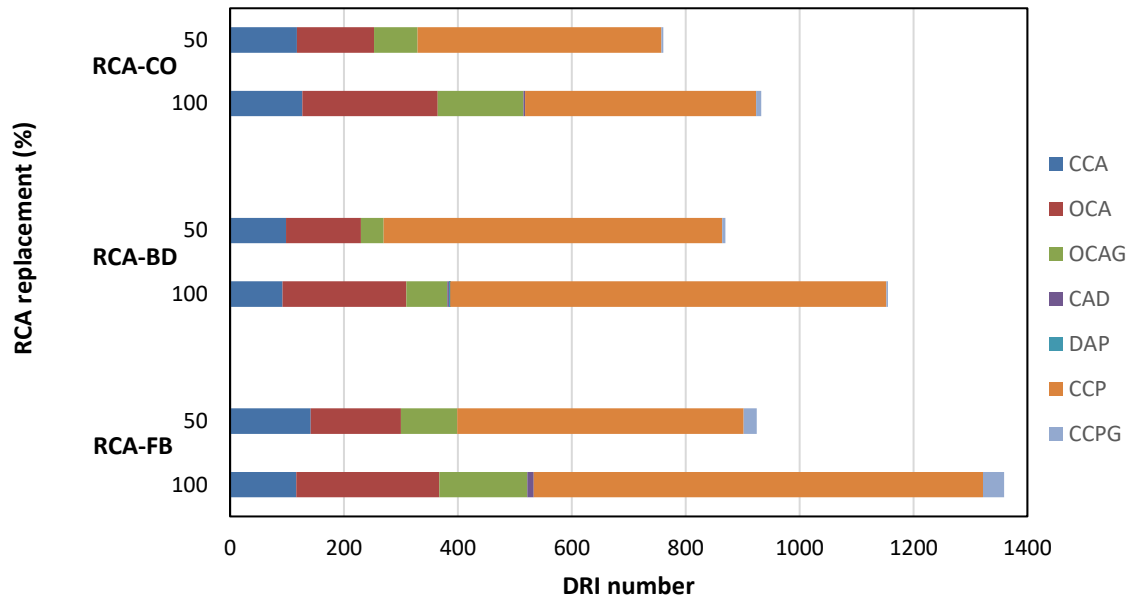


Figure 3.4: DRI charts from the different RCA mixtures manufactured in the laboratory and displaying a 0.12% of “secondary” ASR-induced expansion.

To complement the microscopic damage assessment and thus bring further information to the overall evaluation, supplementary petrographic analyses were conducted according to the DRI extended version (Sanchez *et al.*, 2015, 2016).

- Assessment of damage features in percentage (%), without considering the DRI proposed weighing factors (Figure 3.5);
- Measurements of maximum crack length and width for the open cracks in the aggregates and cement paste (Figure 3.6);
- Crack density calculation (i.e. total number of open cracks in the aggregates and cement paste per area examined) (Figure 3.7).

Figure 3.5 displays the relative proportions 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 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 once more a clear ASR development on these samples as per Sanchez et al. (2015, 2016).

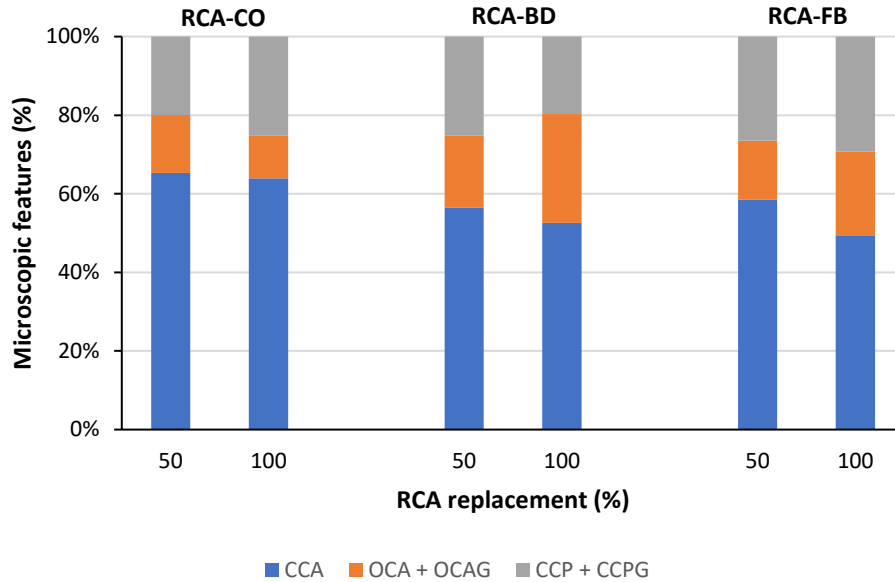
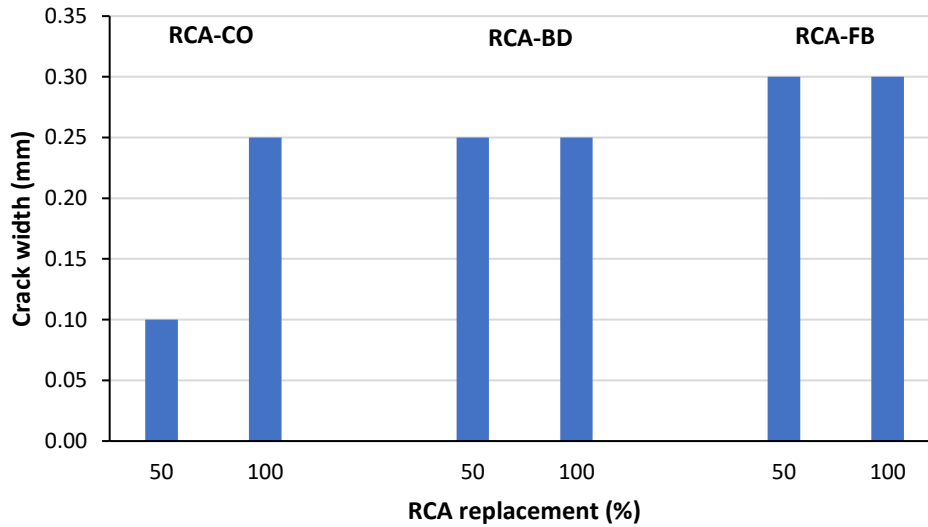


Figure 3.5: Microscopic damage features (in %, without using the DRI weighing factors) normalized for a 100 cm² surface area.

Figure 3.6A illustrates the maximum crack width while Figure 3.6B presents the maximum crack length observed on the ASR-affected RCA concrete specimens evaluated. The specimens made of RCA from the foundation blocks (i.e. RCA-FB) presented both, the highest crack length and width (i.e. 25 mm and 0.30 mm, respectively) for 100% RCA replacement. Likewise, specimens from the bridge deck (i.e. RCA-BD) and columns (i.e. RCA-CO) showed lower and quite close results, yielding crack lengths and widths of about 16 mm and 0.25 mm, respectively. The above results followed the same trend as mixes made of 50% RCA material; yet, the values obtained of both crack length and width were either similar or lower.

A



B

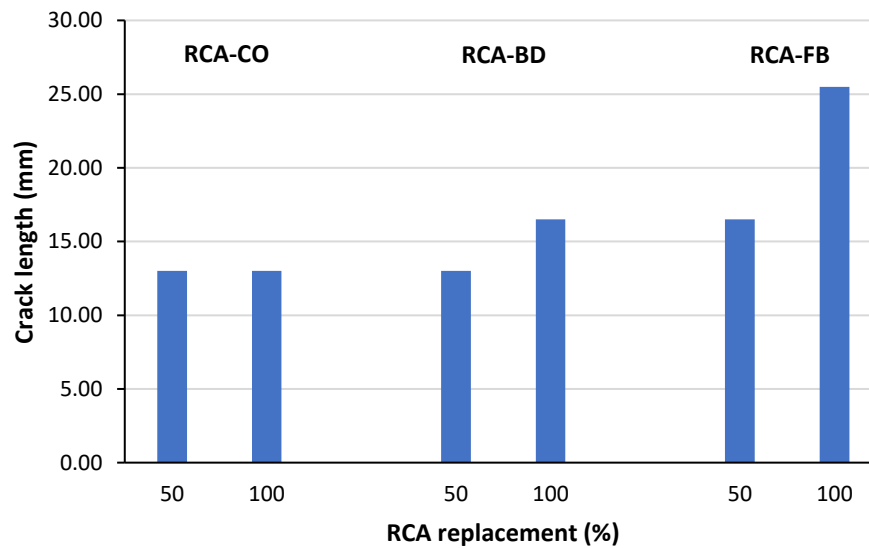


Figure 3.6: Maximum crack length (A) and width (B) of distinct ASR-affected RCA mixtures incorporating 50 and 100% RCA replacement.

Figure 3.7 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 is higher for recycled samples incorporating 100% RCA replacement. Furthermore, samples incorporating RCA from the foundation blocks displayed the highest cracking density (i.e. $CD \approx 5$ counts/cm²), followed by specimens incorporating RCA from the bridge deck (i.e. $CD \approx 4.2$ counts/cm²) and columns

(i.e. $CD \approx 3.5$ counts/cm²). Similar trend is found for 50% RCA replacement, but much lower values were observed (i.e. $CD \approx 3.2, 3.0$ and 2.6 counts/cm², for RCA from foundation blocks, bridge deck and columns, respectively). The variation between the presented crack density values (average of two tested specimens) and each individual tested specimen is less than 5%.

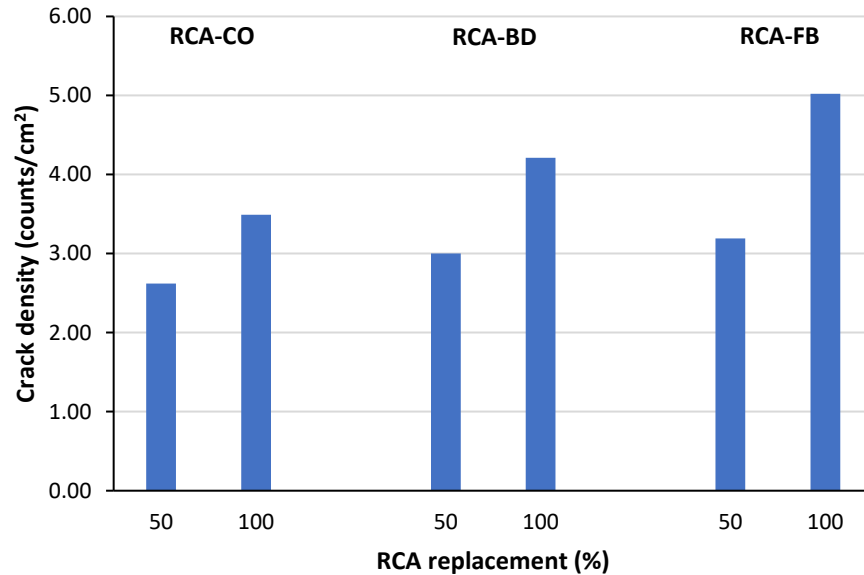


Figure 3.7: Crack density (summation of opened cracks in aggregate particles and cement paste, with and without reaction products - counts/cm²) for all RCA mixtures manufactured in the laboratory.

3.7.3. Mechanical damage assessment

As for the DRI, the *Stiffness Damage Test (SDT)* analyses were conducted with two distinct but related objectives. First, the SDT outcomes (i.e. SDI, PDI, and modulus of elasticity) were assessed on cores extracted from the distinct RBC members from exposed and non exposed to weathering locations as per Sanchez et al. (2014, 2015) (Figure 3.8). It is worth noting that the SDI and PDI indices (i.e. dimensionless) represent the ratio of dissipated energy/plastic deformation to the total energy/deformation implemented over five loading-unloading compression cycles, respectively.

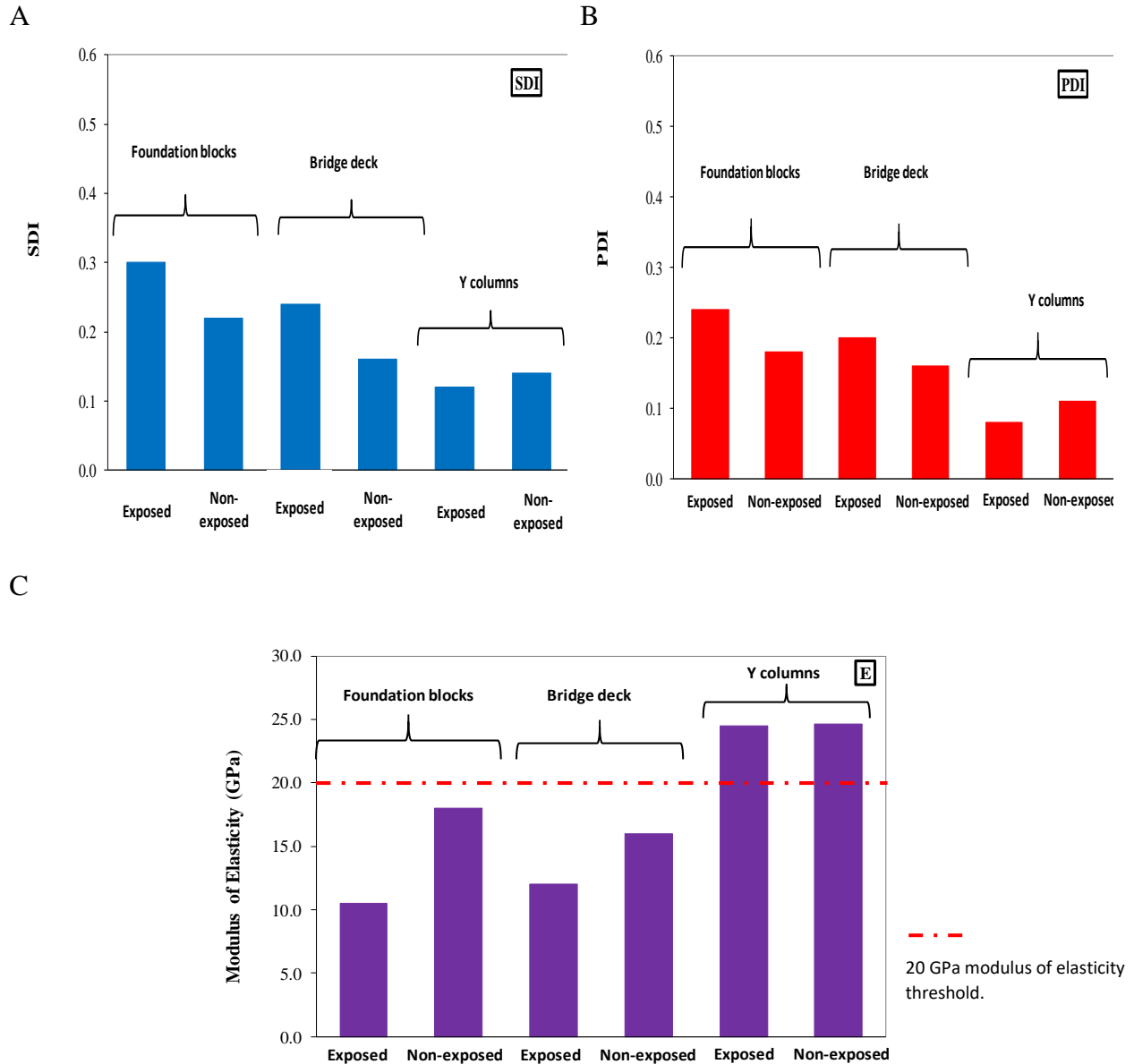


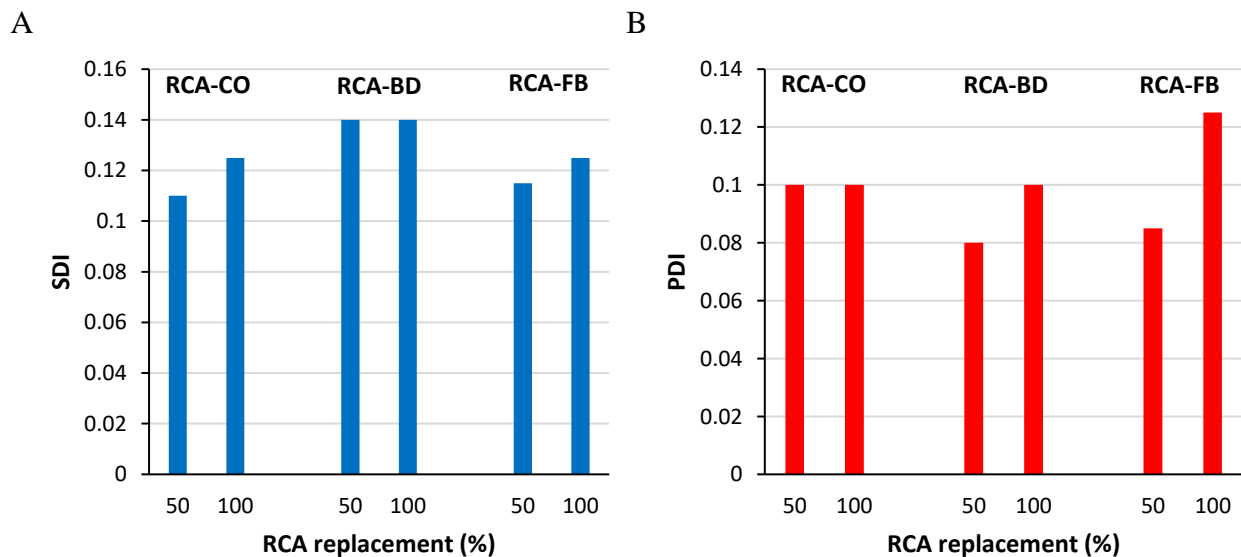
Figure 3.8: Stiffness Damage Test (SDT) outcomes obtained from cores extracted from RBC members: A) SDI, B) PDI, and C) Modulus of Elasticity (GPa) (Sanchez *et al.*, 2019).

Analyzing the data above, one notices that greater SDI and PDI values (Figures 3.8A and B) along with lower modulus of elasticity results (on average, Figure 3.8C) were obtained from cores extracted from the foundation blocks, followed by the bridge deck and the columns. Generally, cores extracted from exposed to weathering conditions displayed higher ASR-induced damage and thus higher SDI and PDI values and lower modulus of elasticity results (except for the columns). The SDI and PDI values ranged from 0.11 to 0.30, and from 0.08 to 0.25, respectively. Furthermore,

one may notice that the cores from the foundation block and bridge deck members presented modulus of elasticity results below 20 GPa (Figure 3.8 C), which may be considered quite low compared to the expected value (34-37 GPa, depending on the member) for a sound concrete with similar strength and aggregate type as per Sanchez et al. (2017).

Figure 3.9 shows the second SDT analysis conducted on the recycled mixtures evaluated in this research. Overall, the SDI and PDI values (Figure 3.9A and B) obtained were either similar or slightly higher for 100% RCA replacement mixtures when compared to 50% replacement mixes. The SDI and PDI values on the ASR-affected RCA mixtures ranged from 0.11 to 0.14, and from 0.08 to 0.13, respectively. Conversely, the modulus of elasticity values varied from 33 to 37 GPa for 50% RCA mixtures, and from 27 to 29 GPa for 100% RCA mixtures; therefore, lower stiffness was obtained on mixes incorporating 100% RCA replacement. The variation between the presented SDI, PDI and modulus of elasticity results (average of two tested specimens) with each individual tested specimen is around 5, 9 and 2.5%, respectively.

Comparing the mechanical performance (i.e. SDI, PDI and modulus of elasticity) gathered on ASR-affected RCA concrete with the affected conventional concrete cores extracted from RBC members, it seems that although the recycled mixtures present some important inner damage (i.e. past expansion and deterioration), and have also been subjected to “secondary” induced expansion, their overall mechanical behaviour is better than the distressed concrete members by the time of RBC deconstruction, since lower SDI and PDI values and higher stiffness results were obtained.



C

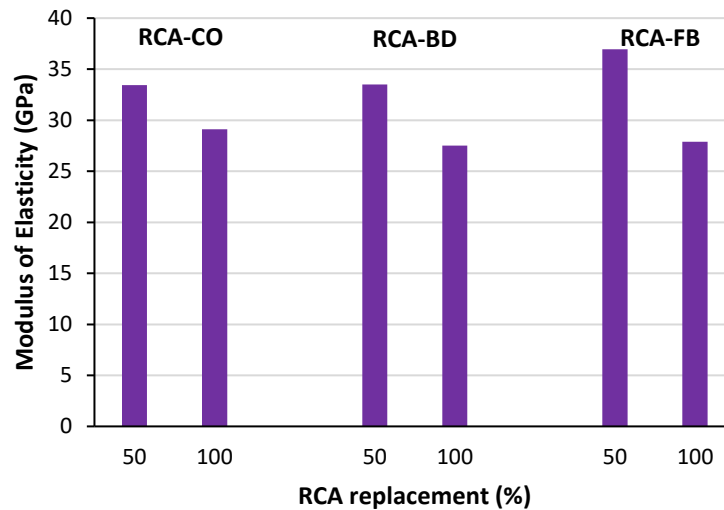


Figure 3.9: Stiffness Damage Test (SDT) outcomes for the ASR-affected RCA mixtures. A) SDI, B) PDI, and C) Modulus of Elasticity (GPa).

3.8. Discussion

3.8.1. Multi-level assessment of conventional and recycled concrete affected by ASR

Sanchez et al. (2017) developed a multi-level approach (mechanical and microscopic) to assess alkali-aggregate reaction (AAR, normally composed of alkali-silica reaction- ASR and alkali-carbonate reaction- ACR) induced expansion and damage in affected conventional concrete. After analyzing a wide range of concrete strengths (25, 35 and 45 MPa), aggregate types (fine vs coarse) and natures (i.e. \neq lithotypes), a chart of values presenting data envelopes has been proposed (Table 3.1), with a confidence level of 5%. It is worth noting that this chart displays some data overlap (i.e. microscopic and mechanical) as a function of the expansion levels evaluated. The latter was found to be due to the intrinsic heterogeneity of conventional concrete and its constituents, especially the type and nature of reactive aggregates. Therefore, Sanchez et al. (2017) proposed that practitioners might use the chart either by 1) selecting data from a similar reactive aggregate from the concrete under analysis (e.g. reactive limestone aggregate in this case – Figure 3.10, where the positive x axis is the expansion attained to date, the positive y axis is the SDI value, the negative y axis is the DRI number/1000 and the negative x axis is a reduction in modulus of elasticity from 0 to 1), or by 2) averaging the envelope values (in case the reactive aggregate is unknown – Table 3.1). Furthermore, Table 3.1 was created using laboratory test

samples under free-expansion conditions whereas it is clear that structures/structural members will present a variety of stress states and confinement conditions. Nonetheless, this chart was established to be used as “reference” and might be considered as the “worst case scenario” for AAR affected concrete.

Table 3.1: Multi-level assessment results of AAR affected concrete (Sanchez et al., 2017).

Classification of ASR damage degree (%)	Reference expansion level (%)	Assessment of ASR				
		Stiffness loss (%)	Compressive strength loss (%)	Tensile strength loss (%)	SDI	DRI
Negligible	0.00 – 0.03	-	-	-	0.06 – 0.16	100 - 155
Marginal	0.04 ± 0.01	5 – 37	(-)10 – 15	15 – 60	0.11 – 0.25	210 - 400
Moderate	0.11 ± 0.01	20 – 50	0 – 20	40 – 65	0.15 – 0.31	330 - 500
High	0.20 ± 0.01	35 – 60	13 – 25	45 – 80	0.19 – 0.32	500 - 765
Very high	0.30 ± 0.01	40 – 67	20 – 35		0.22 – 0.36	600 – 925

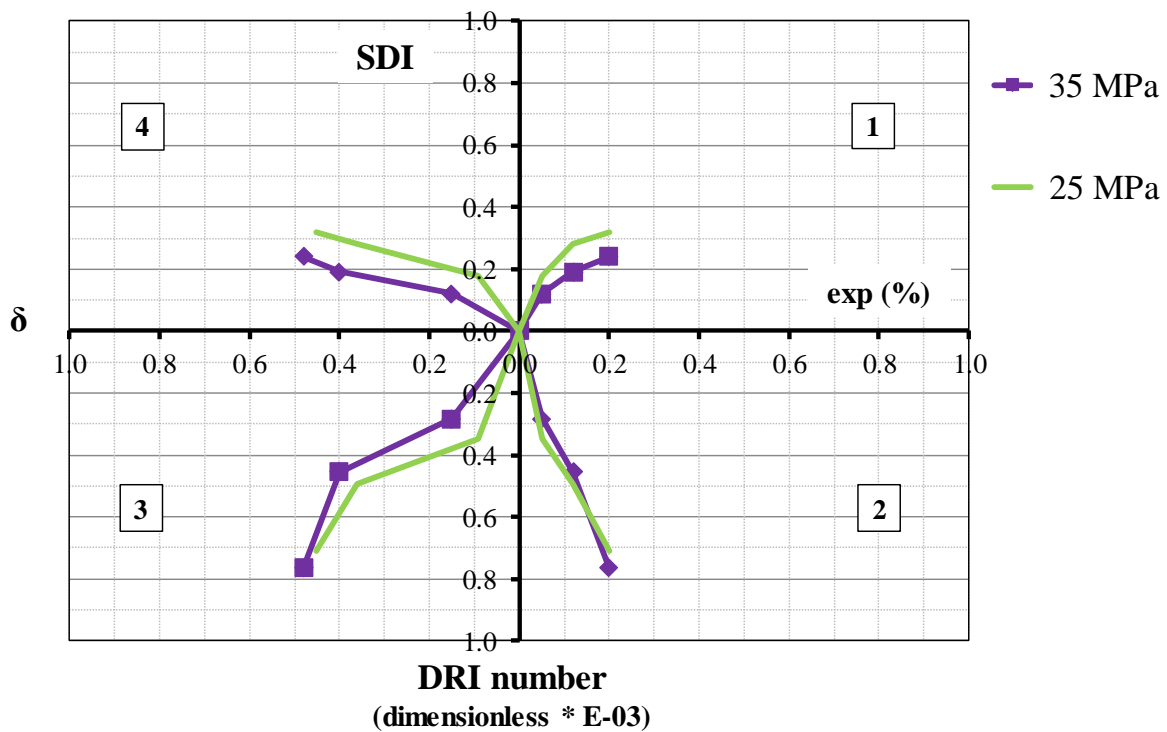


Figure 3.10: Multi-level assessment plots established by Sanchez et al. (2017) for ASR-affected 25 and 35 MPa conventional concrete mixtures incorporating a reactive limestone aggregate similar to the aggregate used in RBC members.

Evaluating the table and plot above and comparing the DRI and SDI outcomes from the specific aggregate used in this study (i.e. siliceous limestone – Figure 3.10), it is possible to notice that the damage displayed by the distinct RBC members would represent induced “free” expansion levels of about 0.05%, 0.12%, and 0.25-0.30%, respectively for the columns, bridge deck and foundation blocks (Sanchez *et al.*, 2017). The latter indicates that although the RCA material produced in this research comes from the same structure (i.e. RBC overpass), its inner quality and preliminary ASR-induced development is different according to the member and location the RCA was reclaimed.

The DRI and SDT results illustrated in Figures 3.2, 3.4 and 3.9 indicate that ASR-induced “secondary” expansion and damage are directly related to the RCA source. The latter seems to suggest that the past expansion of the affected concrete (i.e. prior crushing) and the potential for further distress (i.e. available reactive siliceous phases) may govern the “secondary” ASR development in the recycled material. In this work, a very reactive siliceous limestone from Quebec was selected for use in the concrete mixtures used to build RBC overpass. This aggregate generates about 0.20-0.25% expansion while tested in the concrete prism test (CPT) as per ASTM C 1293 (Sanchez *et al.*, 2017). Comparing the ultimate expansion potential of the aggregate with the likely expansion levels reached by the distinct RBC members after almost 50 years of service, one may notice that the foundation blocks cores (i.e. FB) presented higher expansion levels than forecasted in the CPT (i.e. 0.25-0.30%), while the other two members (bridge deck- BD and columns- CO) were expected to still present a potential of further reaction (e.g. unreacted silica).

Figure 3.2 somewhat indicates the above discussion, since faster ASR kinetics was found for 100% RCA concrete made of BD and CO materials. The latter is even more evident for 50% RCA replacement where CO presented the fastest kinetics, followed by BD and FB, which inversely agrees with the expansion and damage attained to date by these members. Yet, all the above RCA sources were still able to provide the recycled mixtures with an induced “secondary” 0.12% expansion and the damage obtained at this stage were quite different from both the conventional concrete cores previously appraised and from each other (i.e. as per the RCA amount and source).

Figures 3.3 and 3.4 demonstrate the differences in microscopic distress features of ASR-affected RCA and conventional concrete. A much higher number of cracks in the cement paste without gel

(CCP – orange chart) is found for all RCA sources which suggests the induced damage mechanism is distinct in recycled mixtures. Furthermore, the DRI numbers obtained from RCA mixtures were much higher than the ones observed in conventional concrete for the same expansion level. According to Sanchez et al. (2017), conventional concrete mixtures displaying moderate expansion levels should yield DRI numbers ranging from 330 to 500; yet all RCA specimens evaluated in this research presented DRI numbers above and beyond 750. This indicates that the DRI is being able to not only appraise the “secondary” induced distress but the “overall” damage. If one proceeds with the summation of the past expansion as per the distinct members plus the “secondary” expansion that all recycled mixtures were subjected, one would obtain the total ASR-induced expansion as being about 0.42%, 0.24%, and 0.17% for the mixes incorporating recycled aggregates from foundation blocks, bridge deck and columns, respectively. These expansion levels would yield DRI numbers higher than 1000, 850 and 500 for the RCA-FB, RCA-BD, and RCA-CO mixtures respectively. Yet, the values gathered from the recycled mixtures were almost 1400, 1200 and 1000 for RCA from the respective members which emphasizes a distinct mechanism in recycled concrete. The latter is likely due to the increase of pre-existing cracks (i.e. minimum energy principles) within the RCA while the development of the “secondary” induced expansion. Figure 3.7 has proven this by showing that RCA concrete made of FB obtained higher crack width and length for both 50 and 100% replacement. Because the RCA originated from FB had previously experienced a higher expansion level, the pre-existing cracks had extended wider and longer after the “secondary” induced expansion. Yet, this phenomenon should be better explained through the understanding of the cracks generation and propagation in ASR-affected recycled mixtures with controlled raw materials, expansion levels and exposure conditions. The RCA mixtures incorporating 50% RCA yielded exactly the same distress pattern than mixtures with 100% RCA, yet the DRI numbers found were lower, as expected.

Figure 3.9 illustrates the mechanical responses of all ASR-affected RCA concrete mixtures obtained through the SDT. Analyzing the data, one verifies that differently from the DRI, the SDT outcomes (i.e. SDI, PDI and modulus of elasticity) were only able to capture the “secondary” induced damage in the recycled mixtures. In other words, the pre-existing damage that the CDW-RCA has undergone in the past would not have significant impact (or only minor impact) on the SDT outcomes of RCA mixtures. SDI and PDI values ranged from 0.11 to 0.14, and from 0.08 to 0.13, respectively. These results indicate an expansion level of about 0.08-0.12% as per Sanchez

et al. (2017) and Figure 3.10, which corroborates with the statement above. However, similar to the DRI, the SDT was able to distinguish damage from RCA concrete incorporating 50% and 100% replacement, since either similar or higher SDI and PDI values were obtained for 100% replacement. Finally, the modulus of elasticity of ASR-affected RCA specimens also changed whether 50% or 100% of RCA material has been incorporated. The higher the percentage of RCA material incorporated, the lower the stiffness obtained, as expected (due to the inner damage of the RCA). Yet, as the SDI and PDI, the stiffness results (from 37 to 27.5 GPa) only captured the “secondary” induced deterioration of about 20-25% stiffness reduction when compared to sound conventional concrete with similar strength and aggregates (i.e. 34 to 37 GPa); the latter means an ASR-induced expansion of about 0.12% (Table 3.1) and is in agreement with the other mechanical results obtained.

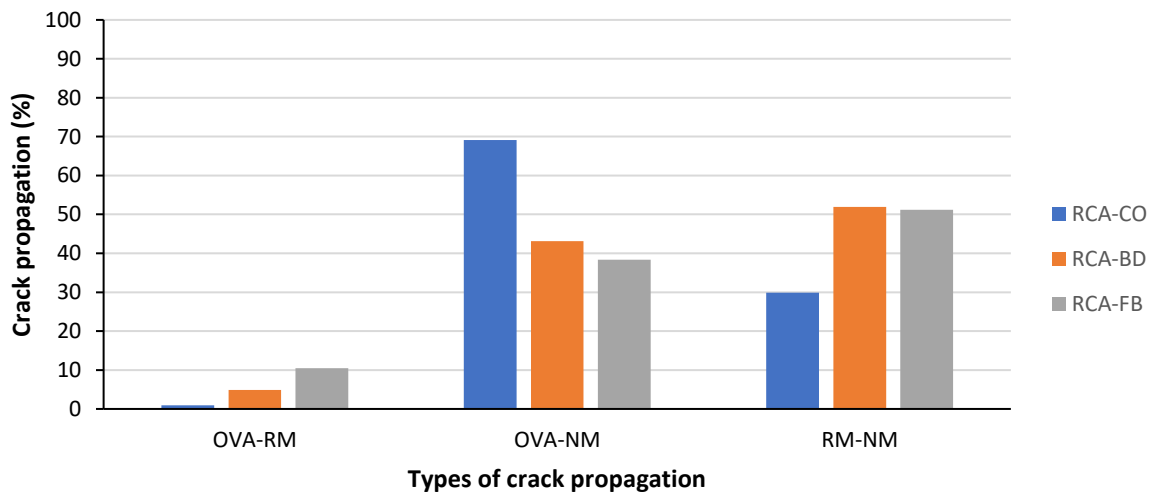
3.8.2. ASR-induced development of RCA concrete

To better understand the “secondary” ASR induced damage development, it is important to investigate the damage pattern displayed in the recycled material or, in other words, to understand ASR-induced cracks generation/propagation in the recycled system.

As verified in the DRI analysis (Figure 3.4), new cracks are indeed generated through the “secondary” ASR development, since higher DRI values were obtained for the recycled mixtures when compared to RBC conventional concrete cores. Furthermore, it has been identified three distinct types of “crack generation/propagation” within the RCA concrete: 1) cracks that are generated in the OVA and then extend to RM prior to reach the NM (OVA-RM); 2) cracks generated in the OVA that extend directly to the NM (OVA-NM) and; 3) cracks generated in the RM that extend directly to the NM (RM-NM). Figure 3.11 demonstrates the proportions (in percentage) of each of the three aforementioned distress features. The variation between the presented crack propagation (%) data (average of two tested specimens) and each individual tested specimen is less than 5%. Analyzing the plots, one sees that either for 50% or 100% replacement, it is not common to have cracks being generated in the OVA, propagating to the RM and finally reaching the NM (i.e. OVA-RM) in the affected recycled concrete. Only up to 15% of the total cracks (and it could have been much lower) were found to be OVA-RM cracks. Conversely, the vast majority of cracks in the recycled mixtures appraised seem to be generated in either the OVA or RM, propagating to the NM as a function of “secondary” induced expansion.

Cracks that are generated in the reactive OVA and extend to the NM are deemed to represent the *potential of further induced expansion and damage* of the RCA mixture since a new amount of alkalis has been brought to the system through the NM and reacts with the remaining siliceous phases from the OVA, inducing new deterioration. This petrographic distress feature ranges from 40 to 70% (depending on the member type and RCA replacement) in the total of cracks observed and represents the most pronounced damage feature verified for almost all mixtures evaluated (except the RCA-BD mix with 100% replacement).

A



B

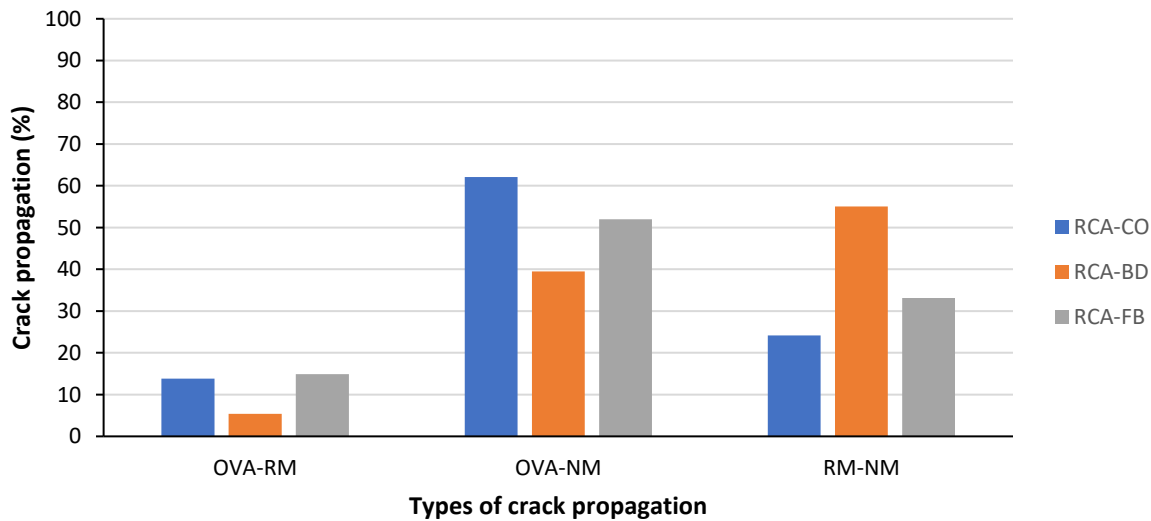


Figure 3.11: Crack propagation (in percentage) for the distinct RCA mixtures studied in this research: A) 50% of replacement B) 100% of replacement.

An important number of cracks was also observed in the RM and extending to the NM as a function of “secondary” induced expansion. These cracks are deemed to propagate from previous deteriorated locations within the RM due to past ASR-induced expansion and or crushing. Therefore, as per the minimum energy principle described by Sanchez et al. (2015), ASR tends to generate new cracks while keep enhancing in length and width the pre-existing cracks in the system through induced expansion. Yet, the latter happens until a point where the generation of new cracks in the system requires more energy than simply increasing in length and width the pre-existing ones; hence, upon further and “secondary” expansion, it is expected that some of the pre-existing RM cracks will be further developed and represent the *amount of pre-existing induced expansion and damage* of the RCA. This petrographic distress feature varies from 25 to 55% in the total amount of cracks verified, being the second most important feature observed. Figure 3.12 illustrates the aforementioned petrographic distress features of ASR-affected RCA concrete.

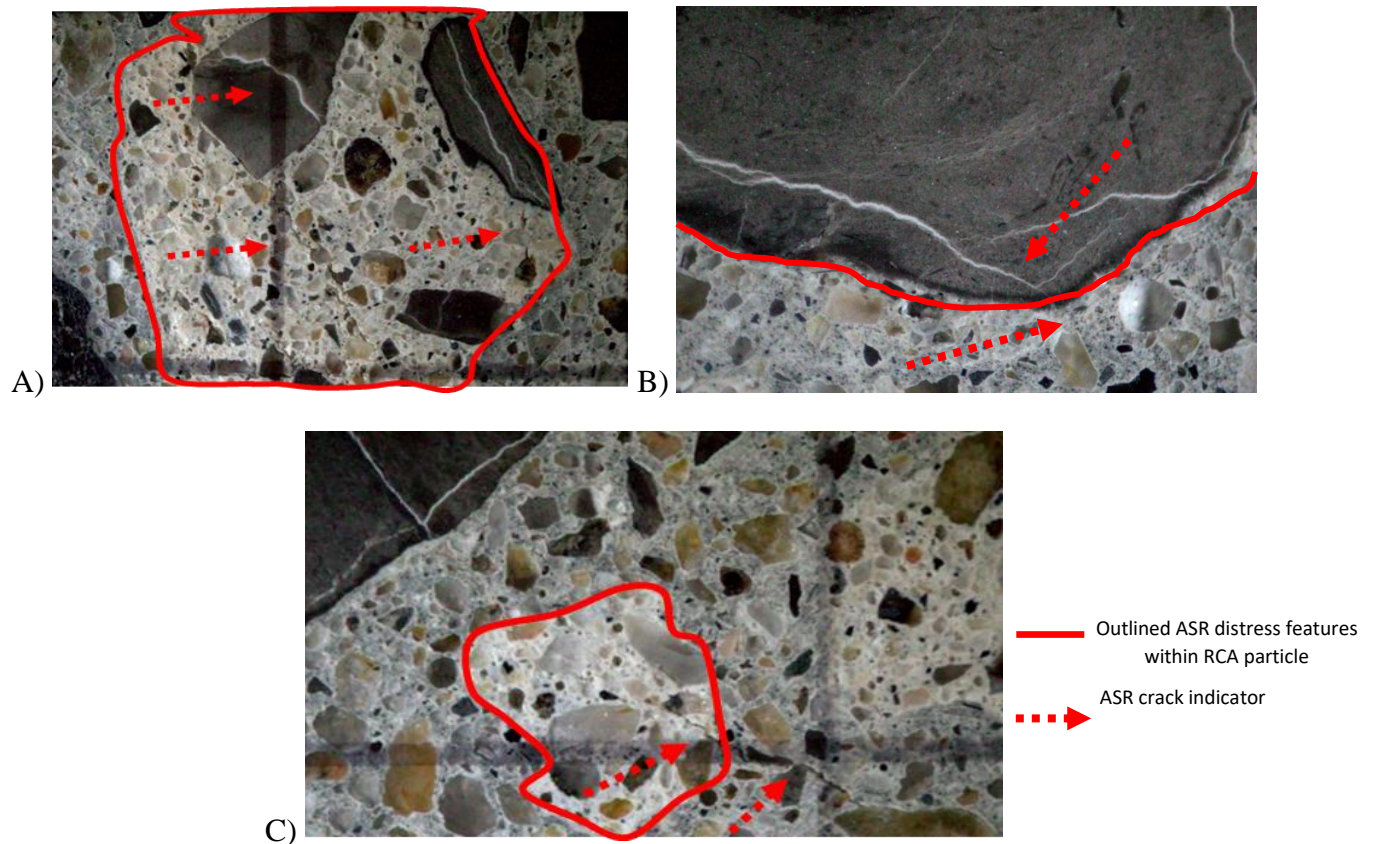


Figure 3.12: Typical petrographic distress features identified in the RCA concrete A) Open crack with gel in the OVA that extends to the RM, B) Crack propagating from the OVA to the NM, and C) Crack propagating from the RM to the NM.

3.8.3. Adapting the DRI to further understand damage in ASR-affected RCA concrete

It is widely known that the DRI is a semi-quantitative test procedure that appraises damage in concrete through the *amount* and *type* of cracks in the affected material. In other words, the number of cracks is multiplied by weighing factors, whose purpose is to balance the relative importance of the distinct petrographic distress features observed; thus a final DRI number is obtained, representing not only the total *number of cracks* but also the *importance of the existing cracks* in the affected material.

The DRI weighing factors have been selected in a logical, yet arbitrarily fashion as per Villeneuve and Fournier (2012) and Sanchez et al. (2015). For instance, a factor of 2 is given for cracks within the aggregate particles while a factor of 3 is proposed for cracks in the cement paste. The latter aims to emphasize that cracks within the cement paste are more deleterious in the mechanical properties and durability point of views than distress features within the aggregates. Yet, to apply the current DRI method to assess RCA concrete may be quite challenging and deserves further discussion.

It is known that RCA is comprised of OVA and RM. The values of RM within the RCA may largely vary, yet significant values ranging from 30 to 60% are often found (De Souza *et al.*, 2019; Ahimoghadam *et al.*, 2020). Therefore, although the RM is accounted for “cement paste” in the current DRI version, it is actually part of the aggregate particle; hence, accounting for the number of cracks within the RM using a factor of 3 may jeopardize the overall DRI analysis, increasing the final DRI number and detaching it from established database of ASR-affected conventional concrete as proposed by Sanchez et al. (2017).

Trying to better use the DRI assessment for ASR-affected RCA concrete along with better understanding the “secondary” induced expansion and damage in the recycled material, an adaptation on the current DRI procedure is discussed in this section. Table 3.2 illustrates the proposed petrographic features to be considered for evaluating RCA mixtures and their corresponding weighing factors. The new petrographic damage features proposed include *closed cracks in the OVA* (“CCA, OVA”), *opened cracks in the OVA with and without reaction product* (“OCA, OVA” and “OCAG, OVA”), *cracks in RM with and without reaction product* (“OCA, RM” and “OCAG, RM”), *OVA debonded* (“CAD, OVA”), and *disaggregate/corroded OVA*

particle (“DAP, OVA”). It is worth noting that, besides distinguishing between RCA and NA features, the proposed DRI version for RCA adopts the weighing factor of cracks in the residual mortar with/out reaction products (“OCA, RM” and “OCAG, RM”) as 2 instead of 3, since RM actually belongs to the aggregate particle (i.e. RCA) and not to the new mortar (i.e. NM) itself. Moreover, it should be noted that the proposed modified DRI is only valid for RCA concrete incorporating coarse RCA; further research is still required to adapt the method to fine RCA.

Table 3.2: Proposed DRI analysis for RCA mixtures.

Petrographic features		Abbreviation	Weighing Factor
Features related to the natural coarse aggregate particles (i.e. when RCA does not represent 100% of the concrete aggregates)	Closed cracks in the natural coarse aggregate	CCA, NA	0.25
	Opened cracks in the natural coarse aggregate	OCA, NA	2
	Crack with reaction product in the natural coarse aggregate	OCAG, NA	2
	Natural coarse aggregate debonded	CAD, NA	3
	Disaggregate/corroded natural coarse aggregate particle	DAP, NA	2
Features related to the recycled concrete aggregate particles	Closed cracks in the original virgin aggregate	CCA, OVA	0.25
	Opened cracks in original virgin aggregate	OCA, OVA	2
	Crack with reaction product in the original virgin aggregate	OCAG, OVA	2
	Original virgin aggregate debonded	CAD, OVA	3
	Disaggregate/corroded original virgin aggregate particle	DAP, OVA	2
	Cracks in residual mortar	OCA, RM	2
	Cracks with reaction product in residual mortar	OCAG, RM	2
Features related to cracking in the new cement paste	Cracks in new cement paste	CCP, NM	3
	Cracks with reaction product in new cement paste	CCPG, NM	3

Figure 3.13 illustrates the DRI results adopting Table 3.2 weighting factors for RCA mixtures. Evaluating the data, one verifies that the new DRI numbers for recycled mixtures derived from the RCA-CO, RCA-BD, and RCA-FB are 722, 766, and 822 respectively, for 50% RCA replacement and 863, 1014, and 1203 respectively, for 100% RCA replacement. These numbers decreased from 84 to 128 for the RCA mixtures incorporating 50% RCA and from 37 to 147 for RCA mixtures incorporating 100% RCA.

The rationale behind the proposed modified DRI is that the procedure allows an in-depth condition assessment on RCA mixtures by roughly distinguishing *past deterioration* (i.e. cracks in the OVA and RM) and “secondary” damage (cracks in the NM, and NA). Therefore, it is possible to appraise which mechanism (i.e. past vs secondary deterioration) is contributing more to the overall damage of the recycled material. For instance, “CCP, NM”, which is considered to represent the “secondary” induced damage, is found to display roughly 42%, 36% and 29% (CO, BD and FB, respectively) of all distress features for 50% replacement RCA mixtures whereas it represents 23%, 33% and 28% (CO, BD and FB, respectively) for the mixtures with 100% RCA replacement. The latter seems to indicate that 1) except for the RCA-CO with 50% replacement, all the other mixtures presented close “secondary” induced expansion, which is expected since the “secondary” expansion was fixed to 0.12%, 2) the higher the RCA replacement, the higher the past deterioration within the system, and 3) for the same fixed secondary expansion level (e.g. 0.12%), RCA mixtures with less past expansion and damage tend to display higher secondary expansion. This agrees with the minimum energy law as per Sanchez et al. (2015). It is worth noting that the “secondary” induced expansion is not only measured by the “CCP, NM”, since some partially affected OVA might keep swelling and generating damage to the RM in the “secondary” mechanism. Yet, the “CCP, NM” is considered to be the main “secondary” expansion feature and should represent a significant amount of new induced expansion in the recycled material.

Finally, it is interesting to notice that if the “secondary” expansion (i.e. CCP, NM) is subtracted from the DRI numbers obtained from the adapted DRI procedure, the new values would have been 419, 560 and 602 respectively for 50% RCA replacement and 657, 668 and 843 respectively for 100% replacement. They would represent from 0.12% to 0.30% expansion as per Sanchez et al. (2017), which better correspond (although still slightly higher, especially for CO mixtures) to the values and estimated expansion obtained from RBC extracted conventional concrete cores.

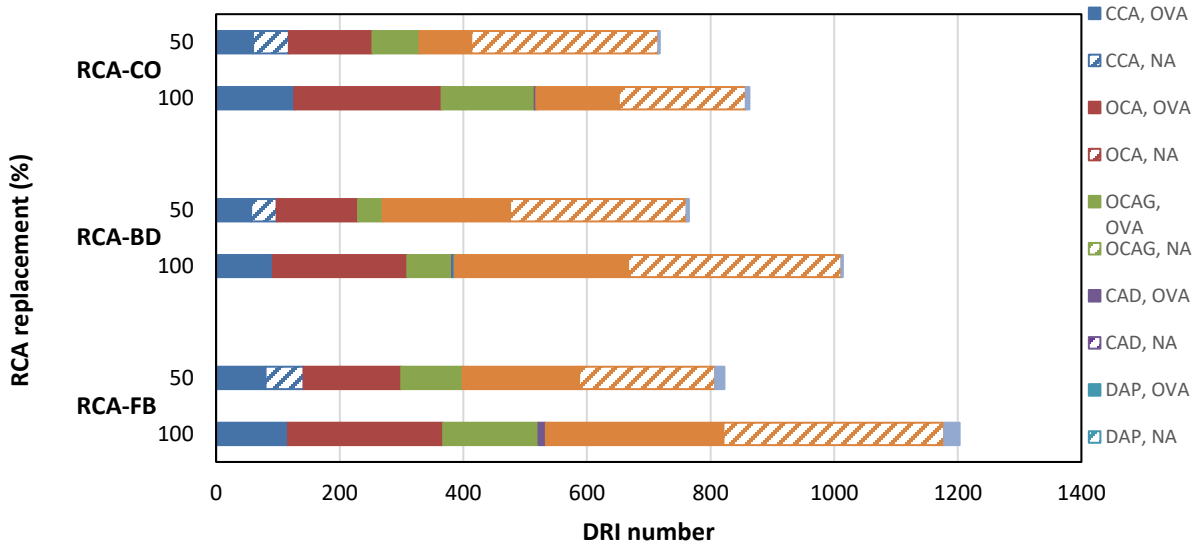


Figure 3.13: DRI analysis with new proposed weighting factor for RCA mixtures.

3.9. Conclusions

The main objective of this study was to assess the condition of ASR-affected RCA displaying 50% or 100% replacement and reclaimed from an ASR-affected overpass (RBC overpass) after nearly 50 years of service. The main findings of the current research are presented hereafter:

- The overall performance of ASR-affected RCA concrete depends on the RCA replacement amount, along with the petrographic distress features (i.e. past expansion) of the RCA;
- Kinetics of ASR-affected RCA concrete depends upon the RCA source (i.e. the higher the past expansion, the slower the “secondary” ASR kinetics) and replacement amount (the higher the RCA replacement, the faster the “secondary” ASR kinetics);
- ASR-induced damage in RCA concrete does not seem to follow the same distress process than a companion conventional concrete. Higher DRI numbers are obtained when compared to both “secondary” expansion levels and the summation of “past expansion” plus “secondary” expansion. The latter is likely due to the enhancement of pre-existing cracks (i.e. minimum energy principles) within the RCA while the development of the “secondary” induced expansion;
- The results presented in this research demonstrate that mechanical test procedures such as the SDT and modulus of elasticity are only able to capture the “secondary” induced

expansion and damage on ASR-affected RCA mixtures, regardless of the RCA source and past expansion experienced. Further research is still needed in this regard to verify the outcomes obtained in this work;

- A thorough petrographic analysis on the ASR-affected RCA concrete verified the presence of three distinct types of cracks generation/propagation within the RCA concrete: 1) cracks that are generated in the OVA and extend to RM prior to reach the NM; 2) cracks generated in the OVA that reach directly the NM and; 3) cracks generated in the RM that extend to the NM. The cracks type 1 are not quite common; the cracks type 2 are considered to represent the *potential for further induced expansion* in the material, whereas the cracks type 3 likely display the *amount of pre-existing induced expansion and damage* of the RCA;
- It has been proposed and adaptation to the current DRI method to further understand ASR-induced expansion and deterioration in RCA concrete. According to the results obtained, the modified version showed to be quite suitable to distinguish “past” and “secondary” expansion within the overall deterioration of the coarse RCA. Furthermore, the DRI values obtained seem to be closer (i.e. fairly similar) to the database gathered in ASR-affected conventional concrete.

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Chapter Four: Summary and recommendations for future research

4.1. Summary and conclusions

In this research, six recycled concrete mixtures were manufactured incorporating 50 or 100% ASR reactive RCA (in mass) from distinct structural members (i.e. columns, bridge deck and foundation blocks) of Robert-Bourassa/Charest (RBC) overpass. Although the source of OVA used was exactly the same (siliceous limestone from Quebec City), it should be noted that the specimens cored from each structural member presented different damage degrees compared to one another; for instance, specimens from columns, bridge deck and foundation blocks were found to display 0.05 to 0.08%, 0.12 to 0.15% and 0.30 to 0.40% expansion levels, respectively.

Once fabricated, all recycled mixtures were stored in environment conditions (38°C and 100% RH) enabling ASR induced development. A “secondary” expansion level of 0.12% was selected for further mechanical (i.e. SDT) and microscopic (i.e. DRI) analyses. The main findings of the current research program are presented hereafter:

- **ASR kinetics**

All RCA mixtures were able to reach a “secondary” 0.12% expansion, regardless of their past expansion and deterioration. The 100% RCA mixtures presented faster kinetics than 50% RCA mixtures, reaching 0.12% expansion level within 200 days. For 50% RCA mixtures, ASR kinetics was found to be faster in RCA mixture produced from members that experienced less past expansion (i.e. columns). Conversely, ASR kinetics was found to be slower in RCA mixtures incorporating RCA derived from the foundation blocks of RBC (i.e. member that experienced the highest past induced expansion and deterioration). Such phenomenon may be attributed to a larger number of reactive phases still available in RCA reclaimed from less deteriorated members. Generally, kinetics of ASR-affected RCA concrete depends upon the RCA source (i.e. the higher the past expansion, the slower the “secondary” ASR kinetics) and replacement amount (the higher the RCA replacement, the faster the “secondary” ASR kinetics);

- **Mechanical assessment**

The results presented in this research demonstrate that mechanical test procedures such as the SDT and modulus of elasticity are only able to capture the “secondary” induced

expansion and damage of ASR-affected RCA mixtures, regardless of the RCA source and past expansion experienced. Further research is still needed in this regard to verify the outcomes obtained in this work.

- **Microscopic appraisal**

ASR-induced damage in RCA concrete does not seem to follow the same distress process than a companion conventional concrete. Higher DRI numbers are obtained when compared to both “secondary” expansion levels and the summation of “past expansion” plus “secondary” expansion. The former is likely due to the enhancement of pre-existing cracks (i.e. minimum energy principles) within the RCA while the development of the “secondary” induced expansion. A thorough petrographic analysis on the ASR-affected RCA concrete verified the presence of three distinct types of cracks generation/propagation within the RCA concrete: 1) cracks that are generated in the OVA and extend to RM prior to reach the NM; 2) cracks generated in the OVA that reach directly the NM and; 3) cracks generated in the RM that extend to the NM. The cracks type 1 were found to not be very common; yet the cracks type 2 are considered to represent the *potential for further induced expansion* in the material whereas the type 3 likely display the *amount of pre-existing induced expansion and damage* of the RCA. It has been proposed adaptation to the current DRI method to further understand the “past” and “secondary” expansion in ASR-affected RCA concrete. According to the results obtained, the modified version showed to be quite suitable to distinguish “past” and “secondary” expansion within the overall deterioration of the coarse RCA. Moreover, the DRI values obtained seem to be closer to the database gathered in ASR-affected conventional concrete.

4.2. Recommendations for future research

The present research is believed to have brought interesting contributions to the understanding of the “secondary” induced expansion and damage of ASR-affected RCA concrete reclaimed from CDW. Yet, further investigations are still required to enhance understanding on the following topics:

- Assessment of the “secondary” induced expansion on RCA concrete at distinct damage levels: e.g. low (i.e. 0.05%) and high (0.30 %);

- Influence of the amount of alkalis presented in the RM on the “secondary” induced expansion of RCA concrete;
- Evaluation of the damage pattern (i.e. cracks initiation and propagation) of ASR-affected RCA concrete incorporating RCA displaying distinct past expansion and distress;
- Study of ASR-gel formation and features (i.e. chemical composition, viscosity, stiffness, etc.) of ASR-affected RCA concrete;
- Appraisal of the durability aspects of ASR-affected RCA concrete including resistance to freeze-thaw, sulphate attack, carbonation, steel corrosion, etc.;
- Investigation of ASR “secondary” development of RCA mixtures manufactured with dry and saturated RCA particles;
- Research of preventive measures to avoid ASR-induced development in recycled concrete containing reactive RCA;
- In-depth evaluation of SDT outcomes to improve its performance in assessing ASR-affected concrete incorporating RCA with distinct “past” expansion and deterioration degree;
- Investigation of the potential ASR-induced development in ASR-affected RCA concrete made of fine recycled concrete aggregate (i.e. FRCA).

Appendix A

RCA Concrete Mixture Proportions (Beauchemin *et al.*, 2018).

Materials	Quantities in the mix, kg/m ³ (35 MPa)	
	50% RCA mix	100% RCA mix
Sand	710	710
Coarse aggregate (HP)	525	/
Coarse RCA (CO, BD, FB)	495	978
Cement	420	420
Water	190	190
W/C	0.435	0.435