Evaluation of ASR-induced damage generation and prolongation in affected recycle concrete

Cassandra Trottier

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Department of Civil Engineering

Faculty of Engineering

University of Ottawa

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Abstract

Recycled concrete is among the rising eco-friendly construction materials which helps to reduce waste and the need for new natural resources. However, such concrete may present previous deterioration due to, for instance, alkali-silica reaction (ASR), which is an ongoing distress mechanism that may keep being developed in the recycled material. This work aims to evaluate the potential of further distress and crack development (i.e. initiation and propagation) of AAR-affected RCA concrete in recycled mixtures displaying distinct past damage degrees and reactive aggregate types. Therefore, concrete specimens incorporating two highly reactive aggregates (Springhill coarse aggregate and Texas sand) were manufactured in the laboratory and stored in conditions enabling ASR development. The specimens were continuously monitored over time and once they reached marginal (0.05%) and very high (0.30%) expansion levels, they were crushed into RCA particles and re-used to fabricate RCA concrete. The RCA specimens were then placed in the same previous conditions and the "secondary" ASR-induced development monitored over time. Results show that the overall damage in ASR-affected RCA concrete is quite different from affected conventional concrete, especially with regards to the severely damaged RCA particles, where ASR is induced by a reactive coarse aggregate, as the RCA particle itself may present several levels of damage simultaneously caused by past/ongoing ASR and newly formed ASR. Moreover, the influence of the original damage extent in such RCA concrete was captured by the slightly damaged RCA mixture, eventually reaching the same damage level as the severely damaged mixture. Furthermore, the original extent of deterioration influences the "secondary" induced expansion and damage of RCA concrete, since the higher the original damage level, the higher the crack numbers and lengths observed in the RCA concrete for the same expansion level, whereas wider cracks are generated by RCA having previously been subjected to slight damage thus indicating the difference in the distress mechanism as a function of original extent of damage. In addition, it has been found that distress on RCA containing a reactive sand generates and propagates from the residual mortar (RM) into the new mortar (NM) as opposed to RCA containing a reactive coarse aggregate, being generated and propagated from the original coarse aggregate (i.e. original virgin aggregate – OVA) into the NM. Likewise, RCA containing a reactive sand caused longer and higher number of cracks for the same “secondary” induced expansion than the RCA made of reactive coarse aggregate. Finally, novel qualitative and descriptive models are proposed in this research to explain ASR-induced distress generation and propagation on RCA mixtures made of reactive fine and coarse aggregates.

Keywords: Recycled concrete aggregates (RCA), alkali-aggregate reaction (AAR), alkali-silica reaction (ASR), internal swelling reaction (ISR), crack initiation and propagation, damage and secondary damage.

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AAR	Alkali-aggregate reaction
ACR	Alkali-carbonate reaction
AMBT	Accelerated mortar bar test
ASR	Alkali-silica reaction
CC	Conventional concrete
CDW	Construction and demolition waste
CPT	Concrete prism test
DRI	Damage rating index
EMV	Equivalent mortar volume
EMV-mod	Modified equivalent mortar volume
EV	Equivalent volume
FT	Freeze and thaw
ISR	Internal swelling reaction
ITZ	Interfacial transition zone
NA	New/natural aggregates
NCP	New cement paste
NM	New mortar
OVA	Original virgin aggregate
PC	Portland cement
RCA	Recycled concrete aggregate
RCA-concrete	Concrete made with RCA
RCP	Residual cement paste
RM	Residual mortar
SCM	Supplementary cementitious material
SDT	Stiffness damage test
SSD	Surface saturated dry

Chapter One: Introduction

1.1. Recycled Concrete and Alkali-Aggregate Reaction (AAR)

Recycled concrete aggregates (RCA) have been an emerging material used in moderation in non-structural concrete applications for the past years and is produced by crushing concrete waste into aggregate sized particles. It is a multi-phase material consisting of the original virgin aggregate (OVA), which is the original coarse aggregate, residual mortar (RM) containing the original cement and fine aggregate and in the case of fine RCA, residual cement paste (RCP). Sources of RCA can include: a) concrete returned to the plant due to a surplus or unwanted site specifications, and b) demolished concrete such as a damaged concrete structure deemed unable to be rehabilitated, or a concrete structure that no-longer complies with the current codes and standards or cannot resist to the increased present service loads, thus a concrete that has reached the end of its service life. Additionally, aggregates are an essential component in concrete consisting of both fine and coarse aggregates. The aggregates make up 60% to 75% of the concrete's volume, adding some economic benefit to concrete production, when the aggregates are appropriately graded, by reducing the required amount of cement to produce concrete [1]. However, the exploitation and transportation of new natural aggregates (NA) is a costly operation as quarries are being depleted nearby urban centers thus further distances must be travelled and natural environment and eco-systems destroyed to retrieve NA [2]. Therefore, RCA presents an ecological alternative to NA in terms of energy consumption, land preservation and waste disposal among many other benefits [3,4]. Yet, their use in concrete is often limited [5], especially to non-structural applications and in terms of quantity of replacement. The lack of the use of RCA is mainly due to doubts related to the variability of the material, such as unknown source concrete from which the RCA is derived, mixed RCA sources, the presence of impurities (i.e. other construction debris, steel corrosion products, etc.), and the presence of adhered RM. The RM is believed to be responsible for the lower quality concrete when RCA is used in concrete construction [6–8], and it can be variable in terms of its quantity and quality. Figure 1.1 shows the difference between the amounts of RM of RCA particles, where in Figure 1.1a a coarse aggregate comprises of the majority of the RCA, and in Figure 1.1b only RM is seen in the RCA particle. Nonetheless, one of the components of the RM is cement paste, which when considered in the mixture proportions of the RCA concrete [5,9–11], can reduce the new cement requirements. The most conspicuous factor in concrete manufacturing is the production of cement clinkers which are responsible for 7% of CO_2 emissions globally [4]. Yet, it is suggested to adjust the water-to-cement ratio of RCA concrete to improve its compressive strength [12]. Consequently, by increasing the amount of cement used in such concrete, the sustainability aspect of the RCA is rendered insignificant. Moreover, there is a misconception that replacing NA with RCA produces a concrete with inferior mechanical and durability properties. However, through proper RCA preparation, characterization, mixing techniques and mix-proportioning accounting for the RCA's multi-phase character, the recycled concrete can achieve targeted mechanical properties [5,10,11,13–16] and durability [17] while remaining environmentally friendly.

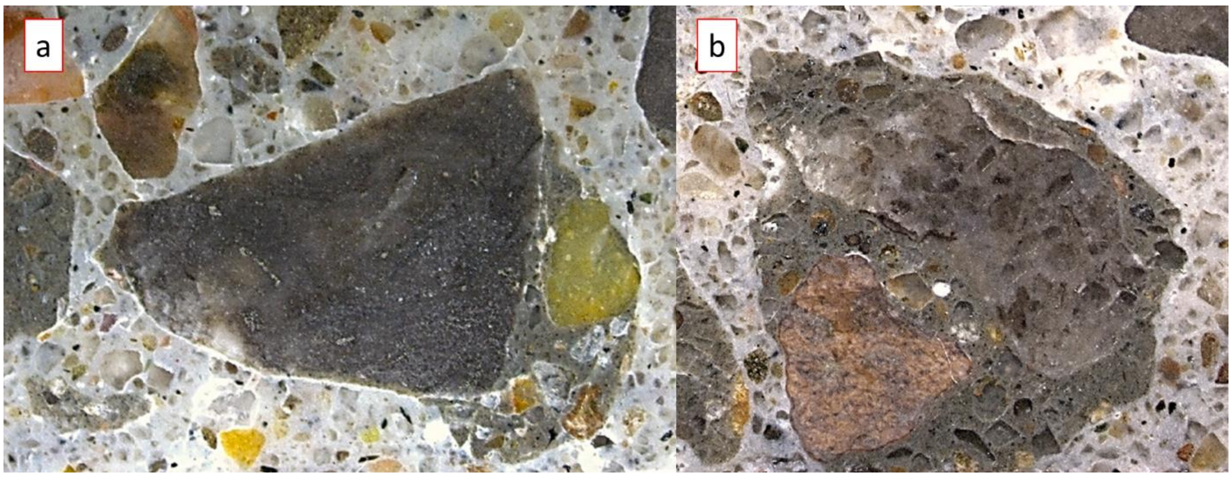

Figure 1.1: a) Coarse RCA particle with coarse OVA and b) Coarse RCA particle without coarse OVA.

In Canada, the majority of the provinces' quarries contain aggregates susceptible to alkali-aggregate reaction (AAR) [18]. As such, many Canadian concrete infrastructure is affected by AAR (Figure 1.2), more specifically alkali-silica reaction (ASR); a deleterious distress mechanism responsible for early concrete deterioration. Without any rehabilitation or mitigation of such AAR-affected structures, the structures will therefore reach the end of their service life before the time for which they were designed. In the most severe cases, it is necessary to demolish the concrete structure, creating large amounts of waste. Accordingly, this concrete waste presents an opportunity to recycle it into RCA to be further used in new concrete. But then again, the presence of ASR in demolished concrete causes even more reservations about RCA as ASR is an ongoing distress mechanism which is not yet fully understood when in RCA concrete.

Figure 1.2: ASR-affected structures in Canada [18].

1.2. Research Objectives and Scope of the Work

The purpose of this research is to evaluate the potential of further induced expansion and damage (i.e. secondary expansion) of ASR-affected RCA concrete incorporating coarse and fine highly reactive aggregates and displaying distinct past damage degrees. First, laboratory made RCA particles are produced to represent two distinct levels of past damage (i.e. slightly damaged - 0.05% of expansion and severely damaged - 0.30% of expansion), which evaluates the influence of the previous damage extent on the RCA secondary expansion and distress. The latter has not yet been fully understood nor addressed in the literature. Thus, four types of ASR-affected RCA concrete are manufactured and stored in conditions enabling further ASR development. At specific secondary expansion levels (i.e. 0.05%, 0.12%, and 0.20%), RCA specimens are microscopically appraised through the Damage Rating Index (DRI) technique, a quite efficient microscopic protocol to assess damage caused by ASR. Comparisons between ASR-affected RCA and conventional concrete are then performed at distinct levels of expansion, which aids in the overall understanding of the deterioration process caused by ASR in recycled concrete mixtures. Finally, qualitative and descriptive models are proposed to thoroughly explain ASR cracks generation and propagation in recycled concrete made of reactive fine and coarse aggregates.

1.3. Thesis Organization

This thesis is divided into five chapters. The first chapter is the introduction of the thesis which includes a concise background on RCA concrete and ASR in concrete. The second chapter includes the extended background on RCA concrete and ASR in conventional and recycled concrete. The background of RCA concrete focuses on RCA as a construction material, its physical properties and the influence of those properties on RCA concrete. Likewise, the background of ASR describes how it initiates/propagates cracks in concrete and their influence on the mechanical properties of the affected material. In the background section, all of the works thus far are included and elaborated to show the variability of ASR-affected RCA concrete in the obtained results followed by the research gaps which highlights the need for further analysis and understanding of the crack initiation/propagation of various types of ASR-affected RCA concrete. The third chapter is a journal paper submitted to the Journal of Cleaner Production (JCP, Elsevier). This paper includes the assessment of RCA concrete where ASR is induced by a reactive coarse aggregate at two damage degrees (i.e. expansion level of 0.05% and 0.30%) to evaluate the effect of the original damage extent on the secondary induced expansion and damage of ASR affected RCA concrete. Moreover, comparisons between petrographic distress features between recycled and companion conventional concrete mixtures are conducted to appraise similarities and differences in the induced damage process. The fourth chapter is a journal paper submitted to the Journal Cement and Concrete Research (CCR, Elsevier) which is the continuation and comprehensive version of a conference paper entitled: “*Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures”* accepted for publication at the

International Conference on Alkali-Aggregate Reaction (ICAAR, Lisbon 2021). This paper includes a thorough microscopic characterization of the cracks initiation/propagation of ASR-affected RCA concrete where the source concrete was slightly or severely damaged (i.e. 0.05% and 0.30% of expansion, respectively) in which ASR was induced by a reactive coarse or fine aggregate. The comparison of the secondary ASR-induced damage in recycled concrete originated from coarse or fine aggregates is non-existent in the literature, and thus it fills a current research gap in the field. Finally, qualitative and descriptive models explaining the induced distress development in recycled concrete are proposed, representing a novel contribution of the thesis. The fifth and final chapter presents the overall conclusions of this research along with proposed future research in the area. Finally, in all of the works shown in this thesis, the laboratory work, measurements, sample preparation, microscopic and data analysis (with the help of co-author Andisheh Zahedi, PhD Candidate), and writing of papers were performed by myself. All of the co-authors, including supervisor Dr. Leandro Sanchez, have individually contributed on the data analysis and reviewing of both papers presented in this thesis.

1.4. References

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Chapter Two: Background and Literature Review

This chapter will provide some general information with respect to physical properties of RCA, RCA concrete and AAR to provide some background followed by a literature review on ASR-affected RCA. The background will focus on factors that affect the crack propagation in RCA and in AAR-affected concrete. The literature review provides studies that have been performed thus far on ASR-affected RCA concrete.

2.1. Background

2.1.1. Recycled Concrete Aggregates

Recycled concrete aggregates (RCA) is a multi-phase material which consists of residual mortar (RM) adhered to coarse original virgin aggregate (OVA) where the RM is composed of residual sand and residual cement paste (RCP). When an RCA particle is directly compared to a natural aggregate particle, it is evident that they differ due to the adhered RM. As such, RCA particles usually have a lower density and higher absorption capacity because of the porous nature and amount of the adhered RM as well as micro-cracks present in the RCA particle due to the RCA crushing process [1,2]. Consequently, the increase in absorption capacity can be as high as 12% [3–5]. Moreover, durability related issues of RCA concrete (i.e. carbonation depths, chloride penetration and freezing and thawing resistance, etc.) [6–12] and fracture properties [13] are often attributed to its high porosity when directly replacing the natural aggregate (NA) with RCA without any pre-treatment [12,14,15]. Direct replacement of NA with RCA increases the overall porosity of the concrete since the adhered RM, generally having a higher porosity than NA, is considered as part of the aggregate (Figure 2.1). Although it is possible to achieve targeted mechanical properties [6,15–17] in RCA concrete using direct replacement, considering the RM of RCA in the mixture proportions [18,19] not only provides the targeted mechanical [18,19] and durability [20] properties while reducing cement consumption, but also influences the overall porosity of RCA concrete. The first method developed to mix proportion RCA concrete was the Equivalent Mortar Volume (EMV) [18] which accounts for the RM where the RCA concrete is designed such that it contains the same amount of total mortar as a conventional concrete (CC) (i.e. companion CC) and designed to have the same compressive strength. However, the EMV presented some issues in the fresh state, and the RCA replacement may be limited if the residual mortar content (RMC) is too high; hence, 100% of RCA replacement is not always feasible. To address the fresh state issues observed while using the EMV, a modified version (EMV-mod) was developed [21]; yet, in order to target the compressive strength of its companion CC, additional cement was required which is undesirable given that RCA concrete is an eco-friendly concrete. Finally, the most recently developed and promising mixture proportioning method is the Equivalent Volume (EV) method [19] which allows for 100% RCA placement and reduces the new cement requirements while conserving the targeted mechanical properties. Additionally, the EV can also be used for fine RCA (FRCA) [22]. The EV is designed such that the RCA concrete has the same total volume of cement paste (i.e. residual and new) and the same total volume of aggregates (i.e. OVA and residual and new sand) as its companion CC which is represented in Figure 2.2.

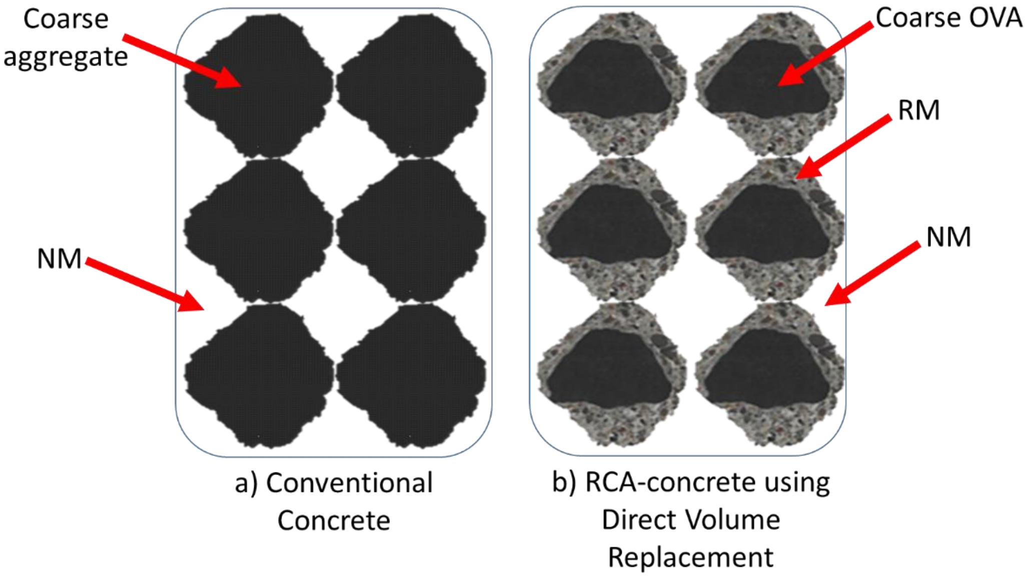


Figure 2.1: Comparison of coarse aggregate volume in CC and RCA concrete using the direct replacement method.

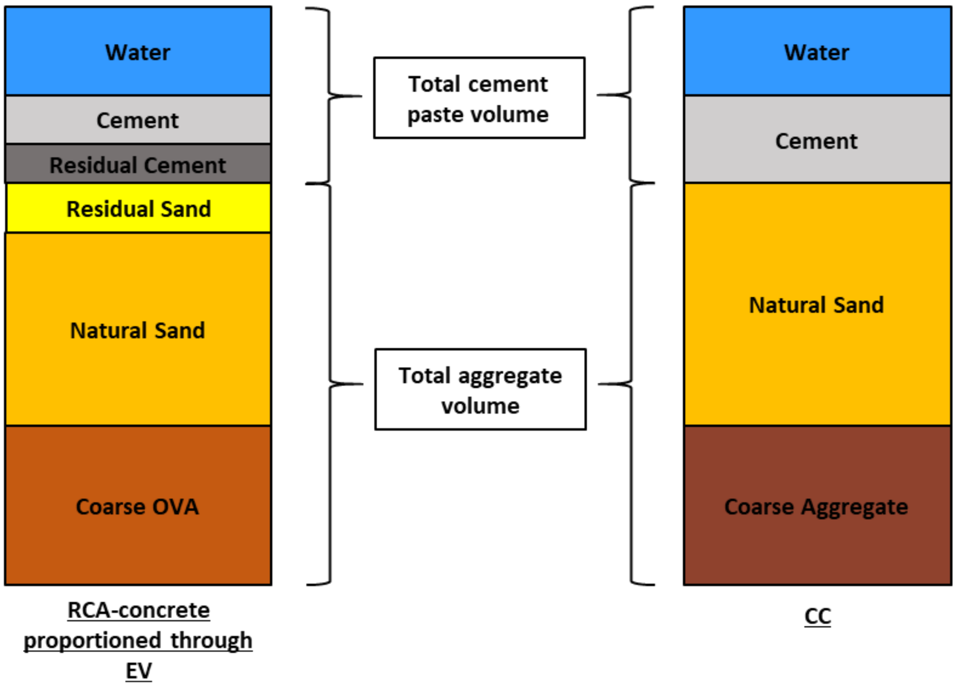


Figure 2.2: Mixture proportions of RCA concrete design with the EV compared to a CC [19].

Moreover, a RCA particle contains an original interfacial transition zone (ITZ) and micro-cracks due to crushing and processing, as well as previous weathering and damage, which may also contribute to the overall porosity of the RCA concrete and absorption capacity of the RCA. However, the absorption capacity of the RCA does not necessarily cause adverse effects in RCA concrete as was determined by Etxeberria et al [23]. It was found that the high absorption capacity of an RCA particle permits some of the cement particles to be absorbed inside of the RCA particle and adsorbed as the surface thus, creating a lower water-to-cement ratio at the interface between the new mortar (NM) and the RCA particle, resulting in a strong interface bond with the NM. Furthermore, some un-hydrated cement particles inside of the RCA particle may even hydrate and provide more strength to the RCA concrete [23]. Yildirim et al. [15] also found that there was an internal curing effect of saturated RCA, enhancing the strength and cracking resistance due to freezing and thawing and shrinkage of RCA concrete. However, it was supposed that the total amount of mortar (i.e. RM and NM) in a concrete pavement is responsible for an increased amount of observed cracks [24].

It is widely known that the weakest link for conventional concrete is the ITZ and other studies were conducted to determine the weakest link of RCA concrete [6,13,16,23,25]. Coarse RCA concrete comprises of a different microstructure which includes RM, NM, coarse OVA, the original ITZ, the ITZ at the OVA to NM interface and the ITZ and the RM to NM interface, as presented in Figure 2.3. Consequently, cracks were often seen in the original ITZ and RM of the RCA particle deeming them the weakest links [13,23], yet fracture was also detected through the RM and NM instead of ITZs since a stronger interface between the RCA and NM was formed due to remaining active silica in the RM [25]. Similarly, a stronger bond between the NM and RM was further identified [17]. Cracks in the RM were therefore attributed to micro-cracks in the RCA particles due to the RCA crushing process [26]. Poon et al. [16] and Otsuki et al. [6] concluded that the strength of RCA concrete is governed by the strength of its weakest ITZ where the weakest link is the ITZ formed by the weaker mortar (i.e. NM or RM). For example, a RM having a lower strength than the NM will provide a weaker ITZ within the RCA particle thus, creating the weaker link in the RCA's ITZ whereas a higher quality RM will provide a stronger ITZ within the RCA particle as opposed to the newly formed ITZ, making the latter the weakest link. Nonetheless, a stronger bond between NM and RCA may be able to compensate for negative effects of weaker aggregates [16]. Moreover, Otsuki et al. [6] reported that the strength of the RCA concrete is not influenced by the quantity of the RM and that the Vicker's micro-hardness of the original ITZ in the RCA particle increases as the quality of the RM increases.

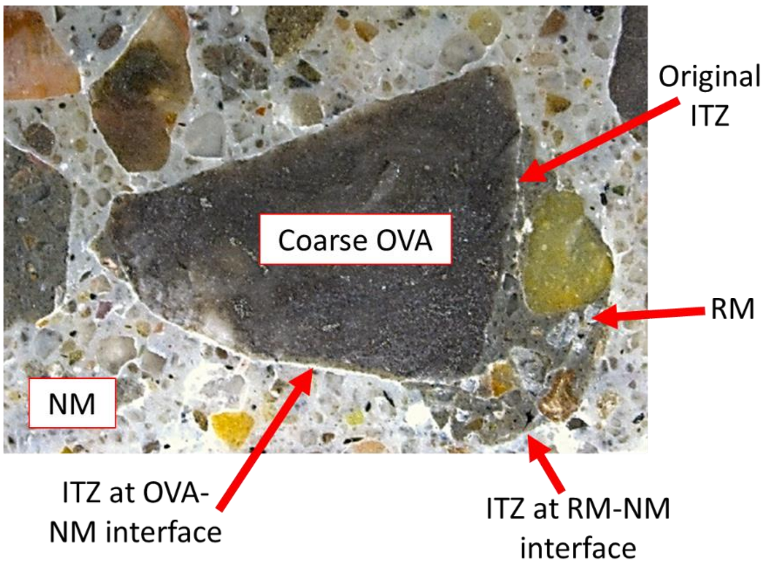


Figure 2.3: Microstructure of a coarse RCA particle.

Although the freezing and thawing resistance of RCA concrete proportioned with the EMV [18] presented suitable results, the difference in the dynamic moduli was attributed to the difference in qualities of RM of the different RCA particles used [20]. Likewise, the cracking susceptibility was found higher in interfaces of larger differential stresses such that cracking occurred more in the interface between the OVA and NM rather than the RM and NM interface [17]. Adams et al.

[17] also found that shrinkage was not significant in RCA when compared to a rounded aggregate (i.e. gravel).

Despite the agreement that the RM and ITZ in RCA concrete is the governing factor in RCA concrete failure, Hayles et al. [21] observed cracks passing through the coarse OVA within the RCA particles as shown in Figure 2.4. This is perhaps due to the presence of micro-cracks in the OVA that were formed during the RCA crushing and processing or past damage and weathering of the original concrete since based on the minimum energy law, it requires less energy to propagate a crack than for it to initiate.

Figure 2.4: Crack propagation in 100% RCA concrete [27].

RCA concrete should therefore not be perceived as a conventional concrete especially in terms of crack initiation and propagation because of its distinct microstructure and presence of micro-cracks. Hence, RCA particles should be characterized prior to their use in concrete to better understand its mechanical behaviour and durability properties. Furthermore, the presence of impurities (i.e. steel corrosion products, alkali-aggregate reaction, other construction debris, etc.) in the RCA particles must be indicated and considered in the design if removal of those impurities is not feasible but only at certain allowable amounts [28,29] as these impurities will impact the microstructure and performance of RCA concrete. Furthermore, extra care must be taken when the original concrete has deteriorated from a distress mechanism or internal swelling reaction (ISR), especially an on-going mechanism such as alkali-aggregate reaction (AAR). As such, understanding the differences in microstructure of RCA concrete can help to better characterize the crack initiation and propagation of an RCA concrete affected by AAR.

2.1.2. Alkali-Aggregate Reaction

Alkali-aggregate reaction (AAR) is a cause for early deterioration of concrete infrastructure and is widespread across Canada and the world [30]. It causes structures to reach the end of their service life well before the time for which they were designed. Along with increasing service loads, concrete structures affected by AAR require mitigation, rehabilitation or even demolition in the most severe cases. It consists of a chemical reaction between the alkalis (Na^+, K^+, OH^-) from the concrete pore solution and some unstable mineral phases from the aggregates used to make concrete. There are two types of AAR in concrete: a) alkali-silica reaction (ASR) which involves reactive silica in the aggregate and b) alkali-carbonate reaction (ACR) involving carbonate aggregates. In this study, only ASR is evaluated. The reaction product formed by ASR is a gel-like product that swells upon water intake. Although ASR occurs in concrete in the aforementioned conditions, cracking of the concrete only takes place when water is present from internal or external sources due to the reaction product's hygroscopic nature [33]. Therefore cracking may not occur in dry conditions yet, ASR continues to develop. These swelling pressures induce tensile stresses greater than the tensile resistance of concrete which ultimately cracks the concrete (Figure 2.5). In Canada, most provinces have these reactive aggregates in proximity of city centers, making them easy to access and affordable to use [31]. However, their detrimental effects on concrete must be supressed in order for them to be used.

Figure 2.5: Severely affected concrete structure [32].

Cracking of concrete begins inside of the aggregate when it is affected by ASR. These cracks are formed as the reaction product (i.e. gel) swells to a pressure exceeding that of the tensile resistance of the aggregate. Generally, the reaction will initiate in areas of the aggregate containing strained silica which can be caused by rock-bed formation, weathering of rocks, crushing processes, etc. Cracks that have begun to propagate will continue to do so based on the minimum energy law [34] because it requires less energy to propagate an existing crack rather than create a new crack elsewhere in the aggregate. In a concrete affected by ASR, new cracks will form at the beginning as a result of the reaction in which cracks having reached their critical length and width will then take precedence in the crack propagation and continue to lengthen and widen, overcoming the formation of new cracks [34].

As the gel inside of the crack absorbs water, the gel continues to swell, increasing the tensile pressures and propagates the crack into the cement paste until cracks are linked, forming a network of cracks. Depending on the nature and texture of the reactive aggregate (i.e. natural or crushed), different types of cracks will be formed in the aggregate yet are not limited to one type of crack being present in the aggregate. Generally, in crushed reactive aggregates where large rocks are transformed into aggregate sized particles, cracks are seen to cut through the aggregate (i.e. sharp cracks). In more rounded aggregates like gravel and natural sand, cracks may also be formed at the periphery of the reactive aggregate (i.e. onion skin cracks) [34]. Moreover, the crack pattern in ASR-affected concrete differs with respect to the origin of the distress (i.e. sand versus coarse aggregate) where cracks tend to be more sparsely distributed in ASR induced by a reactive sand as opposed to a reactive coarse aggregate (Figure 2.6).

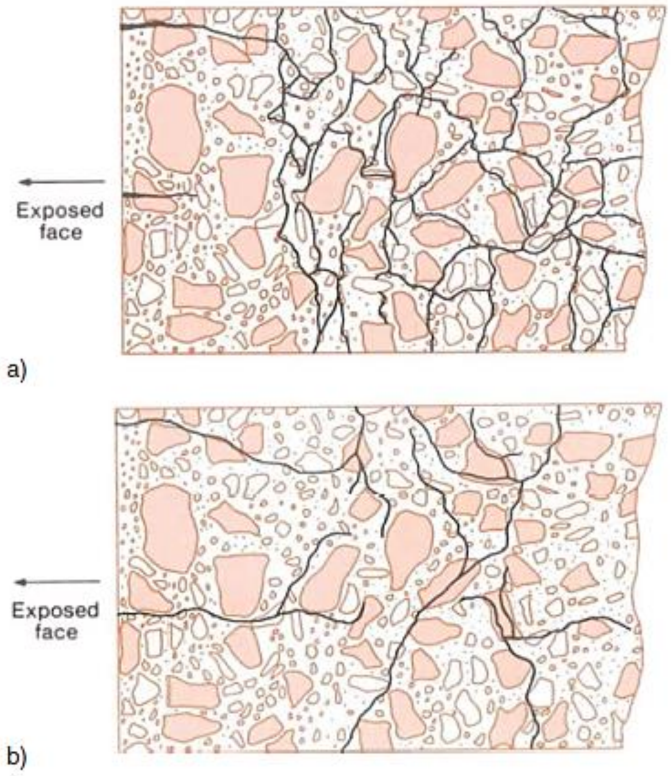


Figure 2.6: Crack distribution of ASR caused by a) reactive sand and b) reactive coarse aggregate from [35].

The damage of a concrete suffering from ASR is represented by an expansion level. Cracks that are seen only inside of the aggregate represent a smaller expansion level and as the cracks propagate further, the expansion level increases and so does the damage extent. Sanchez et al. [34] proposed a qualitative model of the crack propagation in ASR-affected conventional concrete (Figure 2.7) showing the different stages of the crack propagation. At a slightly damaged degree (i.e. expansion level of 0.05%), the cracks are found within the aggregate. As the cracks start to propagate towards the edge of the aggregate and extending on one side or slightly on both sides of the aggregate, the damage degree is said to be moderate (i.e. expansion level of 0.12%). Upon reaching a severe level of damage (i.e. 0.20% of expansion), the aggregates are split and at 0.30% of expansion, the concrete loses its integrity as cracks begin to form a network.

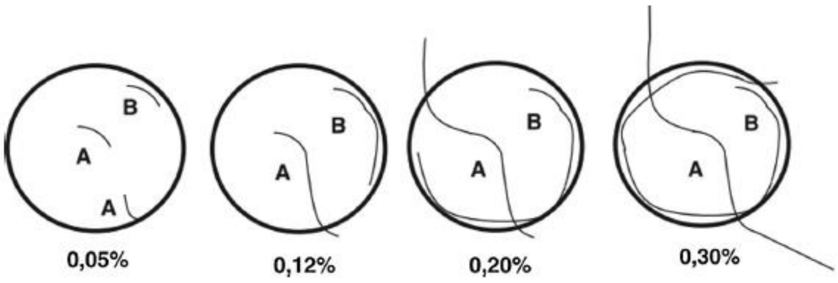


Figure 2.7: Qualitative model of crack propagation in ASR-affected CC with a) sharp cracks and b) onion skin cracks [34].

Evidently, this process advances in stages with respect to surrounding material composition (i.e. aggregate and cement paste). At these various stages of expansion, and thus crack propagation, the mechanical properties consequently exhibit different behaviours (Figure 2.8) [37–39]. A more pronounced reduction in tensile strength, modulus of elasticity and aggregate interlock which is captured by a decrease in the shear resistance [40] are seen at lower levels of expansion (i.e. 0.05%) followed by further decrease but at a slower rate. The tensile resistance of concrete is overcome by the stresses caused by the expansion of the gel, thus the modulus of elasticity of the concrete and aggregate interlock are significantly influenced by the cracks contained in the aggregates. It was also stated that the tensile strength and modulus of elasticity are good predictors of a distress mechanism that generates micro and macro cracks [24]. The compressive strength however is seen to be more affected at higher levels of expansion (i.e. 0.30%) since the cement paste governs the strength of concrete in compression.

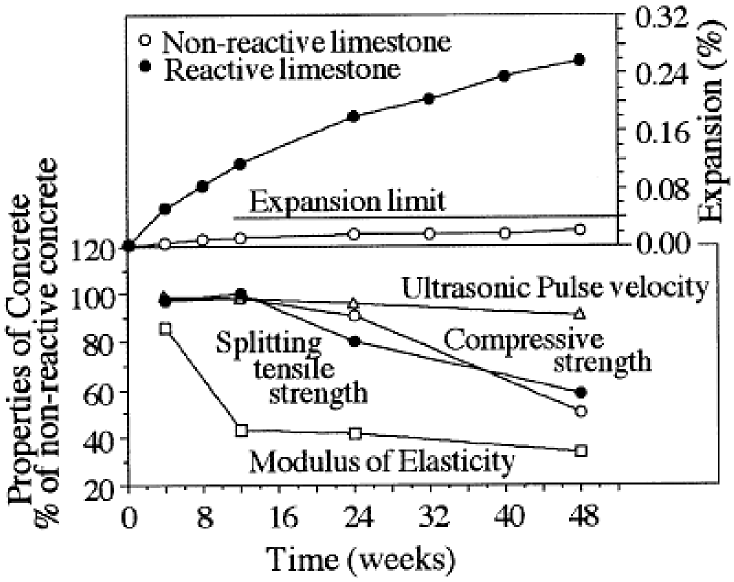


Figure 2.8: Residual mechanical properties as percentage of values obtained from unaffected concrete from [37].

2.2. Literature Review: ASR-Affected Recycled Concrete

Some studies have been performed on recycled concrete affected by ASR, yet inconsistencies exist with regards to expansion levels achieved by the RCA when measuring its reactivity using standard testing procedures as well as the severity of mitigation techniques. Although modifications in terms of RCA preparation prior to testing and the testing methods themselves were proposed to better evaluate the potential reactivity of RCA, their effect on the expansion are not well addressed. Nevertheless, even fewer work has addressed the cause of those inconsistencies and the distress mechanism in ASR-affected RCA concrete.

2.2.1. Effect of RCA preparation on ASR expansion

Although the mere presence of ASR in the RCA particles does not necessarily affect the RCA particles mechanical and physical properties compared to a non-reactive RCA particle [41], the preparation methods used to create RCA and RCA concrete may have an impact on the expansion achieved by the RCA concrete.

2.2.1.1. Crushing

Processing of RCA involves crushing large rubbles of concrete into aggregate sized fractions. The first round of the crushing process will produce both coarse and fine RCA (i.e. crusher's fines) and subsequent crushing of the coarse RCA will evidently produce smaller particles containing more of the coarse OVA, stripping it of its RM, as opposed to the crusher's fines being composed mostly of RM. Therefore, concerns on exposing reactive silica sites within the aggregate during the crushing process were expressed [26,42–45]. It is also believed that RCA produced by the first and second round of crushing will have compositional differences, thus affecting the RCA's reactivity [46]. Shehata et al. [43] compared the effects of using crusher's fines and fine RCA subjected to subsequent crushing using the standardized Accelerated Mortar Bar Test (AMBT) [47] and found that subsequent crushing produces higher expansion levels than the crusher's fines when the origin of ASR is a coarse aggregate which becomes the OVA in the RCA particle. Johnson and Shehata [48] then compared the effects of the crushing procedure and washing of the RCA on the expansion and found that the crushing procedure had the most influence on the expansion of RCA concrete compared to washing the RCA particles. The coarse RCA was produced using a jaw crusher and the subsequent crushing was performed using a compressive machine where two levels of subsequent crushing were attempted: a) re-crushing the RCA and adding more RCA until all grading sizes were retained, resulting in a higher RMC and b) re-crushing the RCA to size without the additional RCA, resulting in a lower RMC. It was then observed that the RCA containing more RM produced less expansion after 28 days using the AMBT. Evidently, the more an RCA particle is crushed, the more its RM is removed and exposes its reactive OVA thus, creating more potentially reactive surface area. However, if a reactive sand is present in the RM of an RCA particle, the opposite would be true. Hence, Etxeberria and Vázquez [49] used an RCA where the sand was the reactive aggregate and compared the expansions of the RM only and the RCA particle which included the non-reactive coarse aggregate (i.e. OVA) and noted that the expansion was higher for the RM.

While crushing may induce micro-cracks and increase the surface area of the reactant (i.e. silica), thus increasing the reaction degree in a chemical sense, ASR is a chemical process that transforms into a physical process and so the expansion doesn't necessarily increase because more reaction product is being formed [50]. Therefore, an increase in expansion of an RCA particle that experienced further crushing stages (i.e. less RM) could be associated to the adhered RM being able to accommodate the reaction product and resulting in less expansion when the direct replacement method is used at the mix-proportions. However, Ideker et al. saw the same expansion levels achieved by both crusher's fines RCA and a re-crushed RCA for one of the RCA types studied [46], and therefore indicating that the expansion/damage is not only influenced by the crushing process.

2.2.1.2. Storage

Although a study by Mukhopadhyay et al. [26] mainly used RCA in a hot-mix asphalt, it was recommended that RCA should be stored in a long-term outdoor storage to enhance carbonation of the RCA which can help to: a) reduce the potential for further gel expansion when water is added to the RCA concrete either while mixing the concrete or in its field exposure and b) lower the alkalinity of the pore solution of the RCA particles. Carbonation of RCA particles has been reported as being able to reduce the expansion by 30% in RCA [51].

2.2.1.3. Washing and preparation

Part of RCA preparation consists of washing the RCA particles to remove finer contaminants. However, in an RCA derived from an ASR-affected concrete, washing the RCA may have a greater impact on the expansion levels achieved by the RCA concrete than only removing contaminants. Stark [36] proposed to use the RCA in an as-received unwashed condition as it is most practical in the construction industry whereas for research purposes, not washing the RCA may conserve the alkalis available for reaction. Consequently, a study by Shehata et al. [43], also proposing to not wash the RCA as to prevent the alkalis from leaching and ensure their effect on the expansion achieved by the RCA concrete, found that washing had no effect on the expansion over a period of 2 years using the standardized Concrete Prism Test (CPT) [52] since the loss of alkalis through washing was overcome by the fresh source of alkalis in the new cement paste. The washing procedure used by Shehata et al. was to let a stream of water flow through a bucket of RCA for 18 hours. Although a different test procedure was used, Johnson and Shehata [48] then observed that the expansion rate of the unwashed RCA was higher at the beginning using the AMBT, while after a given time, the expansion rate of both washed and unwashed RCA were similar with the overall expansion of the washed RCA slightly lower than for the unwashed RCA. Since it is required to wash the aggregate particles prior to using the AMBT, some researchers have recommended that in order to use the AMBT to test for the potential reactivity of RCA, the RCA should be separated into size fractions and washed separately since the time required for the water to run clear while spraying the RCA was reduced significantly compared to washing it in bulk, thus conserving the RCA properties (i.e. RM, alkali content, un-hydrated cement particles) [46,53]. Therefore, there is no clear agreement on whether ASR-affected RCA should be washed prior to its use since the effect of washing seems to be insignificant. Nevertheless, washing of the RCA particles is among the factors that may have an influence on the expansion of RCA concrete. As for other types of surface preparation of RCA, it was seen that impregnating RCA with a silica fume slurry resulted in a reduction in expansion level below the limit for mortar bars [51].

2.2.1.4. Saturation state

The saturation state of an aggregate during mixing of concrete has an effect on the performance of the concrete in both fresh and hardened states [54]. Poon et al. [54] recommended to use RCA in an air-dried condition and avoid using RCA in a saturated surface dried (SSD) condition since poor mechanical properties were achieved and attributed to a higher local water-to-cement ratio near the RCA particles causing weaker bonds with the new cement paste. It has also been reported in several cases that the saturation state of the ASR-affected RCA influences its expansion in RCA concrete. As such, some suggestions from the literature on the saturation state of ASR-affected RCA are presented. Li and Gress [42] proposed to vacuum soak the RCA for 48 hours prior to its use in concrete to avoid early expansion due to RCA's high absorption capacity when testing under ASTM C1293 [55]. In order to avoid losing the soluble alkalis of the RCA, the soaking water should also be included in the mixing water as well as the absorption water [42]. However, Etxeberria and Vázquez [49] stated that the use of soaked RCA is not recommended as water accumulates at the surface of the RCA and renders the ITZ inefficient and proposed to use the RCA in an 80% saturation state to reduce the effect of the high sorptivity of RCA. Moreover, researchers have found that soaking the RCA for 24 hours resulted in 95% of saturation, and 100% saturation could not be achieved after 72 hours [46,53]. Thus, it was recommended that dry RCA is to be soaked in its concrete mixing water for 30 minutes to achieve 85% of saturation, while accounting for only 95% of saturation since the RCA does not fully become 100% saturated [46,53].

Delobel et al. [56] then studied the influence of water absorption of RCA on the expansion level and revealed that similar expansion levels were achieved when the absorption water was considered and the RCA was used in dry or soaked conditions (i.e. at 0.22% and 0.29% of expansion, respectively). Likewise, the porosities of RCA concrete were measured to determine its effect on the expansion. The porosities of dry RCA concrete and soaked RCA concrete were also similar (i.e. 24.28% and 24.08%, respectively) and so the difference in the expansion level was attributed to the pore size distribution where larger pores may have been present in the RCA concrete using dry RCA, allowing for the reaction product to fill these spaces and resulting in a slightly lower expansion [56]. Therefore, the saturation of the RCA consequently affected the overall porosity of the RCA concrete and in turn influenced the expansion level. The effect of porosity with respect to expansion due to ASR was also captured by Gottfredsen and Thøgersen where a concrete with a higher water-to-cement ratio provided lower expansion levels than a concrete with a lower water-to-cement ratio [57]. Likewise, Desmyter and Blockmans saw a decrease in expansion as the water-to-cement ratio increased for water-to-cement ratios above 0.50, yet the opposite was true for a water-to-cement ratio below 0.50 [58]. In addition, Beauchemin et al. [59] found that using RCA in a saturated condition also provided higher expansions than in a dry condition and proposed to use RCA in a saturated condition when using the CPT with RCA even if higher expansion levels may be achieved since it can be a conservative method to evaluate the potential reactivity of RCA. Interestingly, Beauchemin et al. reported a higher expansion level for RCA concrete made with dry RCA as opposed to saturated RCA for more severely damaged portions of a real structure. Though, as previously stated, using RCA in an OD condition may result in early expansions, it is believed that a reduction in the overall expansion or expansion rate is a result of using RCA in a dry condition because it doesn't become fully saturated when mixing the concrete and so, there is a decrease in the ionic exchange which reduces the progression/diffusion of ionic species from the concrete pore solution within the reactive aggregate [59].

A study by Mukhopadhyay et al. [26] on the use of RCA affected by ASR in hot-mix asphalts revealed that expansions seem to be supressed due to an asphalt protective film around the RCA particle, inhibiting moisture to penetrate to the RCA particle and continuing the reaction. However, further expansions of two different types of RCA without incorporation into the HMA were measured using a dilatometer indicating the continuation of ASR [26]. Therefore, if ASR-affected RCA can be used in a dry environment, the potential for recurring ASR could be reduced or even eliminated until moisture is re-introduced to the RCA concrete. Similarly, a concrete that was in service in a dry environment without ASR damage was recycled and used as RCA after which ASR damage was observed [57].

2.2.2. Applicability of standard tests on ASR-affected RCA

Standard tests such as the CPT and AMBT are capable of detecting the potential for reactivity of an aggregate. In a report on the susceptibility of RCA to ASR [29], the reactivity of RCA based on petrographic examination and a British standard method for expansion measurements similar to the CPT (i.e. BS 812-123) were tested and thin sections were also observed at the end of the one year testing period for various RCA types. It was reported that in some cases, the expansion test would indicate that the RCA was reactive while observations of thin sections showed no signs of any ASR distress (i.e. gel and/or cracks) and the opposite also occurred where ASR distress was observed although little expansions were measured. The latter was attributed to the high porosity of the RM of RCA being capable of accommodating the gel, and thus resulting in lower expansion. In addition, the petrographic examinations tended to overestimate the reactivity of RCA when compared to expansion results. Indeed, the petrographic analysis accounts for the potentially reactive minerals present in the RCA particles, yet the amount of remaining reactant (i.e. silica) is unknown thus the overestimation may be associated to the depletion of the reactant.

Though the AMBT raises doubts about its use on coarse RCA since it requires further crushing [29], studies on proposed modifications to the AMBT in order to apply it to RCA were conducted. Gress and Kozikowski [60] adapted the ASTM 1260 and ASTM 1293 to further accelerate the tests for RCA since distress was only observed after 3 years of being in service in an ASR-affected RCA pavement concrete. Likewise, Ideker et al. extended the testing period to accommodate slowly reactive RCA [46]. Adams et al. [53] found expansions of RCA concrete to be similar to those of their corresponding unreacted OVA concrete, all of which were a coarse reactive aggregate. The similarities in expansion levels obtained from the unreacted OVA and the RCA are in accordance with the circumstance that microstructural and textural characteristics play an important role in ASR and its expansion [61]. Adams et al. also tested a slightly damaged slab, which was only one month old prior to being crushed and made into RCA, and two other sources of RCA provided by older affected structures. A larger expansion level was seen for the 1-month old RCA concrete as opposed to the two older structures (i.e. 0.50% and 0.05%-0.06%). Furthermore, due to the variability of RCA and the AMBT, an intra-laboratory study recommended modifications, without modifying the test method itself, to increase the maximum allowable difference between tests within the same laboratory from 8.3% to 17.2% for RCA while modifications are not required for the difference in tests between laboratories [62]. Tanner and Fiore [63] stated that the current imposed limits set for the AMBT may be conservative for RCA because of RCA's ability to endure more strain before cracking [17].

A recent study on the applicability of the CPT performed by Beauchemin et al. [59] found that there is a continuation of ASR in the RCA concrete, which differs with respect to the reactivity of the natural aggregate as well as the extent of damage achieved by the concrete prior to crushing. This study used exposure blocks to produce the RCA with known original expansion levels at which the concrete was crushed to produce the RCA. Beauchemin et al. also accounted for the RM of the RCA by replacing its volume by a non-reactive coarse limestone in the conventional concrete to keep the overall amount of reactive coarse aggregate equal in both concrete [59]. Yet, the lower expansion level achieved in recycled concrete may have been attributed to the lower specific area of the reactive aggregate exposed to the alkalis to induce expansion due to the presence of the RM adhered to the reactive OVA in RCA concrete. No trend was necessarily found with regards to the damage extent prior to crushing and the secondary expansion level achieved by the RCA concrete but ASR did however continue at a lower level than the unreacted OVA. However, the opposite was seen for RCA made from an affected bridge (i.e. Du Vallon – Charest Overpass) where the RCA concrete reached much higher expansion levels than the control concrete using a different reactive aggregate found in a quarry nearby. Moreover, Beauchemin et al. also stated that the reactivity of an aggregate can differ between rock beds in a quarry, which may explain the reason why Adams et al. [53] found a difference in the expansion levels for the Springhill concrete and its corresponding RCA-concrete.

2.2.3. Factors contributing to the continuation of ASR in RCA-concrete

ASR exists when a concrete is composed of silica-reactive aggregates, enough alkalis provided by the cement to supply the reaction and heat. ASR expansion then occurs when water is added to the previously stated conditions. Thus, the potential for ASR in RCA remains provided that a reactive aggregate was used in the source concrete and enough reactants (i.e. silica and alkali content) are remaining in the concrete to continue the reaction.

2.2.3.1. Reactive silica

Silica is one of the reactants required for ASR in concrete and can be present in the fine and/or coarse aggregates. As the reaction progresses, the silica from the aggregate becomes incorporated into the reaction product. Depending on the extent of the reaction at which the ASR-affected concrete was turned into RCA, the silica content may not have been completely depleted, thus causing the RCA to be potentially reactive [29,45]. The earliest study on recycled concrete affected by ASR was conducted by Gottfredsen and Thøgersen in 1994 [57]. Continued expansions had been observed when incorporating RCA derived from existing structures, where the RM was the reactive component thus originating from reactive sand. An RCA made from an ASR-affected demolished concrete represented an RCA containing ongoing reaction, therefore without depletion of silica, whereas an RCA sourced from a severely affected pavement imitated an RCA with silica depletion. Interestingly, the expansion as a function of time showed a delay of 12 weeks in the expansion development for the demolished concrete RCA (i.e. ongoing ASR) and no large expansions were measured for the pavement RCA (i.e. depleted silica). Furthermore, Desmyter and Blockmans used a severely affected RCA and saw some secondary expansion yet the RCA was considered non-reactive and this was attributed to the severity of ASR prior to being used as RCA [58].

The expansion potential of RCA may not be associated to the amount of reactive OVA in the sense that more reactive component causes more expansions such that for some RCA types, the replacement levels do not affect the expansion and therefore the expansion may be independent of the amount of RCA [63]. This phenomenon was also seen in other works, where a 100% RCA replacement level produced lower expansion than 20% and 50% [46,53]. It is believed [29,45,53,63] to be attributed to the pessimum effect where a certain reactive aggregate proportion creates large amounts of expansion but a proportion beyond this amount produces less expansion (Figure 2.9). Furthermore, the amount of RM may even further affect the pessimum proportion, causing even more variability in the RCA as a material [63].

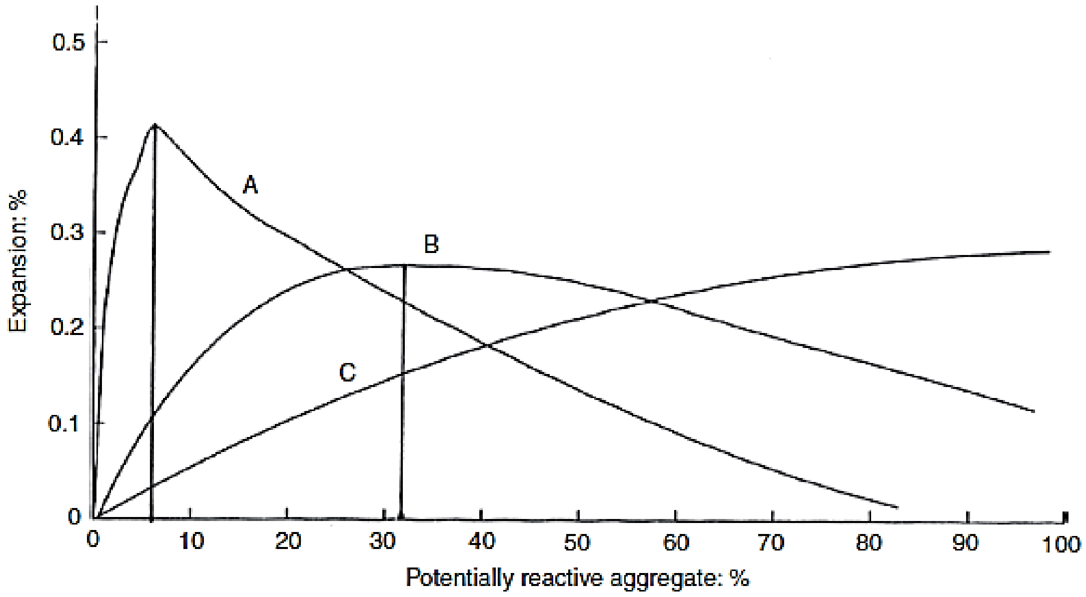
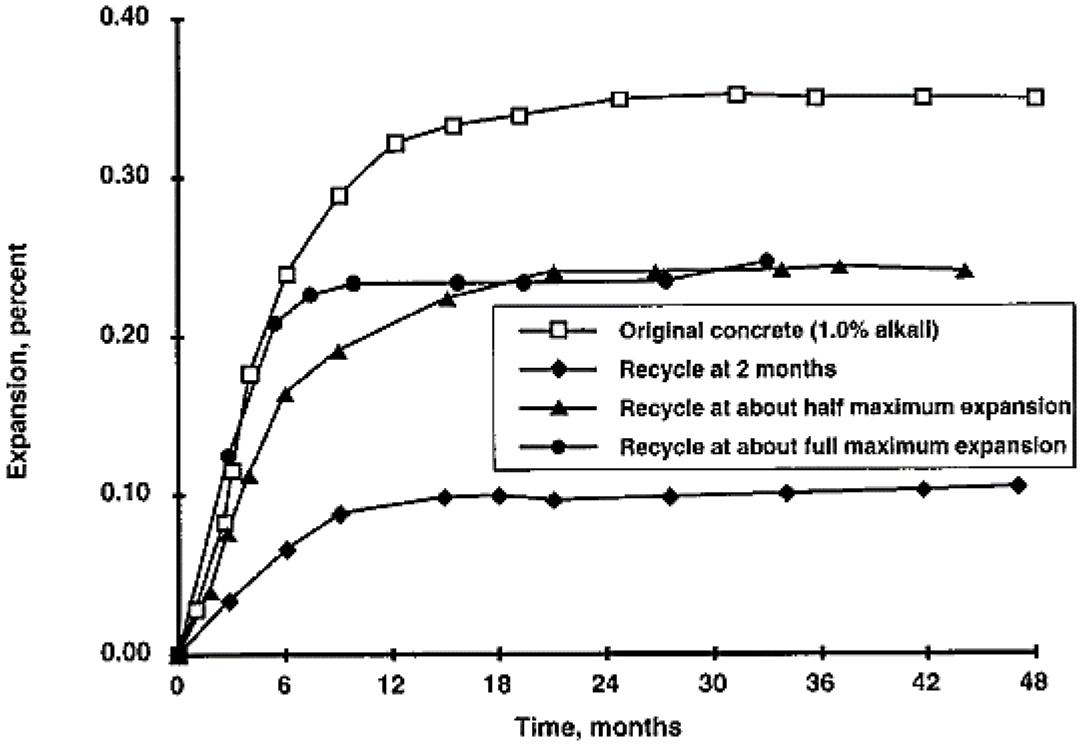


Figure 2.9: Hypothetical examples of curves showing % expansion against % reactive component in a concrete from [64]. A - A pessimum proportion of 5%; B – A pessimum proportion at approximately 30%; and C – No pessimum proportion.

2.2.3.2. Alkalis

Other essential reactants in ASR are the alkalis (i.e. sodium and potassium) supplied by the cement. An early study where laboratory made RCA using highly reactive fine and coarse aggregates combined from New Mexico was conducted by Stark in 1996 [36]. The alkali content of the original concrete varied from a low to a high (i.e. 0.50%, 0.75% and 1.00% as equivalent Na_2O). Both original and RCA concrete were made and tested for expansion according to ASTM C227, which was withdrawn in 2018 [65]; however, the environmental conditions used in this research resemble those of the CPT where samples are stored over water in plastic pails at 38°C. The original concrete was then crushed after: a) 2 months, b) upon reaching half of the maximum expansion obtained and c) at maximum expansion. The unwashed RCA was then used in RCA concrete while varying the alkali content from low to high (i.e. 0.50% and 1.00%) in order to determine the influence of alkali content in the source concrete while also varying the extent of damage and alkali content in the RCA concrete. It was found that the potential of ASR still exists in RCA concrete and it should not be assumed that large ASR induced expansions will not develop in RCA concrete based on the previous level of damage. For example, Stark used RCA made from a high alkali concrete (i.e. 1.00% $Na_2O_{eq.}$) where one RCA had originally reached half of the maximum expansion and the other RCA achieved full expansion (approximately 0.17% and 0.32%, respectively) and found that both RCA concrete made with high-alkali new cement had achieved 0.23% and 0.24% of secondary expansion, respectively (Figure 2.10a). Therefore, even though the reactants in both cases have been previously consumed at different levels, the secondary expansions were similar. For the same original high-alkali concrete, an RCA produced after a 2-month expansion level (approximately 0.02%), which is lower than the expansion achieved at half of the maximum expansion, showed only 0.10% of secondary expansion when made into a new high-alkali concrete. Additionally, using a low-alkali content in the original concrete produced a maximum expansions of only 0.05% but when that concrete was recycled after 2 months and at half of the maximum achievable expansion using a new high-alkali cement, the secondary expansion reached a level of 0.22% and 0.31%, respectively (Figure 2.10b). Therefore, an RCA concrete has the potential to achieve high levels of expansion in a high-alkali environment. Consequently, the alkali content of the new cement has an important influence on the expansion of RCA concrete, despite the alkali content of the original concrete and the achieved original expansion level, thus the new source of alkalis in the new cement reacts with the unreacted or new sites caused by the crushing process within the RCA particle. It was also further reported that using low alkali cement could supress or decrease expansion [55,58]. Though, some of the reaction may be attributed to a reaction between the alkalis and existing ASR gel and further increasing the expansion, this was not investigated in Stark's study [36]. Additionally, Mukhopadhyay et al. [26] studied the impact of external sources of alkalis provided by de-icing salts which resulted in higher expansion levels in the ASR-affected RCA-concrete.

a) Original high-alkali concrete used as RCA in new high-alkali concrete



b) Original low-alkali concrete used as RCA in new high-alkali concrete

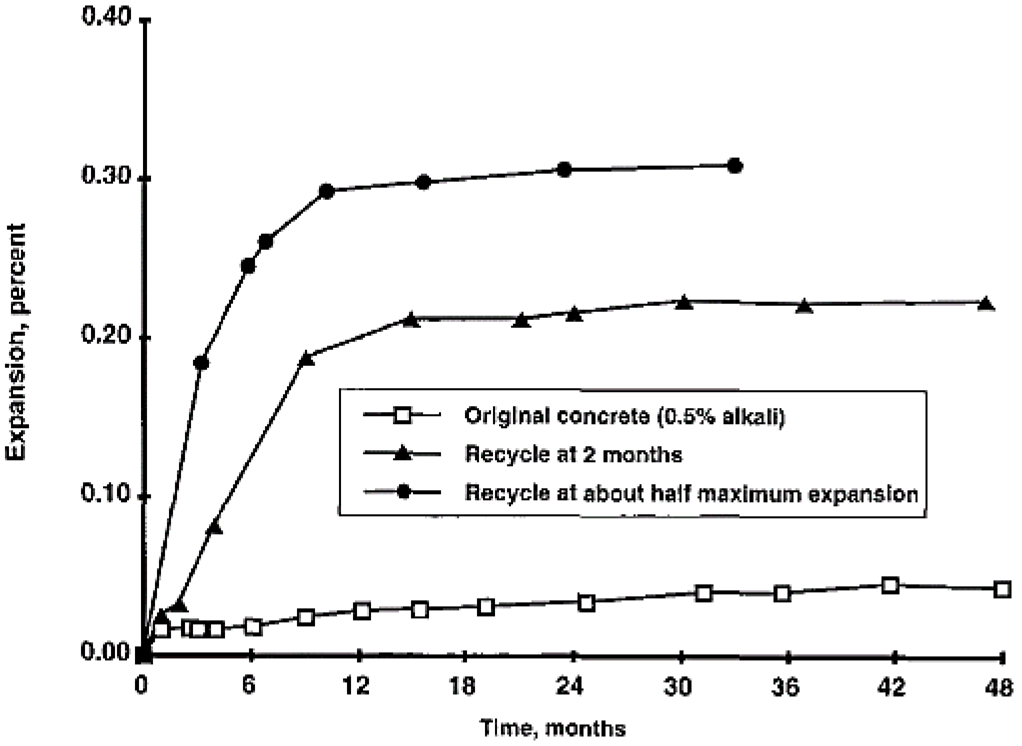


Figure 2.10: Expansions achieved by RCA concrete varying original alkali content from [36].

Concerns of reactivation of ASR due to modern cements containing higher levels of alkalis, re-expansion of existing desiccated reaction product and exposure of unused reactive silica due to RCA processing have led Li and Gress [42] to a study on the mitigation of ASR in RCA concrete. They found that the expansions provided by the AMBT of the source concrete (i.e. pavement concrete) and the RCA concrete were similar. More notably, they found similarities in the amounts of alkalis in the pore solution of both the RCA particle and RCA concrete, indicating that an equilibrium was attained within the original and new cement pastes. Though concerns of an increase in alkalinity of RCA concrete due to the presence of RM were expressed by Calder and McKenzie [29], Li and Gress concluded that the alkalis contained in the RCA particle contributed to the total alkali content of the RCA concrete and did not necessarily increase the alkali content in the pore solution of the RCA concrete [42]. Therefore, the alkalis in the RCA particle were not readily available for reaction. Li and Gress further used fly ash to mitigate ASR in RCA concrete due to its consumption of calcium hydroxide during the pozzolanic reaction, forming an alkali-binding secondary product. As such, fly ash was capable of lowering the alkali content in the pore solution of concrete and little expansions were recorded in RCA concrete incorporating fly ash. Li and Gress have concluded that the limiting factor for ASR in RCA concrete was calcium, since ASR had ceased once the calcium was depleted by the pozzolanic reaction and an increase in the alkali content led to an increase in the expansion of RCA concrete. In contrast, McCarthy et al. [66] observed that recycling a concrete originally containing fly ash produced little secondary expansion of 0.02% using the AMBT at 14 days.

A study conducted by Shehata et al. [43] presented the influence of the alkali content on the expansion of RCA concrete. Shehata et al. used RCA from 12-year old exposure blocks having an expansion level of 0.19% and containing Ottawa Spratt reactive aggregate. They observed similar if not slightly higher expansion levels as concrete made with unreacted Spratt aggregate after a 1-year testing period using the CPT (0.23-0.25% and 0.21%, respectively). Shehata et al. also found that lowering the alkali content in the Spratt concrete to 0.70% Na_2O_{eq} was sufficient to reduce the expansion level to below 0.04% while an alkali content of 0.56% Na_2O_{eq} was still not low enough to keep the expansion level below 0.04% for the RCA concrete (Figure 2.11). Additionally, the RCA concrete produced higher expansion levels than the Spratt concrete when the alkali content was kept below 0.80% Na_2O_{eq} which was believed to be caused by the contribution of alkalis in the RCA particles. Expansion levels started to remain constant once the alkali content was increased from 1% to 1.25% Na_2O_{eq} for the Spratt concrete whereas this trend was only seen when the alkali content increased from 1.25% to 1.50% Na_2O_{eq} for the RCA concrete. Furthermore, Shehata et al. incorporated supplementary cementitious materials (SCM) in the RCA concrete and observed that more SCMs were required to supress expansion in RCA concrete. Ideker et al. [45] and Scott [55] both found the opposite behaviour where expansion could be reduced using SCMs yet the RCA of Ideker et al. was composed of both fine and coarse reactive aggregate while the RCA from Shehata et al. and Scott contained only reactive coarse aggregate.

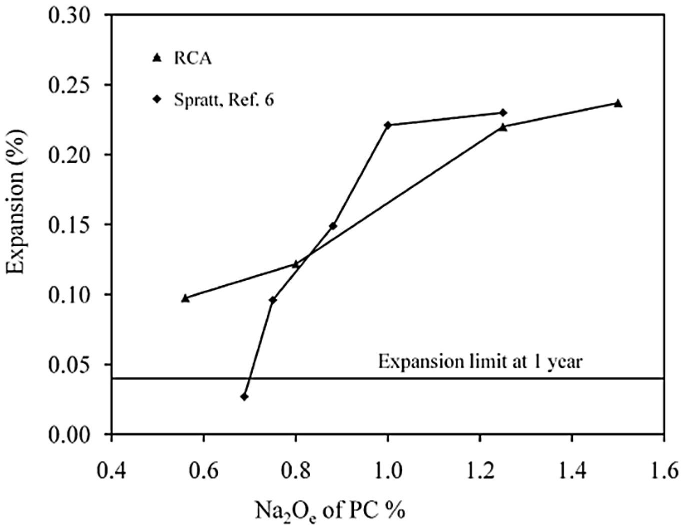


Figure 2.11: Effect of alkali content of PC on the one year expansion of concrete prisms from [43].

McCarthy et al. [66] studied the effects of various construction materials on the expansion of recycled concrete. Demolished bricks and concrete had a lower alkali release than for recently or laboratory produced bricks and concrete which may have been due to the continued hydration of cement for older structures. Recycled concrete made with RCA derived from a 70-year old AAR-affected bridge in Scotland reached the highest expansion level of 0.17% after 186 weeks using the British standard method (i.e. BS 812-123) for testing aggregate reactivity in concrete. McCarthy et al. concluded that a concrete showing signs of AAR distress leads to further distress when recycled and may even exhibit high secondary expansion levels.

2.2.4. Cracks and reaction product in ASR-affected RCA

The newly formed reaction product in ASR-affected RCA concrete can help to indicate the distress mechanism in such concrete. In a report on the susceptibility of RCA to ASR [29], gel was observed in thin sections prepared after a one-year testing period for two of the demolished concrete RCA, one of which had been previously deemed reactive through knowledge of the source concrete (i.e. ASR-affected bridge beams), expansion testing and petrographic examination. The other RCA was said to be of low to normal reactivity; however, cracks within the reactive chert particles accompanied with gel were observed. Remarkably, gel-filled cracks linking the aggregate particles were observed for the ASR-affected bridge beam RCA at an expansion level of only 0.064%. Etxeberria and Vázquez [49] studied RCA concrete where the RM contains a reactive sand, concluding that ASR continues in the recycled concrete. The original expansion achieved was unknown; however, a chemical analysis on the reactive sand revealed that silica was its main constituent. Through a SEM analysis, it was observed that cement, as well as alkalis, had accumulated at the ITZ of the RCA, more specifically at the RM to NM interface. A discolouration was also observed at the interface where silica, calcium and potassium were detected as well as an amorphous material, indicating the presence of ASR gel on the same sample yet in different morphologies (Figure 2.12). Although ASR gel was observed through discolouration there was no indication of cracks in the vicinity. The same trend was seen by McCarthy et al. [66] where gel-rims were discovered using optical microscopy around the RCA particle without any indication of cracks and an increase in the thickness of these rims with time were observed when samples were extracted from exposure blocks at 3 and 8.5 years. Additionally, McCarthy et al. used two different alkali contents of 5.4 kg/m^3 and 7.0 kg/m^3 and reported that the gel-rims were thicker as the alkali content increased.

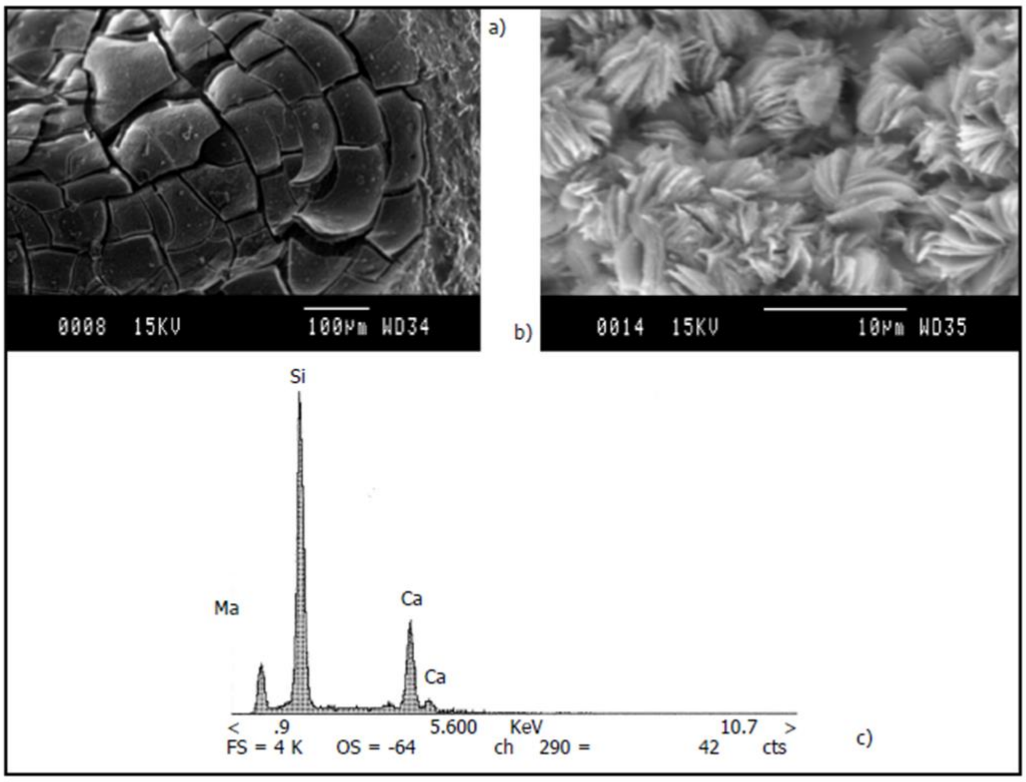


Figure 2.12: a) and b) Alkali-silica gel at different morphologies in RCA concrete and c) chemical map through EDX from [49].

2.2.5. Field studies on ASR-affected RCA

Field evaluations of the performance of ASR-affected RCA are essential to understand its long term behaviour yet are uncommon. A study on ASR-affected concrete rigid pavements of some highways in several states that were recycled and re-used at the same location showed that the potential for ASR still exists in RCA concrete and is significant, yet it indicated that the performance of the ASR-affected RCA concrete rigid pavements was comparable to pavements without ASR [24]. Another ongoing study by Ideker et al. showed that two types of demolished ASR-affected RCA were considered non-reactive since their expansion levels achieved from the AMBT were below the limit while one of these types of RCA showed high expansion levels when used in an exposure block [45].

2.3. Research Gaps

Although it is currently unclear in the literature how the contributing factors influence the secondary induced expansion of ASR-affected RCA concrete, there is however an agreement that ASR continues to take place in the recycled material. Some of the inconsistencies found when comparing the behaviour of the RCA concrete against a conventional concrete were attributed to the original extent of damage of the RCA particles; yet, the evaluation of various original damage extents of RCA and their comparison with conventional concrete using the same reactive aggregate source was only addressed for the first time in 1996 [36]. Moreover, studies on the use of RCA where ASR is induced by a reactive sand is very limited and often the reactive sand is combined with a reactive coarse aggregate. Hence, the effect of the reactive sand contained within the RCA remains mostly unknown. More importantly, ASR-affected RCA particles are always treated as one type of material where indeed it should be characterized prior to being used since the original extent of damage as well as the origin of the reaction/damage (i.e. reactive sand or coarse aggregate) will have an influence on the behaviour and distress mechanism of ASR-affected RCA concrete. As such, some inconsistencies were seen when applying mitigation measures to ASR-affected RCA concrete where at times more severe measures were required to supress ASR in RCA mixes. In addition, there is a lack of research on the crack development (i.e. initiation and propagation) of RCA concrete with or without ASR which is essential to better understand its behaviour and properly design such eco-friendly concrete. Nevertheless, this work aims to characterize different types of RCA particles with respect to the original extent and origin of damage (i.e. reactive particles in which cracks were previously generated) and evaluate their induced propagation.

2.4. References

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Chapter Three: Microscopic assessment of Recycled Concrete Aggregate (RCA) mixtures affected by Alkali-Silica Reaction (ASR)

3.1. Abstract

Recycled concrete aggregates (RCA) is deemed as an efficient approach to reduce waste yet, the presence of previous alkali-silica reaction (ASR) causes reservations towards its use in new construction. In this work, RCA specimens are manufactured in the laboratory incorporating RCA displaying distinct ASR past deteriorations (i.e. slight and severe). The samples are stored in conditions enabling further ASR development and monitored over time. Three levels of "secondary" expansion are selected for analysis, and upon being reached, microscopic evaluations are conducted through the Damage Rating Index (DRI). Results revealed that lower distress is observed in the RCA mixtures when compared to a companion conventional concrete at the same expansion level. Moreover, the damage mechanism of ASR-affected RCA concrete seems dependent on the RCA past deterioration since cracks tend to propagate into the residual cement paste or new cement paste for mixtures made of slightly or severely damaged RCA, respectively.

Keywords: Alkali-aggregate reaction (AAR), alkali-silica reaction (ASR), recycled concrete aggregates (RCA), microscopic assessment, Damage Rating Index (DRI).

3.2. Introduction

Recycling to reduce the use of landfills and decrease the need for new raw materials, lessening the carbon footprint and using renewable resources are among many of the current ecological and sustainable measures implemented in our daily lives. As such, the civil construction industry is also adopting methods to reduce CO_2 emissions and waste by using more sustainable materials. The production of Portland Cement (PC), probably the most important concrete constituent, accounts for 5% of the total man-made CO_2 emissions [1]. Furthermore, many efforts have been made to recycle concrete waste from either surplus concrete returned to the plant or construction and demolition waste (CDW) to be transformed into recycled concrete aggregates (RCA). Yet, a misconception has been created about RCA concrete having inferior mechanical and durability properties due to the adhered residual mortar (RM) or residual cement paste (RCP) depending on coarse or fine RCA, respectively [2–4]. However, accounting for the RM or RCP in the mix-proportioning of RCA concrete not only provides the targeted mechanical properties but also reduces the requirements for new PC, natural aggregate (NA) and landfill use, decreasing thus its carbon footprint [5–7]. On the other hand, the RCA source may have been subjected to irreversible past distress such as sulphate attack, alkali-aggregate reaction (AAR), among others. Alkali-silica reaction (ASR), by far the most common AAR type, is one of the principal causes of early deterioration of concrete infrastructure worldwide [8]. Structures affected by ASR often become out of service well before the end of their service life as the mechanical and durability related properties and performance may no longer be in compliance with national and international standards. Thus, demolition is often required which creates large amounts of waste; yet, it also creates an opportunity to reuse the material in the form of RCA. Nevertheless, there is still much doubt about the performance (i.e. potential for further induced expansion and damage) of previously ASR-affected RCA concrete.

3.3. Background

3.3.1. ASR in conventional concrete

ASR is one of the most harmful distress mechanisms affecting concrete structures worldwide. It consists of a chemical reaction between the alkalis (Na+, K+, OH-) from the concrete pore solution and some unstable mineral phases from the aggregates used to make concrete. ASR produces a secondary product (i.e. alkali-silica gel) which expands upon water intake leading to tensile stresses and damage in the affected material. The degree of deterioration of an ASR-affected conventional concrete (CC) is expressed by its induced expansion level, which corresponds to the initiation/propagation of cracks caused by the tensile stresses within the reactive aggregate and surrounding cement paste.

The cracks resulting from ASR-affected CC begin within the reactive aggregate particles and spread to the cement paste, forming a network of cracks [9]. Two types of cracks may be observed in ASR-affected concrete: A) sharp cracks which can begin in any portion of the aggregate and extend towards the cement paste as expansion increases and, B) onion skin type cracks which generally follow the periphery of the aggregate before entering the cement paste [9]. Regardless of the aggregate type, the same trend in distress generation/propagation was observed with respect to the expansion level achieved; thus, a qualitative model of ASR-induced deterioration in CC was proposed by Sanchez et al. [9], and is illustrated in Figure 3.1. At low expansion levels (i.e. at approximately 0.05%), cracks are mostly observed within the aggregate particles either as sharp or onion skin type cracks. As the reaction progresses, the expansion level increases and cracks within the aggregate particles lengthen and may even begin to slightly extend into the cement paste, at least on one side of the aggregate particle (i.e. at approximately 0.12%). Once the extension into the cement paste reaches both sides of the aggregate at an expansion level of roughly 0.20%, the sharp crack splits the aggregate while the onion skin type crack continues to lengthen. At 0.30% of expansion, the cracks begin to link to one another.

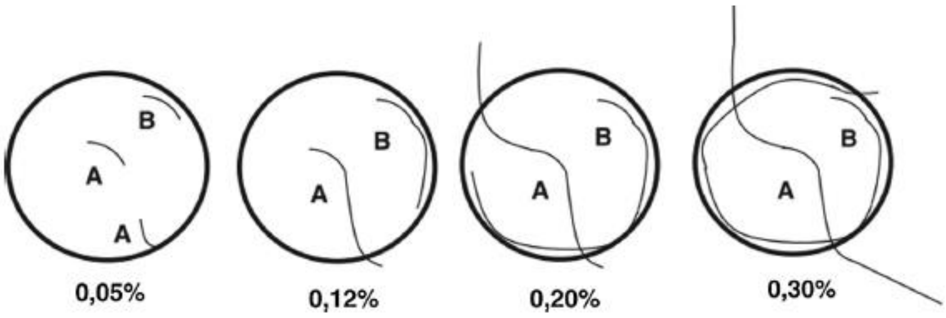


Figure 3.1: Qualitative model of crack propagation in ASR-affected CC [9].

Certainly, the losses of mechanical properties of ASR-affected CC can be attributed to the level of expansion reached [10,11]. However, as the cracks are present in various constituents of the affected material (i.e. aggregate and cement paste), the mechanical properties are influenced accordingly. Concrete's tensile strength can become greatly affected even for marginally damaged concrete (i.e. low expansion levels such as 0.05%) [11]. A loss in stiffness can be accredited to cracks within the aggregate particles, thus resulting in significant losses for slightly to moderately damaged concrete (i.e. expansion levels of 0.05% up to 0.10%). Otherwise, a concrete that is severely damaged by ASR corresponds to a concrete whose cracks have propagated to the cement paste, linking and forming an important network of cracks (i.e. 0.30% of expansion), causing the concrete to lose compressive strength. Moreover, since ASR provides deterioration within the reactive aggregate particles, it has been found that ASR can negatively impact on the aggregate interlock of affected concrete and thus reduce its direct shear strength from the beginning of its development [12].

3.3.2. ASR in coarse RCA-concrete

Coarse RCA is a multi-phase material comprised of original virgin aggregates (OVA) and residual mortar (RM). Even though RCA concrete has been generally found to provide inferior mechanical and durability properties, often attributed to its adhered RM, studies suggest that targeted mechanical properties are achievable with proper RCA preparation, characterization and knowledge of previous mechanical properties [13–16]. However, when accounting for the RM in the mix-proportioning of RCA concrete, not only can the targeted mechanical properties be achieved but also the need for new PC is reduced, creating a more environmentally sustainable concrete [5–7]. Among those RCA concrete mix-proportioning methods, the Equivalent Volume (EV) method [7], which is derived from the Equivalent Mortar Volume (EMV) [5] and its modified version (EMV-mod) methods [6], addresses fresh state issues observed in the EMV which were then corrected in the EMV-mod, yet required more new cement to target the required strength. The EV is therefore based on the concept of matching the RCA concrete's total amount of aggregates (i.e. coarse and fine aggregates) and cement paste (i.e. residual and new) to that of a conventional concrete referred to as a companion CC (Figure 3.2).

Few works have been performed to appraise the potential for further ASR in coarse RCA concrete, including the use of standard testing methods to evaluate the reactivity of RCA and the influence of varying factors on the secondary induced expansion. Evidently, producing RCA itself requires some processing such as crushing which further produces cracks within the RCA particles and thus may influence the secondary ASR expansion due to formation of new reactive sites [17–20]. It has been found that further crushing resulted in more RM removal, and thus higher induced expansion [19,21]. Moreover, similar expansion levels were verified to be reached for different crushing processes and stages [22]. Other important factors that might contribute to the secondary induced expansion/damage in the RCA concrete were the remaining reactive silica and alkali content attributed to the severity of the originally damaged CC. In some cases, using a previously ASR-damaged concrete as RCA resulted in lower secondary expansion levels [23–25]. However, in other cases, the opposite occurred where secondary expansion levels in RCA concrete were seen to exceed that of the unreacted natural aggregate (or OVA in recycled concrete) in a companion CC [19,26].

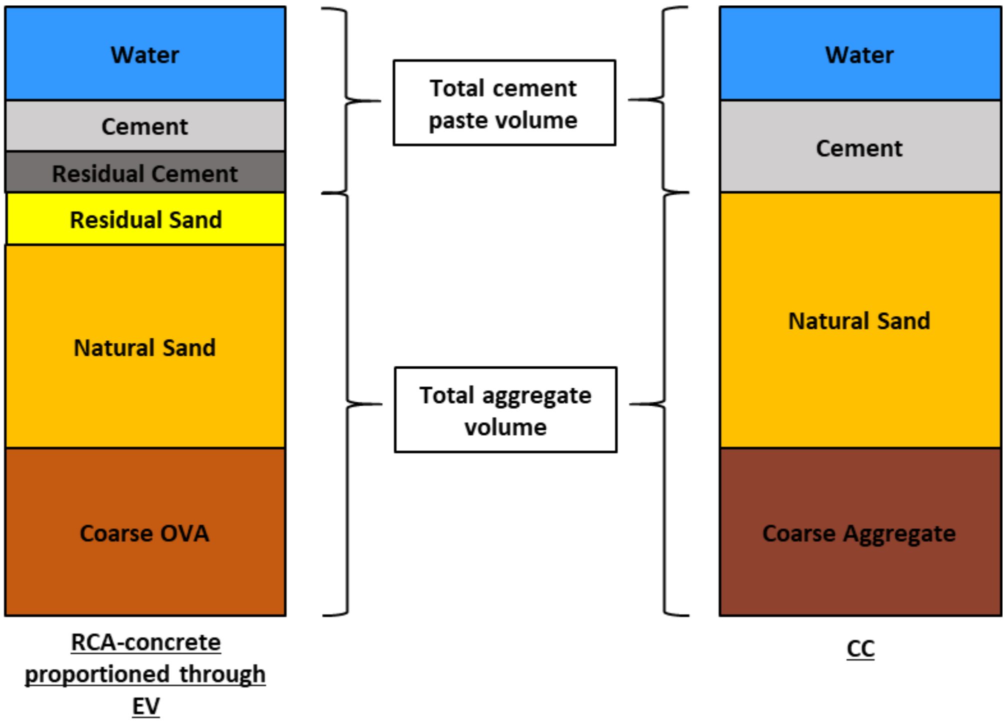


Figure 3.2: Proportions in RCA concrete compared to CC [7].

In even fewer studies, ongoing ASR was indicated where reaction products (i.e. ASR gel) of different morphologies were found at the RCA-to-new mortar (NM) interface [27], and reaction rims observed around the RCA particles [28]; yet new cracks were not detected. Remarkably, gel-filled cracks linking the aggregate particles were verified for an RCA concrete reclaimed from an ASR-affected bridge beam at a low expansion level (about 0.064%) as per [29]. Therefore, it is quite possible that the reaction products formation along with the generation and propagation of cracks of ASR-affected RCA concrete differ from that of CC. Nevertheless, the latter remains mostly unknown.

3.3.3. Techniques used to assess ASR damage in concrete

Numerous techniques (i.e. non-destructive, microscopic, and mechanical) have been developed over the last few years to assess the condition of CC affected by AAR. Promising results were obtained through the use of the Damage Rating Index (DRI), a semi-quantitative microscopic procedure performed on polished concrete sections, where distinct distress features associated with AAR are counted in 1 by 1 cm squares drawn on the surface of the affected concrete sections using a stereomicroscope at 16x magnification [9,11,30,31]. A weighing factor is applied to each of the distress features observed in order to balance their relative importance (i.e. location of distress features) towards an overall damage rating. The resulting value is then normalized to 100 cm^2 for statistical significance. Samples prepared in a laboratory environment required 100 cm^2 to be statistically significant whereas 200 cm^2 is required for field samples. The petrographic features included in the DRI assessment are listed in Table 3.1 with their corresponding weighing factors and are further displayed in Figure 3.3. The weighing factors currently used were selected to describe damage in affected concrete while reducing variability between operators [32]. Moreover, a closed crack in the aggregate (CCA) is a crack in which the fractured surfaces have not yet separated whereas an open crack in the aggregate shows a separation between those fractured surfaces which are differentiated by an experienced petrographer. Normally, for ASR-affected CC, damage is expressed as an expansion level and thus the given DRI number generally increases as the expansion level raises. Although the DRI analysis has barely been performed on RCA concrete, it is anticipated to serve as an effective tool to evaluate the degree of damage of ASR-affected RCA concrete as a function of its induced secondary expansion. Furthermore, the use of the extended DRI version as per [9,31] where the microscopic distress features displayed in Table 3.1 are evaluated in a relative (%) and absolute (counts) manner, without applying any weighing factors, might contribute to a better understanding of ASR damage generation and propagation in recycled mixtures. In addition, the crack density (CD) represents the summation of the number of open cracks in the aggregates and cement paste (both with and without reaction products) counted and normalized per square centimetre. It is also part of the extended DRI version as per [9,31].

Table 3.1: DRI distress features and weighing factors as proposed by [32]

Distress feature	Weighing factor as proposed by [30]
Closed crack in the aggregate (CCA)	0.25
Open crack in the aggregate (OCA) and open crack in the aggregate with gel (OCAG)	2
Disaggregated particle (DAP)	2
De-bonded aggregate (CAD)	3
Crack in the cement paste (CCP) and crack in the cement paste with gel (CCPG)	3

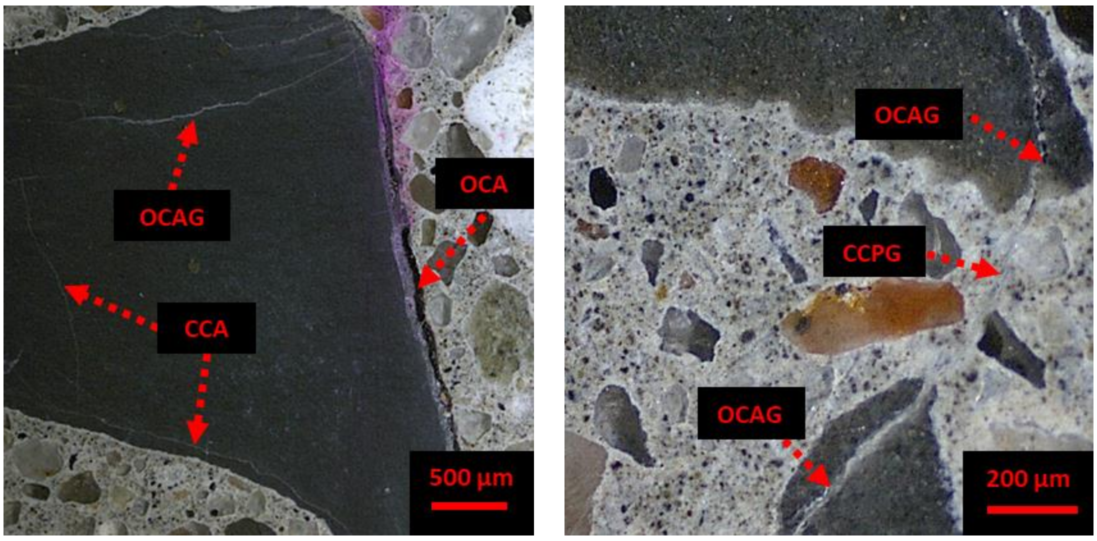


Figure 3.3: Distress features counted through DRI analysis.

3.4. Scope of Work

Some works have been previously performed with regards to the potential for further reaction and damage (i.e. expansion) of RCA concrete and its contributing factors [17,19,26,28,33,34]. Moreover, other studies have evaluated the applicability and efficiency of current standard methods conducted on CC to appraise the potential of further expansion of RCA concrete [21,25,35,36]. However, very few works have addressed the influence of the RCA past expansion (and damage) on the future performance of RCA concrete [23,26]. Inconsistencies observed in the resulting secondary expansion of RCA concrete emphasize the importance of a thorough assessment of ASR-affected RCA concrete through both efficient test procedures and microscopic protocols while varying the original RCA type and extent of damage (i.e. past expansion). This work aims thus to evaluate the differences in ASR-induced expansion and damage development of CC and RCA concrete mixtures made of a highly reactive coarse aggregate (i.e. Springhill - Greywacke). The recycled mixtures were produced with RCA derived from two distinct conditions: a) slightly damaged (i.e. 0.05% of expansion) representing a returned concrete, and b) severely damaged (i.e. 0.30% of expansion) representing a "pure" demolished concrete. Comparisons on the type and extent of damage of CC and RCA concrete at various expansion levels (i.e. 0%, 0.05%, 0.12%, and 0.20%) are then performed.

3.5. Materials and methods

3.5.1. Materials, mixture proportions and manufacture of concrete specimens

A total of seventy-five, 100 mm by 200 mm, cylindrical concrete specimens (i.e. 30 for each of the 2 RCA types and 15 for CC) were produced in the laboratory, including the RCA and its original CC. A highly reactive coarse aggregate (i.e. Springhill) was combined with a non-reactive sand sourced locally to mix-proportion ASR-affected CC following standard mixture proportions [37]. A conventional PC (CSA Type GU, ASTM type 1) containing a high alkali content (0.91% Na_2O_{eq}) was used in the CC mixture. Once manufactured, the CC samples were stored in conditions enabling ASR-induced development (i.e. 38°C and 100% RH) and monitored over time. Upon reaching the targeted 0.05% and 0.30% of expansion levels, the samples were removed from the storage conditions and jaw crushed to produce RCA particles ranging from 4.75 mm to 19.5 mm in size. Then, the recycled particles were used as coarse aggregates, in combination with the non-reactive sand, to proportion RCA mixtures following the EV method [7]. A white PC (CAN/CSA A-3001 Type GU), containing an alkali content of 0.31% Na_2O_{eq}, was used in the RCA concrete mixtures. Reagent grade sodium hydroxide pellets were used to raise the total alkali content to 1.25% Na_2O_{eq}, by cement mass, to accelerate ASR development for both CC and RCA concrete mixtures. Table 3.2 represents the concrete mix-proportions used for CC and the two RCA concrete mixes. It is worth noting that the residual mortar content (RMC), which was determined using the method proposed by Abbas et al. [38], differed for both RCA concrete mixtures which consequently influenced their mix-proportions.

Table 3.2: Concrete mixture proportions

Ingredients	CC	Slightly damaged RCA-concrete	Severely damaged RCA-concrete
Cement (kg/m^3)	420	340	331
Sand (kg/m^3)	823	774	791
Coarse aggregate (kg/m^3)	934	1040	1048
Water (kg/m^3)	189	153	149
RMC (%)		46	51.5

3.5.2. Manufacture of specimens

The 15 CC specimens and 60 RCA concrete specimens (i.e. 30 per RCA type for 2 types of RCA) were manufactured and demolded 24 hours following their fabrication. The specimens were then moist cured at room temperature (i.e. 20°C) for the following 24 hours before small holes, 8.5 mm in diameter and 19 mm long, were drilled on either end of the RCA concrete specimens. Stainless steel gauge studs were then glued using a fast-setting cement paste slurry for longitudinal expansion measurements and left to moist cure at room temperature for an additional 24 hours after which the initial readings were recorded. The RCA concrete specimens were then stored in the same previously mentioned conditions enabling ASR-induced development (i.e. 38°C and 100% RH) and monitored over time.

3.5.3. Experimental procedures

Microscopic analyses were conducted as per the DRI method on the ASR-affected CC and RCA specimens at various expansion levels (i.e. 0.05%, 0.12%, 0.20% for both CC and RCA mixtures and at 0.30% for the CC mix only due to the availability) in order to compare their distress features and extent at distinct phases of the reaction process. Note that these test procedures were expansion based as opposed to time based therefore, the samples used to microscopically evaluate ASR were analysed upon reaching said expansion. Prior to evaluation, the specimens were cut in half longitudinally using a masonry saw with a diamond blade followed by subsequent mechanical polishing with grits of 30, 60, 140, 280 (80-100 microns), 600 (20-40 microns), 1200 (10-20 microns) and 3000 (4-8 microns). Once the surface of the polished section was ready, a 1 cm by 1 cm grid was drawn on the polished surface prior to evaluation (Figure 3.4). The distress features counted in the ASR-affected CC were evaluated using the weighing factors proposed by Villeneuve [32]. To incorporate the distinct multi-phase nature of the RCA into the DRI method, the cracks in the OVA and RCP were treated as aggregates and cement paste, respectively, which is the main premise/concept of the EV mixture proportioning method where the total volume of cement paste (i.e. RCP and NCP) and aggregates (i.e. OVA, residual sand and new sand) in the RCA concrete are the same as in the companion CC mix [7]. The cracks in the new cement paste and new sand were counted and weighed accordingly. A grey PC was used in the source concrete whereas the new PC was white in order to distinguish the distress features in the RCP and NCP which is illustrated in Figure 3.4.

Figure 3.4: Representation of RCA in white cement matrix.

3.6. Results

3.6.1. ASR kinetics and development

The average expansions (i.e. average expansion levels achieved for the concrete specimens tested at a given age with a standard deviation of between 0.01% and 0.04% for the CC mixtures and between 0.02% and 0.04% for the slightly damaged recycled mixture and between 0.02% and 0.03% for the severely damaged recycled mixture) as a function of time of the ASR-affected CC and RCA specimens (made of slightly damaged, 0.05%-SPR-RCA, and severely damaged, 0.30%-SPR-RCA, respectively) are presented in Figure 3.5, which also includes data range bars (maximum and minimum expansions). Analysing the plot, one observes that for the first 29 days of expansion, the expansion levels achieved for each concrete mixture are quite similar (i.e. superimposed data), where the CC and severely damaged RCA concrete reached expansion levels of 0.03% (standard deviation of 0.02%) and the slightly damaged RCA concrete achieved 0.02% expansion (standard deviation of 0.02%). At 51 to 52 days, the overall expansion level reached is higher for the recycled mixtures than the CC mix, with the severely damaged recycled mixture being the highest. Noticeably, the trends of the two RCA mixtures are more similar to each other than to the CC after the 29-day mark. A 0.05% expansion level was then achieved first by the severely damaged RCA concrete at 36 days, followed by the slightly damaged RCA concrete at 44 days. The time required to achieve 0.12% of expansion was similar for the CC and severely damaged RCA concrete (i.e. 75 and 79 days, respectively) while the slightly damaged RCA concrete reached it only at 94 days. Moreover, the CC achieved 0.20% and 0.30% of expansion at 93 and 145 days, respectively. Conversely, the RCA mixtures did not reach 0.20% of expansion (on average) after 109 days; yet due to the scattering of the results, some specimens from both RCA mixtures (slightly and severely damaged) were able to reach over 0.20% of expansion. Nevertheless, the CC expansion data reveals the variability of the Springhill coarse aggregate which is repeated when used in recycled mixtures. This variability in the expansion levels achieved per sample (captured by the data range bars) is due to the variable amount of reactive silica contained within the aggregate particles.

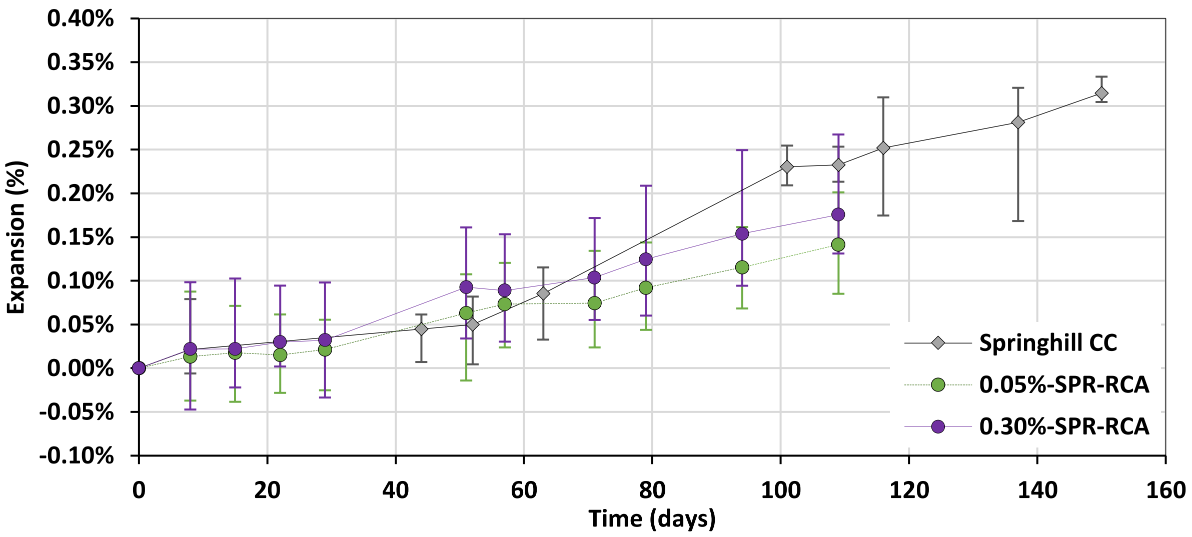


Figure 3.5: Expansion as a function of time for CC and RCA concretes.

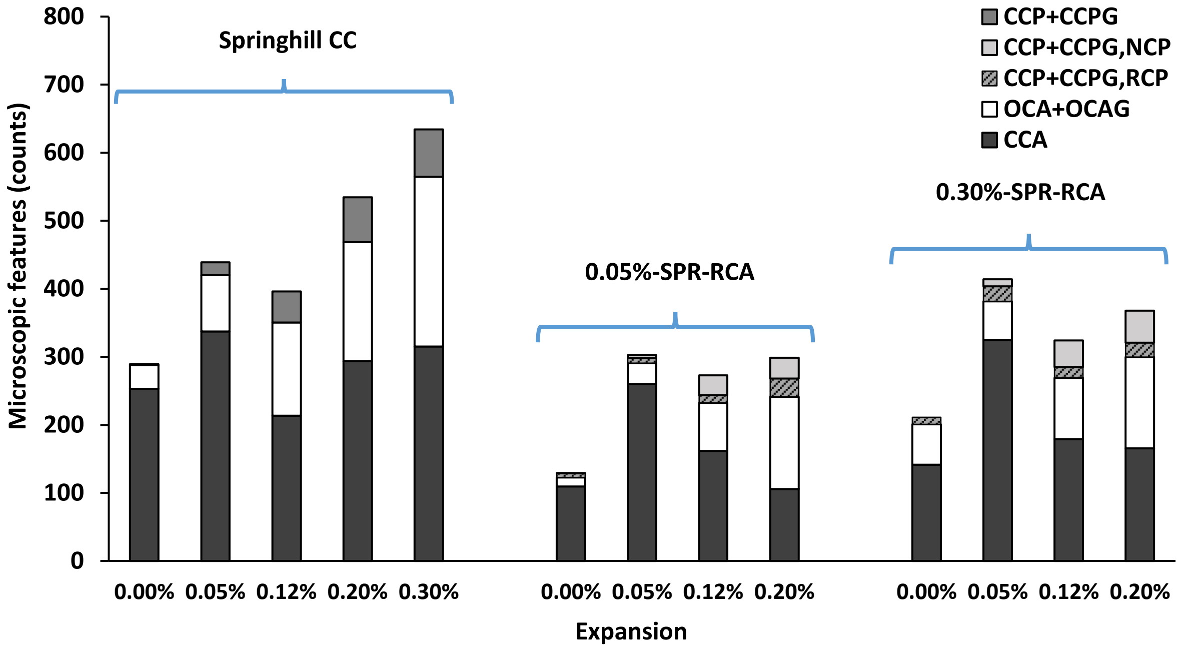
3.6.2. Distress features in CC and RCA concretes

The ASR microscopic distress features of the CC and both RCA concrete mixtures as a function of expansion were first evaluated using the extended version of the DRI as per [9,31]. In this analysis, the distinct petrographic features are appraised in a relative (i.e. counts, normalized to 100 cm2 – Figure 3.6) and absolute (% - Figure 3.7) manner, without the use of weighing factors. The extended DRI version enables the understanding of the damage development (i.e. generation and propagation of cracks) of ASR-affected concrete. To conduct the extended DRI, the microscopic distress features are divided into three groups: Closed cracks in the aggregates (i.e. CCA), Open cracks in the aggregates without and with gel (i.e. OCA + OCAG) and Cracks in the cement paste without and with gel (i.e. CCP + CCPG). To clarify, the closed cracks in the aggregates are cracks in which the fractured surfaces have not yet been separated. In addition, since this work deals with the assessment of conventional and recycled concrete mixtures, the Cracks in the cement paste will be further divided into cracks in the new and residual cement paste (i.e. NCP and RCP, respectively) to better accommodate the multi-phase nature of RCA particles.

Figure 3.6a shows the counts of the distinct microscopic distress features of ASR-affected CC and RCA mixtures (i.e. CCA, OCA + OCAG and CCP + CCPG). In general, the counts as a function of the expansion level are significantly higher in the CC when compared to the RCA concrete mixtures, with the slightly damaged RCA concrete (i.e. 0.05%-SPR-RCA) having somewhat lower counts than the severely damaged RCA concrete (i.e. 0.30%-SPR-RCA). For each concrete type, CCA does not seem to have a clear pattern; it increases from 0% to 0.05% of expansion yet decreases at 0.12%, remaining roughly constant afterwards. It is worth noting that CCA has been verified to have different causes than ASR, being often generated by crushing and/or weathering of the aggregates [9,31]. Yet, CCA features represent weak locations and preferred pathways for ASR damage propagation and while ASR may generate some closed cracks in the aggregate particles at later stages as the reaction evolves, they would be overcome by the opening and propagation of more advanced cracks due to the minimum energy law [9,31]. Otherwise, the Open cracks in the aggregates without and with gel (i.e. OCA+OCAG) increase with expansion for the CC and both RCA concrete mixtures. In all cases, the number of closed and open cracks in the aggregates (i.e. CCA and OCA + OCAG) is the most prominent distress feature, as expected and widely reported in ASR cases [9,31,39,40].

Figure 3.6b shows in detail the counts of the microscopic features observed in the cement paste (i.e. Cracks in the cement paste without and with reaction products - CCP + CCPG) and differentiated as per their location (i.e. RCP or NCP) in the RCA mixtures. Observing the plots, one verifies that the Cracks in the cement paste increase with expansion for CC and both RCA concrete mixtures yet, the increase is more significant in the NCP for the RCA concrete mixes, especially in the severely damaged RCA concrete. Furthermore, the number of Cracks in the cement paste in the CC mix is higher than in the slightly damaged RCA concrete yet lower than the severely damaged RCA concrete for all expansion levels except for: at 0%, as expected since cement paste cracks within the RCP of the RCA particle were preserved after the RCA crushing process; and at 0.20% where the total counts are similar for each mixture.

a) Counts of microscopic features in CC and slightly/severely damaged RCA concrete



b) Counts of microscopic features in cement paste of CC and slightly/severely damaged RCA concrete

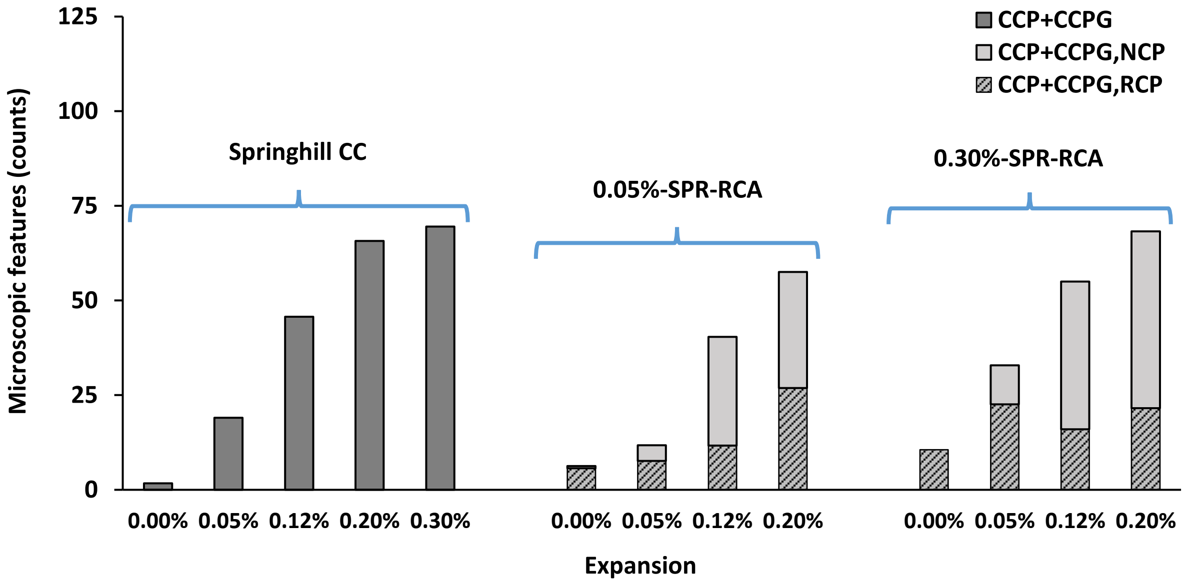


Figure 3.6: Counts of microscopic features of CC and RCA concrete.

The percentage of microscopic distress features for the CC and RCA concrete mixtures are illustrated in Figure 3.7. The Open cracks in the aggregates without and with gel (i.e. OCA + OCAG) and the Cracks in the cement paste without and with gel (i.e. CCP + CCPG) for the CC mix increase up until 0.12% of expansion and remain constant above and beyond this expansion level (from 12% to 40% and from less than 1% to 10%, respectively); the latter indicates that the proportions of those cracks remain fairly similar although new cracks are being generated in the system as per the counts displayed in Figure 3.6a. Conversely, the slightly damaged RCA concrete shows a smaller proportion of Open cracks in the aggregate without and with gel (10%) than the severely damaged RCA concrete (28%); however, the Cracks in the cement paste without and with gel are similar for both RCA mixtures (5%) prior to being subjected to secondary expansion (i.e. 0%). At 0.05% of secondary expansion, the slightly damaged RCA concrete shows the same previous proportions of Open cracks in the aggregate without and with gel and Cracks in the cement paste without and with gel with the latter having 1% of the cracks in the NCP. The proportion of Open cracks in the aggregate without and with gel continues to increase up to 45% in the slightly damaged RCA concrete and 36% in the severely damaged RCA concrete. Furthermore, the percentage of cracks in the new cement paste without and with gel increases with expansion (from 1% to 10% for the slightly and from 2% to 13% for the severely damaged RCA mixtures) while the cracks in the residual cement paste without and with gel remains fairly constant throughout the expansion process (average of 4%) except for an increase at 0.20% for the slightly damaged RCA concrete (9%).

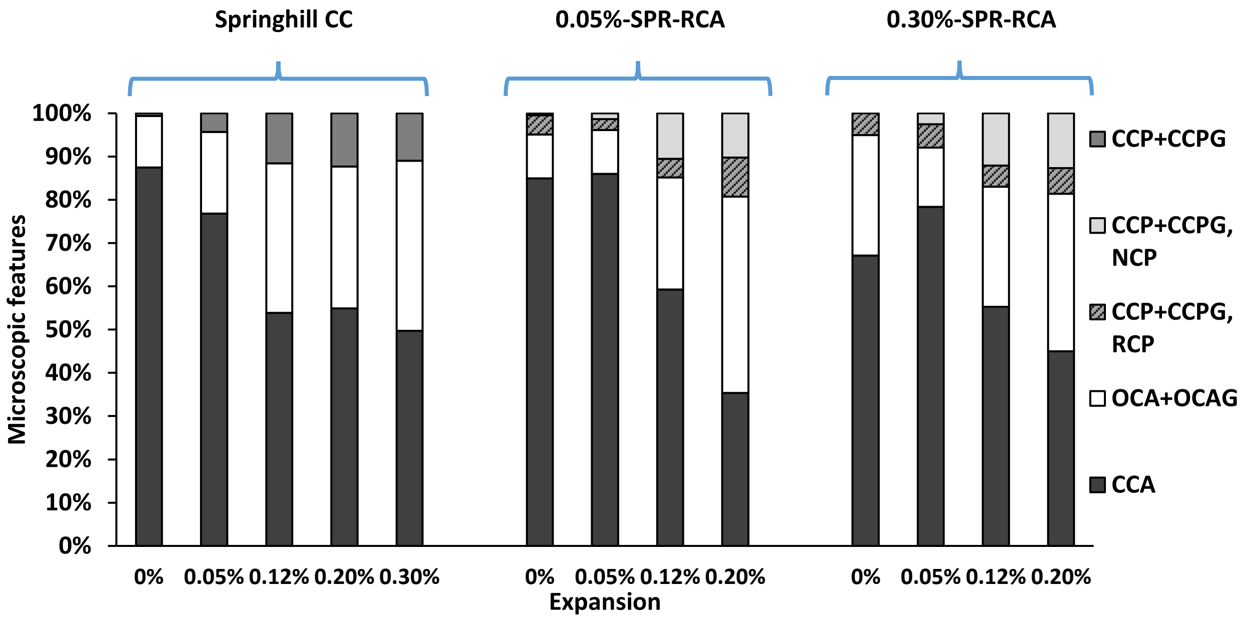


Figure 3.7: Percentage of microscopic features in CC and RCA concrete.

Figure 3.8 displays the CD results obtained for the CC and RCA mixtures. The total CD as a function of expansion is higher for the CC mix followed by the severely damaged RCA then the slightly damaged RCA. The CD of the CC however begins lower than the severely damaged RCA concrete at 0.25 counts/cm^2 and 0.5 counts/cm^2, respectively. Noticeably, the increase in CD for the RCA concrete mixtures are parallel from 0% to 0.05% after which the slightly damaged RCA concrete's CD increases until it reaches that of the severely damaged RCA concrete at 1.25 counts/cm^2 with the CC reaching 2.25 counts/cm^2 at 0.20% of expansion.

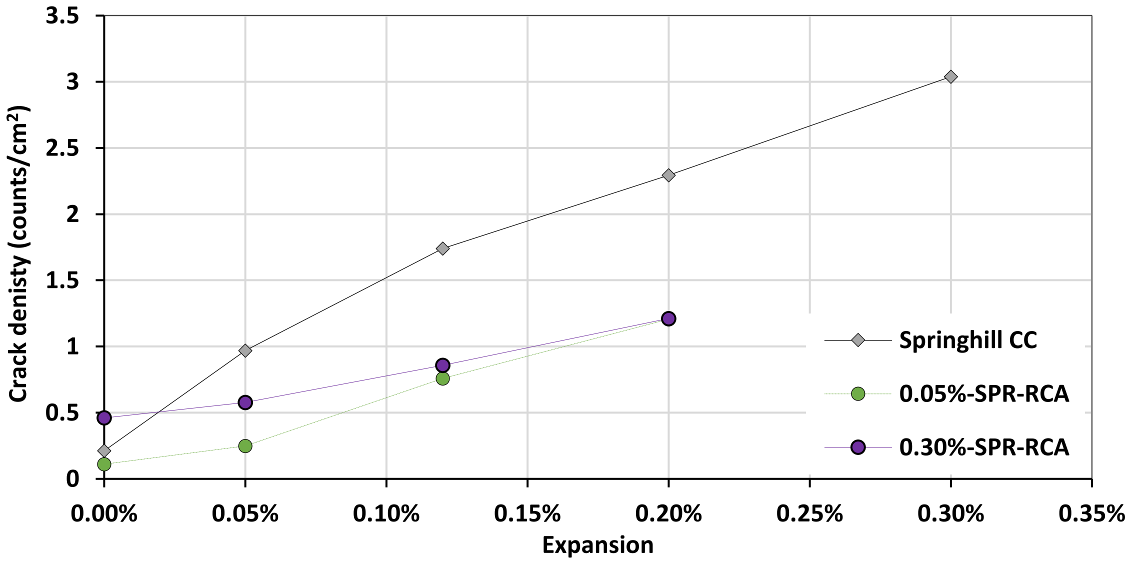


Figure 3.8: Crack density as a function of expansion for CC and RCA concretes.

3.6.3. Quantitative assessment of damage through the DRI

Figure 3.9 illustrates the DRI charts obtained from ASR-affected CC and RCA mixtures made of slightly and severely (i.e. 0.05% and 0.30%, respectively) damaged RCA. In general, the DRI values of the CC and both RCA concrete mixtures increase with increasing expansion, which indicates ASR-induced development in all mixtures. It is clear that for the same expansion level, the CC mix displays the highest DRI value followed by the severely and slightly damaged RCA mixes, respectively.

Prior to being subjected to damage, the DRI values indicate a negligible degree of damage for all concrete mixtures (i.e. DRI values of 138, 73 and 171 for the CC, slightly and severely damaged RCA, respectively). As expansion increases to 0.05%, the CC surpasses the severely damaged RCA concrete reaching a DRI value of 307, while the slightly and severely damaged RCA mixtures reach 161 and 261, respectively. The same trend is observed at 0.12% of expansion where the DRI value is higher for the CC (i.e. 465) than for the slightly and severely damaged RCA concretes (i.e. 268 and 390, respectively). At 0.20% of expansion, the slightly damaged RCA concrete experienced a large increase in the DRI value, reaching 470, while the severely damaged RCA and CC mixtures increased to 514 and 621, respectively.

Overall, all concrete mixtures show a general increase in the Open cracks in the aggregates without and with gel (i.e. OCA and OCAG, respectively) and Cement paste without and with gel (i.e. CCP and CCPG, respectively). Otherwise, the Closed cracks within the aggregates (i.e. CCA) do not seem to change as a function of expansion as previously verified in other works [9,31]. Moreover, the Cracks in the cement paste without gel (i.e. CCP) begin to become visible at early stages (i.e. 0.05%) for all mixes, yet they represent only a minor portion of the total number of cracks. Conversely, ASR products (i.e. ASR-gel) in the cement paste (i.e. CCPG) appears at later stages of the reaction for the CC mix (i.e. 0.30%), while it is observed already at moderate expansion levels (i.e. 0.12%) for the slightly damaged RCA concrete and at low expansion levels (i.e. 0.05%) for the severely damaged RCA concrete. The amount of ASR products produced in both RCA mixtures is significantly larger than for the CC especially in the aggregates.

Comparing the RCA mixtures, one may notice that they generally show similar trends with the severely damaged RCA concrete displaying a larger number of cracks in either concrete location than the slightly damaged RCA concrete throughout the whole expansion process. However, an important increase in Open cracks in the aggregates (without gel) is seen in the slightly damaged RCA concrete at early expansion stages (i.e. from 0% to 0.05% of expansion), yet this feature remains mostly unchanged for the severely damaged RCA mix at this stage. Additionally, at 0.12% of expansion, the slightly damaged RCA concrete shows a larger raise in the Open cracks in the aggregates (without tor with gel) when compared to the severely damaged mix.

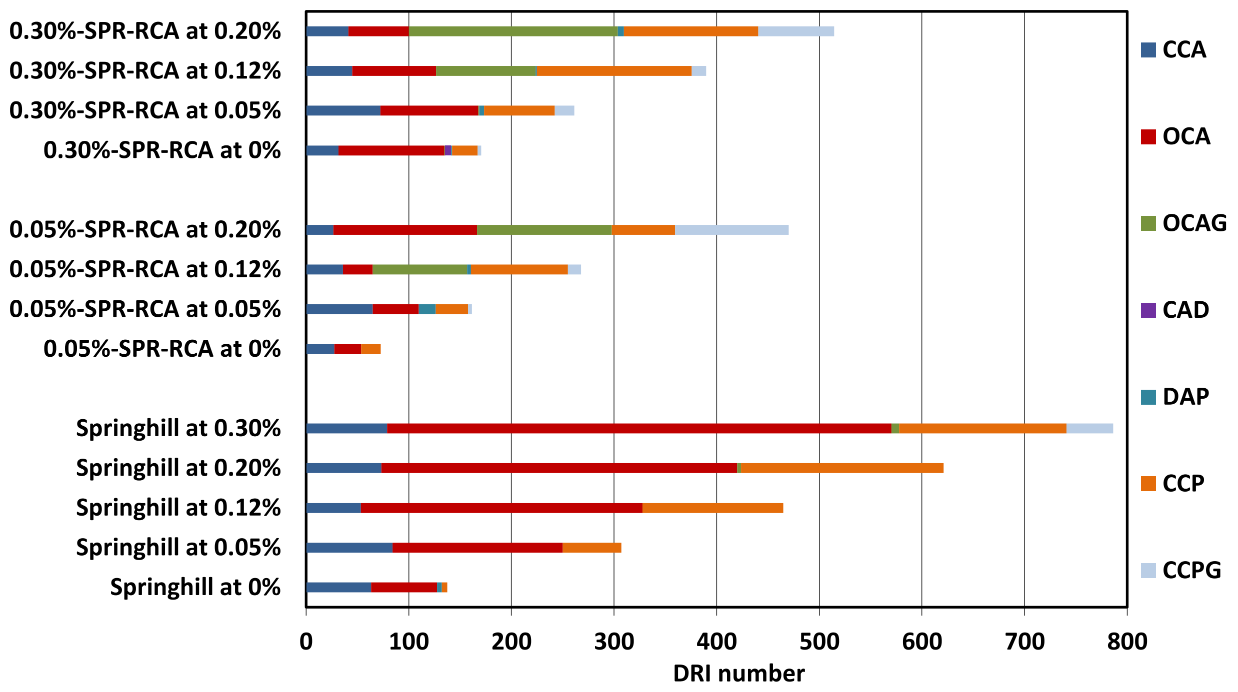


Figure 3.9: DRI charts for CC and RCA-concretes.

The evolution of the DRI number as a function of the expansion level has also been plotted in Figure 3.10. Evaluating the data, one observes that the DRI number clearly increases as a function of expansion for all mixtures, as expected. Furthermore, the RCA concrete mixtures show a parallel trend until 0.12% of expansion, with the slightly damaged RCA concrete having the lowest overall DRI value per expansion level. At 0.20% of expansion, the DRI number of the slightly damaged RCA concrete increases quite significantly, almost reaching that of the severely damaged RCA concrete.

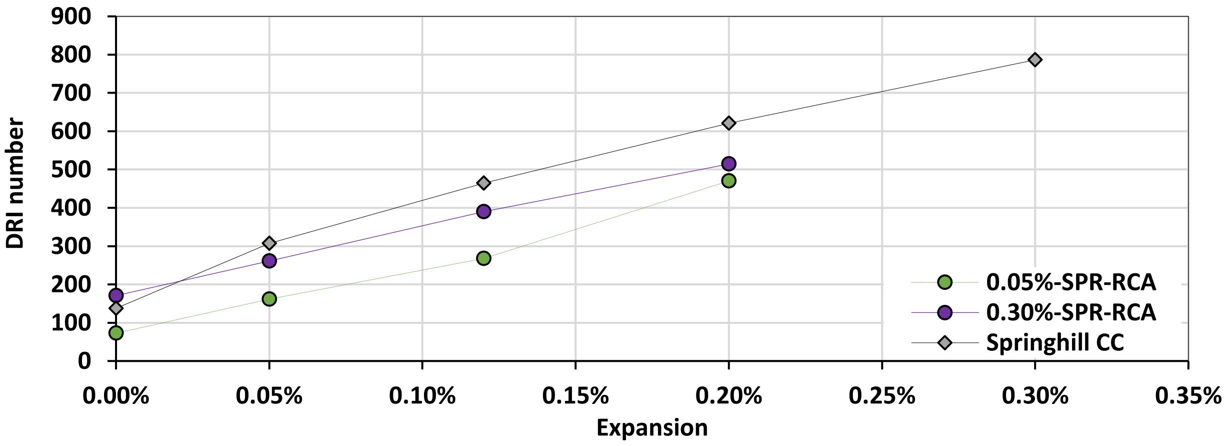


Figure 3.10: DRI number as a function of expansion for CC and RCA-concrete.

3.7. Discussion

3.7.1. ASR kinetics and induced expansion in CC vs RCA concrete

ASR average expansion as a function of time for the CC and recycled mixtures studied generally followed a similar trend, yet some differences were observed. In the beginning of the chemical reaction, all concrete mixtures behaved similarly, which might indicate the so-called induction period, which is the time required to induce expansion. The higher overall expansion level achieved by the recycled mixtures at 51 to 52 days shown in Figure 3.5 suggests that both of the RCA mixtures may initiate their expansion before the CC. Accordingly, in both of the RCA mixtures' cases the reaction/induced expansion had already begun as they have been subjected to past deterioration and therefore, this decrease in the induction period could be associated to previously formed ASR distress features (i.e. cracks in the OVA and RM) acting as "fast track channels", and lessening the time required to reactivate the expansion. Additionally, based on the minimum energy law, less energy is required to propagate than to form new cracks; thus, as the cracks were already present in the two RCA mixes, less energy and consequently time was required to initiate the "secondary induced expansion" (i.e. expansion experienced by the RCA concrete). Furthermore, the overall expansion level for the severely damaged RCA concrete is greater than that of the slightly damaged RCA concrete. This indicates the influence of the extent of damage of the RCA on the secondary expansion. Yet, the opposite was initially expected since the slightly damaged RCA concrete would have presented higher expansion levels due to its remaining reactive components (i.e. silica and alkali content) being less depleted. However, for the severely damaged RCA concrete, the reintroduction to the fresh source of alkalis seems to be able to reinitiate the expansion in the form of secondary expansion, as was determined by Stark in a previous study [26]. Therefore, the abundance and severity of pre-existing cracks in the aggregate and RM acting as "fast track channels" in the severely damaged RCA concrete may have a more significant influence on the secondary expansion than the amount of remaining reactants (i.e. reactive silica and alkalis), resulting in higher expansion levels than the slightly damaged RCA concrete. Yet, the shift in the expansion rates of the CC and two RCA concrete mixes indicate that the kinetics of RCA concrete is different than that of CC due to the previous partial consumption of reactants in the system.

3.7.2. Understanding secondary induced damage in RCA concrete

Secondary damage is the damage that is experienced by the RCA concrete which had previously been subjected to ASR-induced deterioration. As verified in Figure 3.5, recycled mixtures keep having the potential to develop secondary induced expansion regardless of their past deterioration. The generation and propagation of cracks resulting from secondary damage can therefore be characterized by three distinct types of cracks within the RCA concrete: 1) cracks generated in the OVA and extending into the RM before reaching the NM (OVA-RM); 2) cracks generated in the OVA extending directly into the NM (OVA-NM) and; 3) cracks generated in the RM extending into the NM (RM-NM). The latter is likely associated to the elongation of cracks generated in the OVA. Figure 3.11 shows the percentages of the distinct crack types previously mentioned (i.e. % of counts, disregarding the DRI weighing factors) for the slightly and severely damaged RCA concrete mixtures prior to being subjected to secondary expansion (i.e. 0%) and at 0.05% and 0.20% of secondary expansion. This analysis is intended to help in the overall understanding of induced secondary damage of ASR-affected RCA concrete displaying distinct past deteriorations.

Evidently prior to secondary induced expansion, the cracks propagating from the OVA to the RM represent 100% of the petrographic distress features, with the severely damaged RCA concrete having a higher count at 18 counts/100 cm^2 when compared to the slightly damaged RCA concrete at 3 counts/100 cm^2. As the RCA was subjected to past deterioration, some of the previous ASR-induced distress features (i.e. cracks) are expected to be preserved while others removed by splitting of the OVA (Figure 3.12a) or created during the RCA crushing process such as cracks in the cement paste at 0.05% of expansion (Figure 3.12b) which was most likely caused by RCA crushing, since it is quite uncommon to find such cracks at this stage. Note that the crack types are identified on the images as the distinction between certain types of cracks and their visibility may only be apparent using a stereomicroscope. Moreover, Figure 3.12a shows slightly damaged RCA particles before being subjected to secondary damage where closed cracks in the OVA are observed, and could have been caused by either initial weathering of the OVA, initial and/or RCA processing or previously initiated ASR. Conversely, the severely damaged RCA concrete shown in Figure 3.13 contains open cracks in the aggregates observed to be linked through the RCP, which are more indicative of previous ASR. More damage is therefore preserved in the severely damaged RCA particles (Figure 3.13). Consequently, the counts and proportion of open cracks in the aggregates is greater in the severely damaged RCA concrete prior to being subjected to secondary expansion (i.e. 0%) as shown in Figure 3.6 and Figure 3.7, respectively.

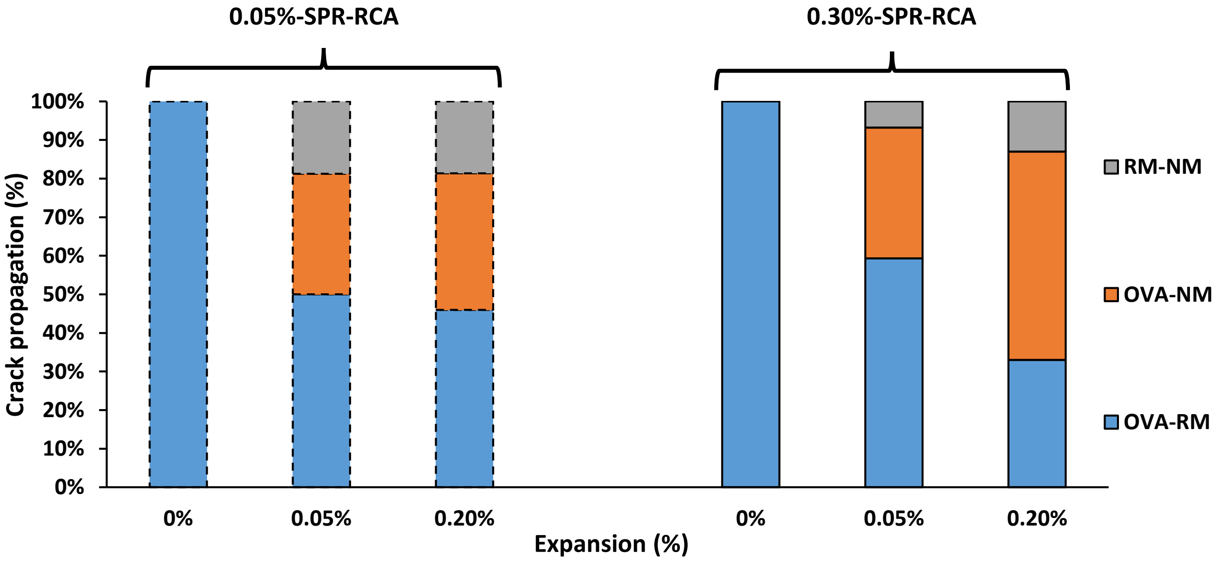
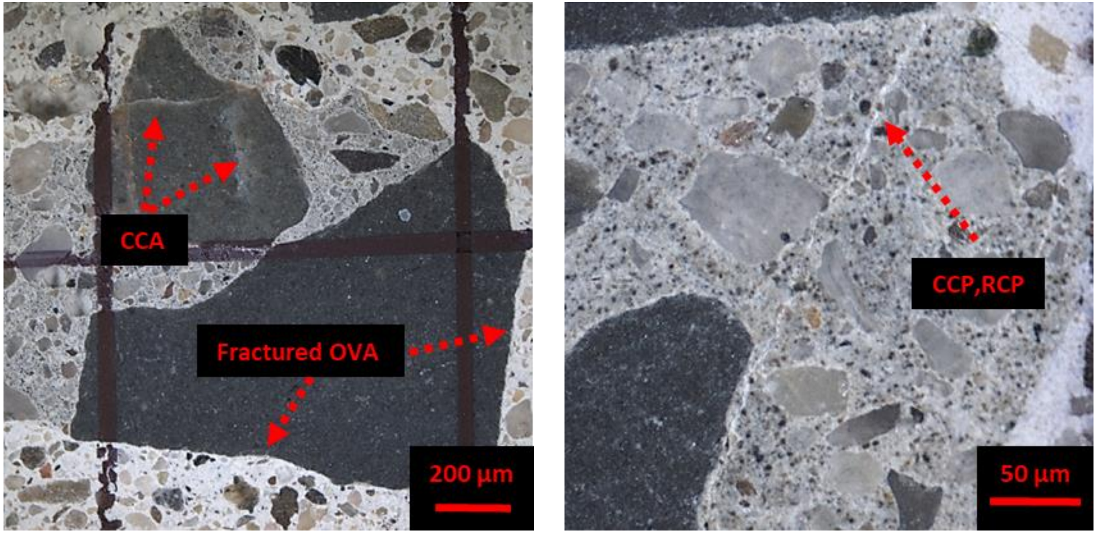


Figure 3.11: Percentage of crack propagation in recycled concrete mixtures.



a) Closed cracks in OVA and fractured OVA of slightly damaged RCA

b) Crack in RCP of slightly damaged RCA

Figure 3.12: Distress features of slightly damaged RCA particles: a) Closed cracks in OVA and fractured OVA and b) Crack in RCP.

Analyzing carefully Figure 3.11 data, one observes that at 0.05% of secondary expansion, the proportions of crack propagation are similar, where 50% and 59% are OVA-RM and 31% and 34% are OVA-NM for the slightly and severely damaged RCA concrete mixtures, respectively. Yet, a larger proportion of RM-NM cracks is observed in the slightly damaged RCA concrete at 19% as cracks continue to propagate through the RM whereas only 7% of these cracks are found in the severely damaged mixture. The most significant difference between both RCA mixtures is at 0.20% of secondary expansion where a change in propagation is observed. As such, OVA-RM cracks are more important in the slightly damaged RCA concrete (46%) compared to OVA-NM cracks (35%). The RM-NM cracks in the slightly damaged mixture on the other hand do not show an increase in the proportion; yet, it increased to 20 counts/100 cm^2 from 2 counts/100 cm^2 indicating the potential for further expansion through the RM. Consequently, as per Figure 3.6b, an increase in RM cracks in the slightly damaged RCA concrete is only seen at 0.20% of expansion, which is due to the original extent of damage having not yet propagated cracks into the cement paste as per Sanchez et al. [9,31]. Since the slightly damaged RCA had only been subjected to 0.05% of expansion as original damage and its cracks were initially contained within the OVA and most likely oriented as to propagate into the cement paste (i.e. RM once in RCA), they continued to propagate into the OVA towards the RM and eventually into the NM. Hence, OVA-RM cracks are deemed to represent the potential of further induced expansion and damage in slightly damaged RCA concrete.

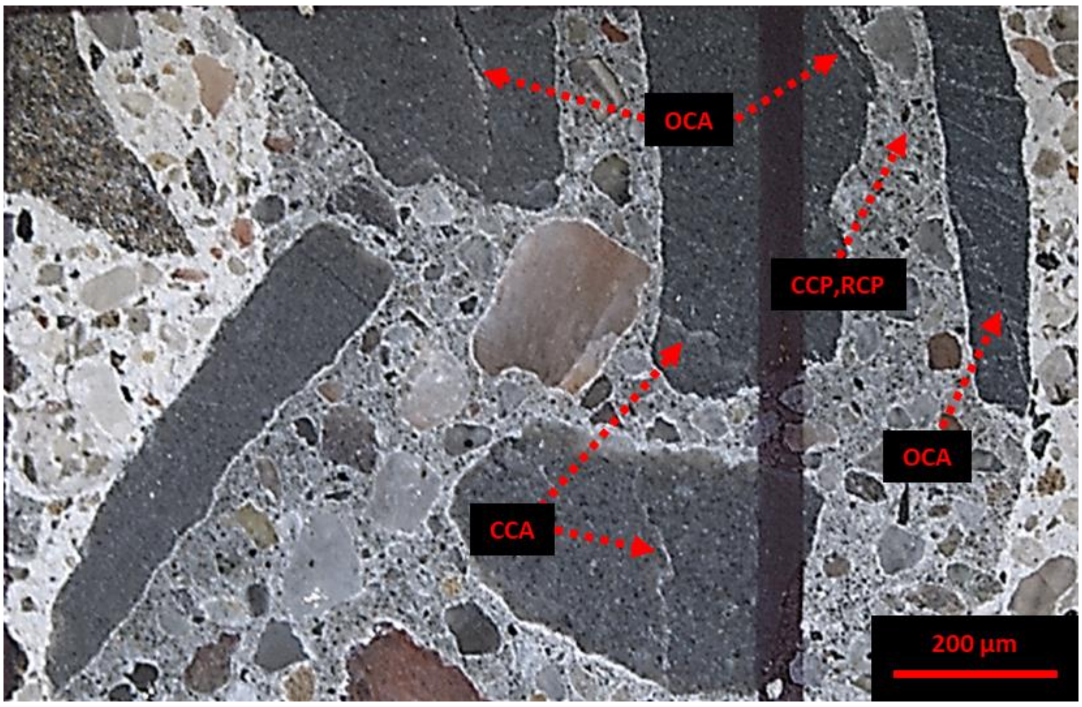


Figure 3.13: Distress features of a severely damaged RCA particle.

As for the severely damaged RCA concrete, the RM-NM cracks do not significantly increase (from 3 counts/cm^2 to 9 counts/cm^2) compared to the slightly damaged mixture indicating a lower potential for further expansion through the RM. Dissimilar to the slightly damaged RCA concrete at 0.20% of expansion, a higher proportion of OVA-NM cracks (54%) is observed compared to the OVA-RM cracks (33%) which do not increase in count from 0.05% to 0.20% of secondary expansion. This therefore indicates the potential of further induced expansion and damage in severely damaged RCA concrete is represented by cracks in the OVA-NM. Although the propagation of each crack type contributes to the overall distress mechanism of the RCA concrete mixtures, this comparison shows that the damage mechanism differs based on the original extent of damage.

3.7.3. Describing damage generation and propagation in ASR-affected RCA concrete

As previously discussed, the severely damaged RCA concrete mix shows an increase in the proportions of closed cracks in the aggregates (CCA) at 0.05% of expansion followed by a sharp decrease (Figure 3.7), which is not observed in both CC and slightly damaged RCA mixtures. Therefore, there is a possibility that severely damaged RCA concrete experiences a continuation of ASR at pre-existing reactive sites and cracks in combination with new ASR at unreacted sites or newly formed unreacted sites caused by RCA crushing. These newly formed reactive sites would be much more (if not only) apparent in severely damaged RCA concrete given its original extent of damage having significantly depleted the reactants at locations close to pre-existing deterioration (i.e. cracks). As such, the secondary damage in RCA concrete could even be further divided into “new” and “ongoing” ASR damage in the case of severely damaged RCA. Moreover, OVA to NM cracks represent secondary damage which may be induced by new ASR whereas OVA to RM cracks represent ongoing ASR cracks, the former being the prevailing crack propagation type in the severely damaged RCA concrete.

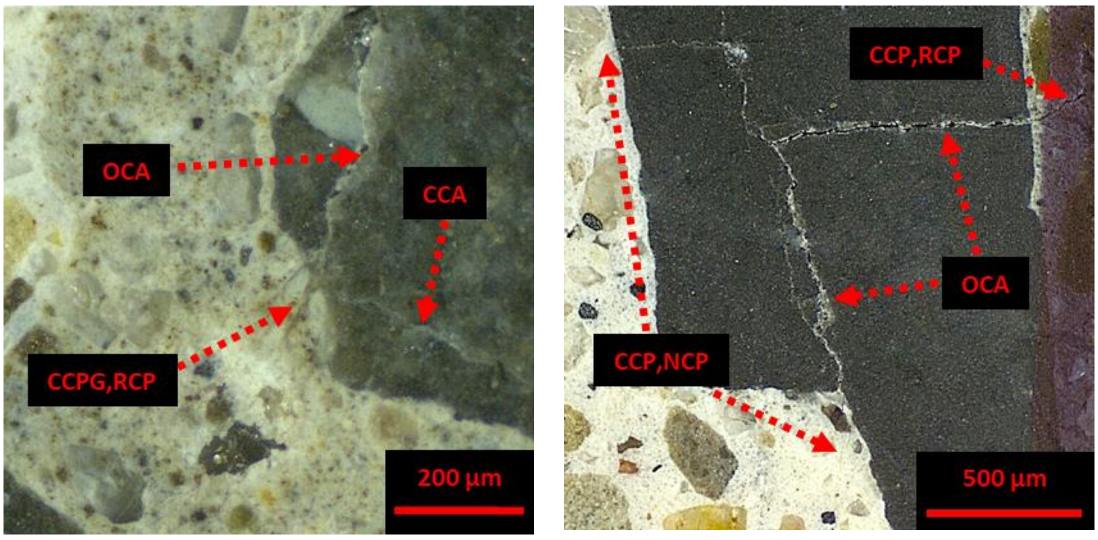
Overall, the secondary damage in both RCA concrete mixtures differs such that more damage in terms of number of cracks is produced in a severely damaged RCA concrete. Thereby, since the severely damaged RCA concrete contains the most damage and in consequence number of cracks, its prevailing damage mechanism could be attributed to the minimum energy law as a more abundant amount of cracks are preserved. However, as previously mentioned, petrographic distress features (i.e. cracks) tend to propagate from OVA to NM as opposed to through the RM due to the remaining reactive potential in the severely damaged RCA concrete. Otherwise, the slightly damaged RCA concrete, having a much lower number of OCA distress, seems to be generating and propagating cracks from CCA and the less abundant OCA, respectively, resulting in a lower microscopic feature count, CD, and DRI value. Therefore, the slightly damaged RCA concrete propagates cracks from OVA to NM and from OVA to RM which continue into the NM. Nevertheless, the remaining reactive potential in the slightly damaged RCA concrete overcomes its lack of initial deterioration features by “catching up” to the severely damaged RCA concrete at 0.20% of expansion. Yet, the same expansion level is achieved at these lower counts of cracks for the slightly damaged RCA concrete indicating again a difference in the distress mechanism with respect to the original extent of damage. Moreover, the CC shows an even greater level of distress in terms of number of cracks for the same achieved expansion level which further indicates that the distress mechanism of CC differs from that of recycled mixtures, as previously reported by Shehata et al. [19].

With the aim of increasing precision and thus better describing the mechanism of damage generation and propagation of ASR-affected RCA concrete displaying distinct past induced deteriorations, one proposes the separation of residual mortar (RM) into residual fine aggregates (RFA) and residual cement paste (RCP). Likewise, the new mortar (NM) should be further divided into fine aggregates (FA) and new cement paste (NCP). Based on the microscopic evaluations conducted in this work, the following deterioration process is described by ASR-affected RCA concrete:

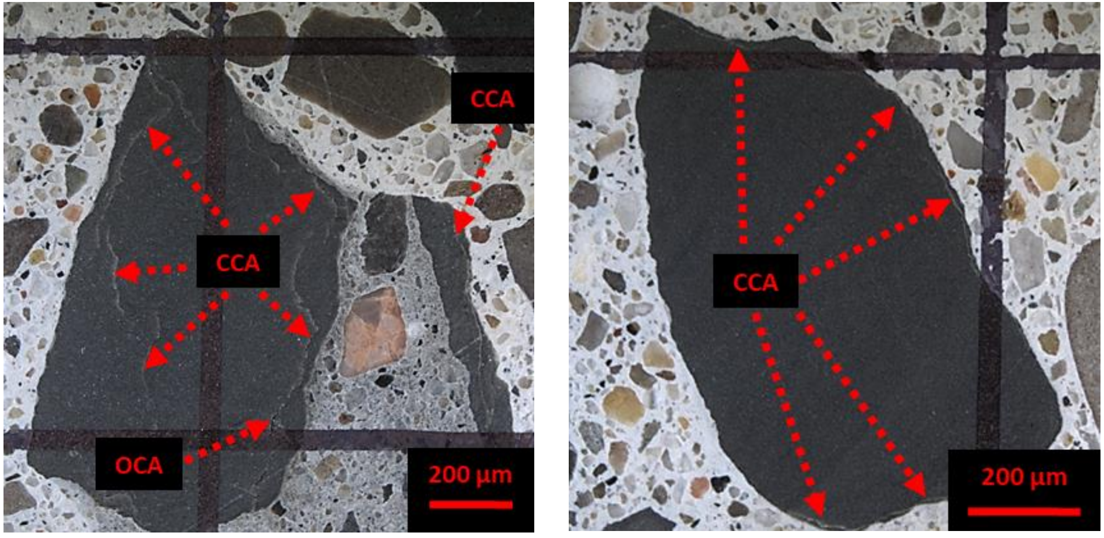
- At early stages (i.e. 0.05% level of expansion) the cracks generally tend to propagate from the OVA to the RCP or from the OVA directly to the NCP in recycled RCA mixes made of reactive RCA particles, regardless of their past induced expansion (i.e. Figure 3.14a and Figure 3.14b, respectively for the slightly damaged RCA concrete and Figure 3.15a and Figure 3.15b, respectively for the severely damaged RCA concrete). In the case of the slightly damaged RCA concrete, cracks propagating from the OVA into the RCP suggests ongoing ASR while for the severely damaged RCA concrete, such cracks which do not yet reach the NCP likely indicating new ASR as secondary damage due to their original extents of damage.

- At moderate expansion levels (i.e. 0.12% of expansion), differences begin to be observed as per the RCA past deterioration. Slightly damaged RCA concrete shows numerous CCA in the OVA (Figure 3.14c) along with important CCA at the periphery (i.e. onion skin type cracks, Figure 3.14d) of aggregate particles, which can be derived from either ongoing ASR as secondary damage (given that the original extent of past damage is low - 0.05%) or most likely from crushing. Conversely, severely damaged RCA concrete displays various cracks in the OVA extending into NCP and joining to another RCA particle through its OVA while also splitting at the interface and continuing into the NCP which is more indicative of new ASR as secondary damage (Figure 3.15e). Therefore, at 0.12% of expansion, severely damaged RCA concrete begins to link cracks among RCA particles, showing a more advanced stage of damage which is not apparent in slightly damaged RCA mixtures at the same level of secondary expansion. Furthermore, the severely damaged RCA concrete extends some of its RCP cracks into the NCP at an expansion level of 0.12% (Figure 3.15d) which indicates further ongoing ASR as secondary damage. Therefore, the slightly damaged RCA concrete continues to propagate its cracks from the OVA into the RCP while generating new cracks extending into the NCP whereas the severely damaged RCA concrete mostly generates its cracks from the OVA into the NCP and from the RM into the NCP.

- Finally, the slightly damaged RCA concrete begins to link cracks formed at distinct RCA particles together (through their OVA) at 0.20% of expansion as seen in Figure 3.14e while the severely damaged RCA concrete continues to propagate its previously formed cracks. At 0.20% of expansion, ASR-gel is observed in the cement paste cracks for the slightly and severely damaged RCA concrete mixtures (Figure 3.14f and Figure 3.15e, respectively) and in the periphery cracks in the OVA of the severely damaged RCA concrete (Figure 3.15f). Furthermore, from Figure 3.14f it can be observed that cracks may propagate through the RCP as opposed to the NCP, indicating that the cracks previously oriented towards the RCP may continue to propagate as such due to the minimum energy law and the remaining reactivity of the RCP.


a) Slightly damaged RCA concrete at 0.05% with CCPG in RCP

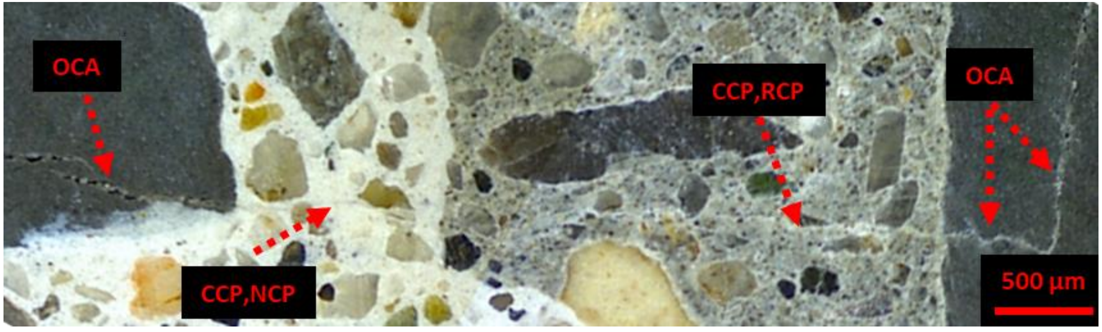
b) Slightly damaged RCA concrete at 0.05% with CCP in NCP and RCP



c) Closed cracks linking in OVA at 0.12% in slightly damaged RCA-concrete

d) Crack at periphery of OVA at 0.12% in slightly damaged RCA-concrete

e) Crack connection RCA particles at 0.20% of expansion



f) Crack filled with gel extending from OVA into RCP at 0.20% of expansion. 1: Magnified of sector

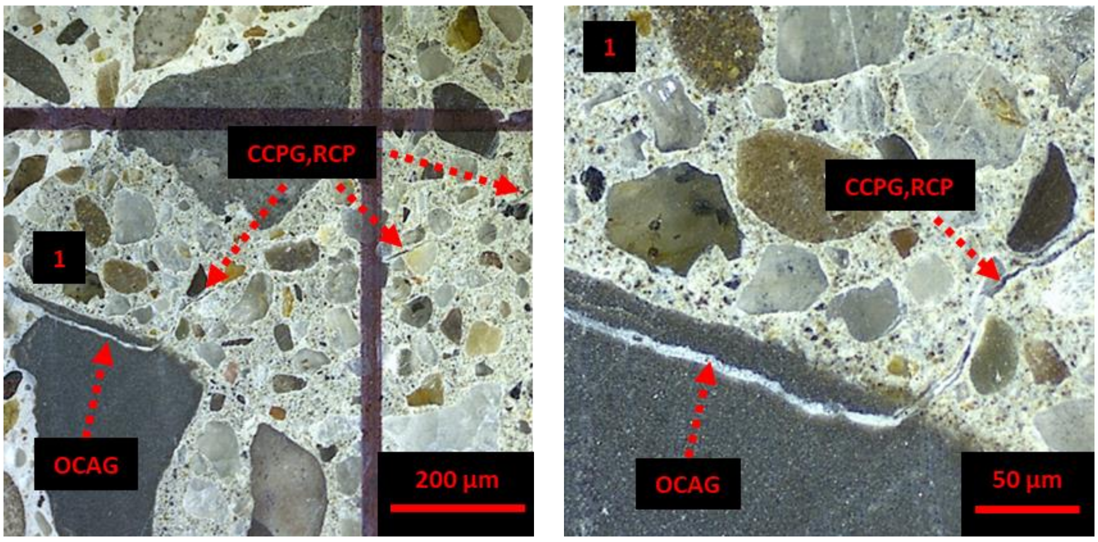
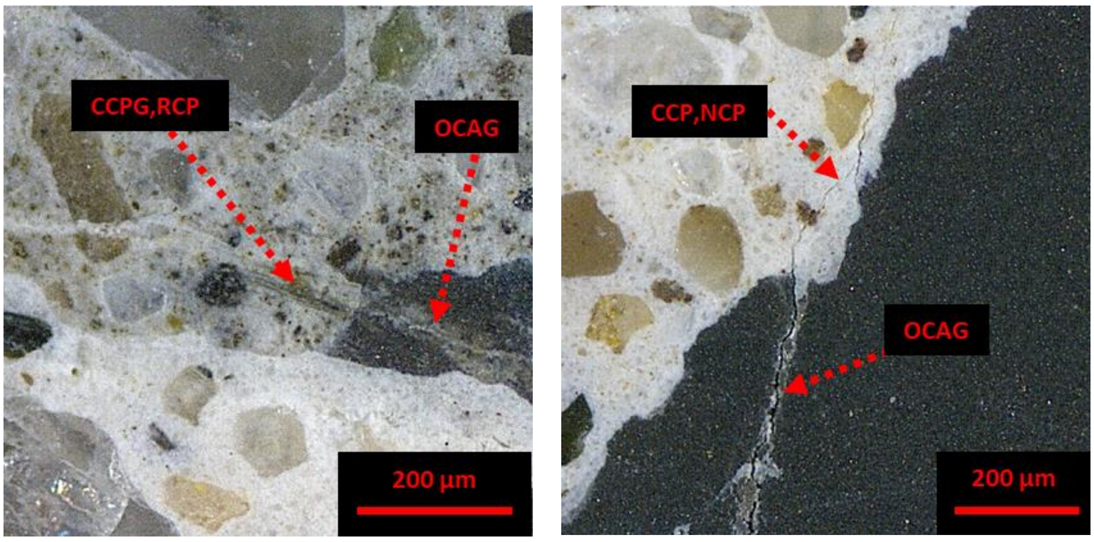
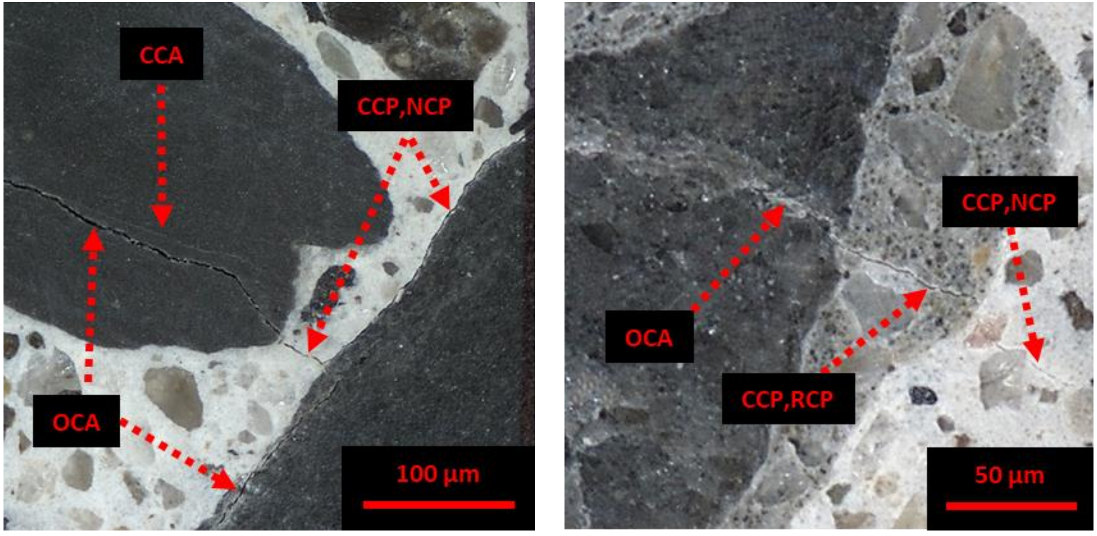


Figure 3.14: Distress features in slightly damaged RCA concrete with respect to expansion.

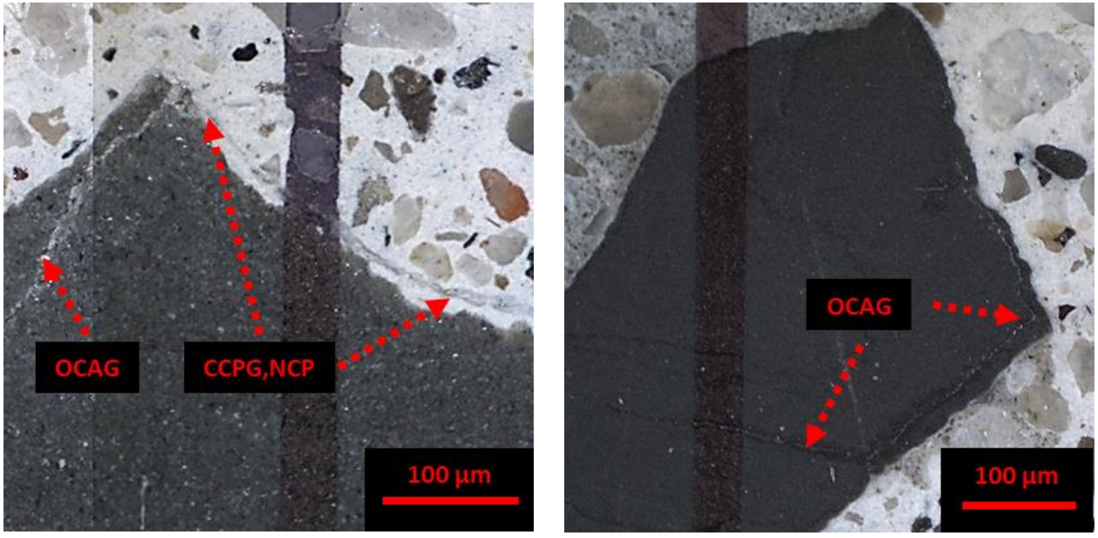


a) Severely damaged RCA concrete at 0.05% with CCPG in RCP

b) Severely damaged RCA concrete at 0.05% with CCP in NCP


c) Severely damaged RCA concrete at 0.12% with linking of RCA particles

d) Severely damaged RCA concrete at 0.12% with extension of OCA to CCP,RCP to CCP,NCP


e) Severely damaged RCA concrete at 0.20% with OCAG extending into CCPG,NCP

f) Severely damaged RCA concrete at 0.20% with OCAG at periphery

Figure 3.15: Distress features in severely damaged RCA concrete with respect to expansion.

3.7.4. Quantitative assessment of secondary damage in RCA

From the microscopic features, CD and DRI results, it is evident that CC mixtures follow the ASR descriptive damage development model proposed by Sanchez et al. [9] and illustrated in Figure 3.1, where cracks begin in the aggregate particles and extend into the cement paste as the expansion increases. As such, the obtained DRI values for CC can estimate the damage degree (i.e. expansion level) achieved by ASR-affected CC (Table 3.3) as per Sanchez et al. [11]. Furthermore, this work indicates that the DRI can also be used to assess damage in RCA concrete; however, some differences are verified with respect to the obtained DRI numbers as a function of the expansion level when compared to CC mixes. According to the results gathered in this work, DRI values from RCA concrete (from either slightly or severely damaged RCA) are somewhat lower (or in the lower bound) than CC mixtures with the same expansion level, especially at earlier stages and for slightly damaged RCA as per Table 3.3. Therefore, care should be taken while estimating total induced expansion of RCA concrete. Finally, further research using a larger amount of reactive aggregate types (i.e. fine vs coarse) and natures (i.e. lithotypes) is required to better understand DRI values for RCA mixes and thus precisely estimate induced expansion.

Table 3.3: Classification of ASR damage degree in CC based on DRI result as proposed by Sanchez et al. [11].

Classification of ASR damage degree	Reference expansion level (%)	DRI results		
		Conventional concrete [11]	Slightly damaged RCA concrete	Severely damaged RCA concrete
Negligible	0.00-0.03	100-155	73	171
Marginal	0.04 ± 0.01	210-400	161	261
Moderate	0.11 ± 0.01	330-500	268	390
High	0.20 ± 0.01	500-765	470	514
Very high	0.30 to 0.50 ± 0.01	600-925	-	-

3.8. Conclusions

The purpose of this study was to microscopically appraise and understand ASR-induced damage (i.e. generation and propagation) in CC and RCA concrete made of two distinct levels of past deterioration to represent slightly damaged RCA (e.g. returned concrete – 0.05% of past expansion) and severely damaged RCA (e.g. demolished concrete – 0.30% past expansion level) through the Damage Rating Index (DRI), a semi-quantitative microscopic procedure. The main findings of the current research are presented hereafter:

- The overall ASR-kinetics and induced development of ASR-affected RCA concrete is in general similar to that of CC; yet, a faster induction period (i.e. time required to induce expansion) was potentially observed for both recycled concrete mixtures. The latter could be associated to the existence of previous ASR distress features (i.e. cracks) acting as "fast track channels" and thus, accelerating the chemical reaction. Furthermore, the expansion levels for both RCA concrete mixtures follow a very similar trend with the severely damaged RCA concrete having faster kinetics and higher expansion levels (on average) as a function of time. This behaviour was somehow unexpected due to the important past deterioration of the severely damaged RCA concrete (i.e. 0.30% of expansion) as opposed to the slightly damaged RCA concrete (i.e. 0.05% of expansion level) given the previous extent of damage;
- The distress experienced by the RCA concrete can be termed as the "secondary" induced damage; yet, the results suggest that ASR-affected RCA concrete experiences simultaneously a continuation of the "previous" ASR and "new" ASR produced by unreacted and newly formed reactive sites and cracks caused by RCA crushing. This concept is more apparent in the severely damaged RCA concrete given its previous extent of damage;

- The results gathered in this research clearly show that the mechanism of damage generation and propagation is different for conventional and recycled concrete mixtures. Moreover, the behaviour of the “secondary” deterioration of ASR-affected RCA mixtures depends on the amount of previous induced distress of the RCA used;
- The most significant difference in terms of “secondary” induced damage (i.e. generation and propagation) of both recycled mixtures are the number of cracks produced as a function of the expansion level reached. The severely damaged RCA concrete displays a higher amount of damage when compared to the slightly damaged mixture due the preserved damaged. However, both recycled mixtures have a lower number of petrographic distress features (i.e. cracks) than the conventional concrete mix.
- Overall, ASR-induced cracks tend to propagate from the original virgin aggregate (OVA) towards the new cement paste (NCP) for the severely damaged recycled mixture without significantly propagating through the residual cement paste (RCP) whereas due to the remaining reactive potential in the slightly damaged recycled mixture, the cracks propagate from the OVA into the RCP, and then new cement paste (NCP).

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Chapter Four: Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates

4.1. Abstract

Alkali-silica reaction (ASR) is one of the most detrimental distress mechanisms leading to early deterioration of concrete infrastructure, creating large amounts of construction and demolition waste (CDW) which however can be transformed into recycled concrete aggregates (RCA). Yet, as ASR is an ongoing distress mechanism, its potential of reoccurrence in RCA could cause adverse effects. Investigation of the crack propagation of RCA concrete revealed that the distress features vary widely thus, indicating different distress mechanisms in all RCA concrete. Concrete made with slightly damaged RCA shows the lease number of cracks yet, wider cracks at high expansion levels. Additionally, the distress in slightly damaged RCA concrete made with reactive coarse aggregate and RCA concrete made with reactive sand, regardless of original damage extent, is governed by cracks propagating through the residual cement paste whereas cracks propagate through the new cement paste in severely damaged RCA made with reactive coarse aggregate.

Keywords: Recycled concrete, recycled concrete aggregates (RCA), reactive coarse and fine aggregate, alkali-silica reaction (ASR), microscopic characterization, crack propagation.

4.2. Introduction

As pressure rises in the civil construction industry to adopt more sustainable measures to reduce waste and CO2 emissions, recycling of concrete directly helps to reduce both of these sustainable aspects. As such, concrete derived from construction and demolition waste (CDW) or unused surplus material returned to the plant (returned concrete – RC) can be transformed into the so-called recycled concrete aggregates (RCA) and thus avoid unnecessary disposal in landfills [1,2]. Moreover, it has been found that RCA concrete, when mix-proportioned using advanced techniques, requires less Portland cement (PC), which lowers the material's carbon footprint since PC production accounts for 5% of the total CO2 emissions globally [3]. However, although RCA concrete is recognized as a valuable alternative towards sustainability in the construction industry, RCA also displays some drawbacks. Amongst others, RCA may be reclaimed from concrete structures presenting past deterioration due to ongoing damage processes such as alkali-silica reaction (ASR); therefore, the use of such ASR-affected RCA causes major concerns towards its potential of further induced distress development in new construction.

In this context, ASR is a chemical reaction between the alkalis from the concrete pore solution (Na+, K+, and OH-) and some unstable siliceous phases encountered in the aggregates used to make concrete. ASR generates a hygroscopic product, the so-called ASR gel that swells upon water uptake from its surroundings causing tensile stresses and ultimately cracking of the material. As the reaction progresses, ASR-induced cracks propagate from the aggregate particles into the cement paste until an important network of cracks is formed and the concrete begins to lose its physical integrity [4]. ASR can even be seen as self-inflicting, since the formed cracks allow for ingress of water and de-icing agents (i.e. alkalis) which may further accelerate the reaction. Hence, if preventive measures are not taken into consideration in newly constructed concrete while using reactive aggregates, rehabilitation or demolition may be required before the end of its service life.

ASR-affected concrete structures display distinct ages and are located in different macro and micro climates, even within the same structure; thus, a wide range of extents of reaction/damage may be found in ASR-affected RCA, which makes it a particularly variable material. Previous research demonstrated that the potential of further induced expansion (i.e. secondary expansion) and crack development of ASR-affected RCA depends on the previous damage (i.e. past expansion) [5,6], yet this relationship is not fully understood. Furthermore, the mechanism of damage development (i.e. cracks generation and propagation) along with its impact on the overall performance of RCA concrete should also rely on the type of reactive aggregate (i.e. fine vs. coarse) present in the RCA particle. Yet, the latter remains currently unknown.

4.3. Background

4.3.1. RCA microstructure

Coarse RCA is composed of residual mortar (RM) adhered to original virgin aggregate (OVA) particles. RM consists of residual sand and residual cement paste (RCP), making RCA a multi-phase material. Moreover, RCA concrete displays a different microstructure than that of conventional concrete (CC) since it contains an original interfacial transition zone (ITZ) between the OVA and RM along with newly formed ITZs between the new mortar (NM) and RM, and the OVA and NM (Figure 4.1). This complex microstructure creates additional weak links in the RCA concrete, which in turn influences the cracks development (i.e. initiation and propagation) in the material. Yet, the impact of the latter on the secondary induced expansion and damage of ASR-affected RCA has not been deeply studied.

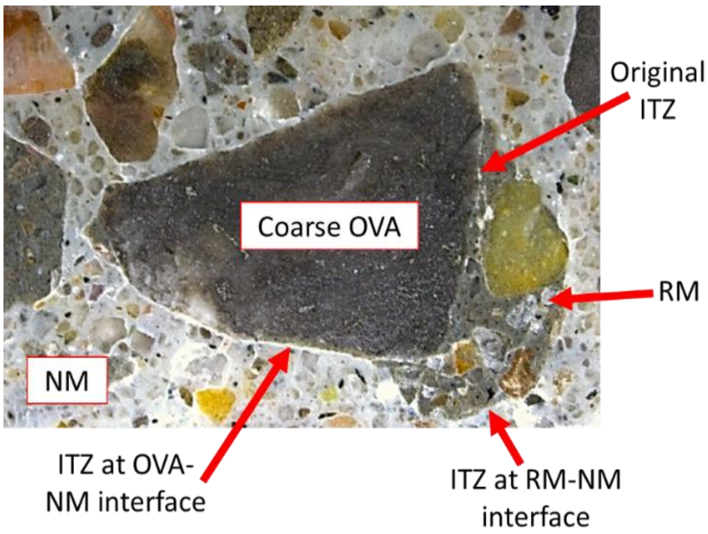


Figure 4.1: Microstructure of a coarse RCA particle.

4.3.2. ASR-induced expansion and damage in CC and RCA concrete

ASR is an ongoing distress mechanism that may keep progressing in recycled concrete given that enough reactants are present to supply the reaction. In some cases, if the reactant (i.e. unstable siliceous phases) has been depleted in the previously affected source concrete, further damage (i.e. expansion) does not take place in the RCA concrete [7]. On the other hand, if the silica has not been completely depleted and the alkalis were the limiting reactant, or the concrete was demolished before the reaction had come to completion, the RCA concrete may exhibit further induced expansion and deterioration. Moreover, if the source concrete had not been exposed to enough alkalis to deplete the silica and is re-introduced as RCA in a high alkaline environment, the resulting expansion could even reach levels greater than what had previously been achieved [8]. Therefore, the extent of previous reaction will influence the behaviour and subsequent induced damage of RCA concrete. Nonetheless, the extent of the reaction is not always known in a demolished concrete structure and is often considered as a severely damaged material hence, the reason for being demolished. Moreover, the properties of the source concrete (i.e. reactive aggregate type and nature, 28-day compressive strength and alkali loading of the recycled concrete, etc.) are also often unknown which limits the overall understanding of the potential secondary induced expansion and deterioration [9].

ASR-induced damage is normally expressed by a level of induced expansion reached by the affected concrete; generally, as expansion increases, so does the severity of ASR-induced damage. In ASR-affected CC, damage is primarily verified through cracks developed within the aggregate particles where a more significant influence on the stiffness, tensile strength [10,11] and aggregate interlock (subsequently influencing the shear strength) [12] is observed. Otherwise, ASR-induced cracks eventually extend to the cement past at later stages (i.e. higher expansion levels), negatively impacting on the compressive strength of the affected material [10,11]. Therefore, understanding the induced distress process (i.e. cracks generation and propagation) is primordial to perceive the current and the potential of further distress of the affected recycled material.

4.3.3. RCA concrete: reactive coarse versus reactive fine aggregates

Previous research [13] has demonstrated that although ASR-induced damage development is not that different whenever triggered from a reactive fine versus a reactive coarse aggregate through a quantitative point of view (i.e. overall number and importance of cracks), the microstructure of an ASR-affected CC made of a reactive sand is quite different (i.e. a more sparsely distributed crack pattern) when compared to a reactive coarse aggregate (i.e. sharper and more localized deterioration pattern). Therefore, it is anticipated that the behaviour of ASR-affected RCA made of reactive fine or coarse aggregate might also differ from one another. However, very few works have incorporated RCA where ASR was induced by a reactive sand [7–9,14], some of which were combined with a reactive coarse aggregate [8,9] and therefore, the differences between their behaviours remain unknown. Moreover, the inconsistencies in expansion levels achieved [15–18] along with mitigation measures using standard testing methods [8,9,15,19] may be a consequence of the various extents of damage of the source concrete in combination with the reactive component in the RCA mix (i.e. reactive coarse OVA or reactive residual sand).

4.3.4. Microscopic assessment of damage in ASR-affected RCA concrete

Damage is attributed to crack formation (i.e. initiation and propagation) which in turn have a negative effect on concrete's hardened performance. However, very few research has been conducted on the crack development and gel formation of ASR-affected RCA concrete. Some authors have observed ASR-gel linking RCA particles [20] along with the presence of ASR-gel bearing various morphologies at the RCA new-mortar (NM) interface [14]. Additionally, reaction rims surrounding RCA particles with increased thicknesses for higher alkali contents were also observed [21]. Yet, the development of induced cracks was not studied nor correlated with expansion over these works.

Although the Damage Rating Index (DRI), a semi-quantitative microscopic procedure, has barely been performed on RCA concrete, promising results were obtained through the use of DRI on assessing ASR damaged in CC, where generally the given DRI number increases as the expansion level raises; therefore, the obtained DRI number can estimate the damage degree (i.e. expansion level) achieved by the affected CC (Table 1) as determined by Sanchez et al. [11]. As such, the DRI might serve as an effective microscopic protocol to evaluate secondary ASR-induced expansion and damage in RCA concrete.

The DRI consists of counting the number of distinct distress features associated with ASR through 1 by 1 cm squares drawn on the surface of polished concrete sections using a stereomicroscope at 16x magnification [4,13]. A weighing factor, as proposed by Villeneuve [22], is then applied to each of the distress features observed in order to balance their relative importance (i.e. location of crack) towards an overall damage score; the resulting value is then normalized to 100 cm^2 for statistical significance. Samples prepared in a laboratory environment required 100 cm^2 to be statistically significant whereas 200 cm^2 is required for field samples. Using the DRI along with supplementary petrographic analyses proposed by Sanchez et al. [4,13] in which the microscopic distress features are counted in a relative (%) and absolute (counts) manner without applying any weighing factors, was verified to precisely appraise the damage degree of an ASR-affected concrete, enabling the understanding of ASR-induced damage (crack formation and propagation) development in the affected material.

4.4. Scope of the work

As previously discussed in the above sections, there are currently a number of inconsistencies in the literature regarding the potential for secondary induced expansion and damage of ASR-affected RCA concrete. This lack of understanding is even more pronounced whether the reactive

RCA particle is comprised of distinct reactive aggregate types (i.e. reactive OVA vs. reactive sand within the RM). Therefore, this work aims to use and adopt the DRI method to evaluate the microscopic differences of ASR-induced expansion and damage development of RCA concrete mixtures made of a highly reactive coarse and fine aggregates, both of which derived from two distinct conditions: a) slightly damaged (i.e. 0.05% of expansion) representing a returned concrete, and b) a severely damaged (i.e. 0.30% of expansion) representing a demolished concrete. Comparisons on the type and extent of damage of CC and RCA concrete at various expansion levels (i.e. 0%, 0.05%, 0.12%, and 0.20%) are then performed.

4.5. Materials and methods

4.5.1. Materials and mixture proportions

All of the RCA particles and RCA concrete specimens (100 mm by 200 mm cylinders) were produced in the laboratory. Four different types of RCA were manufactured: 1 and 2) RCA made from a highly reactive coarse aggregate (i.e. Springhill) at a slightly damaged (i.e. 0.05%) and severely damaged (i.e. 0.30%) degrees, and 3 and 4) RCA made from a highly reactive sand (i.e. Texas) at a slightly damaged (i.e. 0.05%) and severely damaged (i.e. 0.30%) degrees. The Springhill coarse aggregate was combined with a non-reactive local sand (i.e. OS) and the Texas sand was combined with a non-reactive local limestone (i.e. LS) to mix-proportion ASR-affected conventional concrete (CC) used to produce the RCA particles. The characteristics of those aggregates are listed in Table 4.1.

Table 4.1: Natural aggregates and RCA used in this study.

Aggregate	Location	Rock type	Specific gravity	Absorption (%)
Reactive coarse (Springhill - SPR)	Fredericton, New Brunswick (Canada)	Greywacke	2.71	0.70
Non-reactive coarse (Limestone – LS)	Ottawa, Ontario (Canada)	Limestone derived from quarry	2.78	0.42
Reactive fine (Texas – TX)	El Paso, Texas (USA)	Polymictic sand (granites, mixed volcanics, quartzite, chert, quartz) [4]	2.60	0.89
Non-reactive fine (Ottawa sand – OS)	Ottawa, Ontario (Canada)	Derived from granite	2.60	0.82

A conventional PC (CSA Type GU, ASTM type 1) containing a high alkali content (0.91% Na2Oeq) was used in the CC mixtures. Once manufactured, the CC specimens were stored in conditions enabling ASR-induced development (i.e. 38°C and 100% RH) and their length change was monitored over time. Upon reaching the targeted 0.05% and 0.30% expansion levels, the CC samples were removed from the storage conditions and jaw crushed to produce RCA particles. The recycled particles were then used as coarse aggregates to proportion RCA mixtures. All of the RCA particles, ranging from 4.75 mm to 19.5 mm in size (i.e. coarse fractions), were then combined with the same non-reactive sand to produce RCA concrete. A white PC (CSA Type GU), containing an alkali content of 0.31% Na_2O_{eq}, was used in the RCA concrete mixture to better distinguish the cracks in the RCP and new cement paste (NCP). Reagent grade sodium hydroxide pellets were used to raise the total alkali content to 1.25% Na_2O_{eq}, by cement mass, to accelerate the ASR development for both CC and RCA concrete mixtures. The CC mixtures were identically proportioned using the Concrete Prism Test (CPT) [23] mix-proportions. The RCA concrete mixtures were then mix-designed by the Equivalent Volume (EV) method as per Ahimoghadam et al. [24] while following also the CPT mixture proportions. The EV is based on the assumption that the RCA mix displays the same amount of aggregates (i.e. fine and coarse) and cement paste (i.e. residual and new) in volume when compared to a companion conventional concrete. This method enables the proportioning of RCA concrete incorporating 100% RCA particles with suitable performance in the fresh and hardened states [2]. The mixture proportions of each type of RCA concrete as well as the CC to create the RCA particles are shown in Table 4.2.

Table 4.2: Concrete mixture proportions.

Ingredients	Springhill CC	Texas CC	Slightly damaged Springhill RCA-concrete	Severely damaged Springhill RCA-concrete	Slightly damaged Texas RCA-concrete	Severely damaged Texas RCA-concrete
Cement (kg/m^3)	420	420	340	331	336	335
Sand (kg/m^3)	823	760	774	791	648	645
Coarse aggregate (kg/m^3)	934	1024	1040	1048	1177	1177
Water (kg/m^3)	189	189	153	149	151	151
RMC (%)*			46	51.5	44.5	45

*Note that the residual mortar content (RMC) differed for both RCA mixtures which consequently influenced their mix proportions. The RMC was determined using the method proposed by [24] where the particles are subjected to chemical and mechanical stresses to detach the RM from the OVA.

4.5.2. Manufacture of concrete specimens

A total 120 recycled concrete specimens (i.e. 30 per RCA type) and 30 CC test specimens (i.e. 15 per aggregate type) were manufactured and demoulded 24 hours following their fabrication. The specimens were then moist cured at room temperature (i.e. 20°C) for another 24 hours before small holes, 8.5 mm in diameter and 19 mm long, were drilled on the ends of the CC and RCA concrete specimens. Stainless steel gauge studs were then glued using a fast-setting cement paste slurry for longitudinal expansion measurements and left to moist cure at room temperature for an additional 24 hours after which the initial readings were recorded. The RCA concrete specimens were then stored in the same previously mentioned conditions enabling ASR-induced development and the length change was monitored over time.

4.5.3. Experimental procedures

Microscopic characterization such as the microscopic distress features and DRI were performed using a stereomicroscope at 16x magnification on ASR-affected CC and RCA concrete specimens at various expansion levels for the four types of RCA concrete mixtures (i.e. 0%, 0.05%, 0.12%, and 0.20%) and two CC mixtures (i.e. 0%, 0.05%, 0.12%, 0.20% and 0.30%) to characterize the RCA and evaluate the crack generation and propagation. Note that these test procedures were expansion based as opposed to time based therefore, the samples used to microscopically evaluate ASR were analysed upon reaching said expansion. The maximum lengths and widths of cracks were also measured manually using a clear comparator card. The specimens were firstly cut in half longitudinally using a masonry saw with a diamond blade, followed by successive polishing using a mechanical polishing table with grits of 30, 60, 140, 280 (80-100 microns), 600

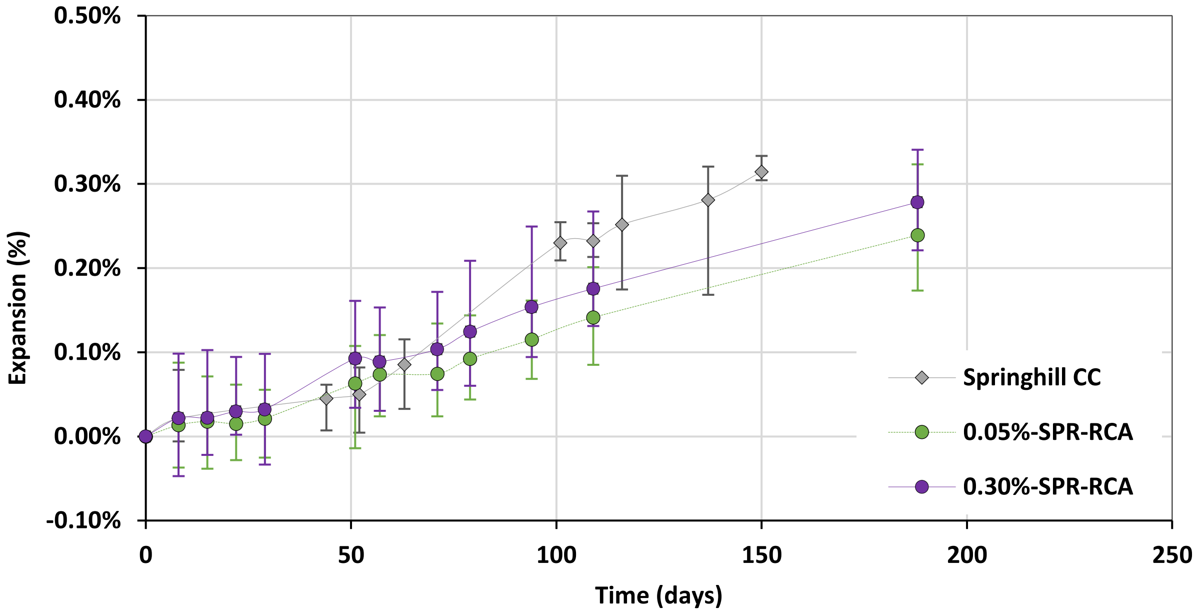
(20-40 microns), 1200 (10-20 microns) and 3000 (4-8 microns). Once the reflective surface was achieved, 1 cm by 1 cm grid was drawn on the polished surface prior to evaluation.

4.6. Results

4.6.1. ASR kinetics and development in RCA-concrete

The average expansions (i.e. average expansion levels achieved for the concrete specimens tested at a given age and the standard deviations are shown in Appendix A) as a function of time of ASR-affected CC and RCA concrete specimens incorporating a reactive coarse aggregate (i.e. Springhill) and reactive sand (i.e. Texas) are presented in Figure 4.2a and Figure 4.2b, respectively. Noticeably, the Springhill CC and Springhill RCA mixtures are generally similar (although present a lower ultimate expansion than the CC mix) throughout all expansion levels evaluated, whereas the level of expansion reached for the CC mixtures made of Texas is significantly higher than the two Texas RCA mixtures. Generally the Springhill RCA mixtures follow a parallel trend reaching 0.24% and 0.28% of expansion at 188 days for the slightly (i.e. 0.05%-SPR-RCA) and severely (i.e. 0.30%-SPR-RCA) damaged recycled mixtures, respectively. Moreover, the severely damaged Texas RCA concrete (i.e. 0.30%-TX-RCA) experiences a delay in expansion after which it increases to 0.19% at 115 days followed by an average expansion level of 0.26% at 224 days. On the other hand, the slightly damaged Texas RCA concrete (i.e. 0.05%-TX-RCA) does not experience any delay but rather increases at a constant rate and reaches an average expansion level of 0.21% at 180 days without any decrease in the rate of expansion. In addition, the same trend is observed for both aggregate types where the severely damaged RCA mixtures present somewhat higher overall expansion levels than the slightly damaged RCA mixtures when considering the upper data range bars. Furthermore, one notices that the overall expansion reached by the recycled mixtures at 180 days is similar ranging from 0.21% to 0.27% of expansion. Nevertheless, the CC expansion data reveals the variability of the used aggregates (i.e. Texas and Springhill) which is repeated when used in recycled mixtures. This variability in the expansion levels achieved per sample (captured by the data range bars) is due to the variable amount of reactive silica contained within the aggregate particles.

a) CC and slightly/ severely damaged RCA concretes made with reactive Springhill coarse aggregate



b) CC and slightly/ severely damaged RCA concretes made with reactive Texas sand

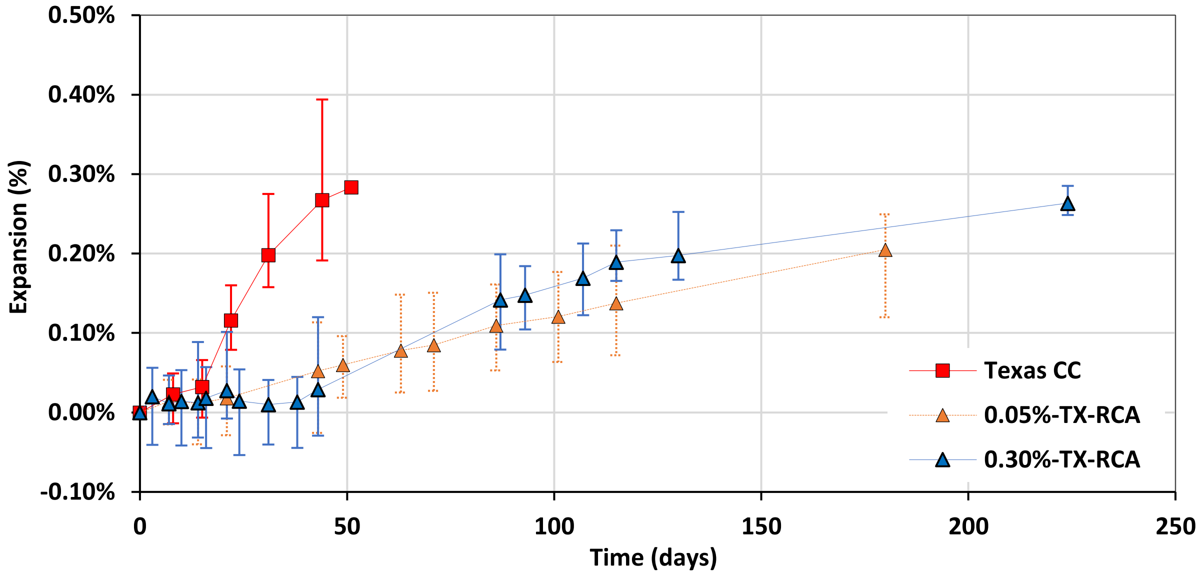


Figure 4.2: Expansion as a function of time for CC and RCA concrete made with a) Reactive coarse aggregate and b) Reactive sand.

4.6.2. Distress in CC and RCA concrete subjected to secondary damage

The ASR microscopic distress features for all concrete mixtures as a function of expansion were evaluated using the extended version of the DRI as per [4,13] analyses in an absolute (i.e. counts, normalized to 100 cm^2) and relative (%) manner as shown in Figure 4.3 for the CC and Figure 4.4 for the RCA concrete mixtures. Without the application of the weighing factors used in the DRI, the distribution of new cracks in the RCA mixtures is assessed herein to better understand the crack development (i.e. initiation and propagation) in recycled mixtures compared to that of CC. As such, the Closed cracks in the aggregates (i.e. CCA), the Open cracks in the aggregates without and with gel (i.e. OCA+OCAG) and the Cracks in the cement paste without and with gel (i.e. CCP+CCPG) will be grouped accordingly. In addition, to accommodate the multi-phase nature of the RCA particle, the Cracks in the cement paste will be divided into new and residual cement paste (i.e. NCP and RCP, respectively).

Figure 4.3 shows the microscopic features as counts per 100 cm^2 (Figure 4.3a) and percentage (Figure 4.3b) for the Springhill and Texas CC where some minor differences are seen yet, the overall counts of microscopic features are quite similar. However, compared to the RCA concrete mixtures (Figure 4.4a), it is evident that cracks were lost during "RCA fabrication" (i.e. crushing process) since the number of counts is larger for both CC mixes. As for the percentage of microscopic features shown in Figure 4.3b, in both CC mixes the proportion of Closed cracks in the aggregates decreases from 87% for the Springhill CC and 85% for Texas CC while the proportion of Open cracks in the aggregates and Cracks in the cement paste increases as expansion increases. An exception is however seen at 0.05% expansion in Texas CC showing an increase in Closed cracks in the aggregates which indicates the formation of new cracks at early stages from 0% to 0.05% followed by a more important increase in Open cracks in the aggregates thus, overcoming the formation of new cracks as was previously determined by Sanchez et al. [4]. Yet, the behavior between the CC mixes differ where the proportions in the Springhill CC stabilize after 0.12% where approximately 50% of the cracks are Closed cracks in the aggregates, 40% Open cracks in the aggregates and 10% Cracks in the cement paste. On the other hand, for the Texas CC a constant increase in the proportion of Open cracks in the aggregates and Cracks in the cement paste is observed as expansion increases reaching approximately 60% of closed cracks in the aggregates and 25% for open cracks in the aggregate and 15% for cracks in the cement paste at 0.30% of expansion.

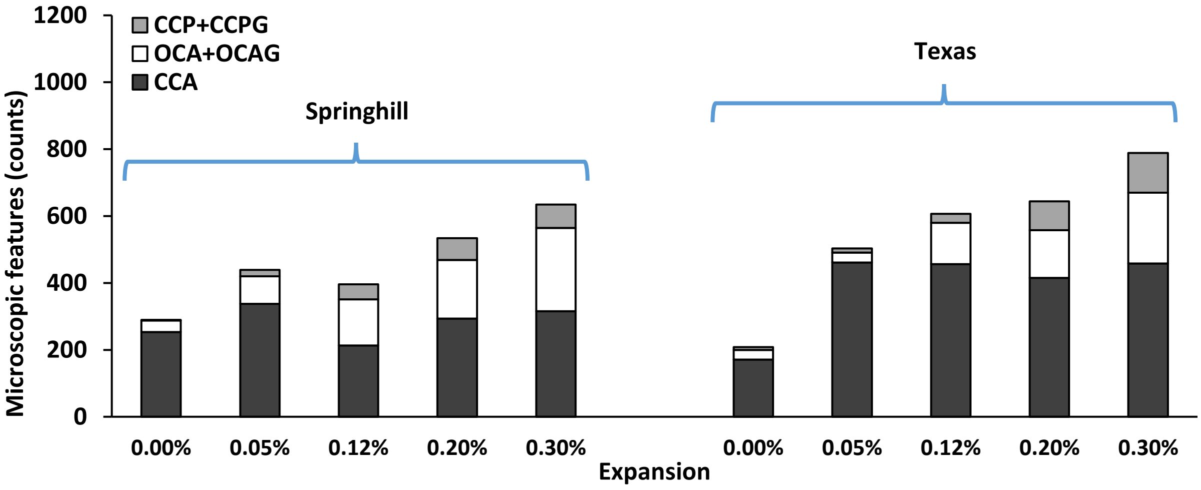


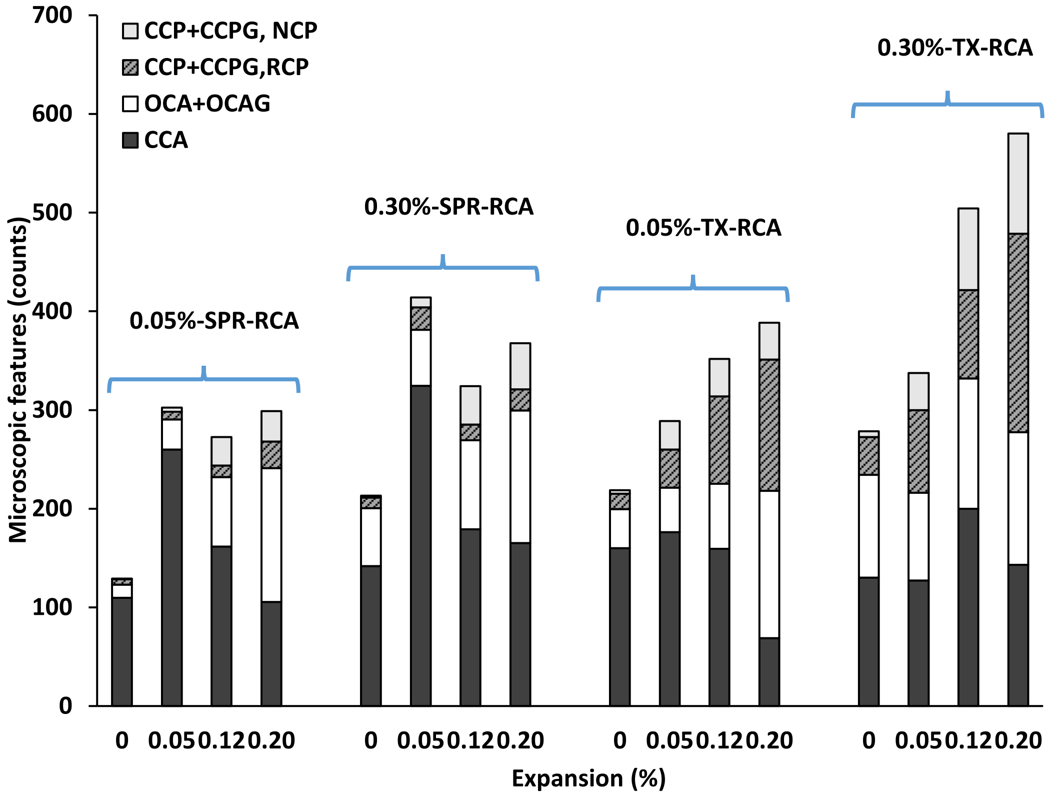
Figure 4.3: Microscopic features of CC shown as counts per 100 cm^2.

As for the counts in microscopic features in the RCA concrete (Figure 4.4a), a general trend of increasing number of cracks as expansion increases is observed. The counts are similar for all RCA mixtures with the exception of the severely damaged Texas RCA concrete having a significantly higher count. Both severely damaged RCA concrete mixtures also present higher counts than the slightly damaged mixtures for the same expansion level. The trends for the Springhill RCA concrete mixtures show a more important increase in the Open cracks in the aggregates (i.e. OCA + OCAG) while the Cracks in the cement paste (i.e. CCP and CCPG – RCP and NCP) increase slightly with expansion. The severely damaged Springhill RCA concrete however, shows a higher increase in cracks in the NCP while both the slightly and severely damaged Springhill RCA mixtures show relatively the same increase in Open cracks in the aggregates (OCA + OCAG). Moreover, the counts of CCA in the Springhill RCA concrete increase only from 0% to 0.05% of expansion yet, do not increase as a function of expansion beyond 0.05% of expansion, as expected because this does not come from ASR-development [4,13]; however, more CCA are seen in the severely damaged Springhill RCA as opposed to the slightly damaged mixture. As for the Texas RCA mixtures, the most apparent distress features are cracks in the RCP followed by cracks in the NCP, both of which are greatest in the severely damaged Texas RCA concrete. The cracks in the aggregates however remain fairly constant for each expansion level and even between both Texas RCA mixtures.

The percentage of microscopic features presented in Figure 4.4b shows that the most prominent distress features (leading the overall damage) of the Springhill RCA concrete mixtures are the open cracks in the aggregates (OCA + OCAG) as opposed to the Texas RCA mixtures which are the cracks in the cement paste (i.e. CCP and CCPG - RCP and NCP) due to its larger and increasing proportion. The distress mechanism of RCA concrete mixtures not only differ from one another but also from that of CC mixtures (Figure 4.3b). In the Springhill RCA concrete mixtures, unlike the stabilization observed in the Springhill CC, the proportion of closed cracks in the aggregates decreases as expansion increases indicating that they are being overcome by open cracks in the aggregates. However, in the severely damaged Springhill RCA concrete, an increase in the proportion of closed cracks in the aggregates in seen at 0.05% of expansion, which may be associated to the formation of new cracks despite the original extent of damage of this particular RCA concrete [5]. Moreover, the Texas RCA concrete mixtures show the largest differences compared to the Texas CC with a significantly smaller proportion of closed cracks in the aggregate and larger proportion of open cracks in the aggregate and cracks in the cement paste, more specifically the RCP, per expansion level.

Figure 4.5 illustrates the crack density (CD), represented by the summation of the number of open cracks in the aggregates and cement paste (both with and without reaction products) counted and normalized per square centimeter. All concrete mixtures begin with a CD between 0 counts/cm^2 to 0.60 counts/cm^2, except for the severely damaged Texas RCA concrete starting at 1.50 counts/cm^2, after which they increase almost linearly with the exception of the slightly damaged Springhill RCA concrete. The CC mixtures, both reaching 2.3 counts/cm^2 at 0.20% of expansion, are situated in between the RCA concrete mixtures. The Texas RCA has the highest CD (i.e. 3.2 counts/cm^2 and 4.4 counts/cm^2, for the slightly and severely damaged mixtures, respectively) and the Springhill RCA has the lowest CD of 1.21 counts/cm^2 at 0.20% of expansion for both slightly and severely damaged mixtures. As was the case for the counts of microscopic features, the CC mixes follow similar trends as do the severely and slightly damaged RCA concrete mixtures. Although most mixtures are generally parallel, the slightly damaged Springhill RCA concrete begins to reach the CD of the severely damaged Springhill RCA concrete at 0.12% of expansion.

a) Counts of microscopic features of RCA-concrete



b) Percentage of microscopic features of RCA-concrete

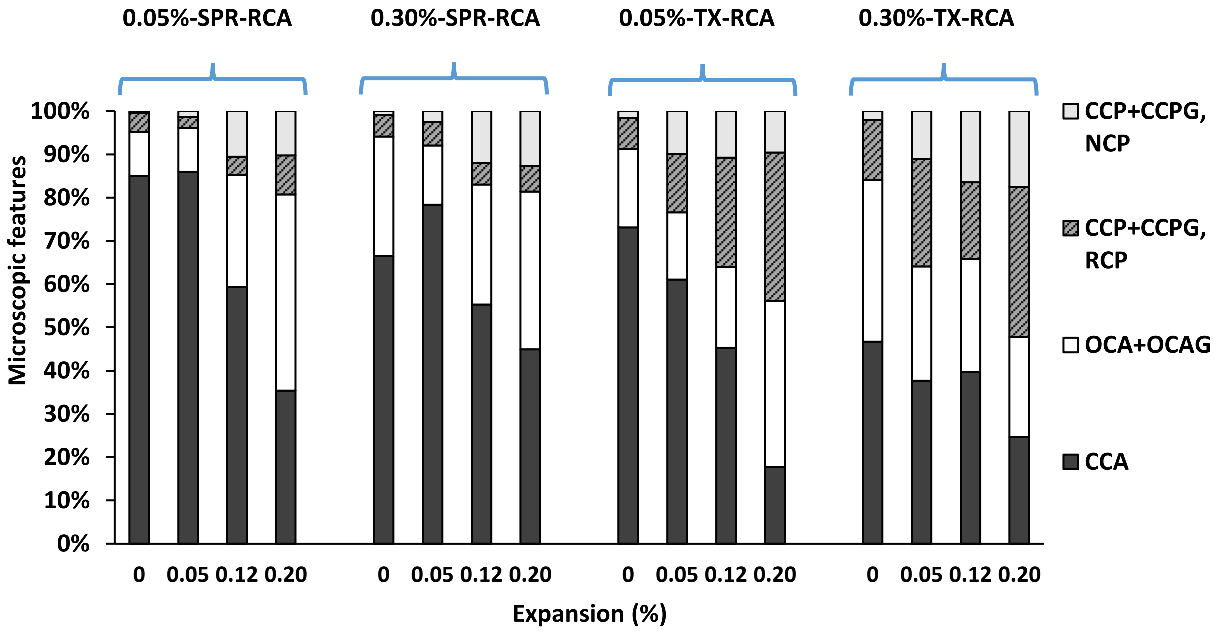


Figure 4.4: Microscopic features of RCA concretes shown as: a) Counts per 100 cm^2 and b) Percentage.

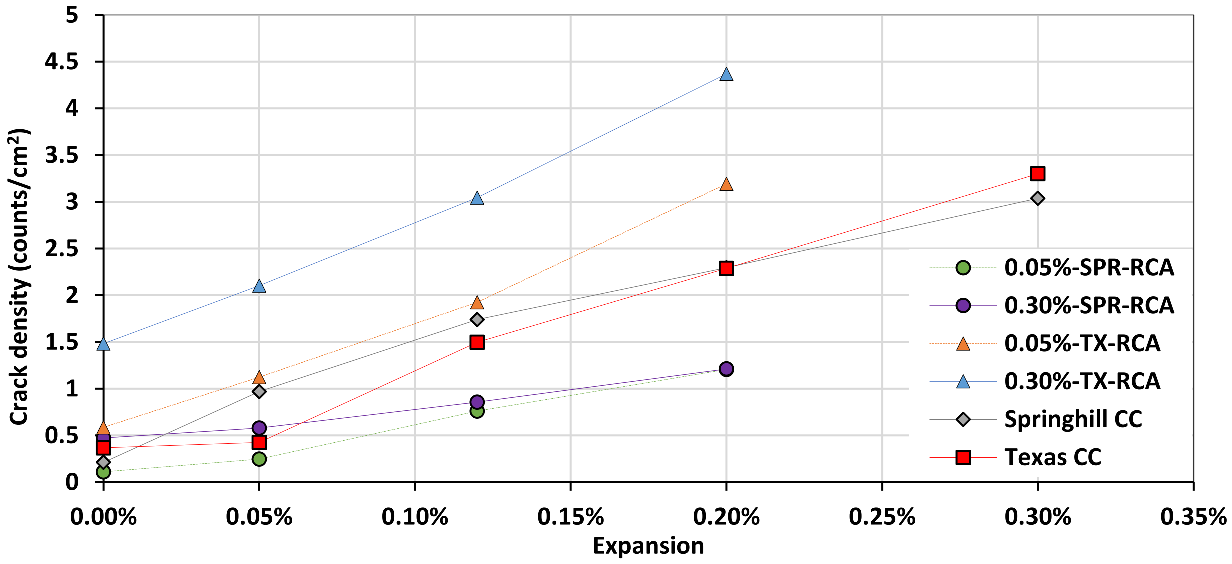


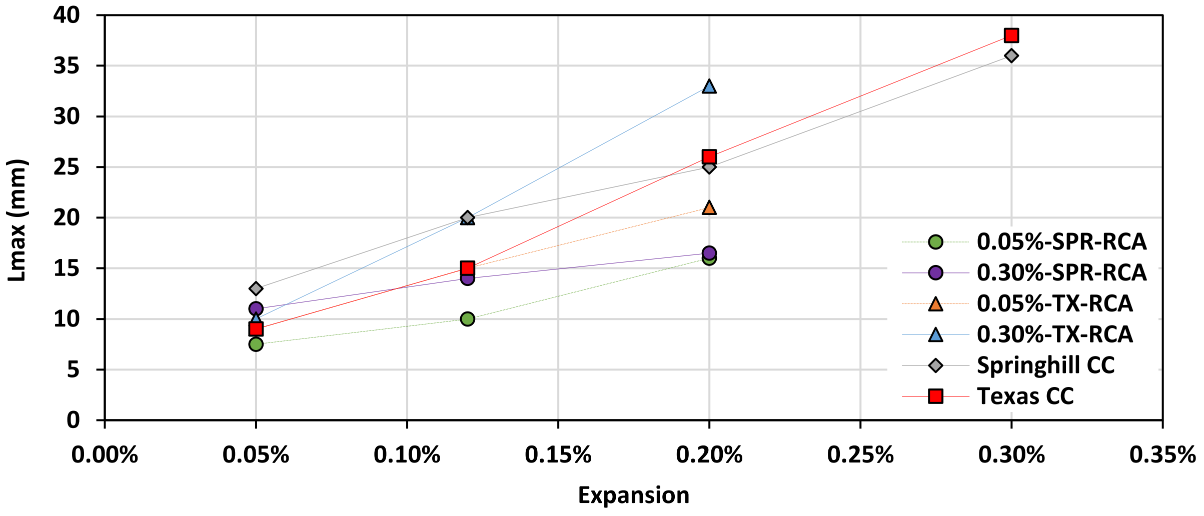
Figure 4.5: Crack density as a function of expansion for CC and RCA concretes.

4.6.3. Crack length and width

The maximum crack length, presented in Figure 4.6a, increases with expansion for each of the concrete mixtures. The Springhill CC has the highest crack length of 13 mm at 0.05% of expansion while the Texas CC is of 9 mm. At 0.20% of expansion, both CC seem to merge towards each other with crack lengths of 25 mm for the Springhill CC and 26 mm for the Texas CC. The slightly damaged RCA concrete mixtures however have lower overall crack lengths (i.e. 7.5 mm for the Springhill RCA and 9 mm for the Texas RCA at 0.05% of expansion) compared to the severely damaged mixtures (i.e. 10 mm for the Springhill RCA and 13 mm for the Texas RCA at 0.05% of expansion). Moreover, the RCA mixtures are somewhat parallel to each other from 0.05% to 0.12% of expansion yet, at 0.20%, the crack length of the slightly damaged Springhill RCA concrete increases and reaches almost the same crack length as the severely damaged Springhill RCA concrete (i.e. 16 mm and 16.5 mm, respectively). Likewise, the longest crack achieved at 0.20% is of 33 mm for the severely damaged Texas RCA concrete followed by the slightly damaged Texas RCA concrete at 21 mm.

Furthermore, the crack widths increase for each of the concrete mixtures as expansion increases (Figure 4.6b). The Springhill CC sees a constant increase from 0.10 mm at 0.05% of expansion until 0.20% of expansion where the cracks no longer widen (i.e. 0.20 mm). On the other hand, the Texas CC presents a gradual increase from 0.10 mm at 0.05% of expansion to 0.25 mm at 0.30% of expansion. As for the RCA mixtures, the crack widths for each RCA concrete is 0.15 mm at 0.05% and 0.12%, after which an increase is seen at 0.20% reaching 0.20 mm for both severely damaged RCA mixtures, whereas 0.25 mm is reached by the slightly damaged RCA concrete.

a) Maximum crack lengths per expansion for each RCA concrete



b) Maximum crack width per expansion for each RCA concrete

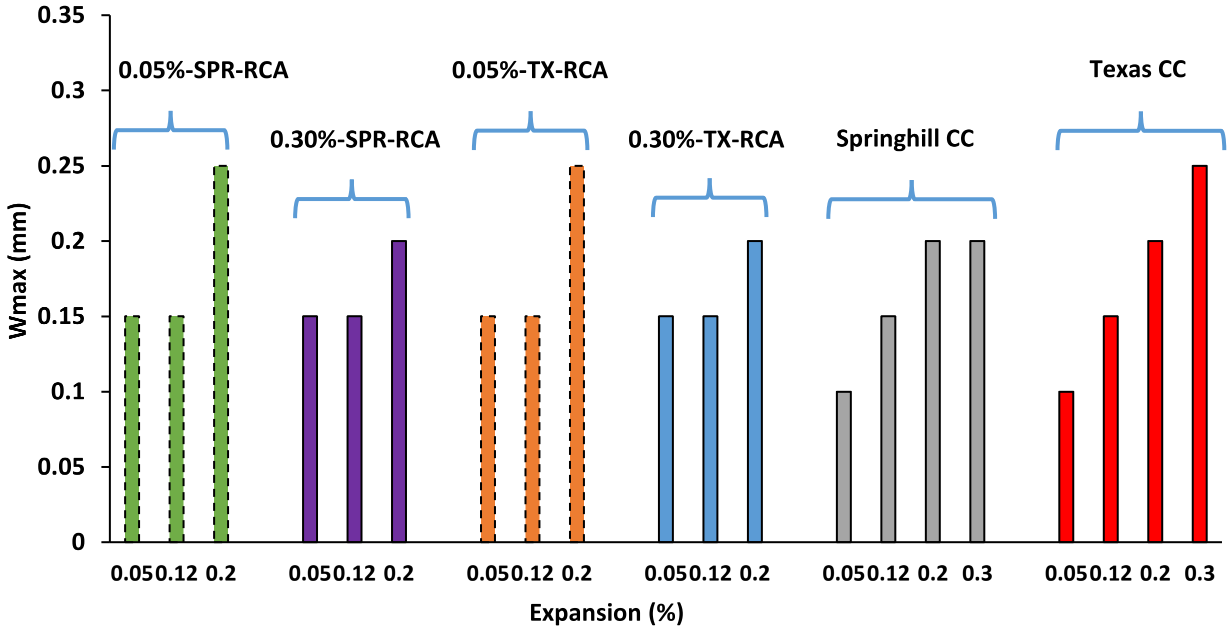


Figure 4.6: Maximum crack length and width of RCA-concrete.

4.6.4. Quantitative assessments of damage

The Damage Rating Index (DRI) number as a function of the expansion level was plotted in Figure 4.7 which also includes the DRI numbers obtained from ASR-affected Springhill and Texas CC. At 0% of expansion, all of the concrete mixtures present a DRI value of under 200 except for the severely damaged Texas RCA having a DRI number of 373. The DRI numbers increase with the expansion level almost in parallel and the order of magnitude follows the same trend as that of the CD. At 0.20% of expansion, the slightly and severely damaged Springhill RCA mixtures reach a DRI value of 470 and 514, respectively, while both CC have similar DRI values (i.e. 621 for the Springhill and 675 for the Texas CC). The Texas RCA mixtures on the other hand present higher DRI values at 0.20% of expansion of 826 and 1213 for the slightly and severely damaged mixtures, respectively. Additionally, the difference between the overall DRI value per expansion is significantly larger between the Texas RCA concretes than for the Springhill RCA. Noticeably, at 0.20% of expansion the slightly damaged Springhill RCA concrete almost reaches the DRI value of the severely damaged Springhill RCA concrete as was seen through the CD (Figure 5) and maximum crack lengths (Figure 6a).

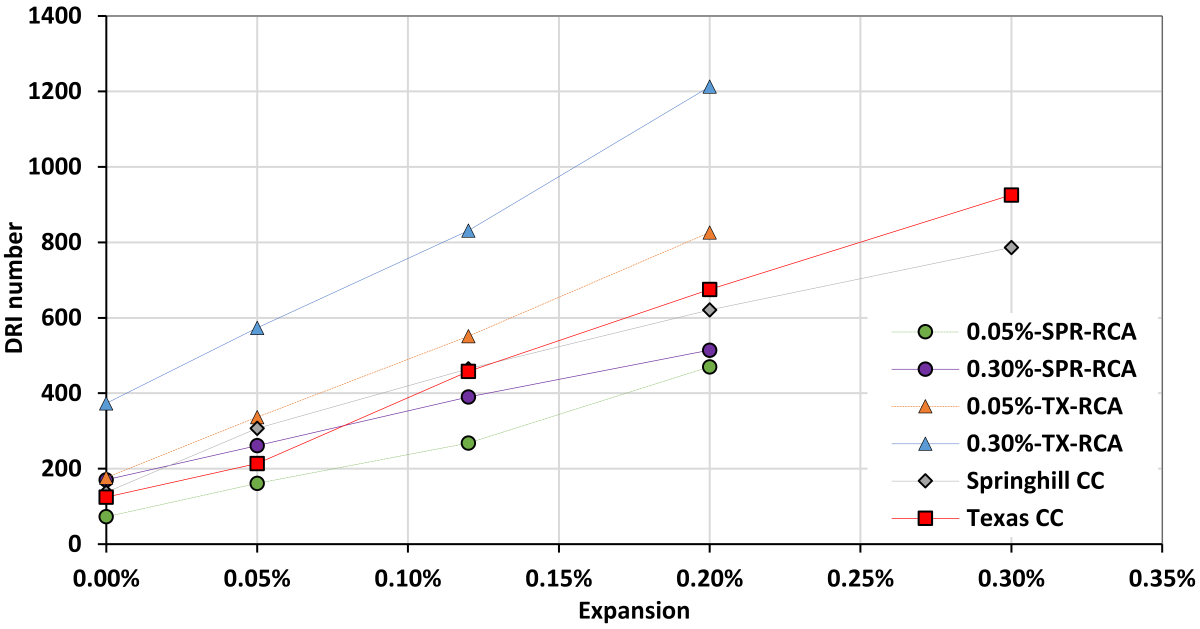


Figure 4.7: DRI number as a function of expansion for CC and RCA concrete.

The DRI chart which includes the distribution of cracks with respect to the distress feature and location was also performed on the RCA concrete to quantify ASR-induced distress and obtain a general idea of the crack generation and propagation within the concrete (Figure 8). Although the DRI values for all of the RCA concrete mixtures increases with expansion, it is evident that the greatest increase between expansion levels is with the Texas RCA concrete where the increase is seen almost exclusively in the cement paste (i.e. RCP and NCP). Evidently, the DRI values are higher for the severely damaged RCA concrete mixtures compared to the slightly damaged mixtures where the difference is most significant in the Texas RCA and prior to 0.20% for the Springhill RCA. A constant increase in Open cracks in the aggregates without and with gel (OCA, OVA and OCAG, OVA) and NCP are observed in the Springhill RCA mixtures as well as a slightly increase in the RCP. On the other hand, there is no increase in closed and open cracks in the aggregates in the Texas RCA concrete mixtures except for the slightly damaged Texas RCA at 0.20% of expansion.

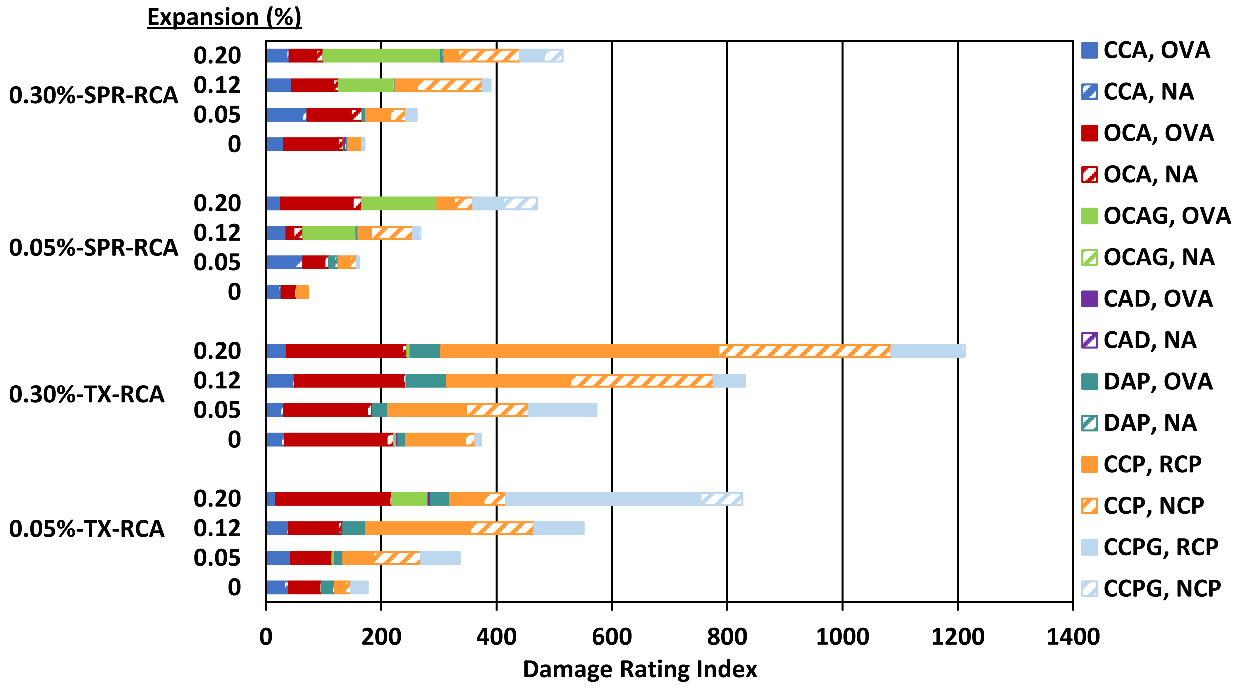


Figure 4.8: Damage Rating Index for the RCA-concretes.

4.7. Discussion

4.7.1. ASR-induced secondary expansion in RCA-concrete

The average expansion as a function of time of the RCA concrete mixtures made with reactive coarse aggregate resembles that of its companion CC while the expansion is significantly lower than its companion for the RCA concrete mixtures made with reactive fine aggregate, indicating a difference between RCA made from a reactive coarse versus reactive fine aggregate. On the other hand, when comparing the expansion levels reached at a certain given time for each of the recycled mixtures, the results are similar with the severely damaged mixtures being slightly higher than the slightly damaged RCA concrete mixtures (after the delay in the case of the RCA made with reactive sand) which is attributed to the abundance of cracks preserved in the RCA particles thus, being comprised of more “open” reactive sites although the opposite could have been expected due to the extent of damage and depletion of reactants (i.e. silica and alkali content) in the severely damaged RCA mixtures. Nonetheless, the potential for further secondary expansion (i.e. expansion experienced by the RCA) exists despite the original damage extent provided that reactants remain in the concrete. Yet, the effect of the remaining reactants in RCA concrete on the expansion is captured by the recycled mixtures made with reactive fine aggregate where the severely damaged recycled mixture begins to flatten after 115 days while the slightly damaged mixture continues to increase in expansion. Meanwhile the recycled mixtures made with reactive coarse aggregate do not show any flattening of the expansion as a function of time curve which demonstrates the difference in behaviour of recycled concrete made with reactive fine or coarse aggregate.

Additionally, based on the mixture proportions for the RCA concrete used in this study [2], the RCA concrete mixtures made with reactive coarse aggregate have a slightly smaller amount of reactive coarse aggregate, as it is embedded in the RCA particle, than the CC thus, their expansion levels generally follow the same trend. On the other hand, the same amount of reactive fine aggregate was not conserved for RCA concrete mixtures made with reactive fine aggregate since the reactive residual sand is only present in the RM while the sand in the NM is non-reactive hence, the proportion of total reactive sand in such RCA concrete is much lower than that of the CC made with reactive fine aggregate. Therefore, the lower expansion levels achieved by the RCA concrete mixtures made with reactive fine aggregate compared to its companion CC may be attributed to the smaller amount of reactive sand particles within that RCA concrete. Etxeberria and Vázquez also observed a lower achieved level of expansion when the entire RCA particle being composed of reactive RM and the non-reactive coarse OVA was used as opposed to only using the RM (i.e. removing the non-reactive OVA) [14]. Therefore, without considering a pessimum proportion, less expansion may be achieved when less of the reactive residual sand is incorporated into the mixture.

Noticeably, the severely damaged RCA concrete made with reactive sand exhibits a delay in the expansion which is not observed in any of the other RCA concrete mixtures. A delay was also seen in a previous study by Gottfredsen and Thøgersen [7] using a coarse RCA made from demolished concrete with ongoing ASR induced by a reactive sand where the expansion initiated only after a 12 week delay; yet, the reason for the delay was not addressed. During the delay in this current study however, the slightly damaged RCA concrete made with reactive sand increased its expansion at a constant rate. As such, the delay in expansion for the severely damaged RCA concrete made with reactive sand, having a lower alkali content due to the extent of the original reaction/damage, may be attributed to a sort of "barrier effect" shielding the reactive sand particles within the RCP from the new source of alkalis in the NCP until the new alkalis reach the reactive sand particles which would not be apparent in a slightly damaged RCA. Although a delay in expansion was not observed nor was the extent of damage known in the study performed by Ideker et al., the difference in the distress mechanism was also attributed to this barrier effect [9]. Therefore, the kinetic behavior of RCA concrete where ASR is induced by a reactive coarse aggregate is more similar to its companion CC and may be slightly decreased because of the slightly smaller proportion of reactive OVA while on the other hand, the behavior of RCA concrete in which ASR is induced by a reactive sand presents a distinct behavior compared to that of its CC due to the multi-phase nature of the RCA particle resulting in a lesser amount of reactive component and the so-called barrier effect.

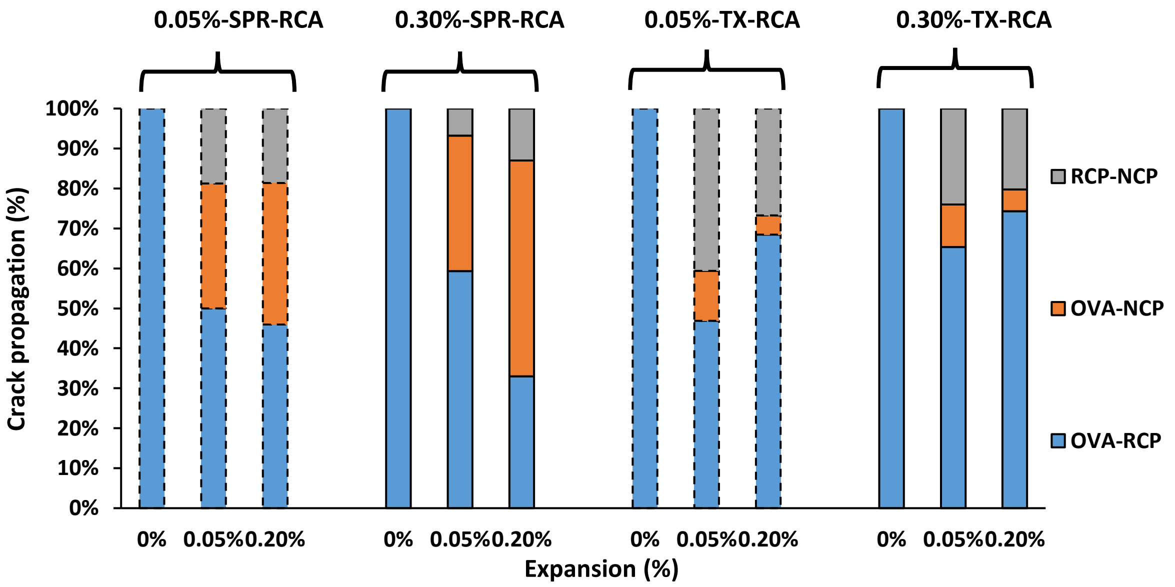
4.7.2. Identifying secondary damaged in RCA concrete

Secondary damage is captured by the propagation of cracks in RCA concrete and is therefore characterized as damage experienced by the RCA concrete where its source concrete had already been subjected to past deterioration due to ASR (i.e. primary damage). Secondary damage may initiate from cracks previously induced by ASR, unreacted sites in the reactive OVA/residual sand previously formed by weathering and processing, or newly formed RCA processing cracks; all of which may induce further damage provided that available reactive silica remains within these sites. Moreover, it was previously found that a severely damaged RCA concrete made with reactive coarse aggregate may present a combination of ongoing ASR and newly formed ASR as secondary damage [5]. As such, the crack generation and propagation resulting from secondary damage can therefore be characterized by three distinct types of cracks within the RCA concrete: 1) cracks generated in the reactive OVA or reactive residual sand and extending into the RCP before reaching the NCP (OVA-RCP); 2) cracks generated in the reactive OVA or reactive residual sand extending directly into the NCP (OVA-NCP) and; 3) cracks generated in the RCP extending into the NCP (RCP-NCP). The latter is likely associated to the elongation of cracks generated in the reactive OVA or reactive residual sand. Figure 9 shows the percentages of the distinct crack types (i.e. % of counts, disregarding the DRI weighing factors) for all RCA concrete mixtures prior to being subjected to secondary expansion (i.e. 0%) and at 0.05% and 0.20% of secondary expansion. This analysis is intended to help in the overall understanding of induced secondary damage of ASR-affected RCA concrete displaying distinct past deteriorations and induced by either a reactive coarse or fine aggregate.

Prior to secondary induced expansion, the cracks propagating from the OVA to the RCP represent 100% of the petrographic distress features (Figure 4.9a). Yet, their counts per square centimeter vary significantly from 3 counts/cm^2 and 18 counts/cm^2 for the slightly and severely damaged RCA concrete made with reactive coarse aggregate, respectively, to 15 counts/cm^2 and 40 counts/cm^2 for the slightly and severely damaged RCA concrete made with reactive sand, respectively, as shown in Figure 4.9b. As the secondary expansion increases, the proportions of OVA-RCP cracks decrease in the recycled mixtures made with reactive coarse aggregate while they increase beyond 0.05% of expansion for the mixes made with reactive sand. Up to 0.20% of expansion however, the counts of OVA-RCP cracks increase for the slightly damaged RCA mixture made with reactive coarse aggregate (49 counts/cm^2) and for the slightly and severely damaged mixtures made with reactive fine aggregate (84 counts/cm^2 and 72 counts/cm^2, respectively) while no significant increase is observed in the severely damaged RCA concrete made with reactive coarse aggregate.

The proportions and counts of OVA-NCP cracks in the recycled concrete mixtures made with reactive sand are similar at each expansion level without increasing with expansion (5-6 counts/cm^2). Similarly, the proportions of OVA-NCP cracks in the slightly damaged RCA concrete made with reactive coarse aggregate are similar throughout the expansion levels yet, the counts per square centimeter increase from 3 counts/cm^2 to 38 counts/cm^2. On the other hand, the proportion of OVA-NCP cracks in the severely damaged RCA concrete made with reactive coarse aggregate increases as do the counts from 13 counts/cm^2 to 36 counts/cm^2, presenting a smaller increase. As for the RCP-NCP cracks, they continue to increase in counts as expansion increases yet, larger counts are observed in both of the slightly damaged mixtures.

a)



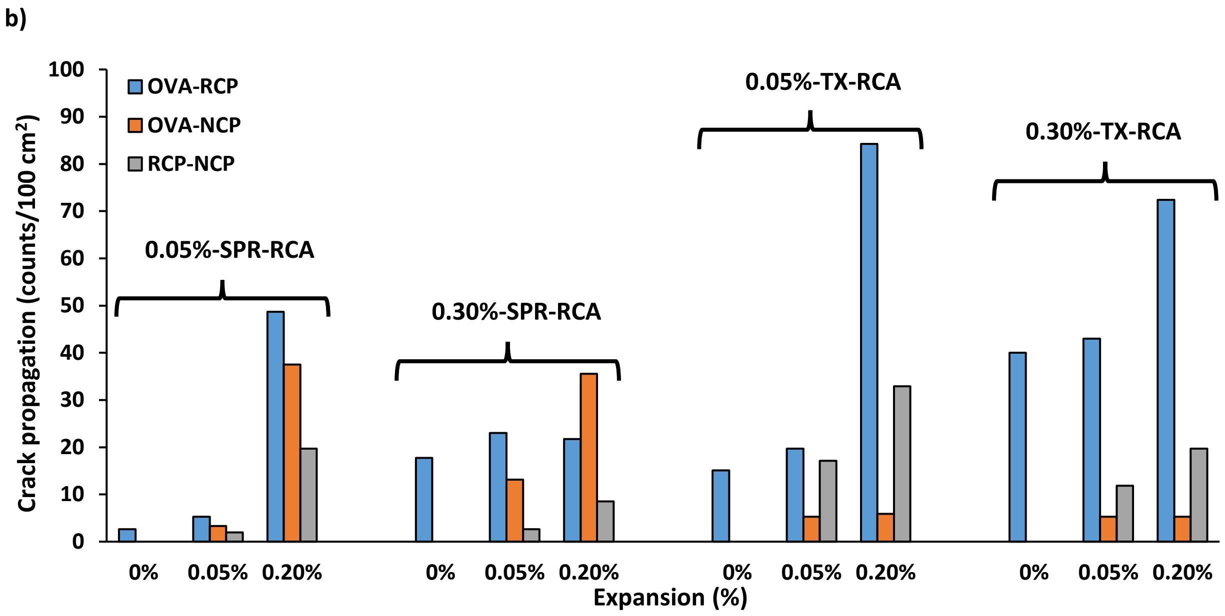


Figure 4.9: Crack propagation in recycled concrete mixtures as a) Percentage and b) Counts per cm^2.

The cracks in the slightly damaged RCA made with reactive coarse aggregate were initially contained within the OVA since it had only been subjected to slight damaged originally (i.e. 0.05% of expansion) and therefore are more likely to be oriented as to propagate into the cement paste (i.e. RCP once in RCA). As such, they continued to propagate into the OVA towards the RCP and eventually into the NCP. Meanwhile, the severely damaged RCA concrete made with reactive coarse aggregate mainly propagates its cracks from the OVA into the NCP which again suggests a newly formed ASR as opposed to ongoing ASR propagating from the RCP into the NCP. Given that, the potential of further induced expansion and damage in slightly/severely damaged RCA concrete made with reactive coarse aggregate is represented by OVA-RCP/OVA-NCP cracks, respectively. On the contrary, the counts of OVA-RCP cracks are predominant in the RCA mixtures made with reactive sand regardless of original extent of damage thus, the potential of further induced expansion and damage in slightly and severely damaged RCA concrete made with reactive sand is represented by cracks in the OVA-RCP. One may notice however that the proportions and more importantly the counts of RCP-NCP of the slightly damaged RCA made with reactive sand are higher than for the severely damaged RCA yet, both are without any increase in OVA-NCP. The difference between the RCP-NCP propagation cracks with regards to the original extents of damage once again suggests that the RCP creates a barrier effect in the severely damaged RCA mixture made with reactive sand shielding its inner reactive sand particles. As such, the alkalis in the NCP do not necessarily react with the reactive sand particles near the surface of the RCA particle due to the depletion of reactive silica at this original extent of damage (i.e. 0.30%) which would otherwise propagate OVA-NCP cracks but do reach the inner reactive sand particles resulting in cracks having to propagate from the inner portion of RCA particles as opposed to near the surface.

4.7.3. Crack characteristics in ASR damaged RCA concrete

Interestingly, even though the same expansion levels are achieved by the distinct CC and RCA mixes, the microscopic features (Figure 4.3 and Figure 4.4, respectively), the CD (Figure 4.5), the DRI values vary greatly (Figure 4.7) as well as the maximum crack lengths and widths (Figure 4.6). From the microscopic features of CC shown in Figure 4.3, it is clear that there are some differences between the CC made with a reactive coarse and reactive fine aggregate with respect to the expansion levels at which the RCA particles were produced where more open cracks in the aggregates and cracks in the cement paste are present (at similar counts in both CC) at 0.30% of expansion than at 0.05%. After crushing, the RCA made with reactive sand particles conserved the more cracks in the aggregates which may be due to the nature of the aggregate whereas the splitting of cracks in the reactive coarse OVA caused those cracks to reduce considerably. Nevertheless, the RCA crushing process reduced the total number of cracks significantly for each type of RCA particles. As expansion increases, the severely damaged RCA mixtures present the highest number of cracks compared to the slightly damaged RCA concrete mixtures which is attributed to the abundance of cracks preserved in the particles due to previous ASR damage followed by the minimum energy law where it takes less effort to propagate a crack than for it to initiate. Furthermore, when comparing the general trend in the crack lengths, both CC follow a more similar trend to one another than any of the RCA concrete mixtures where a larger difference is seen between each of the RCA mixtures. Moreover, the crack widths presented interesting results which clearly indicated that the distress mechanism is different between CC and RCA concrete as a gradual increase in the width is seen for both CC while a sudden increase is observed in the RCA concrete mixtures at 0.20% of expansion with wider cracks for both slightly damaged RCA mixtures at 0.25 mm as opposed to 0.20 mm for the severely damaged RCA mixtures.

When comparing the influence of the ASR damage origin (i.e. reactive sand or coarse aggregate) in RCA concrete, the most apparent difference between the RCA concrete made with a reactive coarse and a reactive fine aggregate is not only the counts of cracks and DRI values per expansion level but more importantly, the number of cracks that were preserved in the RCP of the RCA concrete made with reactive sand and its subsequent increase as expansion increases. In addition, although the severely damaged RCA concrete made with reactive sand is comprised of a more important network of cracks in the RCP, cracks in the RCP continue to increase. Furthermore, the cracks in the RCA concrete mixtures made with reactive sand are longer than the RCA concrete mixtures made with reactive coarse aggregate indicating that the characteristics of cracks generated in RCA concrete are influenced by the origin of damage (i.e. coming from the coarse or fine aggregate) and by the original damage extent since wider cracks are seen in the slightly damaged RCA concrete mixtures at 0.20% of expansion.

When evaluating the influence of the original extents of damage in the RCA concrete mixtures, the severely damaged RCA concrete shows a higher overall number of cracks. Yet, the slightly damaged RCA concrete made with coarse reactive aggregate shows a change in behaviour at mainly 0.20% of expansion in CD, the DRI as a function of expansion as well as the maximum crack length where it reaches those of the severely damaged RCA concrete. Consequently, the damage mechanism of the severely damaged RCA concrete made with reactive coarse aggregate could be associated to the minimum energy law in which the cracks continue to propagate at a constant rate whereas the slightly damaged RCA concrete propagates its cracks from a lesser number yet, is capable of achieving the same damage level as the severely damaged RCA concrete because of its higher remaining reactivity. Likewise, the RCA concrete mixtures made from reactive sand show that the severely damaged RCA concrete is considered as more damaged than the slightly damaged mixture however, there is no indication of a “catching-up” stage at later expansion levels. Therefore, the damage mechanism in both RCA concrete mixtures made with reactive sand may be due to the minimum energy law due to the abundance of pre-existing cracks in combination with remaining reactivity of all sand particles including unreacted sand particles without differentiating between the damage extents.

4.7.4. Qualitative models of crack propagation in ASR-affected RCA-concrete

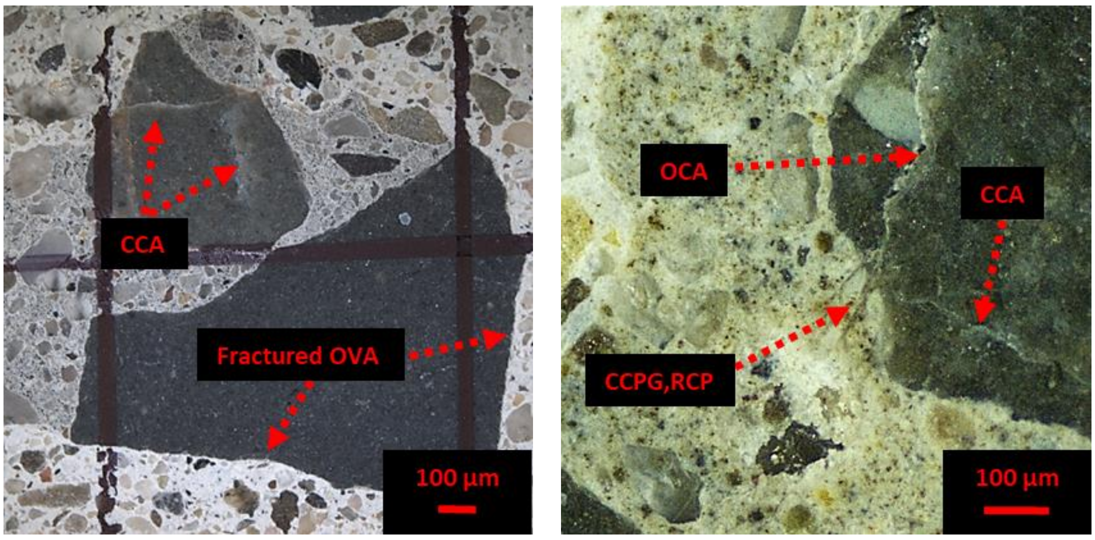
4.7.4.1. Reactive coarse aggregate

Given the results obtained through a thorough microscopic assessment on the slightly/severely damaged RCA mixtures induced by a reactive coarse aggregate per expansion level, models are hereafter proposed to characterize such distress development as shown in Figure 4.12a and Figure 4.12b, respectively.

- 0% expansion: The most significant difference between the slightly and severely damaged RCA concrete made with reactive coarse aggregate is the amount of cracks that were preserved following the crushing process especially with regards to open cracks in the aggregates. Figure 4.10a shows the most frequently observed distress features of a slightly damaged RCA concrete made with reactive coarse aggregate prior to being subjected to secondary damage having some closed cracks in the OVA (i.e. CCA) which could be derived from either the crushing process, past OVA weathering or previous ASR and a fractured OVA due to the crushing process which would be seen in both slightly and severely damaged RCA concrete. Though some open cracks are seen in the slightly damaged RCA concrete made with reactive coarse aggregate prior to being subjected to secondary damage as seen through the microscopic features and DRI (Figure 4.4 and Figure 4.8, respectively), their number is not as significant as the severely damaged Springhill RCA concrete. Figure 4.11a shows the abundance of cracks in a severely damaged RCA concrete made with reactive coarse aggregate prior to being subjected to secondary damage with cracks linking OVA through RCP thus, demonstrating the severity of the damage in such RCA concrete.

- 0.05% of expansion: Both slightly damaged (Figure 4.10b and Figure 4.10c) and severely damaged (Figure 4.11b and Figure 4.11c) RCA concrete mixtures made with a reactive coarse aggregate show cracks in the RCP and NCP extending from the OVA, yet the severely damaged RCA concrete made with reactive coarse aggregate shows a slightly higher increase in such cracks (Figure 4.8). Moreover, at this expansion level, the longest and widest cracks are located in the OVA.

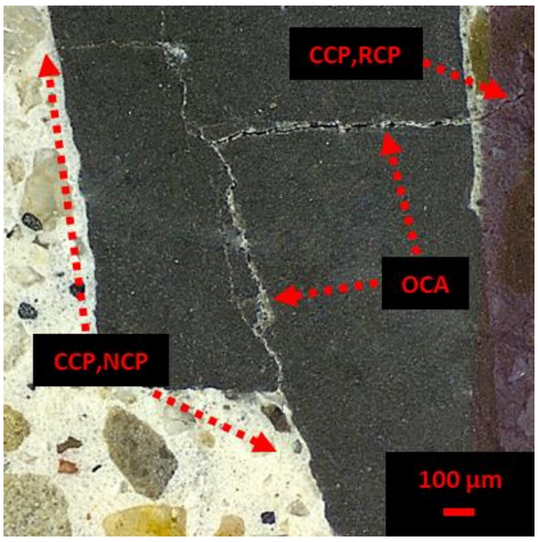
- 0.12% of expansion: The cracks in the slightly damaged RCA concrete made with reactive coarse aggregate lengthen in the OVA (Figure 4.10d) and NCP (Figure 4.8) while the severely damage RCA concrete shows the same increase in cracks yet at a larger magnitude especially in the NCP. Similar to the expansion level of 0.05%, the widest cracks are in the OVA and the longest cracks are seen to extend from the OVA into the NCP. Moreover, at 0.12% of expansion, the cracks extend from the OVA to the RCP and end in the NCP (Figure 4.11d) and the RCA particles begin to link to each other through their OVA (Figure 4.11e) in the severely damaged RCA concrete made with reactive coarse aggregate, which is not yet observed at this expansion level in the slightly damaged RCA concrete.
- 0.20% of expansion: Gel begins to appear in the NCP of the slightly and severely damaged RCA concrete made with reactive coarse aggregate at an expansion level of 0.20% (Figure 4.10e and Figure 4.11f, respectively) and cracks also begin to widen in the OVA (Figure 4.6b). The number of cracks in the OVA and NCP continue to increase and lengthen as shown in the microscopic features, DRI and maximum crack length as a function of expansion (Figure 4.4, Figure 4.8 and Figure 4.6a, respectively). Furthermore, the slightly damaged RCA concrete made with a reactive coarse aggregate begins to link its RCA particles to one another as shown in Figure 10f. At 0.20% of expansion, the distress is captured by the cracks propagating mainly from OVA to RCP and OVA to NCP in the slightly and severely damaged RCA mixtures, respectively.



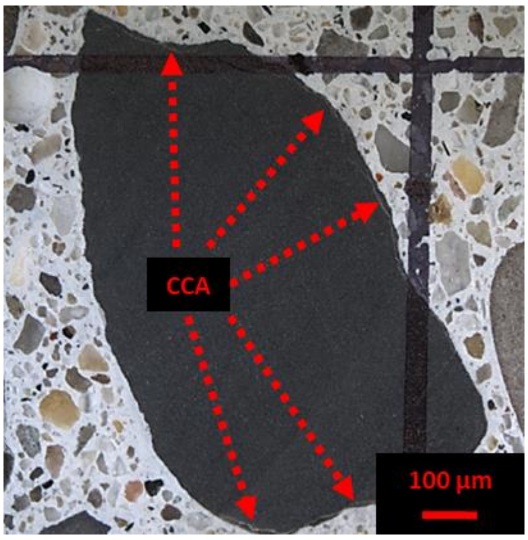
a) 0% expansion, closed cracks in OVA and fractured OVA

b) 0.05% expansion, open crack in OVA extending into RCP with gel and closed crack in OVA

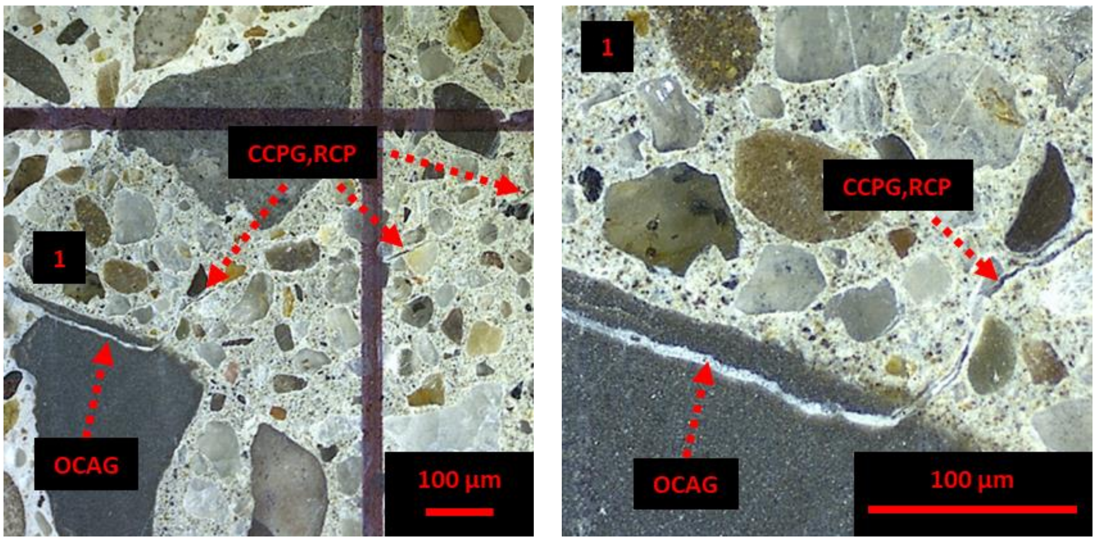
c) 0.05% expansion, many open cracks in OVA with extensions into NCP and RCP



d) 0.12% expansion, crack along periphery of OVA



e) 0.20% expansion, crack filled with gel extending from OVA into RCP. 1: Magnified sector



f) Crack connection RCA particles at 0.20% of expansion

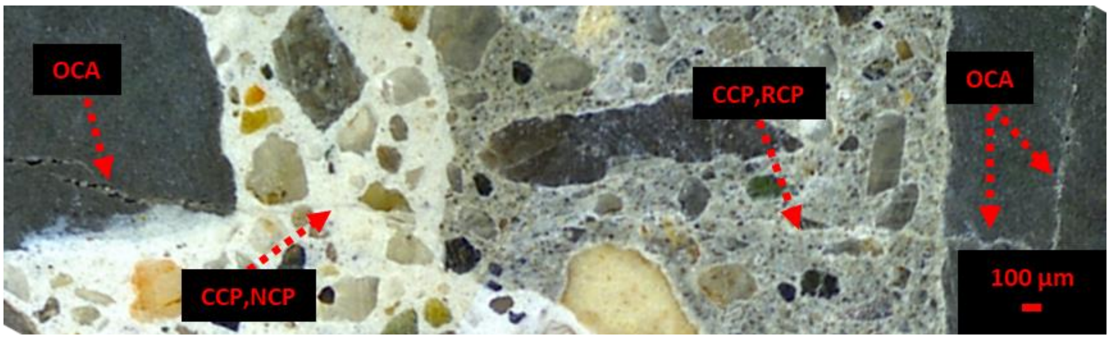
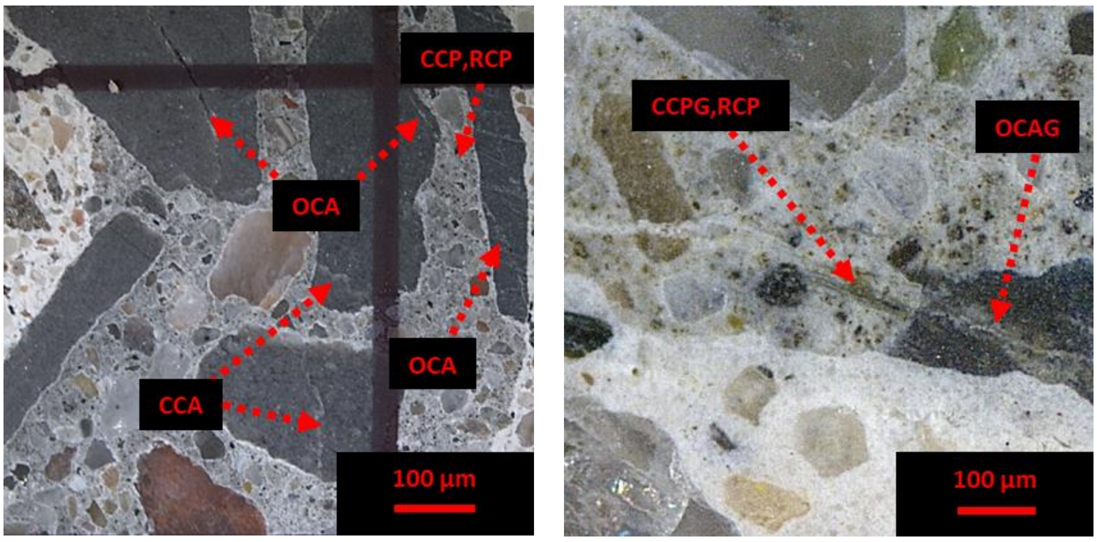
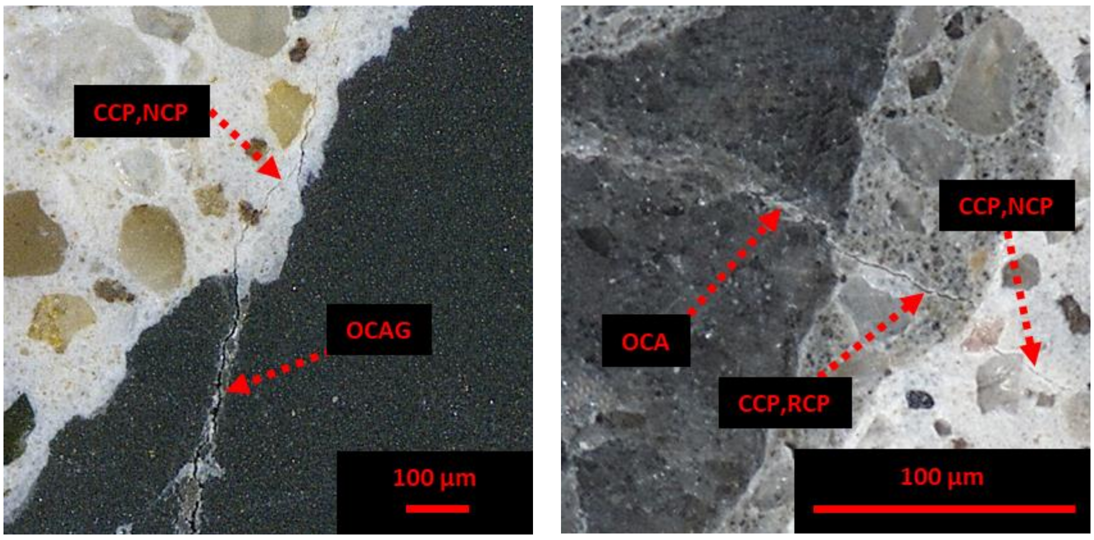


Figure 4.10: Crack progression in slightly damaged RCA concrete made with reactive coarse aggregate.

a) 0% expansion, closed crack in OVA with open cracks in OVA linking through RCP **b) 0.05% expansion, open crack in OVA extending into RCP with gel**



c) 0.05% expansion, open crack in OVA extending into NCP **d) 0.12% expansion, open crack in OVA extending into RCP then NCP**



e) 0.12% expansion, linking of OVA through NCP and extension of NCP crack along OVA **f) 0.20% expansion, open crack in OVA extending into NCP with gel**

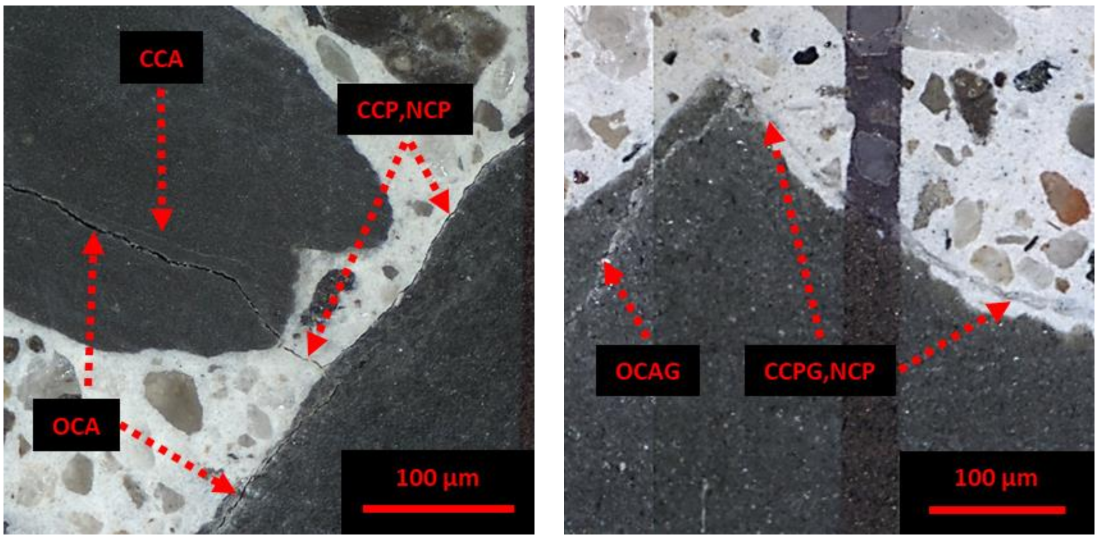


Figure 4.11: Crack progression in severely damaged RCA concrete made with reactive coarse aggregate.

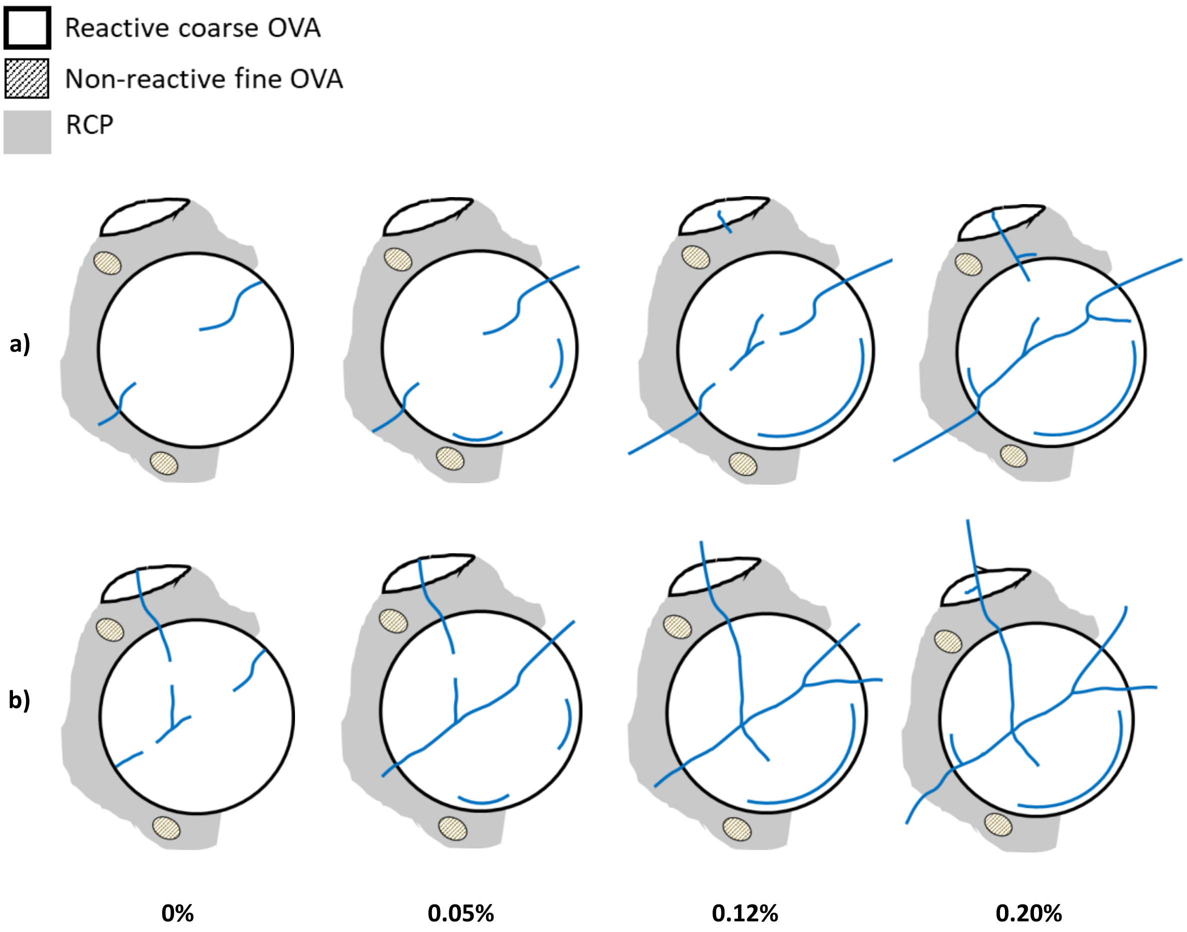


Figure 4.12: Qualitative model of crack propagation of RCA concrete induced by reactive coarse aggregate made from: a) Slightly damaged original concrete and b) Severely damaged original concrete.

4.7.4.2. Reactive fine aggregate

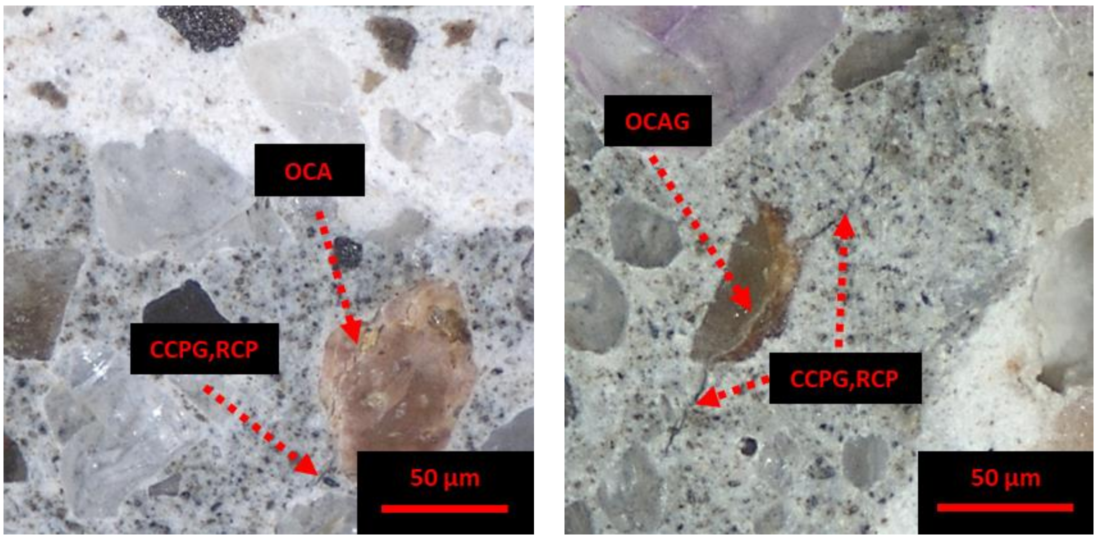
Likewise, models of the crack initiation and propagation of slightly and severely damaged RCA concrete, where ASR was induced by a reactive sand contained within the RM are also proposed to characterize such RCA concrete mixtures as shown in Figure 4.15a and Figure 4.15b, respectively.

- 0% of expansion: The extent of previous damage in RCA concrete made with reactive sand influences the RCA particles more significantly than the RCA made with reactive coarse aggregate particles, where the RCA particles conserved more cracks in the RCP as shown through the microscopic features and DRI analysis (Figure 4.4 and Figure 4.8, respectively). Less cracks in the residual reactive sand are also seen in the slightly damaged RCA concrete made with reactive sand (Figure 4.13a) as opposed to the severely damaged RCA concrete (Figure 4.14a). Both recycled mixtures present cracks extending into the RCP prior to being subjected to secondary damage with the severely damaged mixture having a higher count.

- 0.05% of expansion: For both slightly and severely damaged RCA concrete made with reactive sand, the cracks continue to extend into the RCP (Figure 4.13b and Figure 4.14b, respectively) and slightly into the NCP (Figure 4.13c and Figure 4.14b, respectively) as also shown through the microscopic features, DRI analysis and crack propagation (Figure 4.4, Figure 4.8 and Figure 4.9, respectively). The severely damaged RCA concrete made with reactive sand however, may already have linked reactive sand particles within the RCA (Figure 4.14b) given its previous extent of damage, yet the number of cracks in the RCP increases from 0% to 0.05% indicating the formation of new cracks in the RCP.

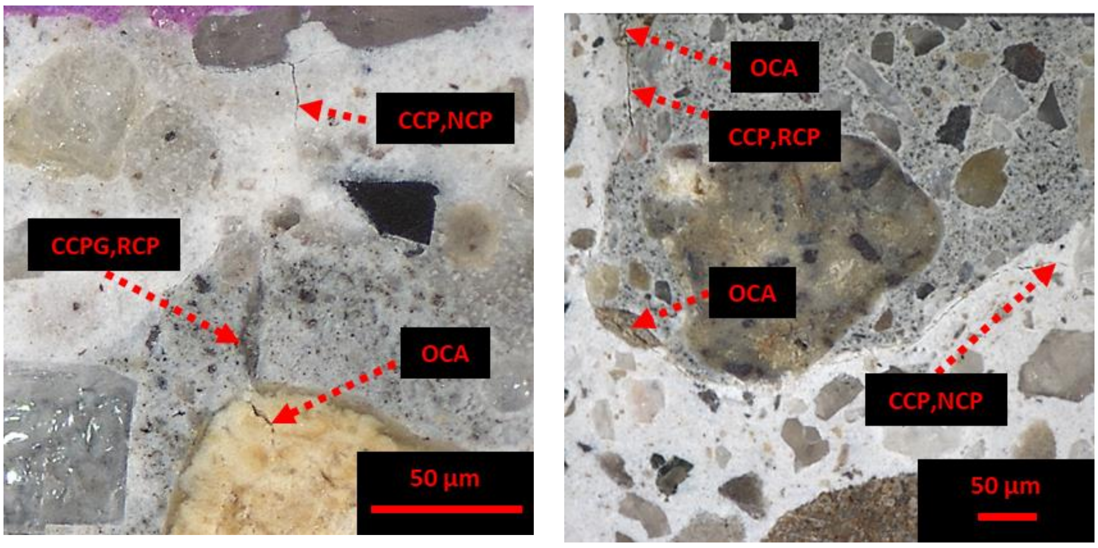
- 0.12% of expansion: Both slightly and severely damaged RCA mixtures made with reactive sand show lengthening of cracks (Figure 4.6a) as well as connection of reactive sand particles within the RCA through RCP and extension into NCP (Figure 4.13d and Figure 4.14c, respectively). The severely damaged RCA concrete made with reactive sand also shows linking of two reactive sand particles within the RCA with a crack passing through the non-reactive coarse OVA (Figure 4.14d) and linking of RCA particles is also observed (Figure 4.14e), though not necessarily linking reactive sand particles within those RCA. Moreover, cracks in the severely damaged RCA concrete made with reactive sand propagate from a reactive sand particle into the RCP, then into the NCP before entering the RCP once more and extending into the NCP, which is a clear indication of secondary damage resulting from ongoing ASR (Figure 4.14c). Furthermore, since the qualities of the RCP and NCP were designed to be the same, the crack takes no preferences over where to propagate such that there is no indication of deviation of a crack when arriving near the RCP to NCP interface as shown in Figure 4.14c.

- 0.20% of expansion: Cracks in the RCP and NCP continue to increase, lengthen and widen in both RCA concrete made with reactive sand (Figure 4.8 and Figure 4.6, respectively), confirming that the distress mechanism is more apparent in the cement paste. The slightly damaged RCA concrete made with reactive sand has the widest cracks apparent as either sharp cracks or onion skin type cracks (Figure 4.13e) and begins to link its RCA particles through the NCP where gel begins to also be observed (Figure 4.13f). As for the severely damaged RCA concrete made with reactive sand, gel begins to be observed in the NCP which was not yet visible at 0.12% of expansion (Figure 4.14f and Figure 4.14g). At 0.20% of expansion, the distress is captured by the cracks propagating mainly from OVA to RCP in the slightly and severely damaged RCA mixtures, respectively.



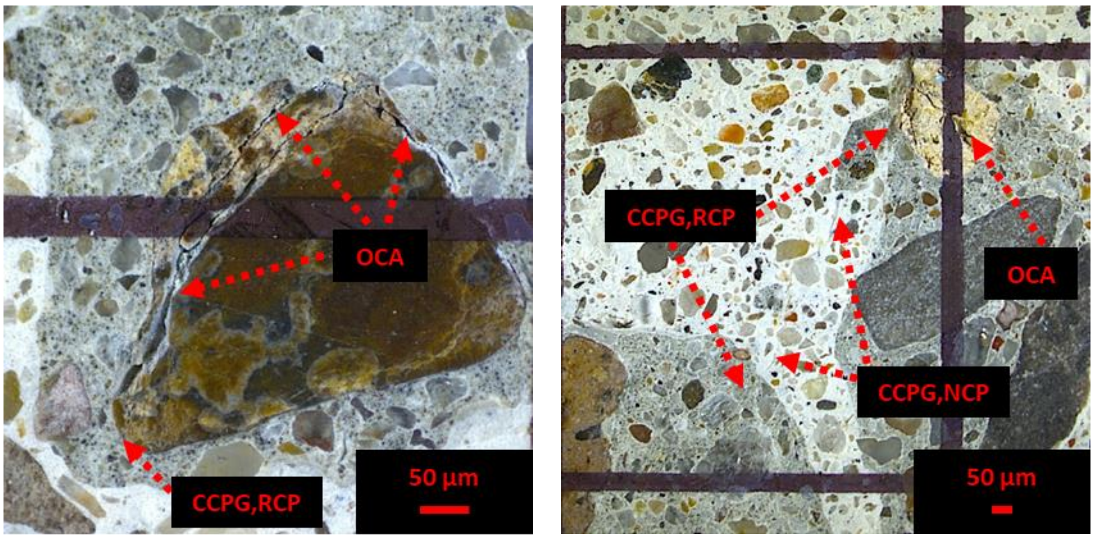
a) 0% expansion, onion skin type crack in OVA and in RCP with gel

b) 0.05% expansion, sharp type crack in OVA with gel with extension on either side into RCP with gel



c) 0.05% expansion, sharp type crack in OVA extending into RCP with gel then to NCP

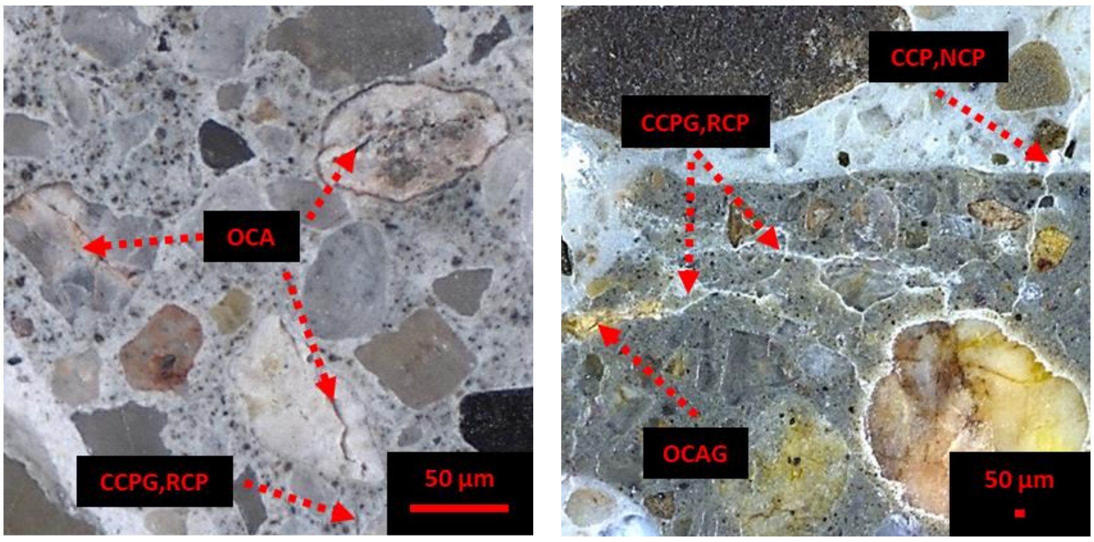
d) 0.12% expansion, sharp type crack in OVA extending into RCP and NCP



e) 0.20% expansion, onion skin type cracks in OVA extending lightly into RCP

f) 0.20% expansion, sharp type crack in OVA extending and connecting into other RCA

Figure 4.13: Crack progression in slightly damaged RCA concrete made with reactive fine aggregate.

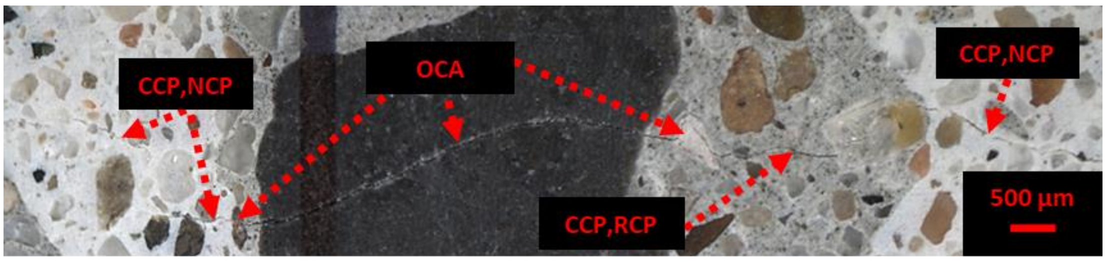


a) 0% expansion, many particles with open sharp type cracks in OVA

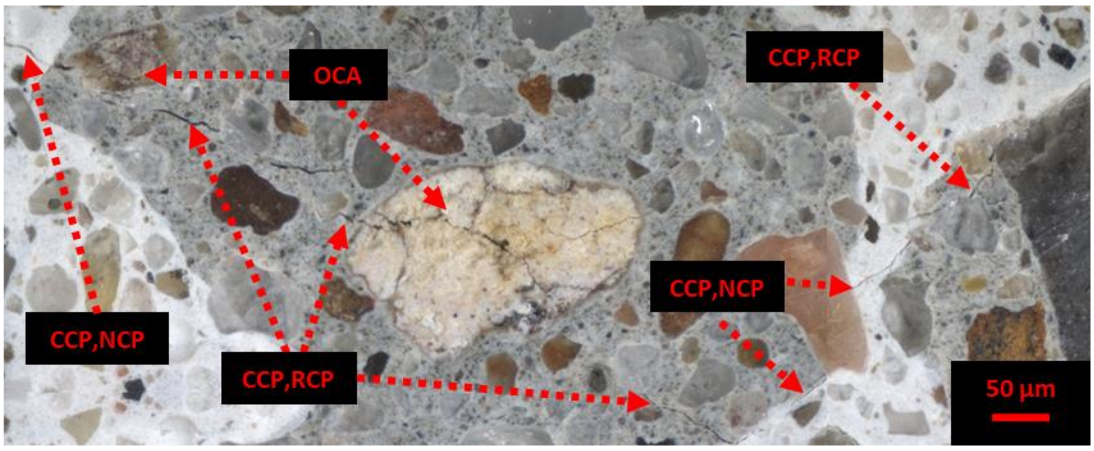
b) 0.05% expansion, many cracks in RCP radiating with slight extension into NCP

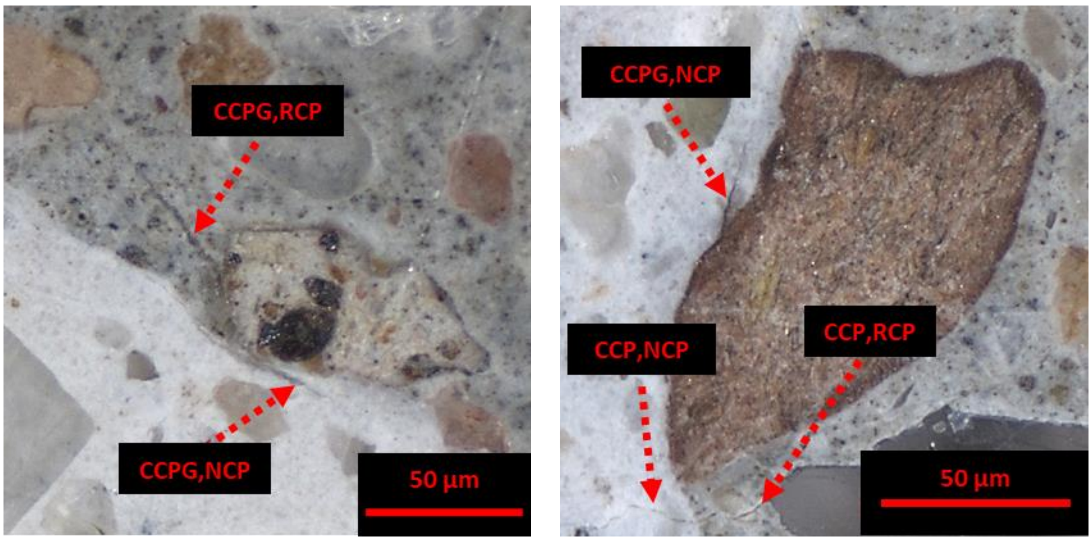
c) 0.12% expansion, cracks in sand particles connecting through RCP and extending into NCP

d) 0.12% expansion, crack in sand extending into RCP then NCP and passing through unreactive coarse aggregate



e) 0.12% expansion, cracks in sand particle extending into RCP and NCP, connecting to another RCA particle





f) 0.20% expansion, RCP and NCP cracks with gel

g) 0.20% expansion, RCP crack extending to NCP and NCP crack with gel

Figure 4.14: Crack progression in severely damaged RCA concrete made with reactive fine aggregate.

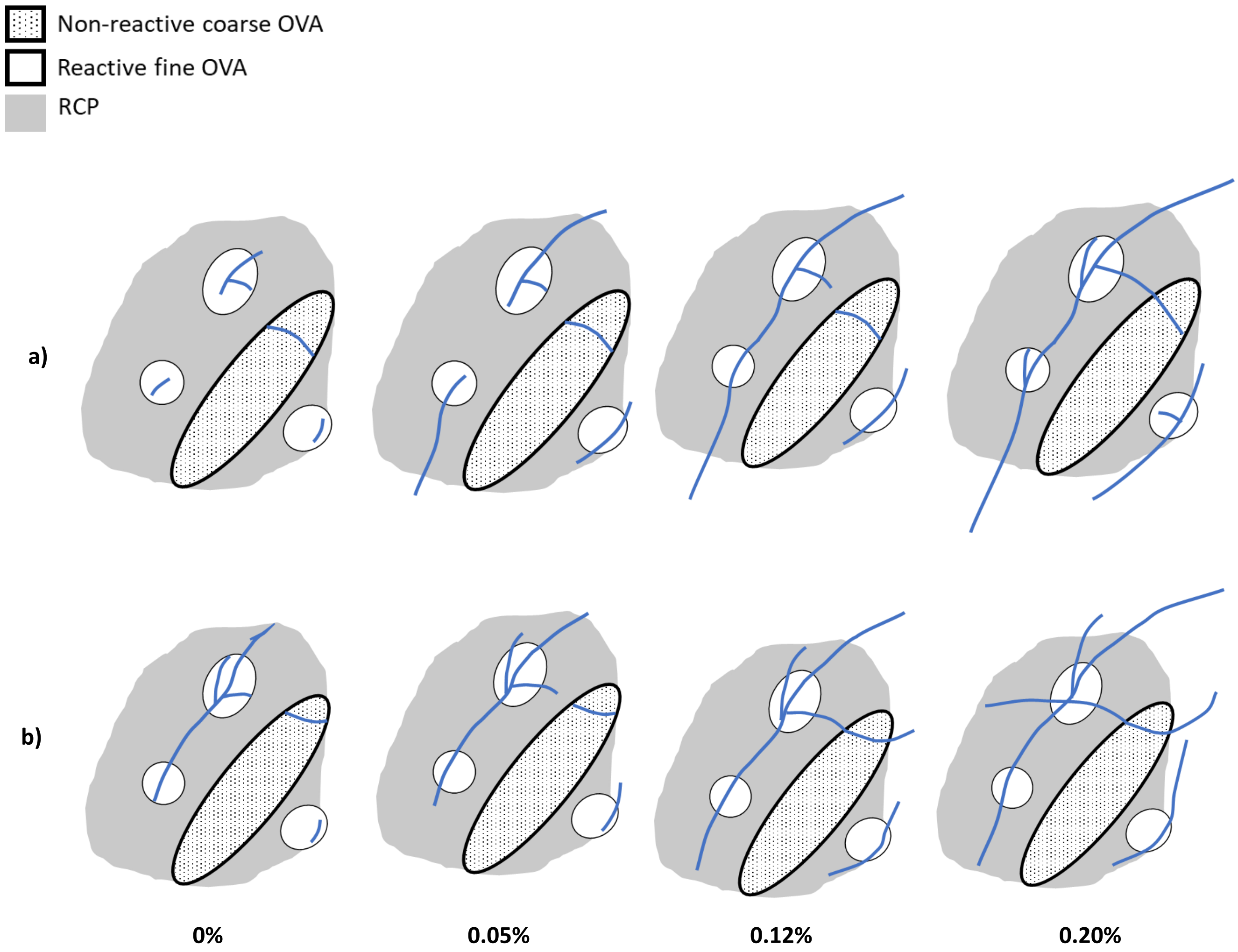


Figure 4.15: Qualitative model of crack propagation of RCA concrete induced by reactive fine aggregate made from: a) Slightly damaged original concrete and b) Severely damaged original concrete.

4.7.5. Quantitative assessment of secondary damage in recycled concrete

The DRI (using the weighing factors proposed by Villeneuve [22]) is capable of assessing damage in RCA concrete (designed with the EV method proposed by Ahimoghadam et al. [24]) made with a reactive coarse aggregate yet, at later reaction stages for the slightly damaged mixture (i.e. 0.20%). The DRI is also capable of assessing damage in a slightly damaged RCA concrete made with a reactive sand while it overestimates the damage degree (presented in Table 4.3) by more than one degree for the severely damaged RCA concrete made with reactive sand due to the abundance and location of cracks (higher weighing factor in the cement paste) thus, resulting in a higher DRI number. Therefore, the DRI may be capable of partially capturing past ASR damage in the case of a severely damaged RCA concrete made with a reactive sand yet, this phenomenon would need to be verified through a mechanical assessment to determine the property losses.

Table 4.3: Classification of ASR damage degree in CC based on DRI result as proposed by Sanchez et al.[11].

Classification of ASR damage degree	Reference expansion level (%)	Conventional concrete DRI	Recycled concrete DRI results			
			Reactive coarse aggregate		Reactive sand	
			Slight damage	Severe damage	Slight damage	Severe damage
Negligible	0.00-0.03	100-155	73	171	177	373
Marginal	0.04 ± 0.01	210-400	161	261	337	573
Moderate	0.11 ± 0.01	330-500	268	390	551	831
High	0.20 ± 0.01	500-765	470	514	826	1213
Very high	0.30 to 0.50 ± 0.01	600-925	-	-	-	-

4.8. Conclusion

The purpose of this study was to characterize different types of ASR-affected RCA induced by either a reactive coarse or fine aggregate at slightly and severely damaged degrees and evaluate the propagation of cracks in such recycled concrete mixtures in order to differentiate their distress mechanisms. Some conclusions can be drawn from the results obtained and are presented hereafter:

The overall levels of expansions achieved by each of the RCA concrete mixtures are somewhat similar with the severely damaged RCA concrete being slightly higher than the slightly damaged RCA concrete. However, differences are seen in the RCA concrete made with the reactive fine aggregate when compared to its companion CC, where the overall expansion level and rate of expansion are significantly lower, while the RCA concrete mixtures made with reactive coarse aggregate generally follow its companion CC. Moreover, the severely damaged RCA concrete made with reactive fine aggregate experiences a delay in expansion which was attributed to the residual cement paste acting as a barrier against the fresh alkalis in the new cement paste. Although different types of cracks were observed for each RCA concrete, the higher level of expansion exhibited by the severely damaged RCA concrete mixtures as opposed to the slightly damaged RCA concrete may be associated to the abundance of cracks originally present in the reactive original virgin aggregate and reactive residual mortar.

The crack propagation in RCA concrete differs with respect to the origin of the reaction where RCA concrete made with reactive coarse aggregate propagates cracks mainly from the OVA into the RCP/NCP for the slightly/severely damaged mixtures, respectively, while the RCA concrete made with reactive sand propagates its cracks from the OVA into the RCP. Nevertheless, the previous extent of damage generally influences the secondary damage by causing more or less damage for the same given expansion level, which is associated to the characteristics of the generated cracks such that a more severely damaged RCA concrete produces longer cracks, hence a higher secondary damage degree. On the contrary, although the same expansion level was achieved, less damage is observed through a smaller number of cracks in a slightly damaged RCA concrete, yet produced wider cracks at later stages (i.e. 0.20% of expansion) thus indicating the difference in the damage mechanism with respect to original extent of damage.

A slightly damaged RCA concrete where ASR was induced by a reactive coarse aggregate may be capable of reaching the same damage degree as the severely damaged RCA concrete at 0.20% of expansion demonstrating that its lack of preserved cracks may be overcome by its remaining reactivity. Therefore, the slightly damaged RCA concrete could potentially “catch up” to the severely damaged RCA concrete after which the DRI could be used to assess its damage. Moreover, the DRI was capable of evaluating the damage in both slightly damaged RCA concrete mixtures, yet it overestimates the damage in the severely damaged RCA concrete made with a reactive sand which may consequently be capable of capturing the effect of past deterioration.

ASR-affected RCA concrete should not be considered as a single material but characterized according to its previous extent of damage and origin of the reaction (i.e. reactive sand or coarse aggregate). The qualitative model of crack initiation and propagation in the evaluated types of RCA concrete mixtures therefore establishes a base line for further mitigation and design of such recycled concrete.

4.9. References

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Chapter Five: Conclusion and Research Recommendations

The main purpose of this research was to evaluate the crack initiation and propagation in ASR-affected RCA concrete with varying original extents of damage and origin of reaction/damage (i.e. reactive coarse or fine aggregate). The most recent studies in such field involves the applicability of standard testing procedures to detect the reactivity of RCA particles yet, presents some inconsistencies with regards to the results obtained. Those discrepancies were often attributed to the age/damage extent of the source concrete however, its influence on the secondary damage in terms of cracks remained unknown. Therefore, some conclusion can be drawn from this research which shows that the crack initiation, propagation and characteristics vary for each type of RCA concrete evaluated in this study and are presented hereafter:

- The term secondary expansion or secondary damage is associated to the expansion that is experienced by the RCA concrete. It is even further divided into two types of secondary expansion/damage where: a) it is produced by ongoing ASR which was originally generated in the source concrete and continue to be present in the RCA concrete and b) newly produced ASR which is formed in new cracks that were introduce in the RCA particle through the RCA crushing process. This concept was mostly apparent in the severely damaged RCA concrete where ASR was originally induced by a reactive coarse aggregate because of the difference in the original extent of damage and secondary damage. However, this was not apparent in the RCA concrete where ASR was originally induced by a reactive sand since its damage mechanism differed from that of the RCA containing a reactive coarse aggregate.
- The expansions as a function of time for each RCA concrete presented unexpected results where the severely damaged RCA concrete showed higher expansion levels compared to the slightly damaged RCA concrete for the same given time. This was attributed to the more abundant number of cracks found in the severely damaged RCA particles prior to being subjected to secondary expansion acting as “fast track channels” and accelerating the damage due to the minimum energy law. However, the trend between the RCA concrete and conventional concrete containing a reactive coarse aggregate were very similar despite the previous levels of damage. On the other hand, expansion levels of the RCA concrete composing of a reactive sand were significantly lower than that of its companion conventional concrete which was attributed to the lower amount of reactive sand in the overall amount of sand in the RCA concrete since the reactive sand is only present in the residual mortar. Furthermore, the severely damaged RCA concrete where ASR was induced by the residual reactive sand showed a prolonged delay in expansion which was not apparent for its slightly damaged counterpart. This delay is believed to be associated to the residual mortar having a lower alkali content acting as a shield against the new source of alkalis within the new mortar thus, creating a barrier effect. Once the

barrier is overcome however, the expansion then increases and surpasses that of its slightly damaged counterpart.

- In terms of cracks caused by secondary damage, the results obtained in this study showed that cracks are distinctively generated with respect to their origin of damage (i.e. reactive sand or coarse aggregate) and previous extent of damage. As such, the secondary damage mechanism in the RCA concrete composed of a reactive fine aggregate is governed by cracks within the residual and new mortar whereas cracks in the original reactive coarse aggregate within the RCA prevails the damage mechanism. Moreover, the severely damaged RCA concrete presented longer cracks and a higher count compared to the slightly damaged RCA concrete however, the latter exhibited wider cracks which resulted in the same given expansion level. Consequently, the expansion levels achieved by each recycled concrete evaluated in this study does not present the same level of damage when damage is associated to the number of cracks produced however the Damage Rating Index can be used to assess damage in RCA concrete since the obtained results were mostly similar to that of range obtained in CC. Furthermore, as cracks influence the mechanical properties of concrete, it is crucial to investigate the effect of cracks in RCA concrete on the mechanical properties and determine whether the observed cracks and expansion levels correspond to the damage degree.
- In general, the crack propagation in RCA concrete (regardless of the presence of ASR) showed that when the RCA concrete is designed to have the same strength as its companion mix thus, having the same quality of residual mortar and new mortar, the cracks do not necessarily differentiate between the mortars but rather travel through them perpendicular to their interface as opposed to inside of the interface. Therefore, the interface between the residual and new mortar indicates that it is not the weakest link in RCA concrete when the mortars are designed to be the same. Nonetheless, ASR served as a tool to better understand the crack propagation in RCA concrete.

Further research is however required to fully understand the behaviour of ASR-affected RCA concrete. Therefore, some research recommendations are presented hereafter:

- Since the expansion as a function of time curves show that the expansions of ASR-affected RCA concrete are not giving any indication of flattening, further readings should be taken as to see if over time, there will be flattening of the curves and if the trends of the slightly damaged RCA concrete having higher expansions for the same given time would change. Additional microscopic assessments at the ultimate achieved expansion would also add interesting results to this research field.
- As it was determined the distress mechanism in various types of RCA concrete differs from RCA type where wider cracks were seen for the slightly damaged RCA concrete. Thus, an investigation on the chemical composition of the reaction products generated is required

to better characterize the RCA particles and to provide the necessary information for ASR mitigation techniques used for RCA concrete.

- An extensive assessment on the mechanical properties and their loss due to ASR is necessary to compare those losses to conventional concrete affected by ASR. Nevertheless, the Equivalent Volume (EV) mix-proportioning should be used as to avoid or minimize reductions in mechanical properties when using RCA instead of natural aggregates. This would add some insight as to whether ASR-affected RCA concrete deteriorates similarly to conventional concrete and those results could further be correlated to the microscopic DRI values obtained in this study.
- Finally, since there is a lack of studies on the crack initiation and propagation of RCA concrete without ASR, it is highly recommended that such research is conducted to understand its behaviour for it to be ultimately used in structural applications.

Appendix A

Texas CC						
Average expansion	0	0.023%	0.032%	0.116%	0.198%	0.267%	0.283%
Days	0	8	15	22	31	44	51
SD	0	0.014%	0.017%	0.020%	0.036%	0.069%	0.000%
Minimum expansion	0	-0.014%	-0.007%	0.079%	0.158%	0.191%	0.283%
Maximum expansion	0	0.049%	0.066%	0.160%	0.275%	0.394%	0.283%

0.05%-TX-RCA												
Average expansion	0	0.014%	0.012%	0.018%	0.052%	0.060%	0.078%	0.085%	0.110%	0.121%	0.138%	0.205%
Days	0	7	14	21	43	49	63	71	86	101	115	180
SD	0	0.012%	0.021%	0.021%	0.030%	0.023%	0.029%	0.032%	0.029%	0.028%	0.040%	0.036%
Minimum expansion	0	-0.015%	-0.040%	-0.029%	-0.026%	0.019%	0.025%	0.027%	0.053%	0.064%	0.072%	0.120%
Maximum expansion	0	0.041%	0.042%	0.058%	0.113%	0.096%	0.148%	0.151%	0.161%	0.177%	0.210%	0.249%

0.30%-TX-RCA																
Average expansion	0	0.020%	0.011%	0.014%	0.012%	0.018%	0.028%	0.014%	0.010%	0.013%	0.029%	0.142%	0.148%	0.169%	0.189%	0.198%	0.26%
Days	0	3	7	10	14	16	21	24	31	38	43	87	93	107	115	130	224
SD	0	0.027%	0.016%	0.027%	0.027%	0.027%	0.026%	0.027%	0.025%	0.023%	0.040%	0.035%	0.030%	0.034%	0.029%	0.039%	0.016%
Minimum expansion	0	-0.041%	-0.015%	-0.042%	-0.032%	-0.045%	-0.008%	-0.054%	-0.040%	-0.045%	-0.029%	0.079%	0.105%	0.122%	0.166%	0.167%	0.248%
Maximum expansion	0	0.056%	0.047%	0.053%	0.089%	0.057%	0.101%	0.054%	0.041%	0.045%	0.120%	0.199%	0.184%	0.213%	0.229%	0.252%	0.285%

Springhill CC										
Average expansion	0	0.000214	0.000449888	0.0005	0.000855	0.00230268	0.002325575	0.002518936	0.002813	0.003146
Days	0	8	44	52	63	101	109	116	137	150
SD	0	0.028%	0.014%	0.019%	0.020%	0.018%	0.013%	0.037%	0.036%	0.007%
Minimum expansion	0	0.049%	0.007%	0.004%	0.033%	0.209%	0.213%	0.175%	0.168%	0.304%
Maximum expansion	0	0.079%	0.061%	0.082%	0.115%	0.255%	0.253%	0.310%	0.321%	0.333%

0.05%-SPR-RCA												
Average expansion	0	0.013%	0.018%	0.015%	0.021%	0.063%	0.074%	0.075%	0.092%	0.115%	0.141%	0.239%
Days	0	8	15	22	29	51	57	71	79	94	109	188
SD	0	0.025%	0.021%	0.023%	0.018%	0.030%	0.031%	0.028%	0.028%	0.025%	0.031%	0.039%
Minimum expansion	0	-0.037%	-0.038%	-0.028%	-0.025%	-0.014%	0.024%	0.024%	0.044%	0.068%	0.085%	0.173%
Maximum expansion	0	0.088%	0.071%	0.062%	0.055%	0.107%	0.120%	0.134%	0.144%	0.161%	0.201%	0.323%

0.30%-SPR-RCA												
Average expansion	0	0.022%	0.022%	0.030%	0.032%	0.093%	0.089%	0.104%	0.125%	0.154%	0.176%	0.278%
Days	0	8	15	22	29	51	57	71	79	94	109	188
SD	0	0.030%	0.023%	0.021%	0.023%	0.031%	0.025%	0.028%	0.034%	0.032%	0.031%	0.030%
Minimum expansion	0	-0.047%	-0.022%	0.002%	-0.033%	0.034%	0.030%	0.055%	0.060%	0.094%	0.131%	0.221%
Maximum expansion	0	0.098%	0.103%	0.094%	0.098%	0.161%	0.153%	0.172%	0.209%	0.249%	0.267%	0.341%