

Investigation on the Overall Performance of Recycled Concrete Affected by Alkali-Silica Reaction

Rouzbeh Ziapourrazlighi

Thesis submitted to the University of Ottawa
in partial Fulfillment of the requirements for the
Doctor of Philosophy in Civil Engineering

Department of Civil Engineering
Faculty of Engineering
University of Ottawa

© Rouzbeh Ziapourrazlighi, Ottawa, Canada, 2023

Abstract

Pressure is mounting in the concrete industry to adopt eco-efficient methods to reduce CO₂ emissions. Portland cement (PC), an essential concrete ingredient, is responsible for over two-thirds of the embodied energy of the concrete, generating about 8% of global greenhouse gas emissions. Extraction and transportation of aggregates and raw materials that comprise concrete mixes are also directly linked to their embodied energy; thus, recycled concrete aggregates (RCA) have been proposed as a promising alternative to increase sustainability in new construction. In this context, many studies have been conducted over the past decades on the properties of RCA concrete. Recent studies have shown that suitable fresh (i.e., flowability) and short-term hardened (i.e., compressive strength) properties might be achieved when the unique microstructural features of RCA are accounted for in the mix-design process of the recycled concrete. However, manufacturing RCA from construction demolition waste (CDW) or returned concrete (RC) presents its unique challenges. Amongst others, the variation in the source of RCA and the presence of damage due to several deterioration mechanisms causes major concern. Due to the presence of reactive aggregates in many quarries in Canada, alkali-silica reaction (ASR) is one of the most common deterioration mechanisms.

The durability and long-term performance of RCA concrete are not fully understood and should be further investigated, especially in regards to a) the potential of further (secondary) deterioration of recycled concrete bearing coarse and fine alkali-silica reactive aggregates b) the impact of the severity of the initial reaction on mechanical properties and kinetics of expansion in recycled concrete and c) the impact of using sound and alkali-silica reaction (ASR) affected RCA on the chloride diffusivity (and thus corrosion initiation) of concrete.

This work aims to appraise the durability performance of RCA concrete made of 100% coarse RCA, particularly two families of RCA selected (i.e., returned concrete RCA, demolished concrete RCA) to represent waste currently being generated. Furthermore, two types of reactive aggregates are selected to investigate the impact of the source of the reaction (i.e. reactive coarse aggregate as original virgin aggregate – OVA and reactive sand within the residual mortar – RM) within the RCA. ASR is the distress mechanism used to introduce damage to the manufactured RCA. A new mix design technique was used to produce recycled concrete mixtures to increase eco-efficiency, improve fresh-state properties, and reduce cement use in RCA concrete.

In conclusion, the initial reaction's location and severity significantly impact the compressive strength, SDT parameters, chloride diffusion rate, and shear strength of concrete specimens. Specifically, the location of the initial reaction can influence the distribution and extension of damage within the various parts of recycled concrete, while the severity of the initial reaction can affect the overall integrity of the aggregates as well as the availability of silica and alkalis for secondary reaction. These results demonstrate the importance of assessing

the severity of the initial reaction and its source in order to ensure the durability and long-term performance of recycled concrete made with reactive RCA.

ACKNOWLEDGMENTS

I am incredibly grateful to my supervisor, Dr. Leandro Sanchez, for his guidance and support throughout my time at the University of Ottawa. He has been not only a mentor but also a friend, and I am deeply grateful for his patience and knowledge in the field. His contribution to my research journey has been invaluable, and I am extremely thankful to have had the opportunity to work with him.

I would also like to extend my sincere thanks to Dr. Muslim Majeed and Dr. Gamal Elnabelsya, who have provided valuable assistance and support during my research. Their expertise and insights have been integral to the success of my project, and I am extremely grateful for their help.

I would like to express my heartfelt gratitude to my wife, Yasaman, who has provided unwavering support and patience throughout the final years of my Ph.D. Her encouragement and understanding have been invaluable, and I am deeply grateful for her presence in my life.

I am also grateful to my colleagues in the UOttawa concrete microstructure team, Dr. Andishe Zahedi, Cassandra Trottier, and Yufeng Zhu, who has been more than just friends during my time here. Their support and camaraderie have made this experience truly enjoyable, and I am grateful for their contributions to my academic and personal growth.

Finally, I would like to thank my parents and sisters for their continuous support and encouragement throughout my academic journey. Their love and confidence in me have been a constant source of motivation, and I am deeply grateful to have such a supportive and loving family. To my mother, I am incredibly thankful for the countless hours she spent reviewing my homework in elementary school; it has truly paid off.

Table of Contents

Abstract.....	II
List of Figures	VIII
List of Tables.....	XI
List of Acronyms.....	XII
Foreword	XIV
1. INTRODUCTION.....	1
Environmental impact of cement.....	1
Environmental impact of aggregates	2
Construction and demolishing waste (CDW).....	2
Returned concrete (RC).....	2
Alkali-silica reaction (ASR) on recycled concrete.....	3
Chloride diffusion in concrete	4
References	7
2. LITERATURE REVIEW.....	9
Recycled concrete aggregate (RCA)	9
RCA production and challenges.....	9
Physical Properties of RCA.....	10
Mix design procedures for recycled concrete.....	12
Properties of RCA concrete.....	14
Alkali-aggregate reaction	20
AAR in conventional concrete	20
Mechanical properties of concrete affected by ASR.....	22
ASR in RCA.....	24
Tools for assessing concrete damaged by ASR.....	29
Corrosion initiation and chloride diffusivity	32
Chloride diffusion.....	32
Effects of microcracking on chloride diffusion.....	33
The effects of the Interfacial Transition Zone (ITZ) on chloride diffusivity.....	34
References	35
3. Objectives.....	44
References	45
4. RESEARCH PROGRAM	46
Experimental procedure.....	46
Compressive Strength.....	48
Direct Shear Test	49

Stiffness Damage Test (SDT).....	50
Chloride diffusion sample preparation	51
References	54
5. CORE OF THE THESIS – SCIENTIFIC PAPERS	55
Overview	55
6. Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete.....	56
Abstract	56
Introduction	56
Background	57
Alkali-silica reaction (ASR)	57
Recycled concrete aggregate (RCA)	58
Techniques used to assess ASR damage in concrete.....	58
Damage Rating Index (DRI)	58
Direct shear setup test.....	59
Scope of work.....	59
Materials and methods.....	60
Concrete manufacturing	60
Experimental procedures.....	61
Direct shear test	61
Damage Rating Index (DRI)	61
Results	62
ASR development and kinetics.....	62
Direct shear test	63
Microscopic assessment	63
Discussion and overall assessment.....	65
Conclusions	66
References	67
7. Mechanical appraisal of ASR-affected recycled concrete made of a reactive coarse RCA displaying distinct deterioration degrees.....	70
Abstract	70
Introduction	70
Background	72
Alkali-silica reaction (ASR) in conventional concrete.....	72
Recycled concrete aggregate (RCA) and ASR.....	73
Mechanical Tools for assessing ASR-induced damage.....	75
Scope of work.....	76

Materials and methods.....	77
RCA fabrication procedure.....	77
RCA Concrete mix design.....	78
Testing Procedures	78
Results	79
ASR kinetics and development.....	79
Stiffness Damage Test (SDT).....	80
Compressive Strength (CS)	82
Discussion	84
Development of secondary expansion.....	84
Understanding the difference between the mechanical properties of various recycled mixtures and conventional concrete	85
Slightly damaged RCA.....	85
Severely damaged RCA	86
Overall appraisal.....	87
The statistical validity of the mechanical results.....	88
Microscopic validation of the SDT results for assessing damage in RCA concrete	90
Conclusion.....	92
References	93
8. Overall assessment of alkali-silica reaction affected concrete made of reactive coarse and fine aggregates	
99	
Abstract	99
Introduction	99
RCA microstructure.....	101
ASR-induced expansion and RCA concrete.....	102
Mechanical properties of ASR-affected recycled concrete	103
Stiffness damage test (SDT).....	104
Direct shear setup test.....	105
Scope of work.....	106
Materials and methods.....	106
Experimental testing procedure	108
Compressive Strength.....	108
Direct Shear Test	109
Stiffness Damage Test (SDT).....	109
Results	110
ASR development.....	110

Direct shear strength.....	111
Compressive strength (CS).....	113
Stiffness damage test (SDT).....	116
Discussion	120
Multi-level assessment	121
Overall appraisal.....	127
The statistical validity of the mechanical results.....	129
Conclusions	130
References	131
9. Chloride diffusivity of recycled concrete made of ASR-affected fine and coarse aggregates	138
Abstract	138
Introduction	138
Recycled concrete.....	138
Corrosion initiation and chloride diffusivity	139
Scope of work.....	142
Materials and methods.....	143
Manufacturing of ASR reactive specimens	143
Sample preparation.....	144
Results	145
Chloride concentration profile.....	145
Chloride diffusion rate.....	148
Discussion	149
Microstructure assessment.....	150
Conclusions	157
References	158
10. Future works.....	161
11. Scientific and engineering contributions	163
12. Conclusions of the Thesis.....	164

List of Figures

Figure 1.1: Cement composition estimates are provided as shares of cement production on a mass basis. 2050 global average cement composition estimates are based on the low variability case of the 2DS [2].	1
Figure 1.2: Location of quarries with reactive aggregate [17].	4
Figure 1.3: Two-stage mechanism of corrosion over time.	5
Figure 2.1: Comparison between the total amount of aggregates in RCA concrete mix designed with conventional methods VS conventional concrete.	12
Figure 2.2: Volumetric material amounts of RCA mixtures designed with EMV and EV methods when compared to their initial CC mixes [18].	14
Figure 2.3: Cross-sectional area of a sample made with CRCA highlighting the various types of ITZ.	15
Figure 2.4 Compressive strength loss VS RCA replacement percentage [37,40,42,48].	17
Figure 2.5: Effect of incorporating increasing RCA content on the relative modulus of elasticity of concrete [55].	19
Figure 2.6: Effect of RCA from different sources on the modulus of elasticity [55,57].	20
Figure 2.7: Gardiner dam spillway in Saskatchewan, Canada, showing map cracking (right) [59].	21
Figure 2.8: An ASR-induced sharp crack (on the left) and an onion skin crack (on the right) [61].	21
Figure 2.9: Crack distribution of ASR caused by a) reactive sand and b) reactive coarse aggregates [62].	22
Figure 2.10: Qualitative model of crack propagation in ASR-affected concrete [60].	22
Figure 2.11: Compressive strength reduction of reactive 35 MPa mixtures [66].	23
Figure 2.12: ME reduction of various reactive mixtures [66].	24
Figure 2.13: Potential reactivity of RCA and virgin aggregate in the AMBT [71].	25
Figure 2.14: Evaluation of expansion [82].	27
Figure 2.15: Expansion of NA with a cement of different alkali content [77].	28
Figure 2.16: Expansion of high alkali mixes with CRCA from A) low alkali original concrete and B) high alkali original concrete [86].	29
Figure 2.17: DRI weighting factors on the left and micrograph displaying some petrographic damage features on the right [60,88].	30
Figure 2.18: Calculation of SDI and PDI adopted from [99].	32
Figure 2.19: Flick's first general law of diffusion [102].	33
Figure 2.20: Various types of microcracking in concrete [103].	33
Figure 4.1: Recycled aggregates incorporating distinct levels of damage in A) original virgin aggregate (OVA) and B) residual mortar (RM).	48
Figure 4.2: compressive strength test setup for cylindrical concrete specimens.	49
Figure 4.3: Shear setup for cylindrical concrete specimens [5].	50
Figure 4.4: SDT test setup for cylindrical concrete specimens.	51

Figure 4.5: Powder extracted from a specimen up to 13 mm.....	52
Figure 6.1: A qualitative model of crack propagation in ASR-affected CC [10].....	58
Figure 6.2: Shear setup for concrete specimens [26].....	59
Figure 6.3: Expansion as a function of time for concrete mixtures [6].	62
Figure 6.4: a) Direct shear strength of ASR-affected specimens, and b) shear loss of ASR-affected specimens at distinct expansion levels.....	63
Figure 6.5: a) Percentage of distress features and b) DRI chart in CC and RCA concrete [6].....	64
Figure 7.1: A model showing A) coarse virgin aggregate and B) coarse RCA (RM and OVA).	71
Figure 7.2: A qualitative crack propagation model in ASR-affected conventional concrete [34].	73
Figure 7.3: Comparison between volumetric differences of various mix design methods [47].....	74
Figure 7.4: Calculation of SDI and PDI adopted from [32].....	76
Figure 7.5: Expansion as a function of time for CC and RCA concrete mixtures partially adapted from [24].	80
Figure 7.6: The results of A) stiffness damage index (SDI), B) plastic deformation index (PDI), C) Modulus of elasticity and D) modulus of elasticity loss (%) for slightly and severely damaged recycled aggregates (0.05% RCA, and 0.30% RCA) and conventional concrete.	82
Figure 7.7: A) Compressive strength (MPa) and B) compressive strength loss (%) for slightly and severely damaged recycled aggregates (0.05% RSPR and 0.30% RSPR) and conventional concrete Vs. Expansion level.	83
Figure 7.8: A 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 [28].	86
Figure 7.9: A) List of DRI distress features and their corresponding weighting factors and B) a 1cm ² grid of RCA concrete where some of the distress features listed in A can be seen.	90
Figure 7.10: Microscopic features of mixtures assessed with the help of DRI, adapted from [24,28].	91
Figure 8.1: Microstructure of a coarse RCA particle highlighting the different ITZs.....	101
Figure 8.2: Internal cracking caused by: A) ASR coming from a reactive coarse aggregate – Spring Hill, and B) ASR coming from a reactive sand aggregate – Texas sand adopted from [43].....	103
Figure 8.3: A qualitative model of crack propagation of RCA concrete induced by a) reactive coarse aggregate and b) reactive fine aggregate at four expansion levels (0.0%, 0.05%, 0.12% and 0.20%) adopted from [4].	103
Figure 8.4: Calculation of SDI and PDI adopted from [19].....	105
Figure 8.5. Shear setup for cylindrical concrete specimens [52].....	106
Figure 8.6: ASR expansion development for A) conventional vs slightly damaged RCA and B) conventional vs severely damaged RCA. For comparison reasons, the CC mixtures are added to both graphs.	111
Figure 8.7: Direct shear strength (MPa) A) Slightly damaged recycled concrete, and B) Severely damaged recycled concrete. For comparison reasons, the CC mixtures are added to both graphs.....	112
Figure 8.8: Direct shear loss (%) for A) slightly damaged recycled concrete and B) severely damaged recycled concrete. For comparison reasons, the CC mixtures are added to both graphs.	113

Figure 8.9: Compressive strength (MPa) for A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)	115
Figure 8.10: Compressive strength loss (%) for A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX).....	116
Figure 8.11: SDI parameter obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX).....	117
Figure 8.12: PDI parameter obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX).....	118
Figure 8.13: ME obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)	119
Figure 8.14: ME loss obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX).....	120
Figure 8.15: A qualitative crack propagation model in ASR-affected conventional concrete [37].	122
Figure 8.16: The extended DRI of all recycled specimens at an expansion level of 0.0%.	122
Figure 8.17: The extended DRI of all recycled specimens at an expansion level of 0.05%.	123
Figure 8.18: The extended DRI of all recycled specimens at an expansion level of 0.12%.	125
Figure 8.19: The extended DRI of all recycled specimens at an expansion level of 0.20%.	126
Figure 8.20: The extended DRI of all recycled specimens at an expansion level of 0.30%.	127
Figure 9.1: Two-stage mechanism of corrosion over time [3].	140
Figure 9.2: Flick's first general law of diffusion [6].....	141
Figure 9.3: Various types of microcracking in concrete [7].....	141
Figure 9.4: Chloride concentration profile for A) Reactive SH coarse specimens and B) Reactive Texas sand specimens.	146
Figure 9.5: Chloride concentration profile for A) Recycled concrete made with reactive coarse aggregates and B) Recycled concrete made with reactive sand.	147
Figure 9.6: A qualitative crack propagation model in ASR-affected conventional concrete [34].	150
Figure 9.7: Apparent chloride diffusivity of conventional concrete specimens.	151
Figure 9.8: Internal cracking caused by A) ASR from reactive sand and B) ASR from reactive coarse aggregates [23].	151
Figure 9.9: Total number of cracks for conventional concrete specimens [21].	152
Figure 9.10: Apparent chloride diffusivity of recycled concrete specimens.	153
Figure 9.11: Qualitative model representing crack propagation in recycled concrete for A) slightly damaged OVA and B) slightly damaged RM at secondary expansion levels of 0.05% and 0.20% [23].	154
Figure 9.12: Qualitative model representing crack propagation in recycled concrete for A) severely damaged OVA and B) severely damaged RM at secondary expansion levels of 0.05% and 0.20% [23].	154
Figure 9.13: crack counts for recycled concrete specimens [22].....	155

List of Tables

Table 2.1 Modified weighting factors for distress features [64].	31
Table 4.1 Aggregates used in this study and their properties.	47
Table 4.2 Mix proportioning of the specimens.....	47
Table 6.1 Description of acronyms used.	57
Table 6.2: Conventional and RCA mix proportioning.	61
Table 7.1: Aggregate types used in this study.	77
Table 7.2: Conventional concrete and RCA concrete mix proportioning.	78
Table 7.3: Overall assessment of ASR-induced damage on mechanical properties.....	88
Table 7.4: Two-variable ANOVA on the SDT outcomes (i.e., SDI and PDI) of all concrete specimens of this study.	89
Table 7.5: Two-variable ANOVA on the mechanical properties results (i.e., ME and CS) of all concrete specimens of this study.....	89
Table 7.6: t-Test analysis on the gathered results from the compressive strength of all concrete specimens of this study.....	89
Table 8.1 Aggregates used in this study and their properties.	108
Table 8.2 Mix proportioning of the specimens.....	108
Table 8.3: Two-variable ANOVA on the SDT outcomes (i.e., SDI, PDI and ME) of all concrete specimens of this study.....	129
Table 8.4: Two-variable ANOVA on the mechanical properties results (i.e., direct shear strength and CS) of all concrete specimens of this study.	129
Table 9.1 Surface chloride content CS, apparent diffusion coefficient D_{app} , and correlation factor R^2 obtained by fitting chloride profiles for cylindrical specimens.....	149

List of Acronyms

Term	Abbreviation
Portland Cement	PC
Recycled Concrete Aggregates	RCA
Construction Demolition Waste	CDW
Returned Concrete	RC
International Energy Agency	IEA
Supplementary Cementitious Materials	SCMs
Coarse Recycled Concrete Aggregates	CRCA
Fine Recycled Concrete Aggregate	FRCA
Original Virgin Aggregate	OVA
Residual Mortar	RM
Natural Aggregates	NA
Alkali-silica Reaction	ASR
Freeze & Thaw	F&T
Specific Gravity	SG
Direct Replacement Method	DRM
Direct Weight Replacement	DWR
Conventional Concrete	CC
Direct Volume Replacement	DVR
Equivalent Mortar Method	EMV
Modified Equivalent Mortar Volume Method	EMV-Mod
Equivalent Volume Method	EV
Particle Packing Models	PPM
Interfacial Transition Zones	ITZ
Saturated Surface Dry	SSD
Self-Compacting Concrete	SCC
Compressive Strength	CS
Silica Fume	SF
Modulus of Elasticity	ME
Alkali-aggregate Reaction	AAR
Accelerated Mortar Bar Test	AMBT
Damage Rating Index	DRI
Closed Cracks Within the Original Aggregate	OVA-CCA
Closed Cracks Within the New Aggregate	NA-CCA
Open Cracks Within the Original Aggregate	OVA-OCA
Open Cracks Within the New Aggregate	NA-OCA
Coarse Original Virgin Aggregate Debonded	OVA-CAD
Coarse New Aggregate Debonded	NA-CAD
Disaggregated/Corroded Original Virgin Aggregate	OVA-DAP
Disaggregated/Corroded New Aggregate	NA-DAP
Cracks in the New Cement Paste	NC-CCP
Cracks in the Residual Mortar	RM-CCP

Stiffness Damage Test	SDT
Stiffness Damage Index	SDI
Plastic Deformation Index	PDI
Rapid Chloride Penetration Test	RCPT
American Society for Testing and Materials	ASTM
Relative Humidity	RH
Springhill	SH
Texas	TX
Recycled Springhill Aggregate	RSH/RSPR
Recycled Texas Aggregate	RTX
Inductively Coupled Plasma Mass Spectrometry	ICP-MS
Concrete Prism Test	CPT
New Cement Paste	NCP
Residual Cement Paste	RCP
The maximum length of the cracks	$L_{\max}$
Maximum width of the cracks	$W_{\max}$
Canadian Standards Association	CSA

Foreword

The focus of this Ph.D. thesis is a thorough investigation of laboratory-made recycled concrete specimens with various ASR reaction sources. The study aimed to improve our understanding of the impact of pre-existing damage and the development of secondary alkali-silica reaction (ASR) and its effect on recycled concrete performance. To achieve this goal, the author conducted an assessment using various mechanical (i.e., Compressive strength, direct shear, and stiffness damage test) techniques and combined them with the microscopic results previously gathered. The results of this investigation provide valuable insights into the relationships between initial ASR-induced damaged and recycled concrete performance.

The first chapter of this thesis provides an overview of the main concepts and a brief introduction to the content of the rest of the thesis. The second chapter includes a literature review on the properties of recycled concrete affected by alkali-silica reaction (ASR) and the factors that influence ASR development in recycled concrete. In the third chapter, the objective of the research is presented, along with a description of the experimental methods used in the study. Chapter 5 provides a more detailed introduction to the four scientific papers that are included in the thesis. The first paper (i.e. Chapter 6), published in the journal *Materiales de Construcción* in June 2022, describes the development of a new direct shear setup to asses damage in concrete affected by ASR. Chapter 7, titled "Mechanical assessment of recycled concrete mixtures made with recycled concrete aggregate (RCA) affected by ASR," examines the impact of the severity of initial damage on the secondary induced expansion and mechanical properties reduction of recycled concrete made of reactive coarse RCA. Chapter 8, titled "Overall assessment of ASR-affected recycled concrete mixtures induced by reactive coarse and fine aggregates," uses a wide range of mechanical test procedures, such as the direct shear strength, stiffness damage test, etc., to appraise the impact of both the severity and location (i.e., fine vs coarse aggregate) of ASR initiation on the mechanical properties reductions of recycled concrete. In Chapter 9, entitled "Chloride diffusivity of Recycled Aggregate Concrete affected by Alkali-Silica Reaction," the results from the previous chapters are used to understand the impact of ASR on the chloride diffusivity of concrete made of recycled aggregates presenting distinct features and deterioration degrees. Finally, Chapters 10, 11 and 12 present future works, scientific and engineering contributions, conclusions and recommendations, respectively.

1. INTRODUCTION

Environmental impact of cement

Concrete is the most commonly used construction material worldwide due to its availability, economic benefits, and outstanding mechanical and durability-related properties. However, in 2018 a report by the *International Energy Agency (IEA)* links concrete production to approximately 7% of global carbon dioxide (CO₂) emissions, mainly due to Portland Cement (PC) production and aggregates processing [1].

PC manufacturing requires about 5 GJ of energy per ton, which places its production as the third most energy-intensive process after aluminum and steel [2]. Moreover, due to massive growth in construction over the last years, CO₂ emissions have constantly been rising from 5% in 2003 to 8% in 2006 [3]; this growth has already caused severe damage to the environment, and this impact may be even more pronounced in the future [4]. Global cement production is expected to increase 2.5 times between 2005 and 2050. From 2010 to 2017, it raised approximately 24%, a growth of around 113 million metric tons per year. Reducing the amount of PC used in concrete is thus essential to decrease the carbon footprint of concrete construction.

The *World Business Council for Sustainable Developments (WBCSD)* report states that changes are required in PC production to achieve a 2-Degree Celsius Scenario (2DS) [2]. The 2DS scenario describes an energy system that will give an 80% chance of limiting the average global temperature increase to 2°C based on the current trends. It sets the target of cutting energy-related CO₂ emissions by more than half in 2050 (compared with 2009) and ensuring that they continue to be lessened [1]. Figure 1.1 shows the cement composition estimate as shares of cement production on a mass basis.

Numerous efforts have been made to reduce the environmental impact of concrete and PC use. The two most effective strategies are replacing PC with supplementary cementitious materials (SCMs) and increasing PC efficiency with the help of advanced mix-proportioning techniques and inert fillers [5].

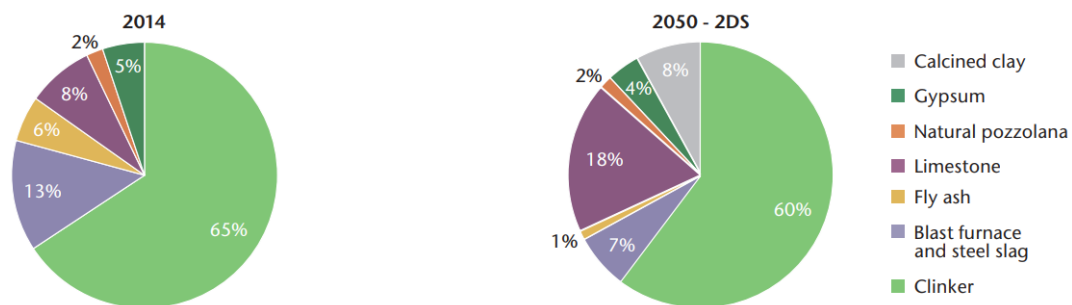


Figure 1.1: Cement composition estimates are provided as shares of cement production on a mass basis. 2050 global average cement composition estimates are based on the low variability case of the 2DS [2].

Environmental impact of aggregates

Portland Cement (PC) production is not the only factor increasing the carbon footprint of concrete construction; the excavation, processing, and transportation of raw materials are also accountable. Aggregates occupy 60 to 70 percent of concrete volume [6]. With the rapid urbanization and growth of population centers, the natural resources close to construction centers are depleted [7]. Sourcing high-quality aggregates near city centers is becoming more demanding; populated areas, such as the Greater Toronto Area, import most of their aggregates from neighbouring districts because nearby supplies have been depleting [8,9]. As the aggregate sources move further away from urban centers, the CO₂ emissions caused by aggregate transportation increase drastically. Ontario uses about 184 million tons of aggregate a year, of which about 13 million tons come from recycled sources [9]. Recycling is thus one of the best strategies to decrease the environmental impact of aggregates [4].

Recycled concrete aggregate (RCA) is produced by crushing hardened concrete reclaimed from either demolished structures (the so-called construction and demolition waste – CDW) or leftover concrete material (the so-called returned concrete -RC). By reducing the need for landfills along with lowering the requirements for excavation and significant processing of raw materials, RCA has proven to be a sustainable alternative to increase sustainability in concrete construction [10,11].

Construction and demolishing waste (CDW)

CDW is produced from demolishing concrete infrastructure, buildings, etc.; it occupies a significant number of landfills leading to soil and water contamination and causing many environmental concerns. In 2003, the United States Environmental Protection Agency (EPA) estimated that 170 million tons of CDW per capita per day were generated from construction, demolition, and renovation [12]. In 2017 the amount of CDW generated almost tripled, reaching 569 million tons [13]. In the United States, the Construction Materials Recycling Association (CMRA) accounts for the recycling of 10 million tons of CDW annually [14]. In Canada, CDW accounts for about 27% of all municipal solid waste disposed of in landfills [15].

Returned concrete (RC)

When concrete supplied is not entirely used or does not meet the requested criteria, the leftover material that returns to the manufacturing plant is defined as returned concrete (RC). The amount of RC varies from 1% to 5% and sometimes could be as high as 10% of the plant's total concrete production [16]. The majority of RC originates from over-ordering. The volume and characteristics of returned concrete from each truck vary significantly, making reusing this product challenging. Concrete plants are utilizing several strategies to reuse RC; some of the options used in the industry are:

- Identifying customers with similar specifications and delivery times.

- Use the leftover material in the development of the plant (i.e., pavements, company properties).
- Produce precast products.

The above strategies cannot be utilized consistently. One alternative method of recycling excess concrete is to dump it at a designated location within the plant, allowing it to harden. Once hardened, the material can be processed by crushing and sieving it to produce recycled concrete aggregate (RCA).

RCA produced from RC is likely to have better properties (i.e., no/minor contamination, lower properties variation, no/less pre-existing damage) when compared to CDW-RCA. Hence, by applying simple processes, concrete plants can utilize leftover concrete to produce high-quality RCA.

RCA derived from CDW and RC can be classified into two main groups: a) coarse recycled concrete aggregates (CRCA) and b) fine recycled concrete aggregate (FRCA). CRCA is a multi-phase material comprised of the original virgin aggregate (OVA) and residual mortar (RM), while FRCA is composed of OVA and the residual cement paste (RCP). Due to this distinct microstructure, CRCA and FRCA often display higher porosity and absorption and lower density when compared to natural aggregates (NA). Therefore, the current industry's perception is that CRCA and FRCA are inferior materials and should only be used in low-risk applications such as sidewalks, paving, and non-structural elements. Furthermore, another challenge when dealing with RCA is the presence of harmful chemicals and the potential for further distress in recycled concrete. In Canada, one of the main concerns when dealing with CDW derived from old structures is the presence of alkali-silica reactive aggregates.

Alkali-silica reaction (ASR) on recycled concrete

Alkali-silica reaction (ASR) is one of the most harmful distress mechanisms affecting concrete infrastructure worldwide. In most Canadian provinces, ASR reactive aggregates can be found. As such, a large number of critical Canadian infrastructures are affected by ASR (Figure 1.2) [17]. In severe cases, affected structures are demolished long before they reach their designed service life, creating significant amounts of waste. This presents an excellent opportunity to recycle the waste into RCA, but previous damage causes concerns since ASR is an ongoing damage mechanism, and its potential to generate further deterioration is not fully understood.



Figure 1.2: Location of quarries with reactive aggregate [17].

Although many studies focus on the potential reactivity of recycled concrete and its extent, inconsistencies exist concerning kinetics and the extent of ASR-induced damage in RCA. In general, the potential reactivity of recycled concrete may be linked to the material's microstructure, which in turn is influenced by the recycling process (i.e., crushing, sieving and washing). Furthermore, the so-called "secondary expansion" in ASR-affected RCA concrete is greatly affected by the quantity of remaining reactants (i.e., unstable siliceous phases and alkalis present in the residual mortar/cement paste) in the recycled concrete. Hence, the RCA replacement ratio, previous expansion level, and the quantity of new alkalis introduced to the system by the new cement could significantly affect ASR "secondary" kinetics and induced expansion in the recycled concrete.

Several studies have focused on the parameters affecting secondary expansion kinetics and potential [18–21]. Studies on ASR-induced cracks [22,23] have proven that the distress features of recycled concrete are greatly affected by initial expansion levels as well as the source of the reaction (i.e., RM and OVA). However, limited data is available on the effects of ASR-induced cracking on various mechanical and durability-related properties of ASR-affected recycled concrete.

Chloride diffusion in concrete

Chloride-induced steel corrosion is a major durability-related issue causing premature deterioration and loss of performance of reinforced concrete structures in Canada and worldwide. Billions of dollars are spent annually

on the upkeep, maintenance, and repair of reinforced concrete structures that have been deteriorated by corrosion [24]. One of the main factors in corrosion initiation is concrete resistance to chloride diffusion. Therefore, the resistance to chloride diffusivity is a crucial parameter affecting the durability of concrete structures. Chloride-induced corrosion can be categorized into two main groups (i.e., internal and external). The primary source of external chloride in cold countries is found in de-icing salts. Chloride-induced corrosion caused by internal chloride occurs due to contaminated components such as seawater in the concrete mix.

It is widely known that concrete is a very alkaline material (i.e., pH between 12.5-13), mainly due to the portlandite formation (i.e., $\text{Ca}(\text{OH})_2$) in the hydrated material. This alkaline environment generates a protection layer outlining the steel rebar, the so-called passivation layer, which prevents corrosion from being initiated. However, chloride ions can break the passivation layer, thus initiating corrosion. The amount of chloride required for the initiation of corrosion is conventionally referred to as the "critical chloride threshold." Moreover, the period required for the chloride ions to diffuse into the concrete cover and break the passivation layer is called the initiation period; it is followed by a propagation period where corrosion products are formed, inducing pressure and cracks in the concrete and causing the cross-section reduction of corroded rebars (Figure 1.3) and ultimately failure of the concrete element.

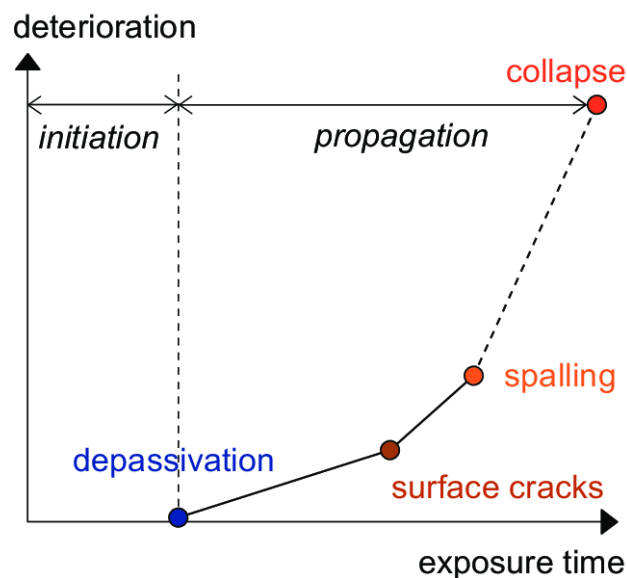


Figure 1.3: Two-stage mechanism of corrosion over time.

Although there are still developments to be done in the chloride diffusivity of conventional concrete, a vast amount of knowledge has been gathered over the last few decades on the matter, yet, much less is known on the chloride diffusivity of recycled concrete and the impact of ASR-induced damage on chloride diffusion. In this context, it is reasonable to think that the time required for chloride ions to de-passivate the steel rebar should be related to the features of the RCA (i.e., amount and quality of the residual mortar/cement paste content) in the recycled concrete. Past research has demonstrated that contradictory results can be obtained if the RCA features

and the mix-design technique are not accounted for [25]. Furthermore, the effects of "initial" deterioration of the RCA (e.g., ASR), which are also anticipated to impact the chloride diffusion into recycled concrete, have not been fully studied yet. Hence, additional research is required to understand better the effects of preliminary deterioration and inner microstructural quality on the chloride ingress parameters.

References

- [1] International Energy Agency. (2018). Cement technology roadmap plots path to cutting CO2 emissions 24% by 2050 - News - IEA. IEA;. Available from: <https://www.iea.org/news/cement-technology-roadmap-plots-path-to-cutting-co2-emissions-24-by-2050>.
- [2] International Energy Agency (2011). Technology Roadmap. Available from: https://doi.org/10.1007/springerreference_7300.
- [3] Müller, N., Harnisch, J. (2008) A blueprint for a climate friendly cement industry. Report for the WWF–Lafarge Conservation Partnership.
- [4] Silva, R. V., Brito, J. de, & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, 65, 201-217. <https://doi.org/10.1016/j.conbuildmat.2014.04.117>.
- [5] Damineli, B. L., Pileggi, R. G., & John, V. M. (2013). Lower binder intensity eco-efficient concretes. In *Eco-Efficient Concrete* (pp. 26-44). <https://doi.org/10.1533/9780857098993.1.26>.
- [6] Portland Cement Assosiacion. How Concrete is Made. Available from: <http://www.cement.org/cement-concrete-basics/how-concrete-is-made>.
- [7] Hansen, T. C. (1986). Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945-1985. *Materials and Structures*, 19, 201–246. Available from: <https://doi.org/10.1007/BF02472036>.
- [8] Hayles M. Investigation into the Mechanical Properties and Structural Behaviour of Recycled Concrete Members [Master’s Thesis]. University of Ottawa; 2018. <http://hdl.handle.net/10393/37801>.
- [9] Ministry of Natural Resources Ontario. (2009). State of the Aggregate Resource in Ontario Study-paper 4. Final report.
- [10] Noël, M., Sanchez, L., & Fathifazl, G. (2016). Recent advances in sustainable concrete for structural applications. In *Sustainable Construction Materials and Technologies*. <https://doi.org/10.18552/2016/scmt4s210>.
- [11] Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A. G., Fournier, B., & Foo, S. (2006). Environmental benefits of green concrete. *IEEE EIC Climate Change Technology Conference, EICCCC 2006*. <https://doi.org/10.1109/EICCCC.2006.277204>.
- [12] Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44, 464-476. Available from: <https://doi.org/10.1016/j.conbuildmat.2013.03.014>.
- [13] United States Environmental Protection Agency (EPA). Proceedings of the Water Environment Federation. 2005;2012:726–737. Available from: <https://doi.org/10.2175/193864705783867675>.
- [14] Construction and Demolition Recycling Association. About CDRA. 2019. Available from: <https://cdrecycling.org/about/>

- [15] Yeheyis, M., Hewage, K., Alam, M. S., Eskicioglu, C., & Sadiq, R. (2013). An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. *Clean Technologies and Environmental Policy*, 15, 81-91. <https://doi.org/10.1007/s10098-012-0481-6>.
- [16] National Ready Mix Concrete Association NRMCA. TIP 19 - Reuse of Returned Concrete; 1798. <https://www.nrmca.org/wp-content/uploads/>
- [17] Sims, I., & Poole, A. B. (2017). *Alkali-aggregate reaction in concrete: A world review*. Taylor and Francis. <https://doi.org/10.1201/9781315708959>.
- [18] Delobel, F., Bulteel, D., Mechling, J. M., Lecomte, A., Cyr, M., & Rémond, S. (2016). Application of ASR tests to recycled concrete aggregates: Influence of water absorption. *Construction and Building Materials*, 124, 714-721. <https://doi.org/10.1016/j.conbuildmat.2016.08.004>.
- [19] Beauchemin, S., Fournier, B., & Duchesne, J. (2018). Evaluation of the concrete prisms test method for assessing the potential alkali-aggregate reactivity of recycled concrete aggregates. *Cement and Concrete Research*, 104, 25-36. Available from: <https://doi.org/10.1016/j.cemconres.2017.10.008>.
- [20] Shehata MH, Christidis C, Mikhael W, Rogers C, Lachemi M. Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction. *Cem Concr Res*. 2010;40:575–582. Available from: <https://doi.org/10.1016/j.cemconres.2009.08.008>.
- [21] Mukhopadhyay AK. An effective approach to utilize recycled aggregates (RAs) from alkali-silica reaction (ASR) affected Portland cement concrete. In: De Brito J, ed. *Handbook of Recycled Concrete and Demolition Waste*. Woodhead Publishing Limited; 2013. p. 555-575. Available from: <https://doi.org/10.1533/9780857096906.4.555>.
- [22] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., & Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. *Cement and Concrete Research*, 144, 106426. Available from: <https://doi.org/10.1016/j.cemconres.2021.106426>.
- [23] Trottier, C., Zahedi, A., Ziapour, R., Sanchez, L., & Locati, F. (2021). Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR). *Construction and Building Materials*, 269, 121250. <https://doi.org/10.1016/j.conbuildmat.2020.121250>.
- [24] Caré, S. (2003). Influence of aggregates on chloride diffusion coefficient into mortar. *Cement and Concrete Research*, 33(2), 223-229. [https://doi.org/10.1016/S0008-8846\(03\)00009-7](https://doi.org/10.1016/S0008-8846(03)00009-7).
- [25] Liang, C., Cai, Z., Wu, H., Xiao, J., Zhang, Y., & Ma, Z. (2021). Chloride transport and induced steel corrosion in recycled aggregate concrete: A review. *Construction and Building Materials*, 282. <https://doi.org/10.1016/j.conbuildmat.2021.122547>.

2. LITERATURE REVIEW

This chapter investigates the literature available on three main topics of interest in this research (i.e., recycled concrete aggregate, alkali-silica reaction, and chloride diffusivity). First, a detailed review of RCA, its physical and chemical properties, and advanced mix design techniques developed solely for recycled concrete is presented. Later, the impact of using recycled concrete aggregates on recycled concrete properties is discussed in detail. Moreover, a complete review of the alkali-silica reaction in conventional concrete and recycled concrete is presented. Lastly, a review of available research on chloride diffusion of concrete is presented, and the research gaps are discussed.

Recycled concrete aggregate (RCA)

Recycled concrete aggregate (RCA) is a by-product of recycling concrete from construction demolition waste (CDW) or returned concrete (RC). With a sudden rise in the construction industry, there are many environmental and economic benefits to using RCA as a sustainable alternative [1]. RCA is a multi-phase material composed of original virgin aggregate (OVA) and residual mortar (RM) [2]. Due to its unique structure, many physical attributes of RCA (i.e., porosity, texture, roughness, absorption, density) are different from those of natural aggregates (NA) [1,3]. The quality of RCA is greatly affected by its source. Typically, concrete produced from CDW contains a much higher amount of impurities and contamination when compared to RC. A few challenges when dealing with RCA are discussed in detail in the following section.

RCA production and challenges

CDW RCA

The lack of standards and specifications combined with the lack of knowledge of CDW recycling plant owners often results in undesirable properties (i.e., the presence of chemicals and contamination) of the final product [3]. As such, many impurities (i.e., glass, asphalt, wood) have been observed when dealing with RCA derived from these recycling plants. Hansen [4] reported that the presence of 30% of asphalt (in volume) could result in a compressive strength reduction of about 30% in recycled concrete made of contaminated RCA derived from CDW. Another factor affecting the hardened state properties of recycled concrete is the presence of harmful chemicals. Due to the exposure of concrete structures to a vast range of environmental conditions and chemicals, it is common to find harmful chemicals (i.e., sulphate, chloride, alkalis) when dealing with RCA manufactured from CDW. Researchers found that concrete subjected to marine environments tends to have higher chloride contents, limiting the use of RCA derived from demolishing those structures in reinforced concrete [5].

RC RCA

The ready-mix concrete research & education foundation [6] estimated that 2-10% of 341 million cubic meters of ready-mix concrete had been returned to the concrete plant. Moreover, returned concrete rarely suffers from significant damage (i.e., ASR, sulphate attack, freeze & thaw - F&T) since it is stored for a short period before being crushed and bears no or minimal amount of contaminants/impurities. Hence, availability and soundness make RC an excellent source for producing high-quality recycled aggregates.

Physical Properties of RCA

Specific gravity (SG)

Since the attached mortar often has a lower density than the OVA, the quality and amount of RM play a significant role in RCA's overall specific gravity (SG). The recycling procedure and the number of processing stages typically define the amount of RM adhered to the OVA particles in coarse RCA. Nagataki et al. [7] found that the higher the number of crushing stages, the higher the material's SG. This is due to the cumulative breaking of the attached RM during the consecutive crushing processes. Aside from the amount of RM, the original concrete's quality also plays a vital role in the material's density. For instance, high-strength concrete usually results in better RCA due to the better quality of the RM, bearing much less porosity than conventional concrete with lower compressive strength. In an experimental study, Nagataki et al. [7] tested RCA manufactured through a similar crushing process from three concrete mixtures presenting different strengths (i.e., 60.7, 49.0, and 28.3 MPa) and displaying saturated-surface dry densities of 2420, 2410, and 2379 kg/m³. The results showed that RCA made from the original concrete presenting the highest strength yielded higher SG values for the same amount of RM and OVA.

Size and features

Similar to natural aggregates, RCA can be classified into two main groups: a) coarse recycled concrete aggregate (CRCA) and b) fine recycled concrete aggregate (FRCA). Previous studies in the literature are mainly focused on CRCA, primarily by replacing a percentage of the coarse NA in the mix [8–11].

CRCA is a multi-phase material comprised of OVA and RM. Similarly, FRCA consists of fine OVA particles attached to residual cement paste (RCP). FRCA is considered a very low-quality material due to its high volume of RCP, resulting in low density, high porosity, and absorption [12–14]. Several studies have shown a correlation between the size of RCA and its density [15,16]. It has been found that in RCA with the same origin, the amount of RM increases as the particle's size decreases, resulting in a lower-density material. Likewise, water absorption is also affected by RM's variation; often, higher water absorption values are obtained in fine recycled aggregates [15].

Quality of the original concrete and RM

As previously stated, RCA is a multi-phase material consisting of OVA and RM. Thus, the quality of each of these components directly affects the overall quality of RCA. For instance, in RCA sourced from concrete mixtures of similar strength and crushing procedures, the mixture incorporating the densest OVA also displays a higher density. Moreover, some studies demonstrated that the cement paste is the weakest region in RCA and tends to govern recycled concrete's mechanical properties [3].

The original strength of concrete is what governs the quality of RM. Numerous studies have found that RCA produced from concrete mixtures displaying higher mechanical properties (i.e., compressive strength) display better resistance against fragmentation [11,16,17]. Furthermore, in a comprehensive experimental campaign, Ahimoghadam [18] showed that recycled concrete mixtures could easily achieve compressive strengths of 25,35 and 45 MPa using RCA sourced from an original 25 MPa mixture when mix-designed properly. Andreu et al. [11] found that it is possible to manufacture high-performance concrete (HPC) with 100% coarse RCA when the original companion concrete displayed compressive strength greater than 60 MPa.

Residual mortar (RM) content

Several studies have emphasized the impact of Residual Mortar (RM) content on the fresh, hardened, and durability-related properties of concrete made of RCA [19–22]. The amount and quality of RM are directly responsible for the unique properties of RCA. Although RM can be removed to attain natural aggregate features, the time, cost, and energy required are counterproductive. There are no standards for assessing the RM content of RCA, yet, various methods have been proposed to characterize it. Nagataki et al. [23] used hydrochloric acid dissolution to remove the attached mortar and applied a correction factor to account for the amount of aggregates dissolved in the acid. Sri Ravindra Rajah and Tam [24] used an electronic digital planimeter to measure the RM content in cubic samples made of white cement. Sanchez de Juan and Gutierrez [20] used a hammer to break and scratch the attached RM after subjecting the RCA samples to soaking and heat treatment.

Perhaps the most effective way to assess the RM content of RCA was developed by Abbas et al. [21]. The test procedure involves soaking the weighed sample of coarse RCA in a 26% by weight solution of sodium sulphate. The soaked sample is subjected to five cycles of F&T (i.e., 16 hours at -17° C in a freezer and 8 hours at 80° C in the oven) to dissolve the attached RM in the solution, and the mass loss is accounted for the percentage of RM (Equation 2.1). The amount of RM may be up to 60% of the total volume of coarse RCA, and it is related to the type and physical properties of OVA and the inner features of RM.

$$RM (\%) = \left(\frac{(W_{RCA} - W_{OVA})}{W_{RCA}} \right) \times 100 \quad \text{Equation 2.1}$$

Where: W_{RCA} = oven-dry mass of RCA before immersing in solution and W_{OVA} = final oven-dry mass after draining residual mortar from RCA.

Several studies have confirmed the testing procedure Abbas et al. [22] proposed to be very effective in quantifying the RM content of RCA without damaging the OVA [9,10,14].

Mix design procedures for recycled concrete

Direct replacement method (DRM)

The direct replacement method (DRM) can be named one of the first approaches to mix-design RCA concrete. DRM does not account for RCA's unique microstructure and treats it as a homogenous material such as natural aggregates. DRM can be divided into two categories: direct weight replacement (DWR) and direct volume replacement (DVR) [9,25]. Due to the presence of the attached mortar when mix-proportioning through DRM, RCA concrete has fewer aggregates compared to companion conventional concrete (CC). The lack of natural aggregates alongside the typically observed low quality of the RM (i.e., high porosity) often results in inferior fresh and hardened state properties [26–28]. Considerable improvement in fresh state properties has been observed when using DWR compared to DVR [27,29]. To counteract the above issues, recent studies have implemented higher amounts of PC and chemical admixtures, along with supplementary cementitious materials (SCMs) [3].

Furthermore, several studies have limited the replacement percentage of RCA to as low as 5% to mitigate the "side effects" of using recycled aggregates [8,28,30]. However, minimizing RCA's use and increasing the amount of PC (or binders in general) offsets the economic and environmental benefits of using RCA. Figure 2.1 compares the total amount of aggregates in the RCA concrete mix designed with conventional methods versus conventional concrete, assuming that the RCA has a 40% attached mortar. The addition of excess mortar poorly affects several properties and reduces the mix sustainability.

DRM RCA concrete vs conventional concrete

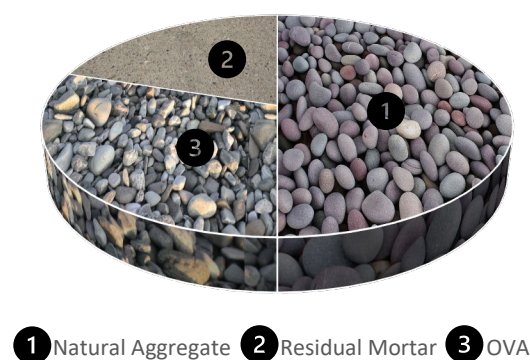


Figure 2.1: Comparison between the total amount of aggregates in RCA concrete mix designed with conventional methods VS conventional concrete.

Equivalent mortar method (EMV)

Due to the inferior mechanical properties achieved when mix proportioning recycled concrete with DRM, more advanced techniques were needed. Fathifazl et al. [2] proposed a new mix design technique that quantifies the amount of residual mortar attached to the OVA. The equivalent mortar volume (EMV) method treats the residual mortar of the RCA as mortar in the new concrete; hence, the new concrete's total mortar is equal to the summation of RM from RCA and freshly added mortar. Therefore, the amount of RCA to be used as a replacement for coarse aggregate is limited according to the amount of the RM of the RCA. RCA concrete proportioned using EMV proved to have similar or even better mechanical properties when compared with CC. However, EMV mixes often display challenging fresh-state properties.

Modified equivalent mortar volume method (EMV-Mod)

To improve RCA mixes fresh state, Hayles et al. [9] proposed a modified version of EMV called EMV-Mod. The EMV-mod mixes proved to have better fresh-state properties when compared to EMV. The EMV-Mod optimized the use of new cement by strategically increasing the amount of cement and reducing the sand content. Although enhanced fresh-state properties (i.e., lower consistency and higher flowability) are achieved with this method, the increase in the mixtures' cement content made EMV-Mod a less sustainable alternative when compared to CC and EMV.

Equivalent volume method (EV)

Ahimoghadam et al. [10] proposed a mix-design technique that aims to proportion recycled concrete mixtures with the same amount of aggregates (i.e., coarse and fine) and cement paste as companion conventional concrete mixtures. The EV mixes significantly improved the fresh state of CRCA concrete while being sustainable. Unlike EMV and EMV-Mod methods, EV mixes usually demonstrate proper fresh-state behaviour and cement efficiency (PC contents $\approx 300 \text{ kg/m}^3$). Moreover, it is worth noting that EV-proportioned mixtures display a significantly higher amount of fine aggregates in the system [18,31]. Figure 2.2 shows a comparison between the various mix design techniques used for proportioning recycled concrete.

Particle Packing Models (PPM)

To increase performance in the fresh and hardened states, Macedo [14] used particle packing methods (PPMs) to proportion recycled concrete made of fine RCA. The author adopted the same concept of the EV to proportion the recycled concrete mixtures; i.e., PPM-designed mixtures presented the same amount of aggregates and cement paste as companion CC mixtures. This approach proved to be an efficient method to increase the recycled mixtures' sustainability and fresh-state properties. Moreover, some durability-related properties of the recycled mixtures designed with PPM principles (i.e., resistance against freeze-thaw) presented a significant improvement compared to EV, and DRM approaches [14].

Pradhan et al. [25] applied PPM principles using a two-stage mixing approach to achieve a similar 28-day compressive strength for concrete mixtures made of 100% RCA compared to conventional companion concrete. The results showed that PPM approaches effectively increase the mechanical properties of recycled concrete, such as modulus of elasticity and tensile strength. All of the above demonstrates that using PPM to proportion recycled concrete is very promising to improve performance and decrease the carbon footprint of the recycled material.

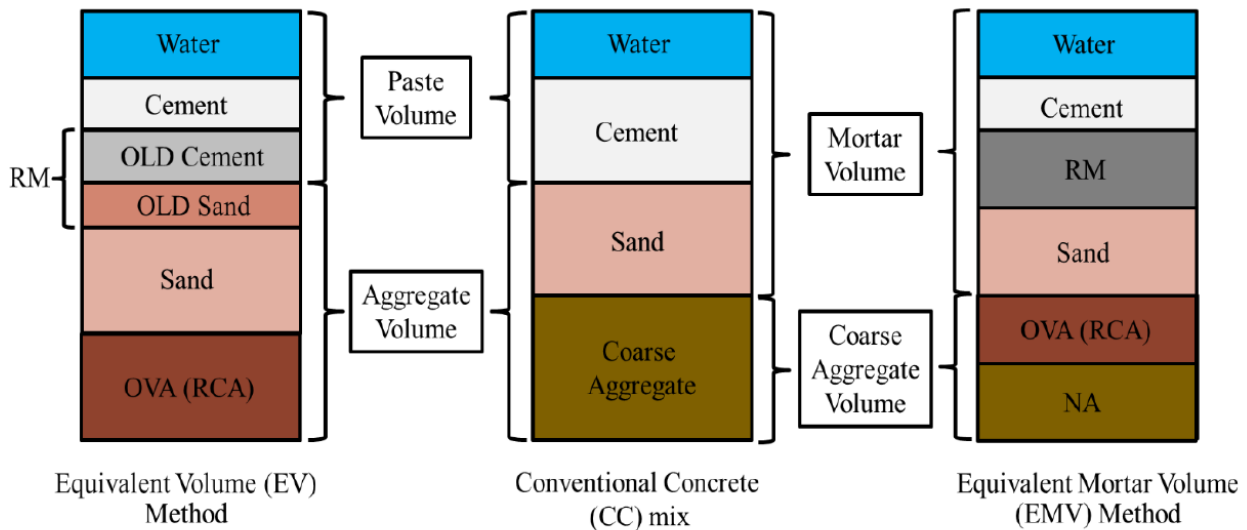


Figure 2.2: Volumetric material amounts of RCA mixtures designed with EMV and EV methods when compared to their initial CC mixes [18].

Properties of RCA concrete

Microstructure

The multi-phase microstructure of RCA (i.e., the presence of OVA and RM) significantly changes the microscopic features of RCA concrete. This unique microstructure brings a compositional difference from conventional concrete and the presence of distinct types of interfacial transition zones (ITZs). Figure 2.3 illustrates the three different types of ITZs presented in a recycled mixture made of 100% RCA:

- ITZ between new mortar (NM) and RM;
- ITZ between OVA and new mortar;
- ITZ between OVA and RM;

In conventional concrete with a compressive strength lower than 50 MPa, the failure mechanism starts at the ITZ (i.e., weakest zone), running to the cement paste as a function of loading, outlining the aggregate particles. Hence, one may claim that the failure of conventional concrete is dependent on the quality and inner properties

of the ITZ and cement paste and mostly independent of the aggregate features. However, due to its unique microstructure and the number of distinct ITZs in the system, one may expect that failure in recycled concrete will be described by a different mechanism than conventional concrete. Further investigations are still required on this matter.

Literature results indicate that the governing factor for RCA concrete strength and failure mechanism/mode is the quality of the RM. In the case of RCA produced from moderate to high-strength original concrete ($>35\text{MPa}$), the failure mechanism tends to happen around the RCA particles, starting at and propagating from the ITZ formed between the new and old mortar.

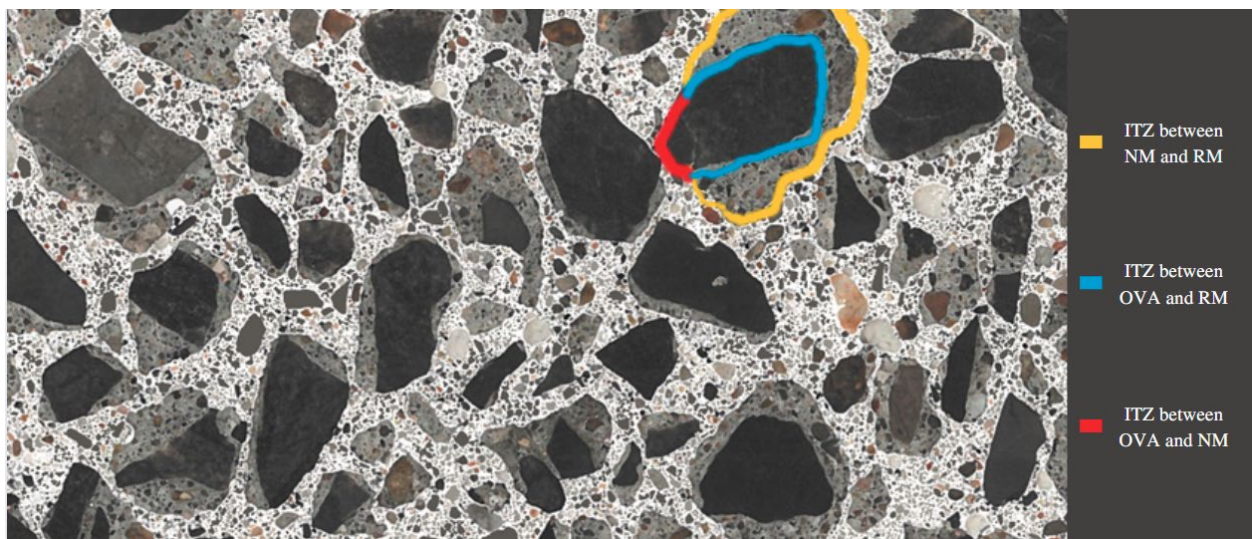


Figure 2.3: Cross-sectional area of a sample made with CRCA highlighting the various types of ITZ.

Fresh state properties of RCA concrete

As previously mentioned, RCA's physical properties (i.e., rough texture, high absorption, high porosity, low density) may cause inferior fresh state behaviour in recycled mixtures when compared to companion CC of similar water-to-cement ratio (W/C). To address the effect of high absorption during the early stages of concrete, Poon et al. [32] found that oven-dry CRCA had a higher initial slump and quicker slump loss when compared to saturated surface dry (SSD) CRCA. Zhao et al. [33] observed higher slump values for mortars containing oven-dry FRCA than mortars made of SSD FRCA. Aslani et al. [34] successfully used FRCA to mix-design high-performance self-compacting concrete (SCC) and mitigate the adverse effects of using FRCA by incorporating chemical admixtures and limiting FRCA use. The authors [34] recommended reducing the replacement percentage of natural sand and using chemical admixtures. Andal et al. [1] reported desirable fresh state properties (i.e., slump, slump loss) by limiting the replacement percentages and introducing manufacturing protocols to increase the quality of the RCA final product. Another approach to increase the fresh state performance of RCA concrete is by optimizing the mix-design procedure. Macedo [14] verified a significant

improvement in the rheological parameters (i.e., minimum torque required to enable flow, lower viscosity) in mixtures incorporating 100% FRCA by applying particle packing models (PPMs) principles to mix-proportioning recycled mixtures.

Durability and hardened state properties

Compressive Strength (CS)

Many researchers and construction industry experts consider compressive strength to be one of the most important properties (if not the most important) of concrete in the hardened state. The most critical factor that sets the hardened state properties (and thus compressive strength) of concrete is the W/C; other parameters such as PC type, maturity (i.e., time x temperature), aggregate features (i.e., shape, texture, lithotype), air content and curing process also play a crucial yet "secondary" role on the hardened state properties of the material.

Studies on the compressive strength of RCA concrete can be divided into five main categories:

- Studies treating RCA similar to NA: there are several studies [9,25,35] reporting RCA as an inferior product. In these studies, RCA is mainly treated as a NA, and conventional mixing techniques are used for proportioning the mixtures.
- Studies focusing on novel mix-design techniques: several studies [2,9,10,24,25,31,36,37] have proven that addressing the unique properties of RCA (i.e., presence of RM) during the mix design procedure is an effective way to improve the mechanical properties of RCA concrete.
- Studies using RCA treatment methods: researchers found that removing the RM is beneficial when mixing as per the DRM. Ismail and Rami [38] used low-concentration acid to manufacture high-quality RCA. In another study, Rajhans et al. [39] used a coat of sodium silicate and silica fume to improve the properties of a self-consolidating RCA mixture.
- Studies focusing on multiple-stage mixing techniques: Rajhans et al. [40] found that applying Two-Stage Mixing Approaches (TSMA) is an effective tool for improving the microstructure between the old and new cement paste, resulting in better mechanical properties by filling up cracks and pores.
- Studies using SCMs to improve the mechanical properties: several studies [36,41] have used SCMs to improve RCA's mechanical and durability-related properties. In experimental research, Çakır [41] claimed that the compressive strength of specimens containing 5%-50% silica fume (SF) significantly increases.

Although several research data are available for the compressive strength of RCA mixtures, the variability in the mix-design methods implemented, materials proportions, RCA replacement percentage, RCA source, and quality makes comparing studies very difficult. Numerous research projects using 100% RCA replacement [41–44] have reported significant compressive strength reductions (15-20%). Topcu & Sengel [45] reported a

reduction of down to 30% for specimens mix-designed using DRM. However, the use of advanced mix design techniques has proven very effective in mitigating the compressive strength loss of recycled concrete. Fathifazl et al. [2] achieved a similar compressive strength for recycled mixtures with 75% replacement levels by using the EMV method compared to CC.

Figure 2.4 illustrates the compressive strength loss in percentage vs. RCA replacement percentage for specimens displaying compressive strengths ranging from 35 to 55 MPa from several studies using the various approaches mentioned above. Studies incorporating slag and silica fume show a 20-30% compressive loss for concrete mixed with only RCA. Ismail and Ramli [38] showed that a treatment technique using hydrochloric acid is effective in removing the adhered mortar. In this study, the authors soaked the aggregates for one day in a 0.1 molar hydrochloric acid (0.1M1D).

Evidently, from Figure 2.4, the authors' selected approaches could not produce good quality concrete with desirable mechanical properties in specimens with 100% replacement levels. The most effective technique for using RCA is incorporating an appropriate mix-design technique, such as EMV or EV mix-design procedures.

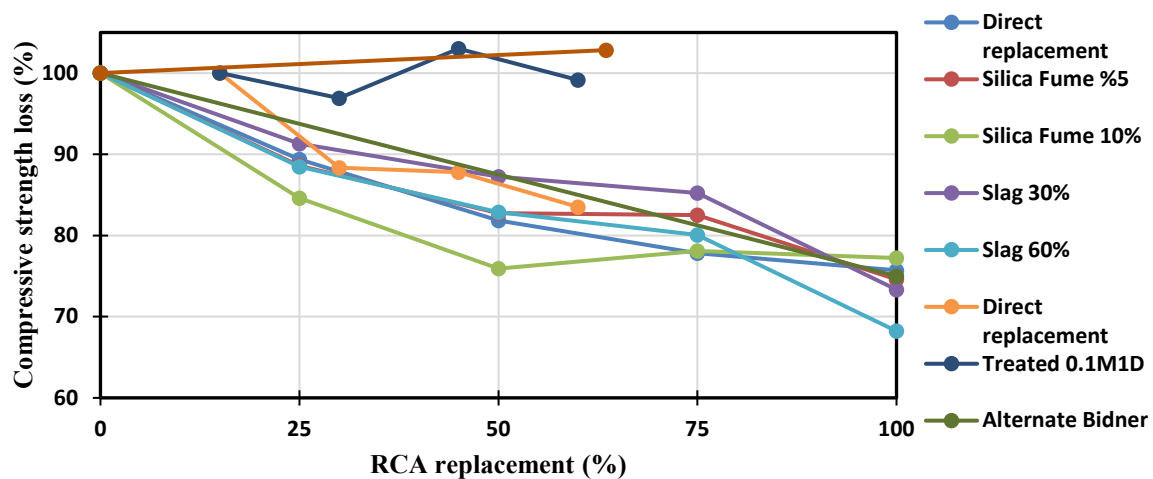


Figure 2.4 Compressive strength loss VS RCA replacement percentage [36,39,41,46].

Shrinkage

Similar to compressive strength, there are many discrepancies in reporting shrinkage values for RCA concrete. Domingo et al. [47] reported no significant difference for the first month of testing. After six months of testing, recycled mixtures incorporating up until 20% of replacement reported similar shrinkage values (i.e., 4% difference); yet, shrinkage values increased at replacement levels above 50%, where shrinkage was found to be higher in recycled mixtures (i.e., about 12% higher) compared to CC. Moreover, replacement ratios of 100% resulted in a significant shrinkage increase (i.e., about 70%) in recycled mixtures at six months.

Several studies [4,48,49] have also reported significantly higher values of shrinkage for RCA concrete with 100% replacement levels. Some researchers argued that this variation could be explained by the volume

difference of ingredients in RCA concrete mix-design using DRM instead of CC. Fathifazl et al. [50] investigated this phenomenon by mix-designing RCA concrete using the EMV method, resulting in a system with the same mortar and aggregate volume as the control mix. Fathifazl et al. [50] concluded that "the RCA-concrete mixes proportioned by the EMV method experienced lower or comparable shrinkage as the companion CC mixes."

Modulus of Elasticity (ME)

The elastic modulus of concrete is directly correlated to the coarse aggregates' amount and quality present in the cementitious system [51]. However, many factors have been linked to the modulus of elasticity in conventional concrete; Neville [52] found that the modulus of elasticity could be influenced by factors such as the cement paste, aggregate nature, and the ITZ.

When RCA concrete is mix-designed using the DRM (i.e., not accounting for the RM adhered in the RCA particles), the resulting recycled mixture presents much less coarse aggregates (in volume) than a companion conventional concrete (CC), which may impact the modulus of elasticity of recycled concrete. It has been found that recycled mixtures display a lower modulus of elasticity than conventional concrete, especially for mixtures with amounts of replacement higher than 50% [53].

Silva et al. [53] categorized the factors affecting the modulus of elasticity in RCA concrete. The main categories are RCA replacement level, RCA size, quality of the original concrete, mix design procedures, presence of admixtures and SCMs, environmental exposures in the original concrete, and age. Dhir et al. [54] found that low replacement values ($\leq 30\%$) have minimal impact on RCA concrete modulus of elasticity, while several studies [55,56] found that at 100% replacement values for CRCA elasticity modulus may fall as much as 20% to 40%. Figure 2.5 shows the results gathered by Silva et al. [53] from 476 concrete mixes made with various RCA types and sizes sourced from 35 publications.

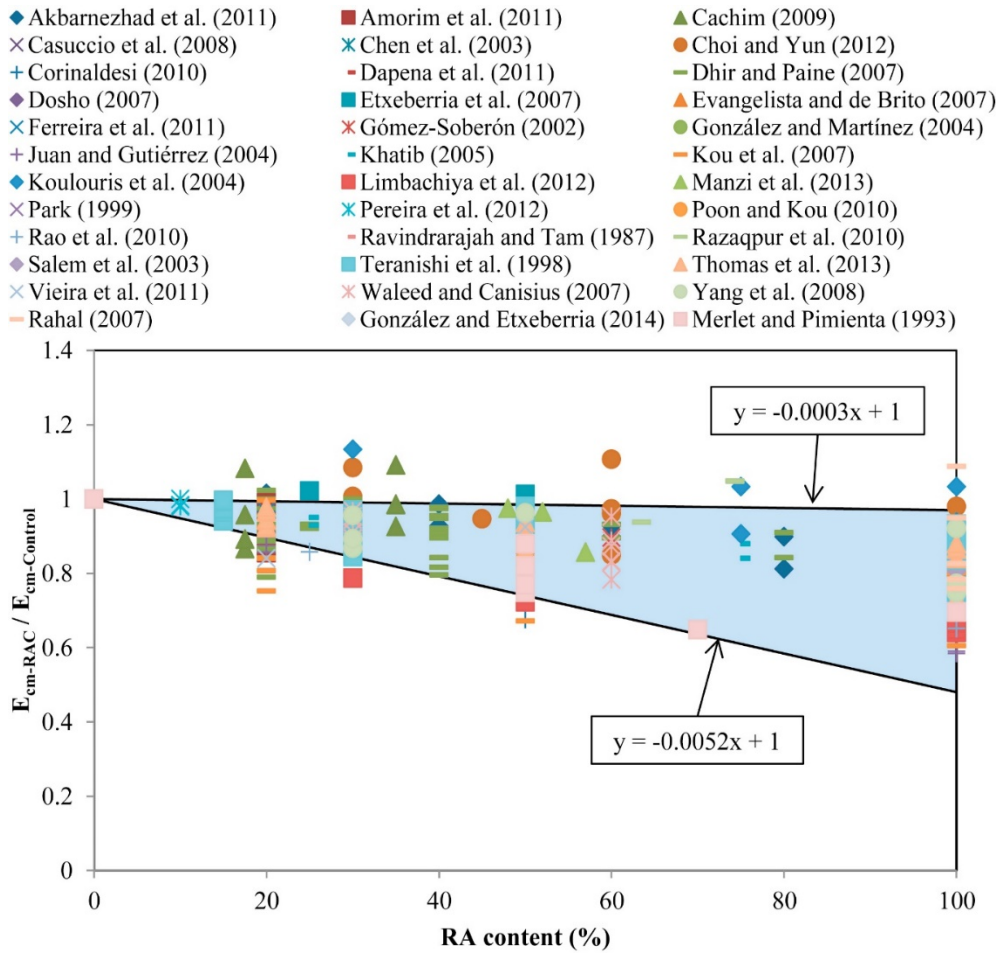


Figure 2.5: Effect of incorporating increasing RCA content on the relative modulus of elasticity of concrete [53].

Hansen and Boegh [55] linked the quality of the original concrete and replacement values to the modulus of elasticity loss. Figure 2.6 presents the modulus of elasticity of concrete with different target strengths produced with RCA sourced from materials with varying strength classes. Evidently, RCA from low-strength concrete materials (RAC-L) caused a more significant loss in the modulus of elasticity than RCA from high-strength concrete (RAC-H) [53].

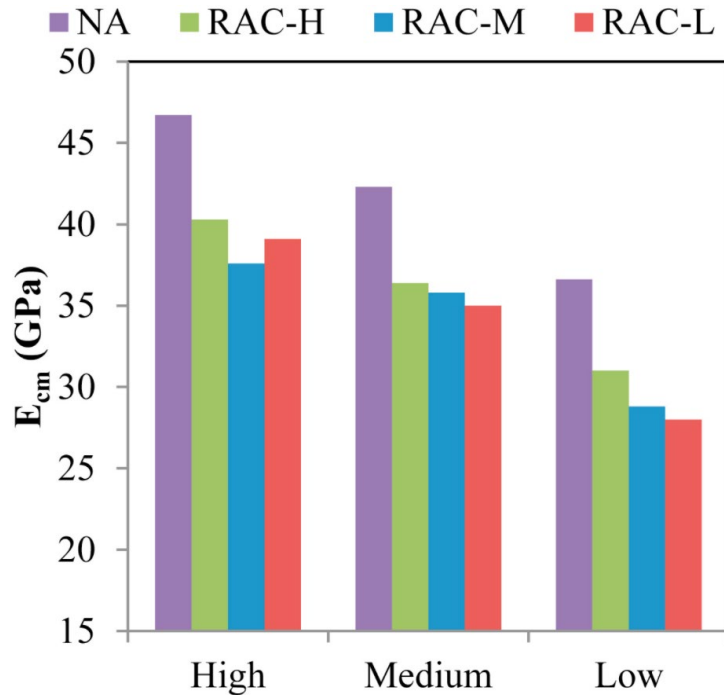


Figure 2.6: Effect of RCA from different sources on the modulus of elasticity [53,55].

Aside from the fresh state and hardened state challenges of recycled concrete, the presence of pre-existing damage in RCA could be another cause for concern. Among many other mechanisms impacting concrete inner structure, the alkali-silica reaction and freeze and thaw (F&T) are perhaps Canada's most common deterioration mechanisms.

Alkali-aggregate reaction

AAR in conventional concrete

Alkali-aggregate reaction (AAR) is one of the leading causes of concrete deterioration in Canada and worldwide [57]. The AAR-induced expansion causes the structures to reach their end of service life much before the time they were designed. Concrete structures affected by AAR require mitigation, rehabilitation, and in some severe cases, demolition. AAR is the reaction between the alkalis (Na^+ , K^+ , OH^-) from the pore solution of concrete and some mineral phases of the aggregates used in concrete production. AAR can be divided into two main categories: a) alkali-silica reaction (ASR) and b) alkali-carbonate reaction (ACR). ASR is the far more common form of AAR in Canada; thus, this thesis focuses on the effects of ASR on RCA concrete's mechanical and durability-related properties.

ASR reaction generates a gel-like product that swells upon water intake causing volumetric expansions and distress in concrete. The swelling pressure induces tensile stresses that may surpass concrete tensile strength

capacity, inducing cracking (Figure 2.7). In most Canadian provinces, quarries with reactive aggregates are within city centers, making them affordable and accessible.



Figure 2.7: Gardiner dam spillway in Saskatchewan, Canada, showing map cracking (right) [59].

In most cases, the cracking caused by ASR-induced expansion starts inside the aggregate particles where strained or poorly crystallized silica is present [58]. The cracks initiated inside the aggregate particles will continue propagating into the cement paste, forming an extensive network of cracks [58]. The cracking pathway is governed by the minimum energy law [58], along with the nature (i.e., mineralogy) and physical properties of the aggregates (i.e., texture and size). Generally, ASR developed within crushed aggregates form shaper cracks cutting through the particles, whereas, in natural round aggregates like gravel, ASR-induced cracks tend to outline the reactive aggregate particles (i.e., onion skin cracks). Figure 2.8 shows a sharp crack going through a greywacke aggregate and an onion skin crack surrounding polymictic gravel from New Mexico.

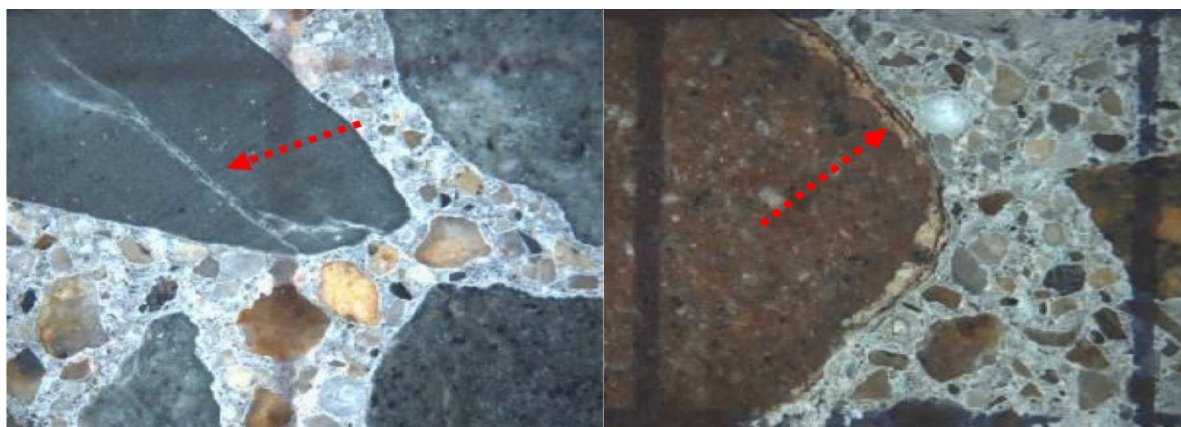


Figure 2.8: An ASR-induced sharp crack (on the left) and an onion skin crack (on the right) [59].

Another factor affecting the crack pattern in ASR-induced cracking is the aggregate type (i.e., fine vs coarse aggregate) [58]. In concrete affected by ASR initiating in reactive fine aggregate particles, the cracking network

is more dispersed as opposed to reactive coarse aggregates presenting widened and more localized cracks (Figure 2.9).

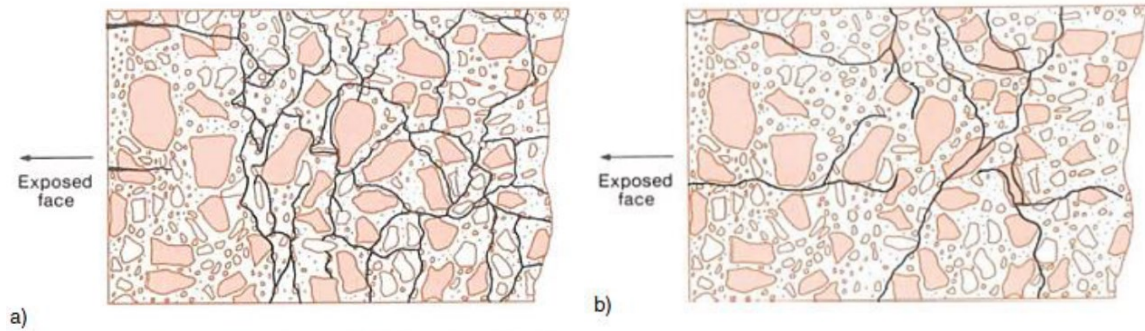


Figure 2.9: Crack distribution of ASR caused by a) reactive sand and b) reactive coarse aggregates [60].

ASR-induced damage can be categorized based on its expansion level. Sanchez et al. [58] proposed a qualitative model of crack propagation in ASR-affected conventional concrete (Figure 2.10). After a thorough investigation of concrete specimens incorporating various reactive aggregate particles, Sanchez et al. [58] proposed a qualitative ASR-induced crack development (Figure 2.10), where they initiate within the reactive aggregates at a low expansion level (i.e., 0.05%). As the reaction progresses, more cracks are generated, and the previously generated cracks are expanded into the cement paste at moderate expansion levels (i.e., 0.12%). As ASR continues to develop further (i.e., 0.20%), the previously generated cracks are lengthened and further propagate into the cement paste. Finally, at very high expansion levels (i.e., 0.30%), the previously mentioned cracks start linking together and generate a network of cracks [58]. Such induced cracking could significantly reduce the mechanical properties of ASR-affected concrete [61–64].

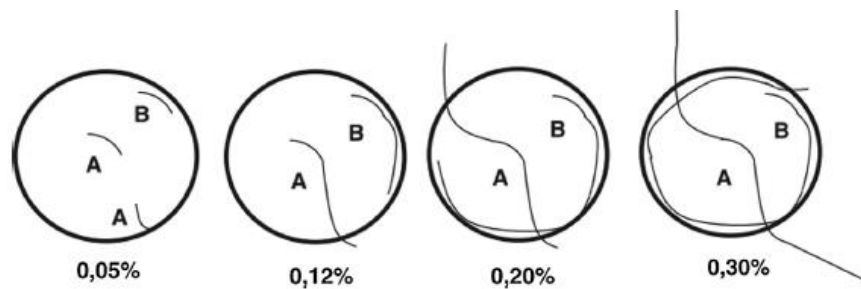


Figure 2.10: Qualitative model of crack propagation in ASR-affected concrete [58].

Mechanical properties of concrete affected by ASR

Concrete mechanical properties are greatly affected by ASR-induced cracks. However, not all aggregate types (i.e., coarse vs. fine aggregates) and nature (i.e., mineralogy) impact affected concrete similarly [64]. This section focuses on how these properties are affected in different stages of ASR (i.e., crack initiation and

propagation). The mechanical properties of conventional concrete affected by ASR, presented in this section, are later investigated for RCA.

Compressive strength (CS)

Concrete compressive strength reduction is directly correlated to ASR-induced expansion. Although the reduction percentage may vary from one aggregate to another, Sanchez et al. [64] found that at low expansion levels (i.e., crack initiation), concrete loses 10% of its compressive strength (on average). The low impact on the compressive strength of affected concrete is mainly due to ASR-induced cracks occurring within the aggregate particles. However, as the reaction proceeds (i.e., stable crack propagation), compressive strength reductions varying from 10% to 20% are observed [64]. At high expansion levels (i.e., $\geq 0.20\%$ expansion), concrete loses 20% to 30% of its compressive strength due to the formation of cracks in the cement paste, linking to one another in most cases [64]. Figure 2.11 illustrates the compressive strength loss of numerous concrete mixtures incorporating a variety of reactive aggregates as a function of ASR-induced expansion.

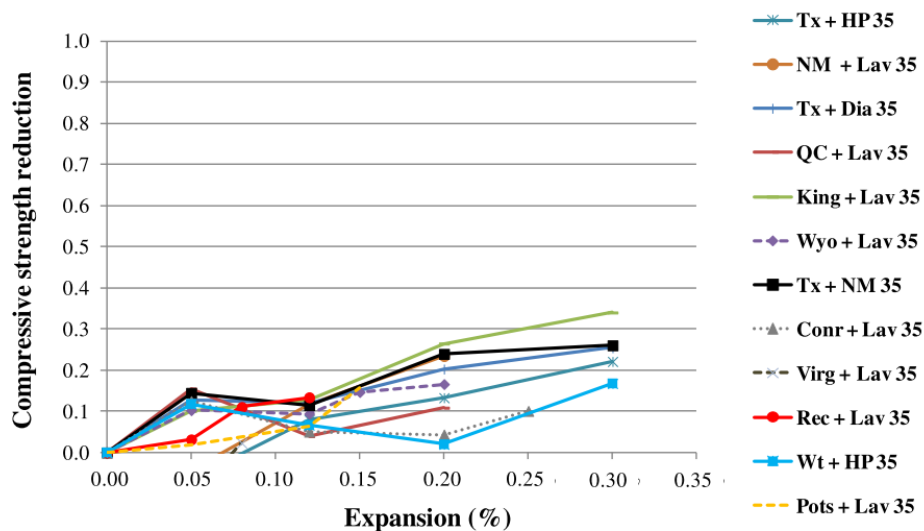


Figure 2.11: Compressive strength reduction of reactive 35 MPa mixtures [64].

Modulus of elasticity (ME)

As mentioned earlier, the elastic modulus of concrete directly correlates to the aggregates' amount and quality present in the cementitious system [51]. Generally, the modulus of elasticity is reduced as the reaction proceeds; at the early stages of the reaction (i.e., 0.05% and 0.12% expansion), crack initiation and propagation take place mainly within the reactive aggregate particles. As such, the modulus of elasticity of affected concrete is significantly reduced. Sanchez et al. [64] observed a reduction of 5-30% at low and 40-65% at very high expansion levels (on average), forming a "concave" lessening trend.

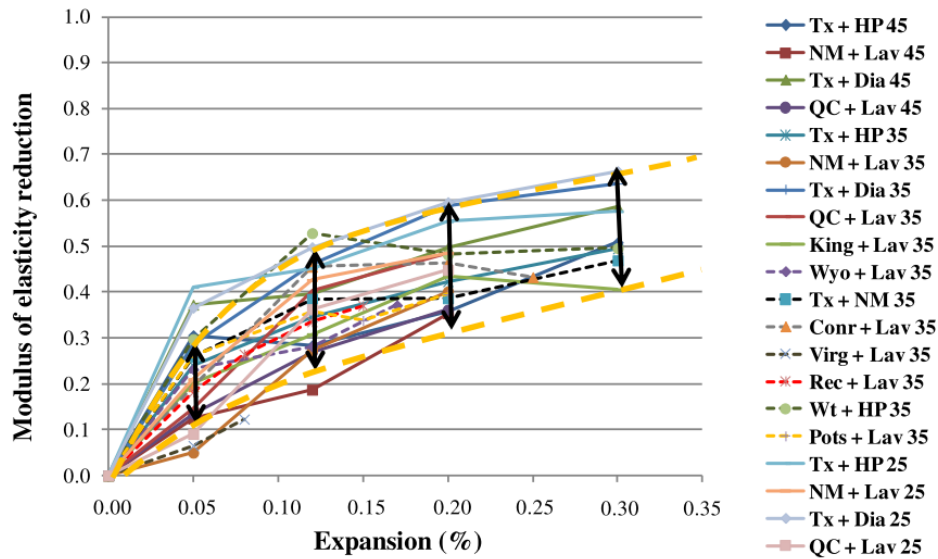


Figure 2.12: ME reduction of various reactive mixtures [64].

Direct shear strength

ASR seems to significantly influence the direct shear strength of affected concrete as a function of its development [65]. Although a reduction in shear strength towards ASR-induced development is observed for both fine and coarse reactive aggregates, the shear strength reduction kinetics are slightly different [65,66]. As per De Souza et al. [65], in the case of fine reactive aggregates, the main reduction in shear strength is observed at low expansion levels (0.05%), while the shear strength of specimens bearing reactive coarse aggregates remains intact. At moderate expansion levels (0.12%), the specimens incorporating reactive coarse aggregates experience a sudden reduction in shear. This could be explained by the models presented in Figure 2.10, which demonstrate that the aggregate interlock may be lost due to the presence of ASR-induced cracks in the aggregate particles at the early stages of the deterioration process. Furthermore, the direct shear strength of concrete specimens continues to lessen as a function of ASR expansion resulting in a reduction of up to 40% at the very high level of expansion [65]. Overall, reactive fine aggregates seem to have a more severe impact on the direct shear strength of CC [65,67].

ASR in RCA

The current European standards for *aggregates for concrete* (EN 12620) consider RCA bearing the potential to induce secondary expansion and deterioration in concrete. Although several studies have focused on evaluating the potential reactivity of RCA from distinct sources, inconsistencies were found in laboratory results, particularly regarding the secondary expansion kinetics (i.e., expansion rate and ultimate expansion) and deterioration of affected recycled concrete. This section focuses on the factors affecting the reactivity of recycled concrete.

The influence of the recycling process on ASR-induced development

The concrete recycling process involves crushing large rubbles of concrete into aggregates of different sizes. The RCA properties may vary depending on the number of crushing stages and crusher types. Subsequent crushing tends to decrease the size of particles, besides reducing the RM content of the particles. The initial concrete strength, aggregate type (i.e., stiff or non-stiff), and the presence of past damage are factors affecting crushed RCA properties. Concerns were expressed since subsequent crushing might expose OVA's reactive silica sites previously encapsulated to alkalis in the new mortar [68–72].

Shehata et al. [69] used ASR-affected concrete specimens under natural exposure for 12 years. The material was a concrete block ($0.6 \times 0.6 \times 2$ m) placed in 1991 using CSA Type 10 cement (a normal Portland cement) and a highly expansive alkali-reactive siliceous limestone coarse aggregate from the Spratt quarry in Ottawa, Ontario. The concrete block was used to produce two types of recycled concrete (i.e., primary crushing RCA and secondary crushing RCA). The authors used the accelerated mortar bar test (AMBT) to test the reactivity of RCA. In both cases of crushing, significant levels of expansion were observed. However, the subsequent crushing seems to be producing higher levels of expansion when the origin of ASR is the OVA, as shown in Figure 2.13 [69]. In another study by Johnson and Shehata [73], the effects of subsequent crushing and washing of the RCA on the secondary expansion potential were investigated. The results showed that the crushing procedure had the most influence on the reactivity potential of recycled concrete. It was observed that RCA with higher RMC resulted in lower expansions after 28 days using the AMBT [74]. Evidently, subsequent crushing reduces the RMC, and opening new exposure sites of the OVA increases the reactivity of RCA. On the contrary, if the reactivity originated in the RM (reactive sand in original concrete), the opposite would be true. However, further investigation is needed due to the lack of information on the effects of cracks introduced by crushing and RM potential in containing the expansion.

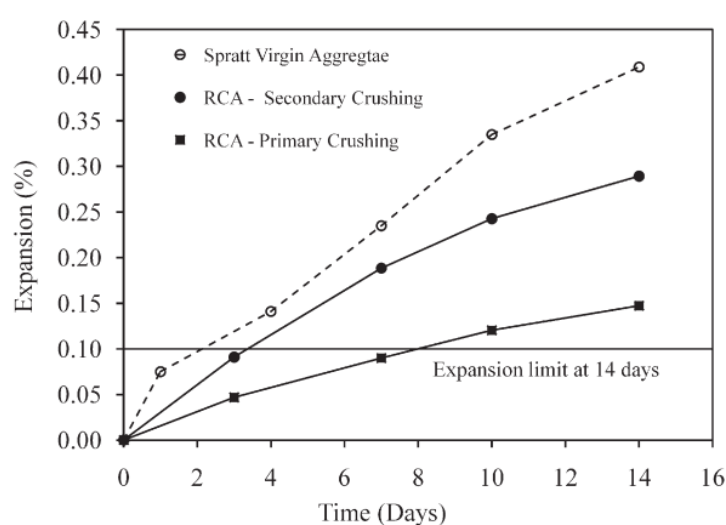


Figure 2.13: Potential reactivity of RCA and virgin aggregate in the AMBT [69].

The influence of washing and preparation on ASR-induced development

Washing the RCA particles is an effective way of removing contamination and finer particles. However, washing may impact secondary expansion kinetics and potential in ASR-affected RCA due to the potential of leaching of alkalis of RM and exposure of the gel to water. To preserve the alkali content of the pore solution (RM), Stark [75] proposed following the standard commercial practice of not washing the RCA. Shehata et al. [69] found that washing did not affect the expansion of recycled concrete over two years using the concrete prism test (CPT). Shehata et al. [69] concluded that the fresh source of alkalis in the new cement overcomes the loss of alkalis from washing the aggregates. This phenomenon could be affected if the new source of alkalis in the new cement is insufficient to generate secondary expansions in RCA concrete. While performing the standard washing practice prior to mixing the natural aggregates for the accelerated mortar bar test (AMBT), Adams et al. [76] observed that the water never ran clear. Hence, to avoid prolonged washing, which may further erode the RM, hydrate the un-hydrated cement, and leach calcium or alkalis from aggregate and the cement paste, the authors proposed a new washing method for RCA. Although the effect of washing seems negligible in long-term expansion potential, there is no agreement on whether ASR-affected RCA should be washed before mixing and the casting procedures.

The influence of RCA absorption and saturation degree on ASR-induced development

Due to the presence of RM, the absorption capacity of RCA is significantly higher than NA [32]. If not appropriately addressed, the RCA saturation state could lead to poor performance in fresh and hardened state properties [32]. The high water-to-cement ratio near the RCA particles in recycled concrete was correlated to poor mechanical properties observed when using RCA in saturated surface dry (SSD) conditions [32].

Delobel et al. [77] studied the influence of water absorption on the early expansion of reactive recycled concrete. Similar expansion levels (i.e., 0.22% and 0.29% of expansion) were observed for RCA in dry and soaked conditions. Moreover, the porosity of both recycled concrete specimens (dry and soaked) was also similar. This led the authors to believe the slight change in expansion was due to the difference in the pore size distribution (where larger pores were present in RCA with dry RCA allowing the reaction products to fill these voids and reducing the overall expansion). Beauchemin et al. [78] recommended using RCA under SSD conditions when concrete prism testing is to be performed. The authors [78] concluded that the RCA might only get partially saturated when mixed in dry conditions despite having a similar total water content resulting in lower expansion levels.

Factors affecting the secondary ASR-induced expansion in recycled concrete

ASR requires uncrystallized or poorly crystallized silica from the aggregates, alkalis from the cement, and moisture to be developed. Hence, the potential for the continuation of ASR in recycled concrete is affected by

the reactivity of OVA, the alkalinity of the original mortar, the alkalinity of new cement, and the previous expansion level achieved by the conventional concrete from which RCA derives.

RCA replacement ratio and reactive silica

Silica is one of the reactants provided by the aggregates in ASR-affected concrete. Depending on the initial expansion level, it may not have been completely depleted, thus, providing enough reactant for further expansions in recycled concrete.

The reactivity level of concrete also depends on the volume of reactive aggregates in the system. Hence, the replacement ratio seems to directly impact the reactivity of recycled concrete. Grattan-Bellew [79] showed that the specimens incorporating only 20 % reactive RCA and 80% non-reactive NA experienced no significant expansion. Santos et al. [80] confirmed this phenomenon by testing specimens incorporating various replacement ratios (i.e., 20%, 50%, 100% reactive RCA) (Figure 2.14). The specimens with 100% recycled aggregates reached an expansion level of 0.05% in less than 140 days, while it took specimens with a replacement ratio of 50% roughly 200 days and specimens with only 20% RCA did not achieve an expansion level of 0.05% after a year.

On the contrary, Tanner et al. [81] found that replacement percentages of 20% and 50% experienced the same reactivity potential. This phenomenon was also observed in the works of [82,83], where a 100% RCA replacement percentage resulted in lower expansions. It is believed that up to certain replacement levels, an increase in reactivity is observed [81–83].

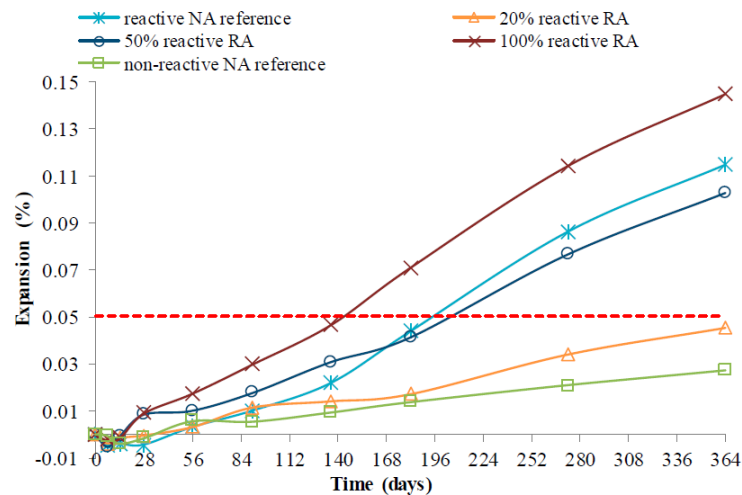


Figure 2.14: Evaluation of expansion [80].

Alkalis

The total alkali content in the system is another essential factor for ASR secondary expansion in recycled concrete. Stark [75] combined highly reactive coarse and fine aggregates to produce lab-made RCA; the NA was then mix-proportioned with Portland cement with 0.50, 0.75, and 1.00% of $\text{Na}_2\text{O}_{\text{eq}}$. The specimens were exposed for 48 months in accordance with ASTM C 227 test conditions. Stark observed that the highest expansion levels were achieved in the mixture with high alkali content (Figure 2.15).

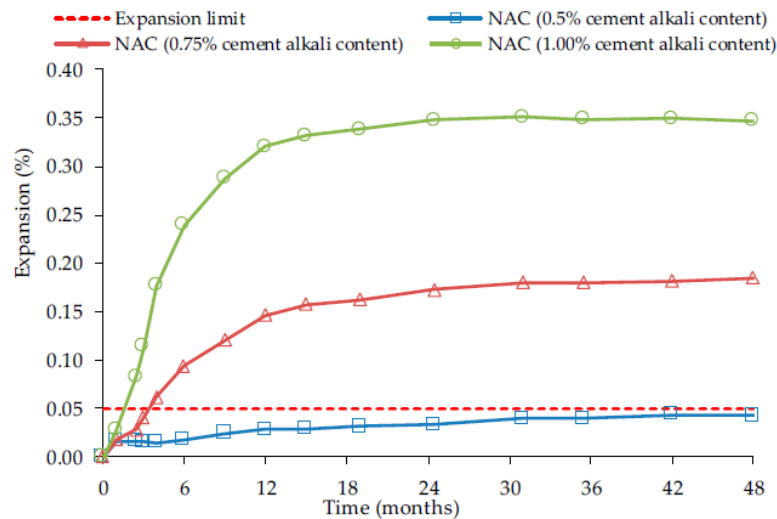
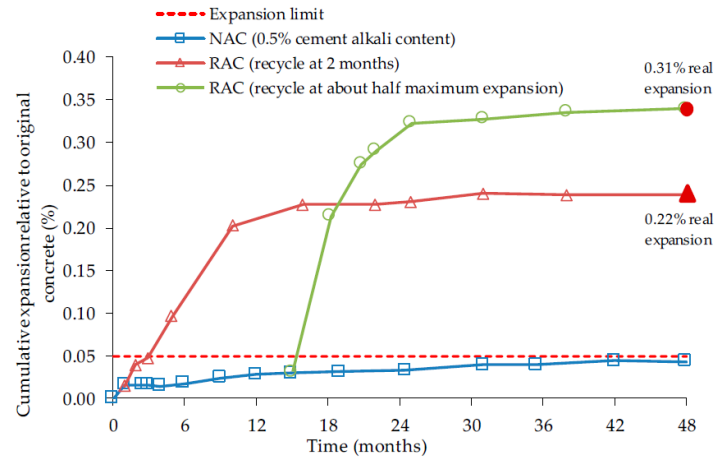


Figure 2.15: Expansion of NA with a cement of different alkali content [75].

To investigate the effect of original concrete alkali content on secondary expansions, the original concrete with the lowest and highest alkali content was then crushed at a) 2 months, b) half of the expansion potential, and C) at full expansion potential to produce RCA. In the case of low alkali content original concrete, regardless of the original expansion (i.e., half of the maximum expansion and after two months of exposure), recycled concrete has significant reaction potential when exposed to high alkali cement. For mixtures with high alkali content in the original concrete, the secondary expansion levels of 24% and 23% were observed for specimens recycled at full maximum expansion and recycled at half maximum expansion, respectively. The specimens crushed after two months showed no significant secondary expansions (Figures 2.16 A and B). Therefore, the alkali content of recycled concrete significantly impacts ASR-affected recycled concrete's reactivity regardless of the RM alkali content and initial expansion of the original concrete. It seems by creating new cracks in the system, the crushing process introduces a significant source of uncrystallized silica for secondary expansions. It must be noted that the cumulative expansion shown in Figures 2.16 A and B cannot be considered as “secondary expansion” and directly compared to ASR-induced expansion in CC.

A)



B)

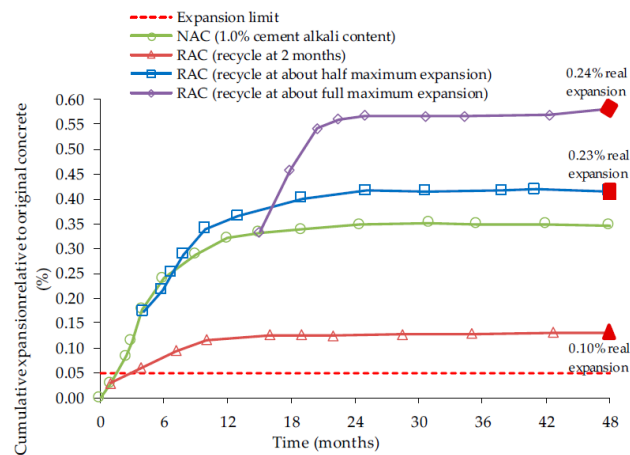


Figure 2.16: Expansion of high alkali mixes with CRCA from A) low alkali original concrete and B) high alkali original concrete [75].

Tools for assessing concrete damaged by ASR

Damage rating index (DRI)

The Damage Rating Index (DRI) is a semi-quantitative microscopic analysis developed by Grattan-Bellew and Danay [79], whose primary purpose is to appraise the extent of the internal damage in affected concrete. The DRI is performed on polished concrete sections using a stereomicroscope (15 to 16x magnification), where damage features are counted through one cm² grid drawn on the surface of a polished concrete section. Later, these distress features are multiplied by weighting factors proposed by Villeneuve & Fournier [84], which aim is to balance their relative importance towards the corresponding distress mechanism (e.g., ASR), and ultimately the final DRI number is thus calculated, and the higher the damage degree represented by a higher DRI number [64]. Ideally, a surface of at least 200 cm² should be used. However, the final DRI value is normalized to a 100 cm² area for comparative purposes. Sanchez et al. [58,85,86] performed the DRI on concrete samples presenting different strengths and fabricated with a wide range of coarse and fine aggregates. The authors proposed a slight

modification to the method to increase its performance and reliability [85]. Several studies have confirmed the relationship between ASR-induced expansion and DRI results [58,62,85–88]. Thus, the DRI is considered to be a very effective technique for assessing ASR-affected concrete regardless of the aggregate type and concrete strength [84].

The petrographic features included in the DRI assessment are listed in Figure 2.17, along with their corresponding weighting factors; some of the distress features can be observed and identified.

Crack Type	Weighting Factor
Cracks in coarse aggregate (CCA)	0.25
Opened cracks in coarse aggregate (OCA)	2
Crack with reaction product in coarse aggregate (OCAG)	2
Coarse aggregate debonded (CAD)	3
Disaggregate/corroded aggregate particle (DAP)	2
Cracks in cement paste (CCP)	3
Cracks with reaction products in cement paste (CCPG)	3

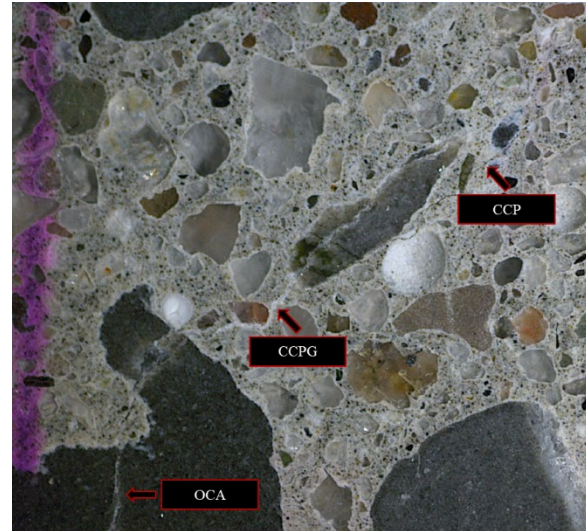


Figure 2.17: DRI weighting factors on the left and micrograph displaying some petrographic damage features on the right [59,87].

Sanchez et al. [86] proposed the utilization of petrographic damage features captured in DRI to develop an extended version. In the extended version of DRI, microscopic damage features presented in Figure 2.17 are evaluated in an absolute and relative (%) manner without applying weighting factors. The results obtained help towards a more comprehensive assessment and understanding of the ASR-induced development of affected concrete.

Zhu et al. [62] proposed a "modified extended DRI" to better understand ASR-induced expansion and deterioration in RCA concrete. The modified DRI method proved more suitable for capturing past (initial) and secondary expansions. The modified DRI factors are presented in Table 2.1.

Table 2.1 Modified weighting factors for distress features [62].

Crack Type	Abbreviation	Weighting Factor
Closed Cracks Withing the original aggregate Pericles	OVA-CCA	025
Closed Cracks Withing the New aggregate Pericles	NA-CCA	0.25
Open Cracks Withing the original aggregate Pericles	OVA-OCA	2
Open Cracks Withing the New aggregate Pericles	NA-OCA	2
Coarse Original Virgin Aggregate Debonded	OVA-CAD	3
Coarse New Aggregate Debonded	NA-CAD	3
Disaggregated/Corroded original virgin aggregate particle	OVA-DAP	2
Disaggregated/Corroded new aggregate particle	NA-DAP	2
Cracks in the new Cement paste	NC-CCP	3
Cracks in the residual mortar	RM-CCP	3

Stiffness Damage Test (SDT)

SDT is a mechanical and cyclic test procedure designed to assess damage in concrete specimens. SDT was first established by Walsh (1965) for evaluating rock specimens [89], being later adapted for concrete by Crouch (1987) [90]. Later, Chrisp et al. [91] and then Smaoui et al. [92–93] adopted this technique to assess the degree of ASR-induced damage on concrete specimens after performing the SDT using the fixed loads of 5.5 MPa and 10 MPa, respectively at the loading rate of 0.10 MPa/s. Finally, after an in-depth analysis of concrete with various reactive aggregates (sand and coarse) and compressive strength (i.e., 25, 35, and 45 MPa), Sanchez et al. [94] optimized the SDT procedure for appraising the condition of ASR-affected concrete specimens where they should be undergoing a 40% of the compressive strength instead of a fixed load. Furthermore, the authors [94] suggested using indices as outcomes of the test procedure, namely stiffness damage index (SDI) and plastic deformation index (PDI), representing the ratio of dissipated energy/plastic deformation and the total energy/deformation implemented in the system (i.e., $SI / (SI+SII)$ and $DI / (DI+DII)$) over the five cycles, respectively (Figure 2.18). Moreover, the modulus of elasticity, as an average secant modulus of elasticity value of 2nd and 3rd cycles of stiffness damage testing, would also be another output parameter for determining the extent of damage in the affected concrete. Very few works have been conducted to date on the effect of ASR-induced mechanical degradation on RCA concrete. As such, Zhu et al. [62] used SDT to assess the damage caused by past (i.e., low, moderate and high) and secondary (i.e., only moderate) expansion on RCA mixtures using the direct replacement of recycled concrete derived from construction demolition waste (CDW). Accordingly, the authors [62] suggested that the SDT is a reliable tool for assessing secondary damage regardless of the RCA's past expansion experience. Although the SDT has been shown to be quite suitable to

appraise ASR-induced deterioration in RCA concrete, the effect of various secondary damage on the mechanical degradation of RCA mixtures using advance mix design and SDT outcomes remains mostly unknown.

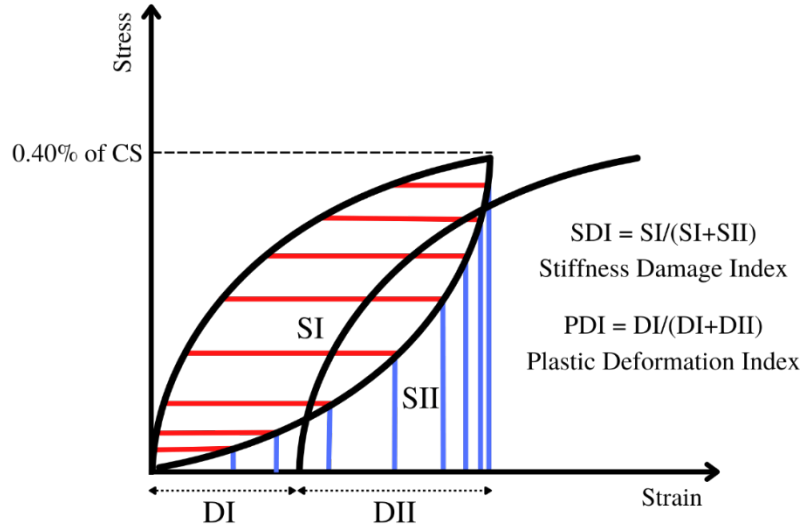


Figure 2.18: Calculation of SDI and PDI adopted from [94].

Corrosion initiation and chloride diffusivity

Chloride diffusion

Chloride diffusion is defined as the transfer of chloride driven by the difference in chloride concentration in various zones [95]. Along with other mechanisms, diffusion is often referred to as the primary chloride transport mechanism under most exposure conditions [96]. The theory behind diffusion is mainly based on the mathematical model proposed by Adolph Eugen Fick. Fick's diffusion theory assumes that the transport in the concrete of chloride ions through a unit area of a section of the concrete per unit of time (the flux F) is proportional to the concentration gradient of the chloride ions measured normally to the section (Equation 2.2).

$$F = -D \times \frac{\partial C}{\partial x} \quad \text{Equation 2.2}$$

Where D is called the chloride diffusion coefficient, D is not a constant but depends on many parameters, like the time for which diffusion has taken place, the concrete's location, and the concrete's composition (Figure 2.19).

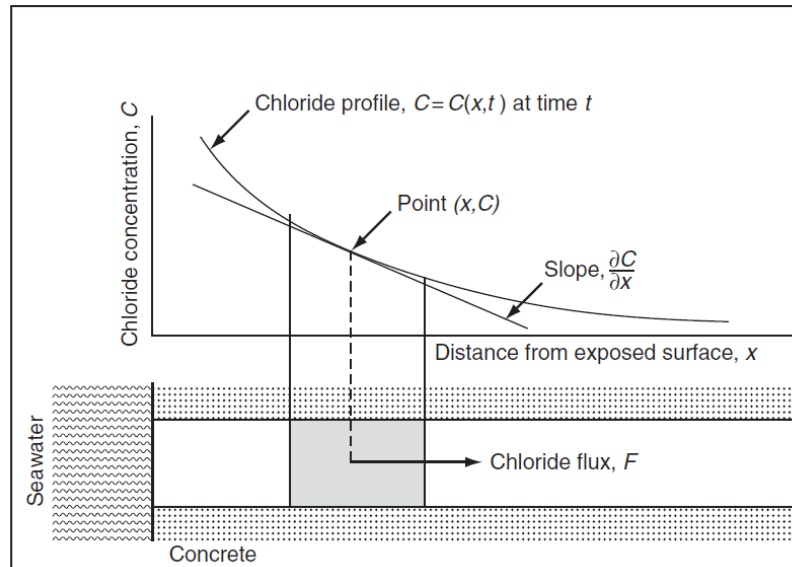


Figure 2.19: Flick's first general law of diffusion [95].

Effects of microcracking on chloride diffusion

Microcracks are present in concrete due to several causes, such as bleeding, shrinkage, thermal gradients, freeze-thaw, and alkali-aggregate reaction. Microcracks can act as flow channels and provide easy access to harmful chemicals and ions such as chloride ions [97]. The importance of microcracks has been highlighted recently [98]. The concrete cover's ability to protect could be significantly affected by microcracking. Lim et al. [97] studied the effects of micro-cracking on the chloride permeability of loaded specimens. Due to microcracks' ability to open and close under loading and unloading conditions, the authors [97] concluded that microcracks' influence on concrete transportation parameters could not be measured solely based on the crack length, and the specific crack area is a more sensitive parameter. Figure 2.20 shows a variety of microcracks present in concrete.

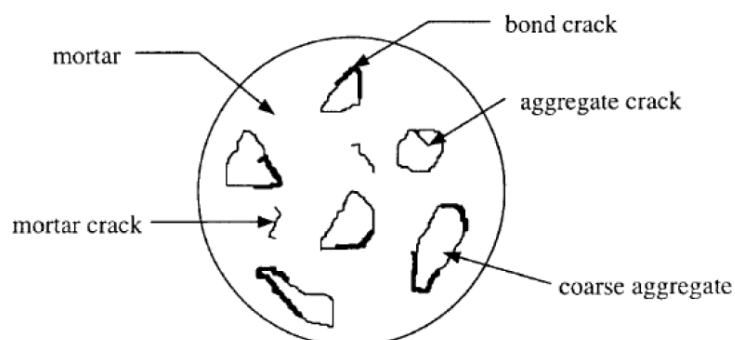


Figure 2.20: Various types of microcracking in concrete [97].

In another study by Samaha & Hover [99] on the influence of micro cracking on the mass transport properties, it was found that the proportion of aggregate in the concrete mix has a significant effect on the Rapid Chloride Penetration Test (RCPT) results and Internal microcracking damage caused by oven drying shrinkage has a greater effect on chloride transport than the damage caused by short term loading of concrete that is air-dried cured. Aside from cracks due to various loading types, deterioration mechanisms (i.e., F&T, ASR, and internal sulphate attack) could be another source of cracking in concrete.

Chung et al.[100] found that the specimen's chloride ion diffusivity is significantly increased after being subjected to F&T cycles. This could be explained by the increase in potential flow channels caused by F&T's extensive cracking network. ASR is another cracking mechanism affecting aggregates and cement paste. Trejo et al. [101] studied the effects of ASR-induced microcracks on corrosion. A fine reactive aggregate was used to generate ASR cracking. Trejo et al. [101] concluded that the time to corrosion initiation was not affected by ASR. The ASR gel had a significantly lower chloride value compared to hardened cement paste. In a similar study by Mazarei et al. [102], ASR affects corrosion initiation time in two ways: a) by increasing the chloride diffusion coefficient and b) by reducing the critical chloride threshold (C_T). The authors [102] concluded that the ASR gel reduces concrete's overall chloride diffusion coefficient by filling the cracks and the ITZ.

The effects of the Interfacial Transition Zone (ITZ) on chloride diffusivity

Due to the high porosity of the ITZ caused by the wall effect, the presence of ITZ can provide channels that facilitate the transport of chlorides [103,104]. The chloride diffusion coefficient of concrete can be significantly affected by the ITZ content. Delagrave et al. [105] reported that increasing the sand volume fraction in the mortar results in more connectivity of ITZs, facilitating the transport of chlorides into the mortar. The effective diffusion coefficient's main factor could be the Interfacial Transition Zone (ITZ) content [104,105]. In general, the ITZs diffusivity coefficient is reported to be 1.6 to 16.2 times greater than the bulk cement paste [104–106]. The presence of various types of ITZs due to the two-phase microstructure of the RCA could create new channels for chloride diffusion. Although there are some data on the impact of ASR-induced damage on the chloride diffusion of CC, no data is available on the chloride diffusion parameter of ASR-affected recycled concrete.

References

- [1] Andal J, Shehata M, Zacarias P. Properties of concrete containing recycled concrete aggregate of preserved quality. *Construction and Building Material*. 2016;125:842–855. Available from: <https://doi.org/10.1016/j.conbuildmat.2016.08.110>.
- [2] Fathifazl G, Abbas A, Razaqpur AG, Isgor OB, Fournier B, Foo S. New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*. 2009;21:601–611. Available from: [https://doi.org/10.1061/\(asce\)0899-1561\(2009\)21:10\(601\)](https://doi.org/10.1061/(asce)0899-1561(2009)21:10(601)).
- [3] Silva Rv, Brito Jde, Dhir RK. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Material*. 2014;65:201–217. Available from: <https://doi.org/10.1016/j.conbuildmat.2014.04.117>.
- [4] Hansen TC, RILEM Technical Committee 37-DRC Demolition and Reuse of Concrete. Recycling of demolished concrete and masonry; report of Technical Committee 37-DRC Demolition and Reuse of Concrete; 1992.
- [5] Paine KA, Dhir RK. Recycled aggregates in concrete: A performance-related approach. *Magazine of Concrete Research*. 2010;62:519–530. Available from: <https://doi.org/10.1680/macr.2010.62.7.519>.
- [6] Obla, K., Kim, H., & Lobo, C. (2007). Crushed Returned Concrete as Aggregates for New Concrete. National Ready Mixed Concrete Association. <https://trid.trb.org/view/1485308>
- [7] Nagataki S, Gokce A, Saeki T, Hisada M. Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and Concrete Research*. 2004;34:965–971. Available from: <https://doi.org/10.1016/j.cemconres.2003.11.008>.
- [8] Sadati S, Arezoumandi M, Khayat KH, Volz JS. Shear performance of reinforced concrete beams incorporating recycled concrete aggregate and high-volume fly ash. *Journal of Cleaner Production*. 2016;115:284–293. Available from: <https://doi.org/10.1016/j.jclepro.2015.12.017>.
- [9] Hayles M, Sanchez LFM, Noël M. Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. *Construction and Building Materials*. 2018;169:724–732. Available from: <https://doi.org/10.1016/j.conbuildmat.2018.02.127>
- [10] Ahimoghdam F, Sanchez LFM, de Souza DJ, Andrade GP, Noël M, Demers A. Influence of the Recycled Concrete Aggregate Features on the Behavior of Eco-Efficient Mixtures. *Journal of Materials in Civil Engineering*. 2020;32:04020252. Available from: [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003323](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003323).
- [11] Andreu G, Miren E. Experimental analysis of properties of high performance recycled aggregate concrete. *Construction and Building Materials*. 2014;52:227–235. Available from: <https://doi.org/10.1016/j.conbuildmat.2013.11.054>.
- [12] Fan CC, Huang R, Hwang H, Chao SJ. The effects of different fine recycled concrete aggregates on the properties of Mortar. *Materials*. 2015;8:2658–2672. Available from: <https://doi.org/10.3390/ma8052658>.

- [13] Florea MVA, Brouwers HJH. Properties of various size fractions of crushed concrete related to process conditions and re-use. *Cement and Concrete Research*. 2013;52:11–21. Available from: <https://doi.org/10.1016/j.cemconres.2013.05.005>.
- [14] De Freitas Macedo, H. (2019). Concrete Made with Fine Recycled Concrete Aggregate (FRCA): A Feasibility Study. University of Ottawa. <https://ruor.uottawa.ca/handle/10393/39619>.
- [15] Poon CS, Chan D. Paving blocks made with recycled concrete aggregate and crushed clay brick. *Construction and Building Materials*. 2006;20:569–577. Available from: <https://doi.org/10.1016/j.conbuildmat.2005.01.044>.
- [16] Gokce A, Nagataki S, Saeki T, Hisada M. Identification of frost-susceptible recycled concrete aggregates for durability of concrete. *Construction and Building Materials*. 2011;25:2426–2431. Available from: <https://doi.org/10.1016/j.conbuildmat.2010.11.054>.
- [17] Hansen, T. C., & Narud, H. (1983). Strength of Recycled Concrete Made From Crushed Concrete Coarse Aggregate. *Concrete International*, 5(1), 79-83. <https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=9140>.
- [18] Ahimoghadam, F. (2018). Effect of Recycled Concrete Aggregate Properties on the Behaviour of New Concrete (Master's thesis). University of Ottawa. <https://ruor.uottawa.ca/handle/10393/37588>.
- [19] Shayan, A., Xu, A. Performance and Properties of Structural Concrete Made with Recycled Concrete Aggregate. *ACI Materials Journal* 100 (5) (2003) 371-380. <https://doi.org/10.14359/12812>.
- [20] de Juan, M.S., Gutiérrez, P.A. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and Building Materials* 23 (2) (2009) 872-877. <https://doi.org/10.1016/j.conbuildmat.2008.04.012>.
- [21] Abbas A, Fathifazl G, Fournier B, Isgor OB, Zavadil R, Razaqpur AG, et al. Quantification of the residual mortar content in recycled concrete aggregates by image analysis. *Mater Charact*. 2009;60:716–728. Available from: <https://doi.org/10.1016/j.matchar.2009.01.010>.
- [22] Abbas, A., Fathifazl, G., Fournier, B., Isgor, O.B., Zavadil, R., Razaqpur, A.G., Foo, S. Quantification of the residual mortar content in recycled concrete aggregates by image analysis. *Materials Characterization* 60 (7) (2009) 716-728. <https://doi.org/10.1016/j.matchar.2009.01.010>.
- [23] Nagataki, S., Gokce, A., Saeki, T. Effects of Recycled Aggregate Characteristics on Performance Parameters of Recycled Aggregate Concrete. *ACI Symposium Publication* 192 (2000). <https://doi.org/10.14359/5741>.
- [24] Ravindrarajah, R.S., Tam, C.T. Properties of concrete made with crushed concrete as coarse aggregate. *Magazine of Concrete Research* 37 (130) (1985) 29-38. <https://doi.org/10.1680/mac.1985.37.130.29>.
- [25] Pradhan, S., Kumar, S., Barai, S.V. Recycled aggregate concrete: Particle Packing Method (PPM) of mix design approach. *Construction and Building Materials* 152 (2017) 269-284. <https://doi.org/10.1016/j.conbuildmat.2017.06.171>.

- [26] Manzi, S., Mazzotti, C., Bignozzi, M.C. Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement and Concrete Composites* 37 (2013) 312-318. <https://doi.org/10.1016/j.cemconcomp.2013.01.003>.
- [27] Knaack, A.M., Kurama, Y.C. Behavior of Reinforced Concrete Beams with Recycled Concrete Coarse Aggregates. *Journal of Structural Engineering* 141 (3) (2015) B4014009. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001118](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001118).
- [28] Tabsh, S.W., Abdelfatah, A.S. Influence of recycled concrete aggregates on strength properties of concrete. *Construction and Building Materials* 23 (2) (2009) 1163-1167. <https://doi.org/10.1016/j.conbuildmat.2008.06.007>.
- [29] Knaack, A.M., Kurama, Y.C. Design of Concrete Mixtures with Recycled Concrete Aggregates. *ACI Materials Journal* 110 (5) (2013). <https://doi.org/10.14359/51685899>.
- [30] Gomez-Soberon, J.M.V. Shrinkage of Concrete with Replacement of Aggregate with Recycled Concrete Aggregate. *ACI Symposium Publication* 209 (2002). <https://doi.org/10.14359/12516>.
- [31] de Freitas Macedo, H. (2017). Experimental Investigation of Recycled Concrete Fine Aggregates for Structural Applications. In Seminar of the Quebec and Eastern Ontario Chapter of ACI.
- [32] Poon, C.S., Shui, Z.H., Lam, L., Fok, H., & Kou, S.C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, 34(1), 31-36. [https://doi.org/10.1016/S0008-8846\(03\)00186-8](https://doi.org/10.1016/S0008-8846(03)00186-8).
- [33] Zhao, Z., Remond, S., Damidot, D., & Xu, W. (2015). Influence of fine recycled concrete aggregates on the properties of mortars. *Construction and Building Materials*, 81, 179-186. <https://doi.org/10.1016/j.conbuildmat.2015.02.037>.
- [34] Aslani, F., Ma, G., Law {Yim Wan}, D., & Muselin, G. (2018). Development of high-performance self-compacting concrete using waste recycled concrete aggregates and rubber granules. *Journal of Cleaner Production*, 182, 553-566. <https://doi.org/10.1016/j.jclepro.2018.02.074>.
- [35] Hayles, M. (2018). Investigation Into the Mechanical Properties and Structural Behaviour of Recycled Concrete Members (Master's thesis). University of Ottawa. <http://hdl.handle.net/10393/37801>.
- [36] Abbas, A., Fathifazl, G., Isgor, O.B., Razaqpur, A.G., Fournier, B., & Foo, S. (2009). Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Cement and Concrete Composites*, 31(8), 555-563. <https://doi.org/10.1016/j.cemconcomp.2009.02.012>.
- [37] Razaqpur, A. G., Fathifazl, G., Isgor, B., Abbas, A., Fournier, B., & Foo, S. (2010). How to produce high quality concrete mixes with recycled concrete aggregate. In 2nd International Conference on Waste Engineering Management (ICWEM 2010) (Vol. 73, pp. 11-35). <https://experts.mcmaster.ca/display/publication150983>.
- [38] Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44, 464-476. <https://doi.org/10.1016/j.conbuildmat.2013.03.014>

- [39] Rajhans, P., Gupta, P.K., Kumar, R.R., Panda, S.K., & Nayak, S. (2019). EMV mix design method for preparing sustainable self compacting recycled aggregate concrete subjected to chloride environment. *Construction and Building Materials*, 199, 705-716. <https://doi.org/10.1016/j.conbuildmat.2018.12.079>.
- [40] Rajhans, P., Panda, S.K., & Nayak, S. (2018). Sustainable self compacting concrete from C&D waste by improving the microstructures of concrete ITZ. *Construction and Building Materials*, 163, 557-570. <https://doi.org/10.1016/j.conbuildmat.2017.12.132>.
- [41] Çakır, Ö. (2014). Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives. *Construction and Building Materials*, 68, 17-25. <https://doi.org/10.1016/j.conbuildmat.2014.06.032>.
- [42] Al-Mutairi, N., & Haque, M.N. (2003). Strength and Durability of Concrete Made with Crushed Concrete as Coarse Aggregates. In *Recycling and Reuse of Waste Materials* (pp. 499-506). <https://www.icevirtuallibrary.com/doi/abs/10.1680/rarowm.32521.0052>.
- [43] Abd Elhakam, A., Mohamed, A.E., & Awad, E. (2012). Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete. *Construction and Building Materials*, 35, 421-427. <https://doi.org/10.1016/j.conbuildmat.2012.04.013>.
- [44] Kou, S.C., & Poon, C.S. (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. *Cement and Concrete Composites*, 37, 12-19. <https://doi.org/10.1016/j.cemconcomp.2012.12.011>.
- [45] Topçu, İ.B., & Şengel, S. (2004). Properties of concretes produced with waste concrete aggregate. *Cement and Concrete Research*, 34(8), 1307-1312. <https://doi.org/10.1016/j.cemconres.2003.12.019>.
- [46] Gurdían, H., García-Alcocel, E., Baeza-Brotons, F., Garcés, P., & Zornoza, E. (2014). Corrosion Behavior of Steel Reinforcement in Concrete with Recycled Aggregates, Fly Ash and Spent Cracking Catalyst. *Materials*, 7(4), 3176-3197. <https://doi.org/10.3390/ma7043176>.
- [47] Domingo, A., Lázaro, C., Gayarre, F. L., Serrano, M. A., & López-Colina, C. (2010). Long term deformations by creep and shrinkage in recycled aggregate concrete. *Materials and Structures*, 43(8), 1147-1160. <https://doi.org/10.1617/s11527-009-9573-0>.
- [48] Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and Structures*, 33(9), 574-580. <https://doi.org/10.1007/BF02480538>.
- [49] Hansen, T. C. (1986). Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945–1985. *Materials and Structures*, 19(3), 201-246. <https://doi.org/10.1007/BF02472036>.
- [50] Fathifazl, G., Razaqpur, A. G., Isgor, O. B., Abbas, A., Fournier, B., & Foo, S. (2011). Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate. *Cement and Concrete Composites*, 33(10), 1026-1037. <https://doi.org/10.1016/j.cemconcomp.2011.08.004>.
- [51] Mindess, S., Young, J. F., & Darwin, D. (2003). *Concrete* (2nd ed.). Prentice Hall.
- [52] Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson.

- [53] Silva, R. V., de Brito, J., & Dhir, R. K. (2016). Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. *Journal of Cleaner Production*, 112, 2171-2186. <https://doi.org/10.1016/j.jclepro.2015.10.064>.
- [54] Dhir, R. K., Limbachiya, M. C., & Leelawat, T. (1999). Suitability of recycled concrete aggregate for use in BS 5328 designated mixes. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 134(3), 257-274. <https://doi.org/10.1680/istbu.1999.31568>.
- [55] Hansen, T. C., & Boegh, E. (1985). Elasticity and Drying Shrinkage Concrete of Recycled-Aggregate. *ACI Journal Proceedings*, 82(5). <https://doi.org/10.14359/10374>.
- [56] Xiao, J., Li, J., & Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research*, 35(6), 1187-1194. <https://doi.org/10.1016/j.cemconres.2004.09.020>.
- [57] Sims, I., & Poole, A. (Eds.). (2017). *Alkali-Aggregate Reaction in Concrete: A World Review* (1st ed.). CRC Press. <https://doi.org/10.1201/9781315708959>.
- [58] Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74-92. <https://doi.org/10.1016/j.cemconres.2014.08.002>.
- [59] Trottier, C. (2020). *Evaluation of Alkali-Silica Reaction (ASR)-Induced Damage Generation and Prolongation in Affected Recycle Concrete* (Master's thesis). University of Ottawa. Retrieved from <http://dx.doi.org/10.20381/ruor-25317>.
- [60] British Cement Association. *Diagnosis of alkali-silica reaction*. London: 1992.
- [61] Zahedi, A., Trottier, C., Sanchez, L., & Noël, M. (2022). Evaluation of the induced mechanical deterioration of alkali-silica reaction affected concrete under distinct confinement conditions through the Stiffness Damage Test. *Cement and Concrete Composites*, 126, 104343. <https://doi.org/10.1016/j.cemconcomp.2021.104343>.
- [62] Zhu, Y., Zahedi, A., Sanchez, L. F. M., Fournier, B., & Beauchemin, S. (2021). Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. *Cement and Concrete Research*, 142, 106350. <https://doi.org/10.1016/j.cemconres.2020.106350>.
- [63] Sanchez, L.F.M., Fournier, B., Jolin, M. (2012). Critical Parameters of the Stiffness Damage Test for Assessing Concrete Damage Due to Alkali-Silica Reaction (ASR). In: *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction*.
- [64] Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17-31. <https://doi.org/10.1016/j.cemconres.2016.12.001>.

- [65] De Souza, D. J., Sanchez, L. F. M., & De Grazia, M. T. (2019). Evaluation of a direct shear test setup to quantify AAR-induced expansion and damage in concrete. *Construction and Building Materials*, 229, 116806. <https://doi.org/10.1016/j.conbuildmat.2019.116806>.
- [66] Ziapour, R., Trottier, C., & Sanchez, L. (2022). Assessment of AAR-induced expansion and damage through the direct shear test. 16th International Conference on Alkali-Aggregate Reaction in Concrete (ICAAR).
- [67] Ziapour, R. ., Trottier, C. ., Zahedi, A. ., & Sanchez, L. . (2022). Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete. *Materiales De Construcción*, 72(346), e280. <https://doi.org/10.3989/mc.2022.17621>.
- [68] Mukhopadhyay, A. K., Geiger, B. J., & Button, J. (2010). Use of Alkali-Silica Reaction-Affected Recycled Concrete Aggregate in Hot-Mix Asphalt. *Transportation Research Record*, 2179(1), 1-9. <https://doi.org/10.3141/2179-01>.
- [69] Shehata, M. H., Christidis, C., Mikhael, W., Rogers, C., & Lachemi, M. (2010). Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction. *Cement and Concrete Research*, 40(4), 575-582. <https://doi.org/10.1016/j.cemconres.2009.08.008>.
- [70] Li, X., & Gress, D. L. (2006). Mitigating Alkali-Silica Reaction in Concrete Containing Recycled Concrete Aggregate. *Transportation Research Record*, 1979(1), 30-35. <https://doi.org/10.1177/0361198106197900105>.
- [71] Mukhopadhyay, A.K. (2013). An effective approach to utilize recycled aggregates (RAs) from alkali-silica reaction (ASR) affected Portland cement concrete. In F. Pacheco-Torgal, V.W.Y. Tam, J.A. Labrincha, Y. Ding & J. de Brito (Eds.), *Handbook of Recycled Concrete and Demolition Waste* (pp. 555-568). Woodhead Publishing. <https://doi.org/10.1533/9780857096906.4.555>.
- [72] Pacheco-Torgal, F. (2013). Introduction to the recycling of construction and demolition waste (CDW). In F. Pacheco-Torgal, V.W.Y. Tam, J.A. Labrincha, Y. Ding & J. de Brito (Eds.), *Handbook of Recycled Concrete and Demolition Waste* (pp. 1-6). Woodhead Publishing. <https://doi.org/10.1533/9780857096906.1>.
- [73] Johnson, R., & Shehata, M. H. (2016). The efficacy of accelerated test methods to evaluate Alkali Silica Reactivity of Recycled Concrete Aggregates. *Construction and Building Materials*, 112, 518-528. <https://doi.org/10.1016/j.conbuildmat.2016.02.155>.
- [74] ASTM International. (2021). Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). ASTM C1260-21. <https://www.astm.org/c1260-21.html>
- [75] Stark, D. (1996). The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silico Reactivity. Research and Development Bulletin RD114. Portland Cement Association. https://www.cement.org/docs/default-source/fc_concrete_technology/durability/rd114-the-use-of-recycled-concrete-aggregate-from-concrete-exhibiting-alkali-silica-reactivity.pdf?sfvrsn=4&sfvrsn=4

- [76] Adams, M. P., Gray, B., Ideker, J. H., Tanner, J. E., Jones, A., Fournier, B., Beauchemin, S., Shehata, M., & Johnson, R. (2012). Applicability of standard alkali-silica reactivity testing methods for recycled concrete aggregate. In Proceedings of the 14th International Conference on Alkali Aggregate Reaction (ICAAR), Austin, TX, USA. <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-AdamsMP-1.pdf>
- [77] Delobel, F., Bulteel, D., Mechling, J.M., Lecomte, A., Cyr, M., & Rémond, S. (2016). Application of ASR tests to recycled concrete aggregates: Influence of water absorption. Construction and Building Materials, 124, 714-721. <https://doi.org/10.1016/j.conbuildmat.2016.08.004>.
- [78] Beauchemin, S., Fournier, B., & Duchesne, J. (2018). Evaluation of the concrete prisms test method for assessing the potential alkali-aggregate reactivity of recycled concrete aggregates. Cement and Concrete Research, 104, 25-36. <https://doi.org/10.1016/j.cemconres.2017.10.008>.
- [79] Grattan-Bellew, P. E. (1995). Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station. ACI Materials Journal, 92(2). <https://doi.org/10.14359/9763>.
- [80] Barreto Santos, M., Santos Silva, A., de Brito, J. (2016). ASR Impact on Concrete With Recycled Aggregates. 15th International Conference on Alkali-Aggregate Reaction, ICAAR, Sao Paulo. Available: <https://icaarconcrete.org/icaar-15/>.
- [81] Tanner, J., Fiore, B. (2015). Risk of Alkali-Silica Reaction When Using Recycled Concrete Aggregate in New Concrete: [Project Brief]. MPC 15-302. Available: <https://rosap.nrl.bts.gov/view/dot/39917>.
- [82] Adams, M. P., Jones, A., Beauchemin, S., Johnson, R., Fournier, B., Shehata, M., Tanner, J. E., & Ideker, J. H. (2013). Applicability of the Accelerated Mortar Bar Test for Alkali-Silica Reactivity of Recycled Concrete Aggregates, Advances in Civil Engineering Materials, vol. 2, no. 1, pp. 78-96. <https://doi:10.1520/ACEM20120030>.
- [83] Ideker, J. H., Adams, M. P., Tanner, J., Jones, A. (2013). Durability Assessment of Recycled Concrete Aggregates for use in New Concrete: Phase I - Revised. TREC Final Reports. <https://doi.org/10.15760/trec.15>.
- [84] Villeneuve, V., Fournier, B., Duchesne, J. (2012). Determination of the damage in concrete affected by ASR-the damage rating index (DRI). In 14th International Conference on Alkali-Aggregate Reaction (ICAAR). Austin, Texas (USA). <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-VilleneuveV-1.pdf>.
- [85] Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., Duchesne, J. (2016). Use of Damage Rating Index to Quantify Alkali-Silica Reaction Damage in Concrete: Fine versus Coarse Aggregate. ACI Materials Journal, 113(4). <https://doi.org/10.14359/51688983>.
- [86] Sanchez, L., Fournier, B., Jolin, M., Bastien, J., Mitchell, D., Noel, M. (2016). The use of the damage rating index (DRI) for the condition assessment of aging distressed concrete. In 15th International Conference on Alkali-Aggregate Reaction, Sao Paulo, Brazil. <https://icaarconcrete.org/wp-content/uploads/2020/11/15ICAAR-SanchezL-2.pdf>.

- [87] Trottier, C., Zahedi, A., Ziapour, R., Sanchez, L., Locati, F. (2021). Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR). *Construction and Building Materials*, 269, 121250. <https://doi.org/10.1016/j.conbuildmat.2020.121250>.
- [88] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. *Cement and Concrete Research*, 144, 106426. <https://doi.org/10.1016/j.cemconres.2021.106426>.
- [89] Walsh, J. B. (1965). The effect of cracks on the uniaxial elastic compression of rocks. *Journal of Geophysical Research* (1896-1977), 70(2), 399-411. <https://doi.org/10.1029/JZ070i002p00399>.
- [90] Crouch, R. S. (1987). Specification for the determination of stiffness damage parameters from the low cyclic uniaxial compression of plain concrete cores. Revision A, Mott, Hay & Anderson, Special services division, internal technical note.
- [91] Chrisp, T. M., Waldron, P., Wood, J. G. M. (1993). Development of a non-destructive test to quantify damage in deteriorated concrete. *Magazine of Concrete Research*, 45(165), 247-256. <https://doi.org/10.1680/mac.1993.45.165.247>.
- [92] Smaoui, N., Bérubé, M. A., Fournier, B., Bissonnette, B., Durand, B. (2004). Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part I: Experimental study. *Canadian Journal of Civil Engineering*, 31(5), 826-845. <https://doi.org/10.1139/104-051>.
- [93] Bérubé, M. A., Smaoui, N., Fournier, B., Bissonnette, B., Durand, B. (2005). Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part III: Application to existing structures. *Canadian Journal of Civil Engineering*, 32, 463-479. <https://doi.org/10.1139/L04-104>.
- [94] Sanchez, L.F.M., Fournier, B., Jolin, M., Bastien, J., & Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. *Construction and Building Materials*, 125, 1178-1188. <https://doi.org/10.1016/j.conbuildmat.2016.08.101>.
- [95] Poulsen, E. (2005). *Diffusion of Chloride in Concrete: Theory and Application* (1st ed.). CRC Press. <https://doi.org/10.1201/9781482295108>.
- [96] Karam, A. (2014) *Chloride Ingress into Submerged Concrete Under Sustained Load* (Ph.D. thesis). University of Ottawa, 2014. <http://dx.doi.org/10.20381/ruor-3507>.
- [97] Lim, C.C., Gowripalan, N., & Sirivivatnanon, V. (2000). Microcracking and chloride permeability of concrete under uniaxial compression. *Cement and Concrete Composites*, 22, 353-360. [https://doi.org/10.1016/S0958-9465\(00\)00029-9](https://doi.org/10.1016/S0958-9465(00)00029-9).
- [98] Rostam, S. (1996). High performance concrete cover—why it is needed, and how to achieve it in practice. *Construction and Building Materials*, 10(5), 407-421. [https://doi.org/10.1016/0950-0618\(96\)00007-4](https://doi.org/10.1016/0950-0618(96)00007-4).

- [99] Samaha, H.R., & Hover, K.C. (1992). Influence of microcracking on the mass transport properties of concrete. *ACI Materials Journal*, 89(4). <https://doi.org/10.14359/2585>.
- [100] Chung, C.-W., Shon, C.-S., & Kim, Y.-S. (2010). Chloride ion diffusivity of fly ash and silica fume concretes exposed to freeze-thaw cycles. *Construction and Building Materials*, 24(9), 1739-1745. <https://doi.org/10.1016/j.conbuildmat.2010.02.015>.
- [101] Trejo, D., Mazarei, V., Ideker, J. H., & Isgor, O. B. (2017). Influence of Alkali-Silica Reaction Reactivity on Corrosion in Reinforced Concrete. *ACI Materials Journal*, 114(5). <https://doi.org/10.14359/51689895>.
- [102] Mazarei, V., Trejo, D., Ideker, J. H., & Isgor, O. B. (2017). Synergistic effects of ASR and fly ash on the corrosion characteristics of RC systems. *Construction and Building Materials*, 153, 647-655. <https://doi.org/10.1016/j.conbuildmat.2017.07.097>.
- [103] Climent, M.A., de Vera, G., Viqueira, E., & López-Atalaya, M.M. (2004). Generalization of the possibility of eliminating the filtration step in the determination of acid-soluble chloride content in cement and concrete by potentiometric titration. *Cement and Concrete Research*, 34(12), 2291-2295. <https://doi.org/10.1016/j.cemconres.2004.04.012>.
- [104] Caré, S., & Hervé, E. (2004). Application of a n-Phase Model to the Diffusion Coefficient of Chloride in Mortar. *Transport in Porous Media*, 56(2), 119-135. <https://doi.org/10.1023/B:TIPM.0000021730.34756.40>.
- [105] Delagrave, A., Bigas, J. P., Ollivier, J. P., Marchand, J., & Pigeon, M. (1997). Influence of the interfacial zone on the chloride diffusivity of mortars. *Advanced Cement Based Materials*, 5(3-4), 86-92. [https://doi.org/10.1016/S1065-7355\(96\)00008-9](https://doi.org/10.1016/S1065-7355(96)00008-9).
- [106] Yang, C. C. (2003). Effect of the interfacial transition zone on the transport and the elastic properties of mortar. *Magazine of Concrete Research*, 55(4), 305-312. <https://doi.org/10.1680/macr.2003.55.4.305>.

3. Objectives

Although research has been done studying various aspects of ASR-affected recycled concrete, contradictory results of the RCA's influence on ASR-induced development are often found in the literature [1], and the impact of secondary damage is not fully understood. However, there is an agreement on factors affecting the potential of secondary induced expansion of RCA concrete, such as RCA type (i.e., fine vs coarse) and nature (i.e., reactivity degree, the remaining amount of poorly crystallized silica, amount of RM). Moreover, although several studies focused on assessing the potential secondary ASR-induced expansion, very little data are available on evaluating ASR-induced deterioration (i.e., cracks generation and propagation, mechanical properties losses, and physical integrity reductions). Furthermore, the effects of initial expansion (i.e., previous damage) on RCA's mechanical and durability-related properties, such as compressive strength, direct shear strength, SDT parameters, ME and chloride diffusivity, are not fully understood. In this regard, this work aims to answer the following questions:

1. What is the difference between ASR-induced damage in CC and secondary ASR-induced damage in RCA concrete?
2. How does the severity of pre-existing damage in original concrete (i.e., CDW and RC) affect ASR-induced development in recycled concrete?
3. How does secondary ASR-induced damage (i.e., crack generation and propagation) impact the mechanical properties of recycled concrete?
4. How does the reaction's location (source – OVA or RM) affect the properties of recycled concrete?
5. How does primary and secondary ASR-induced deterioration generated at distinct locations (i.e., fine vs coarse aggregate) and displaying different degrees (i.e., low vs very high) influence the chloride diffusivity of recycled concrete?

Hence, this work aims to appraise the implications of secondary ASR-induced development on damage generation and propagation, mechanical properties and physical integrity reductions, and durability-related properties (i.e., chloride penetration) of recycled concrete mixtures incorporating 100% of coarse RCA replacement displaying reactive aggregates bearing ASR reactive mineral phases in the OVA or RM and representing construction demolition waste (i.e., high deterioration) and returned concrete (i.e., low deterioration). Conventional concrete mixtures are manufactured incorporating reactive fine (Tx sand - Jobe) and coarse (i.e., SPR coarse) aggregates and then stored in conditions enabling ASR-induced development. At low (i.e., 0.05%) and very high (i.e., 0.30%) expansion levels (representing returned and demolished concrete, respectively), these materials were crushed into coarse RCA particles and were again stored in conditions enabling secondary ASR-induced development and monitored over time. Microscopic (i.e., DRI), mechanical

(i.e., SDT, direct shear, compressive strength) and durability related (i.e., chloride penetration) analyses were conducted at numerous secondary expansion levels selected for further analysis (i.e., 0.05%, 0.12%, 0.20%, and 0.30%). Analysis and comparison of the results obtained are finally conducted.

References

- [1] Barreto Santos, M., De Brito, J., & Santos Silva, A. (2020). A Review on Alkali-Silica Reaction Evolution in Recycled Aggregate Concrete. *Materials*, 13(11), 2625. <https://doi.org/10.3390/ma13112625>.

4. RESEARCH PROGRAM

As discussed in the previous sections, there are currently significant concerns in the concrete industry on the use of RCA in new concrete, particularly on the long-term and durability-related as well as mechanical properties of recycled concrete made of ASR-affected RCA. Therefore, this work aims to comprehensively investigate the mechanical (i.e., compressive and direct shear strengths, physical integrity, modulus of elasticity) and durability (i.e., secondary induced expansion and chloride penetration) properties of ASR-affected RCA concrete.

Experimental procedure

Due to the variability caused by the use of CDW in making recycled concrete and the minimal control over the original concrete properties, a reactive coarse aggregate (Springhill) and a reactive fine sand (Texas sand - Jobe) were selected for this research. The Springhill coarse aggregate (SH) was combined with non-reactive sand sourced locally in Ottawa to produce a set of concrete specimens. Moreover, Texas reactive sand was combined with a non-reactive Limestone coarse aggregate from Ottawa to produce another set of specimens. As per ASTM C1293 [1], all concrete specimens presented a cement content of 420 kg/m³ using a GU cement (i.e., similar to ASTM type1) and a water-to-cement ratio of 0.45. To accelerate alkali-silica reaction (ASR) induced development, the total alkali content in the mixture was raised to 1.25% Na₂O_{eq} by cement mass. A pan rotary mixer was used, and specimens were moulded into plastic cylindrical moulds. The specimens were de-moulded after 24 hours. To measure the longitudinal expansion of the specimens, stainless steel gauge studs (i.e., 5 mm in diameter by 15 mm deep) were drilled and glued in at both flat ends of the samples with the help of a fast-setting cement. Prior to the first reading, the specimens were left at room temperature for 24 hours. A 22-litre plastic container lined with an absorbent cloth was used to store the specimens in 38°C and 100% relative humidity (RH) environmental chambers. The longitudinal expansion of the specimens was measured weekly until the desired expansion levels (i.e., 0.05% - representing RC, and 0.30% - representing CDW) were achieved. It is worth noting that prior to the periodic expansion measurements, the containers were cooled down by placing them outside the chambers at room temperature (23°C) for 16 ± 4 hours. Upon reaching the desired expansion levels, the specimens were wrapped in plastic sealers and placed in a separate environmental chamber at 12°C to stop ASR's further development. Once all specimens reached the desired expansion levels, they were crushed using a jaw crusher to produce RCA. Once all the specimens were crushed, the aggregates were sieved, and the RM content of the aggregates was tested following the procedure proposed by Abbas et al. [2]. In order to calculate the RM content, the oven-dried RCA aggregates were weighed and then placed in a 26% by weight sodium sulphate solution. Later the soaked aggregates were placed in a controlled freezer (i.e., 17°C) for 16 hours and then placed in an oven (i.e., 80°C) for 8 hours. This cycle was repeated five times to remove the RM.

The RCA aggregates were then weighted, and the percentage of RM was calculated [2]. The aggregates used in this study are presented in Table 4.1.

Table 4.1 Aggregates used in this study and their properties.

Aggregate	Location	Rock Type	Specific gravity	Absorption (%)
Reactive coarse (Springhill-SH)	Fredericton, New Brunswick (Canada)	Greywacke	2.71	0.70
Non-reactive Coarse (Limestone – LS)	Ottawa, Ontario (Canada)	Limestone	2.78	0.42
Reactive fine (Texas – TX)	El Paso, Texas (USA)	Polymictic sand (granite mixed volcanic, quartzite, chert, quartz)	2.60	0.89
Non-reactive fine (Ottawa sand – OS)	Ottawa, Ontario (Canada)	Derived from granite	2.60	0.82

Using the four types of recycled aggregates shown in Figure 4.1, 0.05% recycled Springhill aggregate (0.05% RSH), 0.30% RSH, 0.05% recycled Texas aggregate (0.05% RTX), and 0.30% RTX, 250 recycled concrete specimens (i.e., 60 specimens for each type of reactive RCA) were produced. The equivalent volume method (EV) was used to ensure that the total volume of aggregates in the recycled concrete was equivalent to a companion CC; the mix proportions are presented in Table 4.2.

Table 4.2 Mix proportioning of the specimens.

Ingredients	Springhill CC	Texas CC	Slightly damaged Springhill RCA-concrete (0.05% RSH)	Severely damaged Springhill RCA-concrete (0.30% RSH)	Slightly damaged Texas RCA-concrete (0.05% RTX)	Severely damaged Texas RCA-concrete (0.30% RTX)
Cement (kg/m³)	420	420	340	331	336	335
Sand (kg/m³)	823	760	774	791	648	645
Coarse aggregate (kg/m³)	934	1024	1040	1048	1177	1177
Water (kg/m³)	189	189	153	149	151	151
RMC average (%)			46	51.5	44.5	45



Figure 4.1: Recycled aggregates incorporating distinct levels of damage in A) original virgin aggregate (OVA) and B) residual mortar (RM).

Compressive Strength

The compressive strength test was performed with two objectives. The main objective was to see the impact of ASR-induced expansion on the compressive strength of ASR-affected recycled concrete and how the source of the reaction affects the compressive strength. Due to the impact of ASR-induced damage on compressive strength and the time required for ASR development, ASTM C 39 [3] could not be followed. Instead, upon reaching the desired secondary expansion levels (i.e., 0.05%, 0.12%, 0.20%, and 0.30%), the specimens were wrapped in plastic and stored at 12° C, which has proven to prevent further ASR development. Later the specimens were tested following the procedure proposed by Sanchez et al. [4]. Three specimens were tested per expansion level, and to have similar maturity, companion conventional concrete samples were manufactured and stored at similar conditions (i.e., 38°C and 100% RH).

The second objective of the compressive strength test was to obtain the equivalent 28-day compressive strength to be later used as the ultimate load for the stiffness damage test (SDT).



Figure 4.2: compressive strength test setup for cylindrical concrete specimens.

Direct Shear Test

Similar to the previous mechanical testing, three specimens per concrete mixture (i.e., CC, 0.05% RCA and 0.30% RCA) and the desired expansion levels of this study (i.e., 0%, 0.05%, 0.12%, 0.20% and 0.30%) were prepared for the direct shear test. In this regard, initially, a circumferential 22 ± 1 mm deep [5] and 5 mm wide (i.e., the width of the diamond blade on the masonry saw) notch at the center of the specimens was cut to ensure a shear failure at the notch (Figure 4.2). The specimens were then tested in accordance with the setup and procedure proposed by Barr and Hasso [5]. The investigation by the authors [5] showed that the notch depths of 20 mm and 25 mm would result in a coefficient of variation of less than 10%. After further investigation of the notch depth and loading rate, a loading rate of 100 N/s and a notch depth of 22 ± 1 mm were selected for this study to minimize the variability of the results. Using the obtained failure load, the following equation was then used to calculate the direct shear strength:

$$\tau = \frac{4 \times P}{(\phi_{cylinder} - 2a)^2 \times \pi} \quad \text{Equation 4.1}$$

Where P denotes the failure load (N), $\phi_{cylinder}$ denotes the cylinder diameter (mm), and a denotes the depth of the notch (mm).

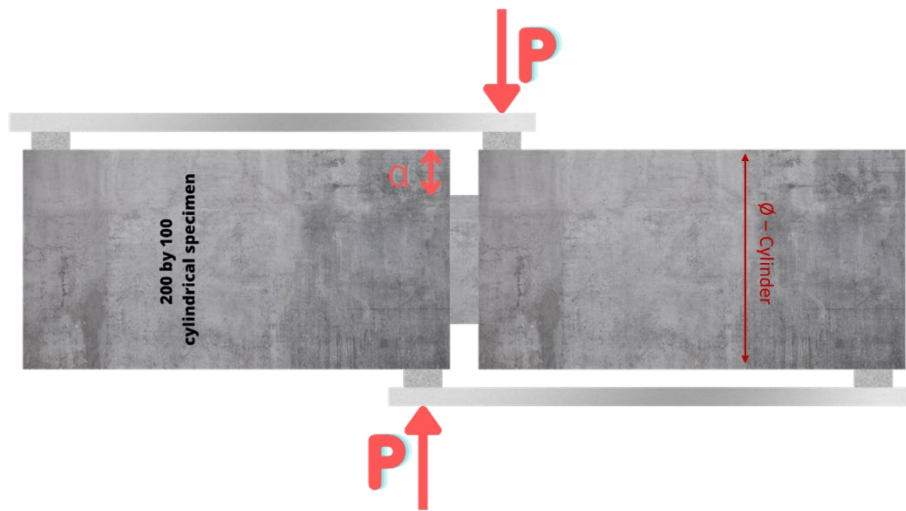


Figure 4.3: Shear setup for cylindrical concrete specimens [5].

Stiffness Damage Test (SDT)

The SDT was performed following the procedure proposed by Sanchez et al. [6]. After obtaining the equivalent 28-day compressive strength, three specimens per concrete type per expansion level were removed from the

environmental chamber, and the studs used for expansion measurements were removed. Later, both ends of the specimens were flattened using a profile grinder. Prior to testing, specimens were stored in a bucket filled with a film of water for at least 48 hours; this has proven to reduce the variability of the results. The specimens were later placed in the SDT cage, and five cycles of loading and unloading at a fixed loading rate of 0.10 MPa/s and up to 40% of the ultimate strength of the sound/undamaged concrete were applied.



Figure 4.4: SDT test setup for cylindrical concrete specimens.

Chloride diffusion sample preparation

To achieve a one-directional flow, the specimens had to be sealed with a water repellent. Hence, once the desired expansion levels were achieved, the specimens were taken out of the environmental chamber, and the stainless-steel studs were removed. A water-based high-performance clear hydro-stop sealer was applied to all the surfaces of the specimens, and the specimens were placed in a 60°C chamber for two hours to dry off the coating. This process was repeated two times, and once all the surfaces of the specimens were covered with the clear coat, a plastic-coat spray was used until a thick layer of coating was visible on the specimens. The specimens were then dried for 24 hours at room temperature. The specimens were weighed and placed in a water bath for 72 hours to ensure that specimens were entirely waterproof. Later, to remove the sealant, the flat top surface of the specimens was grinded off using a profile grinder.

Exposure conditions

As per ASTM C1556-11a [7], the specimens were immersed in a saturated calcium hydroxide water bath at 23 ± 2 °C in a tightly closed container until the mass of the specimens did not change by more than 0.1% in 24 hours. After removing the specimens from the calcium hydroxide bath, the specimens were completely rinsed using tap water and then immediately placed inside the exposure solution. Using 22-litre airtight buckets, the specimens described in Table 4.2 were immersed for six weeks at a temperature of 23 ± 2 °C in a NaCl exposure solution (165 g NaCl per 1 L of solution). The specimens were placed in a chamber with 50% relative humidity at 23 ± 2 °C for 24 hours. The specimens were then removed and stored in watertight polyethylene bags in a freezer maintained at -15 ± 5 °C until the time of grinding.

Powder extraction

The powder was extracted at eight distinct depths (i.e., 0-1, 1-3, 3-5, 5-7, 7-10, 10-13, 13-16, 16-20, 20-25 mm) as per ASTM 1556 using a profile grinder. The profile grinder and all the other equipment used in the process were thoroughly cleaned at each interval. A minimum of 5 g of concrete powder passing sieve number 20 was extracted at each depth interval.



Figure 4.5: Powder extracted from a specimen up to 13 mm.

Inductively coupled plasma mass spectrometry

Inductively coupled plasma mass spectrometry (ICP-MS) is a type of analytical technique used to determine the elemental composition of a sample. It works by introducing a sample into a high-temperature plasma, which ionizes the sample and creates a cloud of charged particles. These ions are then separated based on their mass-to-charge ratio using a mass spectrometer and detected by a detector. The resulting data is used to identify and

quantify the elements present in the sample. ICP-MS is a highly sensitive technique and is able to detect trace levels of elements in the sample [8,9]. The results gathered from the ICP-MS were later used to obtain the apparent chloride diffusion coefficient by means of a non-linear regression analysis following the procedure mentioned in ASTM C1556 [10].

References

- [1] ASTM International. ASTM C1293 - 20a Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction, (2020). URL: <https://www.astm.org/Standards/C1293/>
- [2] Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A. G., Fournier, B., & Foo, S. (2008). Proposed method for determining the residual mortar content of recycled concrete aggregates. *Journal of ASTM International*, 5(1), 1-12. <https://doi.org/10.1520/JAI101087>.
- [3] ASTM International. ASTM C39/C39M-14, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, 2014. https://www.astm.org/c0039_c0039m-14.html.
- [4] Sanchez, L.F.M., Fournier, B., Jolin, M., & Bastien, J. (2015). Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses. *Construction and Building Materials*, 77, 20-32. ISSN 0950-0618. <https://doi.org/10.1016/j.conbuildmat.2014.11.071>.
- [5] Barr, B. and Hasso, E.B.D. (1986) Development of a compact cylindrical shear test specimen. *Journal of Materials Science Letters*, 5(12), pp.1305-1308. ISSN 1573-4811. <https://doi.org/10.1007/BF01729401>.
- [6] Sanchez, L.F.M., Fournier, B., Jolin, M., Bastien, J., & Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. *Construction and Building Materials*, 125, 1178-1188. <https://doi.org/10.1016/j.conbuildmat.2016.08.101>.
- [7] Karam, A. (2014) Chloride Ingress into Submerged Concrete Under Sustained Load (Ph.D. thesis). University of Ottawa, 2014. <http://dx.doi.org/10.20381/ruor-3507/>
- [8] Bonta, M., Eitzenberger, A., Burtscher, S., & Limbeck, A. (2016). Quantification of chloride in concrete samples using LA-ICP-MS. *Cement and Concrete Research*, 86, 78-84. ISSN 0008-8846. <https://doi.org/10.1016/j.cemconres.2016.05.002>.
- [9] Silva, N., Tang, L., & Rauch, S. (2013). Application of LA-ICP-MS for meso-scale chloride profiling in concrete. *Materials and Structures*, 46(8), 1369-1381. <https://doi.org/10.1617/s11527-012-9979-y>.
- [10] ASTM C1556-11a, Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion, ASTM International, 2016, www.astm.org/c1556-11ar16.html.

5. CORE OF THE THESIS – SCIENTIFIC PAPERS

Overview

This thesis is submitted in a paper-based format and is divided into four scientific papers. Papers 1 and 2 address objectives 1-3, while papers 3 and 4 address objectives 4 and 5, respectively.

Paper 1 - Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete:

This paper focuses on the direct shear strength of ASR-affected RCA mixtures where the coarse OVA induces ASR. The results are combined with the microscopic assessment performed in previous studies on similar RCA mixtures. The results are then compared to the direct shear strength of conventional concrete incorporating similar reactive aggregates. The main objective of this paper was to assess the validity of the direct shear test as a diagnostic tool for ASR-affected RCA concrete.

Paper 2 - Mechanical appraisal of ASR-affected recycled concrete made of a reactive coarse RCA displaying distinct deterioration degrees

This paper focuses on the impact of ASR secondary damage initiated within the OVA with two distinct levels of the initial damage (i.e., 0.05% and 0.30%). The mechanical properties (i.e., SDT, ME, CS) of recycled specimens were evaluated, and the results were compared with a companion CC. In addition, statistical analysis (i.e., ANOVA and “t-test” for CS) were also performed to determine whether the conclusions drawn through the data analysis could be considered statistically significant based on the levels of secondary expansion.

Paper 3 - Overall assessment of alkali-silica reaction affected concrete made of reactive coarse and fine aggregates:

This paper aims to understand the impact of severity and location of reactive aggregates (i.e., OVA – reactive coarse aggregate or RM – reactive fine aggregate) on the mechanical properties of four families of recycled concrete. Four levels of secondary expansion were selected for analysis. Later, the specimens were tested for compressive strength, direct shear strength and stiffness damage test (SDT). The results showed that the source and extent of initial deterioration impact the mechanical properties loss of recycled concrete. Additionally, the results obtained were combined with the microscopic assessment (i.e., extended DRI) of the specimens for each secondary expansion level.

Paper 4 - Chloride diffusivity of recycled concrete made of ASR-affected fine and coarse aggregates

This paper aims to understand the impact of initial and secondary damage on the chloride diffusion rate of recycled concrete. The previously mentioned recycled concrete mixtures were subjected to a chloride bath, and the chloride diffusion parameter obtained was compared with a companion CC. The extended DRI was finally used to evaluate the outcomes obtained in this work.

6. Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete

Abstract

Recycled concrete aggregates (RCA) have been adopted as one of the most efficient methods to reduce the carbon footprint of the concrete industry. However, the performance of recycled concrete mixtures made of Alkali-silica reaction (ASR)-affected RCA is primarily unknown. In this work, two types of RCA were produced from ASR-affected concrete with distinct levels of deterioration (i.e., slight and severe). Three levels of secondary damage (i.e., expansion levels of 0.05%, 0.12%, and 0.20%) were selected and evaluated through the direct shear test. Results revealed that RCA concrete's shear strength depends on the severity of the RCA's past deterioration. Moreover, the performance of the concrete specimens subjected to direct shear is in accordance with the cracks features formed in the microstructure of the recycled concrete as a function of ASR-induced secondary expansion observed through the damage rating index (DRI).

Keywords: alkali-silica reaction (ASR), direct shear test, microscopic assessment, damage rating index (DRI), recycled concrete aggregate (RCA).

Introduction

Concrete is the most commonly used construction material worldwide due to the availability of its ingredients, economic benefits, and outstanding mechanical and durability-related properties. However, in 2018, the *International Energy Agency (IEA)* linked concrete production to approximately 7% of global carbon dioxide emissions, mainly due to Portland cement production and aggregate processing [1]. In light of the current urgency to adopt new measures to reduce the environmental impact of the production of concrete, recycling and reusing concrete can help reduce the consumption of non-renewable aggregates by transforming them into recycled concrete aggregates (RCA) while utilizing the adhered residual cement paste to reduce the new cement demand. However, there are still doubts about the material's variability and quality, especially concerning alkali-silica reaction (ASR), one of the most damaging distress mechanisms impacting concrete, which significantly reduces the service life of affected structures, leading to early demolition, thus creating large amounts of waste.

Recent studies have evaluated the potential for “secondary” induced expansion of ASR-affected recycled concrete made of reactive coarse and fine RCA [2–7]; these studies found that the source of the reaction (i.e., reactive coarse or fine aggregates) significantly affects the deterioration mechanism through its crack generation and propagation, kinetics, and potential of secondary expansion [6,7]. Nevertheless, very few works appraised the impact of ASR on the mechanical properties of RCA concrete [8]. This work aims to evaluate the influence of ASR on the direct shear strength of RCA-affected concrete to better understand the role of the aggregate in

such concrete mixtures. Moreover, correlations with microscopic analysis are also conducted to enhance understanding of the findings [6,7]. It is worth noting that to improve the text's readability, a description of all acronyms (in order of appearance) used in this work is presented in Table 6.1.

Table 6.1 Description of acronyms used.

Acronyms	Description
ASR	Alkali-silica reaction
RCA	Recycled concrete aggregate
DRI	Damage rating index
CC	Conventional concrete
OVA	Original virgin aggregate
RM	Residual mortar
EV	Equivalent volume mix design method
CCA	Closed crack in the aggregate
OCA	Open crack in the aggregate
OCAG	Open crack in the aggregate with gel
DAP	Disaggregated particles
CCP	Crack in the cement paste
CCPG	Crack in the cement paste with gel
CAD	Debonded aggregate
CPT	Concrete prism test
RH	Relative humidity
ITZ	Interfacial transition zone
NCP	New cement paste
RCP	Residual cement paste

Background

Alkali-silica reaction (ASR)

Alkali-silica reaction (ASR) is a reaction between the alkalis from the cement paste (i.e., Na^+ , K^+ , OH^-) and uncrystallized silica within the aggregates. ASR is one of the leading causes of early concrete deterioration in Canada and worldwide [9]. Concrete expansion levels are generally used to reflect ASR-induced damage. Figure 6.1 shows a qualitative crack propagation model in ASR-affected conventional concrete (CC), presenting A) sharp cracks and B) onion skin type cracks [10]. Sharp cracks are generally initiated within the aggregate particles at a slightly damaged degree (i.e., 0.05% expansion level). As the reaction continues to a moderate expansion level (i.e., 0.12%), the previously generated sharp cracks propagate toward the aggregate's edges. At high expansion levels (i.e., 0.20%), the sharp cracks begin to extend into the cement paste. At very high expansion levels (i.e., 0.30%), the sharp cracks formed in the aggregates and the cement paste form an extensive cracking network and decrease the physical integrity of the material. Meanwhile, onion skin type cracks follow

the aggregate's edge, elongating with increasing expansion until entering the cement paste. Mechanical properties (i.e., compressive strength, tensile strength, and modulus of elasticity) of concrete affected by ASR are therefore reduced as a function of the expansion level, regardless of the aggregate type (i.e., coarse vs. fine aggregates) and nature (i.e., mineralogy) [10,11]. De Souza et al. (12) observed that the direct shear strength of ASR-affected specimens reduces as a function of ASR expansion, observed even at low expansion levels, which was attributed to the adverse effect of ASR on the aggregate interlock of the concrete specimens.

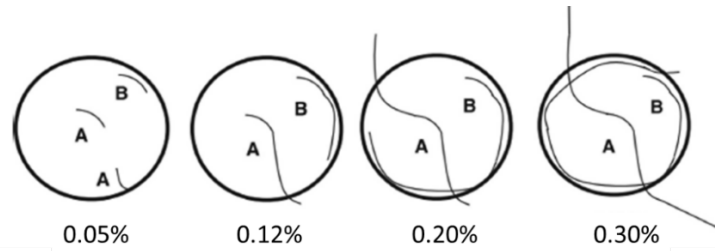


Figure 6.1: A qualitative model of crack propagation in ASR-affected CC [10].

Recycled concrete aggregate (RCA)

Recycled concrete aggregate (RCA) is a multi-phase material composed of original virgin aggregate (OVA) and residual mortar (RM). RCA is often considered a lower quality material (i.e., presence of residual mortar - RM, impurities, deterioration, and high variability, among many others), resulting in lower concrete performance. Several mix-design procedures have been developed to increase the overall performance of recycled concrete. Among these mix-design techniques, the Equivalent Volume (EV) method [5] improves the hardened and fresh state properties and results in a more sustainable concrete mixture. The EV method is based on the mix-design technique developed by Fathifazl et al. [3] and its modified version [4]. The EV mix-design technique aims to proportion recycled concrete mixtures with the same volume of aggregates (coarse and fine) and cement paste as a companion CC. Indeed, there are concerns regarding the use of RCA due to the presence of past deterioration, such as ASR [12,13], which can be influenced by the RCA production (i.e., aggregate crushing, washing, and storage) and the remaining reactivity potential [14–18]. Trottier et al. [6,7] found that the kinetics and deterioration process (i.e., crack width, crack length, and propagation path) are affected by the severity of initial damage and its location (i.e., OVA or RM). However, the influence of this type of aggregate on the aggregate interlock, determined through the direct shear test, remains unknown.

Techniques used to assess ASR damage in concrete.

Damage Rating Index (DRI)

The damage rating index (DRI) is a microscopic tool developed [19] and further modified [10,20] to appraise damage in ASR-affected concrete. After polishing the surface of a concrete section (i.e., cut longitudinally), distress features are counted with the help of a stereomicroscope (15 to 16x magnification) in a 1 cm² grid drawn

on the reflective surface. The distress feature counts are then weighted according to their location and importance (i.e., 0.25 for closed cracks in the aggregate – CCA; 2 for open cracks in the aggregate without and with gel and disaggregated particles – OCA, OCAG, and DAP, respectively; and 3 for cracks in the cement paste without and with gel and debonded aggregate – CCP, CCPG, and CAD, respectively). The overall assessment is then normalized to 100 cm² resulting in the DRI number. This microscopic tool is an effective technique for assessing the degree of damage of ASR-affected concrete regardless of the aggregate type and concrete strength [10,20,21], as well as for recycled mixtures [6–8]. Furthermore, the extended version of DRI, presenting characteristics in absolute (counts/100 cm²) and relative (%) values without the weighting factors, gives a more thorough evaluation and comprehension of the ASR-induced damage development. [8,10].

Direct shear setup test

The direct shear strength of concrete measures the material's aggregate interlock; compression and tension are the governing forces in measuring the latter. The transfer of shear forces across inner cracks occurs through two mechanisms: a) the dowel effect and b) shear friction [22]. While the dowel effect is related to reinforcement used in concrete, shear friction is the frictional resistance of cracks to sliding [22] used in reinforced concrete design, known as aggregate interlock [23]. Barr and Hasso [24] proposed a setup using a modified cylindrical concrete specimen, where a semi-circular notch was applied on each side, expected to ensure a shear failure at this location. Gao et al. [25] introduced a new setup to evaluate the brittle fracture of reinforced concrete composites. The setup proposed by Gao et al. [25] was adopted by Barr and Hasso [26] for further analysis in 100 by 200 mm cylindrical specimens, using a circumferential notch of 20-25 mm in depth (Figure 6.2). Ultimately, De Souza et al. [27] utilized the last version of the setup proposed by Barr and Hasso [26] to evaluate the effects of ASR on the direct shear strength of affected concrete specimens.

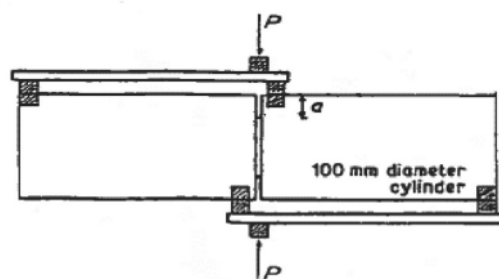


Figure 6.2: Shear setup for concrete specimens [26].

Scope of work

As aforementioned, only a few works have evaluated the impact of RCA's initial damage on the mechanical properties and deterioration of concrete made of ASR-affected RCA, while the influence of ASR on the

mechanical properties of CC is somewhat well understood. This work aims to assess the influence of previously damaged RCA and its severity on the aggregate interlock captured by the direct shear strength test. As such, CC specimens incorporating a reactive coarse aggregate (i.e., Springhill - Greywacke) were manufactured in the laboratory and stored under conditions enabling ASR-induced expansion and deterioration. The specimens were split into two groups: slightly deteriorated (i.e., 0.05%) and severely deteriorated (i.e., 0.30%) concrete; upon reaching the above expansion levels, the specimens were crushed, and RCA material was obtained. RCA concrete specimens made of slightly and severely ASR-deteriorated coarse aggregates were fabricated and stored at conditions enabling secondary ASR-induced development. Secondary damage (i.e., expansion levels) was monitored over time to compare the ASR kinetics of recycled concrete with a companion CC affected by ASR. The direct shear test was then conducted on specimens reaching expansion levels of 0.05%, 0.12% and 0.20%, followed by complementary microscopic analysis (i.e., damage rating index) on a separate set of specimens at each expansion level to better understand the role of the RCA in concrete affected by ASR.

Materials and methods

Concrete manufacturing

To fabricate the control CC specimens (i.e., 100 mm by 200 mm, 35 MPa concrete cylinders) and concrete specimens to be used to produce the RCA, a highly reactive coarse aggregate (i.e., Springhill – Greywacke) was combined with natural non-reactive sand sourced locally in Ottawa. All concrete specimens were mix-proportioned following the concrete prism test (CPT) as per ASTM C1293 [28]; CSA general use (ASTM type 1) Portland cement was used in the mixture. To accelerate ASR development, the total alkali content of the mixture was raised to 1.25% $\text{Na}_2\text{O}_{\text{eq}}$ by cement mass after adding reagent grade NaOH. The specimens were moisture-cured in 100% relative humidity (RH) and 20°C and then de-moulded after 24 hours. Holes of 5 mm in diameter by 15 mm in depth were then drilled on both ends of the specimens, and stainless-steel gauge studs were glued using a fast-setting cement paste slurry on both ends for the length change measurements. The specimens were left to moist-cure for an additional 24 hours before the initial reading. The specimens were then stored over a film of water in 22-litre plastic containers lined with an absorbent cloth and then placed in an environmental chamber (i.e., 100% RH and 38°C). The abovementioned absorbent cloth was installed on the lid and inside the buckets to prevent the formation of droplets and minimize the effect of leaching. Prior to the periodic monitoring of the length change measurements, the containers were removed from the environmental chamber and cooled down to 20°C for 16 ± 4 hrs. The specimens were taken out one by one during the measurement period, and buckets were returned to the environmental chamber immediately after each measurement. Two levels of expansion representing distinct damage degrees were selected to produce the RCA: 0.05% and 0.30% (i.e., slight and severe, respectively). The specimens were then jaw crushed to produce reactive coarse RCA ranging from 4.75 mm to 19 mm in size. After crushing, the RCAs were stored in sealed buckets in conditions preventing further ASR development (12°C). The RM content of slightly damaged RCA

and severely damaged RCA was 46% and 51.5%, respectively. The RM content was determined following the procedure proposed by Abbas et al. (29), which involves five cycles of freezing and thawing. All recycled mixtures were proportioned using the EV method [5] while keeping the total cement content of the system equal to 420 kg/m³ (i.e., using the CPT mixture proportions as the companion mixture), as presented in Table 6.2. To raise the alkali content, the recycled mixtures also incorporated reagent grade NaOH and were cast, cured, prepared, stored, and monitored over time, following the same procedures as aforementioned for the CC. It is worth noting that to assess the effect of initial damage on the future performance of the RCA concrete, only the alkali contribution from the new cement paste was considered. The total alkalis of the system were kept constant, and the stage of the initial reaction was not considered in the total alkali content calculation.

Table 6.2: Conventional and RCA mix proportioning.

Ingredients	Springhill CC	Slightly damaged RCA- concrete (0.05% -SPR-RCA)	Severely damaged RCA- concrete (0.30% -SPR- RCA)
Coarse aggregate highly reactive (kg/m ³)	934	1040	1048
Sand non-reactive (kg/m ³)	823	774	791
Cement (kg/m ³)	420	340	331
Water (kg/m ³)	189	153	149

Experimental procedures

Direct shear test

The direct shear test was used to evaluate the direct shear strength (i.e., aggregate interlock) of the recycled mixtures. Three specimens per concrete mixture (i.e., CC, slightly and severely damaged recycled mixtures) and expansion levels selected for this study (i.e., 0%, 0.05%, 0.12% and 0.20%) were prepared for the direct shear test. A circumferential 22 mm deep [26] and 5 mm wide (i.e., the width of the diamond blade on the masonry saw) notch at the center of the specimens was cut to ensure a shear failure at the notch. The specimens were then tested in accordance with the setup and procedure proposed by Barr and Hasso [26], as shown in Figure 6.2. A loading rate of 100 N/s was selected for this study. The following equation was then used to calculate the direct shear strength:

$$\tau = \frac{P \times 4}{(\phi_{cylinder} - 2a)^2 \times \pi} \quad \text{Equation 6.1}$$

where P denotes the failure load (N), $\phi_{cylinder}$ denotes the cylinder diameter (mm), and a denotes the depth of the notch (mm).

Damage Rating Index (DRI)

One specimen per mixture (i.e., CC, slightly and severely damaged recycled mixture) and expansion level (i.e., 0%, 0.05%, 0.12% and 0.20%) was cut in half longitudinally and polished with diamond-impregnated rubber

disks of successive grits (i.e., 30, 60, 140, 280, 600, 1200, 3000) through the use of a mechanical polishing machine prior to conducting the microscopic assessment. A grid of 1 cm by 1 cm was drawn on the reflective surface, and each square was observed through a stereomicroscope at 16x magnification. Distress features were then counted in each square while applying a weighting factor to each feature as per [20]. The sum of the weighted counts was normalized to 100 cm² to obtain a DRI number. Moreover, the extended version of the DRI (i.e., without the application of the weighting factors) was also performed as per Sanchez et al. [10].

Results

ASR development and kinetics

Figure 6.3 illustrates ASR-induced average expansion levels as a function of time. A standard deviation of 0.01%-0.04%, 0.02%-0.04% and 0.02%-0.03% was obtained for the CC and recycled mixtures made of slightly damaged and severely damaged RCA, respectively. Expansion measurements were carried out for 150 days on the CC at which an expansion level of 0.31% was reached, whereas after 188 days, levels of expansion of 0.24% and 0.28% were obtained for the slightly and severely damaged recycled mixtures, respectively. A similar trend is observed at the beginning from 0-0.03% of expansion (i.e., 29 days), after which both recycled mixtures increase in expansion up to 0.09% and 0.06% at 51 days for the severely and slightly damaged RCA, respectively, while the CC attains only 0.05% at 52 days. After approximately 63 days, the CC swelled at a faster rate when compared to both recycled mixtures. The severely and slightly damaged recycled mixtures, as well as the CC, reached an expansion level of 0.05% at 36, 44 and 49 days, and an expansion level of 0.12% at 79, 94 and 75 days, respectively. Meanwhile, an expansion of 0.20% was observed after 94, 128, and 157 days for the CC, severely and slightly damaged recycled mixtures, respectively.

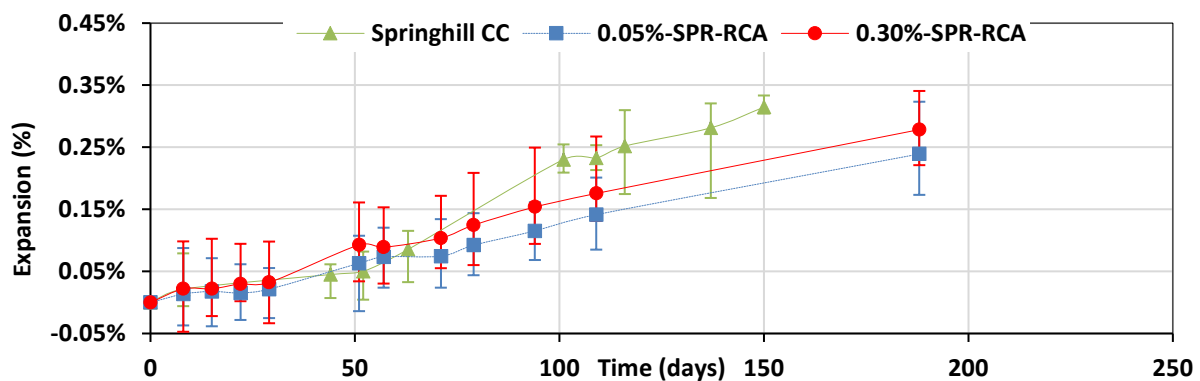


Figure 6.3: Expansion as a function of time for concrete mixtures [6].

Direct shear test

The direct shear strength and reductions at distinct expansion levels of the CC and recycled concrete mixtures are presented in Figures 6.4a and 6.4b, respectively. Results indicate that the direct shear strength of all mixtures lessens as a function of induced expansion and ASR development. The CC's direct shear strength begins to decrease only after 0.05% of expansion (i.e., initially at 8.81 MPa), which can be attributed to the cracks being present within the aggregates as presented in Figure 6.1; thus, cracks propagating through the interfacial transition zone (ITZ) during shear failure. Hereafter, the decrease in direct shear strength is linear for the CC, reaching 5.82 MPa at 0.20% of the expansion. The recycled mixtures on the other hand, present a lower initial shear strength when compared to the CC. The slightly damaged RCA displayed an initial direct shear strength of 7.2 MPa. As expansion advanced, at low and moderate expansion levels (i.e., 0.05% and 0.12%, respectively), the direct shear strength reduced to 5.81 MPa and 5.44 MPa (i.e., losses of 20% and 24%, respectively). At an expansion level of 0.20%, a significant loss is observed (i.e., a loss of 44%), reducing the direct shear strength to 4.02 MPa. Likewise, the severely damaged RCA with an initial direct shear strength of 6.8 MPa presented a similar trend through the low and moderate expansion levels (i.e., losses of 20% and 29%, respectively). Interestingly, no significant loss was observed at a high expansion level (0.20%), unlike the slightly damaged RCA (i.e., from 29% to 34%).

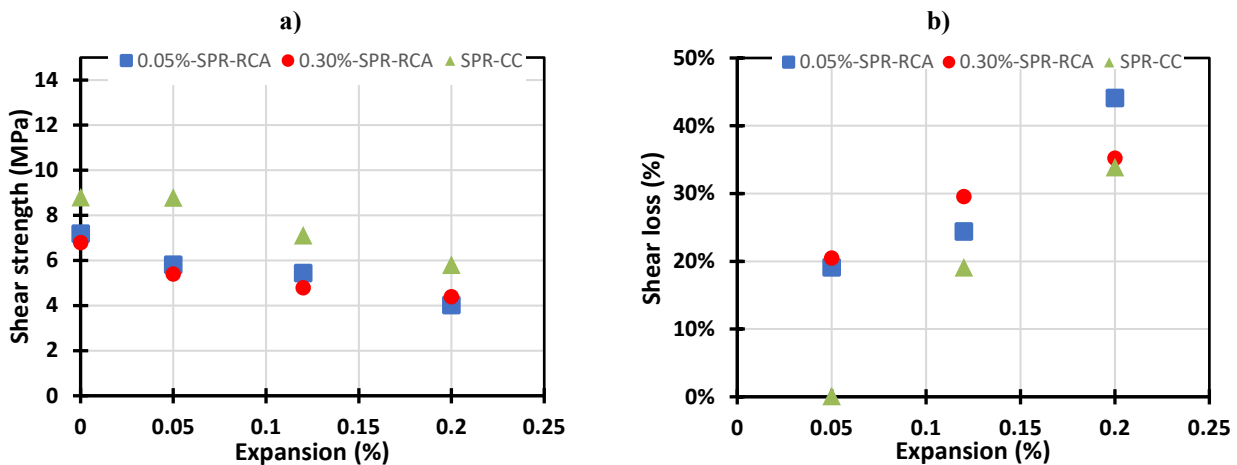


Figure 6.4: a) Direct shear strength of ASR-affected specimens, and b) shear loss of ASR-affected specimens at distinct expansion levels.

Microscopic assessment

The result from another study by Trottier et al. [6], with the same RCA particles and mixture proportions, was used to complement the results obtained through the direct shear test and understand the role of the RCA particles. Due to the multi-phase nature of the aggregates, the cracks observed in the cement paste were classified into two categories: a) cracks in new cement paste (NCP) and b) cracks in the residual cement paste (RCP). It should be noted that the crushing and weathering of the aggregates could result in closed cracks inside

the aggregates, and these cracks are not necessarily attributed to ASR [30]. However, a decrease in such cracks is a result of closed cracks in the aggregates opening due to the expansion of silica gel within these sites. As such, the CC mixture shows an increase in the proportions of *open cracks in the aggregates* (from 12% to 40%), as well as *cracks in the cement paste* (from less than 1% to 10%) up to moderate expansion level (i.e., 0.12%). Afterwards, their proportions remain constant (Figure 6.5a), although the number of cracks keeps increasing, as shown in Figure 6.5b. The severely damaged mixture (i.e., 0.30%-SPR-RCA) displays a significantly higher portion of *open cracks in the aggregate with and without gel* when compared to the slightly damaged mixture (i.e., 0.05% -SPR-RCA) before being subjected to secondary damage (28% and 10%, respectively). The proportion of *open cracks in the aggregate without and with gel* increases up to 45% for slightly damaged RCA and 36% for the severely damaged RCA concrete at 0.20% of expansion (Figure 6.5a). Meanwhile, the cracks in the cement paste present a significantly smaller proportion overall, yet, similar proportions in both recycled mixtures are observed, increasing with expansion (i.e., from 5% to 20%).

The DRI numbers generally increase with increasing expansion, as presented in Figure 6.5b. The CC mixture displays the highest DRI values, followed by the severely then slightly damaged RCA mixtures. Before being subjected to ASR, only negligible damage was observed for all concrete mixtures (i.e., DRI values of 138, 73, and 171 for CC, slightly damaged, and severely damaged RCA, respectively). At 0.05% and 0.12% of expansion levels, the CC mixture presents the highest DRI numbers (i.e., 307 and 465, respectively) between all mixtures, while the slightly and severely damaged RCA mixtures achieve 161 and 261 for low (i.e., 0.05%) expansion and 268 and 390 for moderate (i.e., 0.12%) expansion, respectively. A significant increase in the DRI number is found for the slightly damaged RCA concrete at the expansion of 0.20%. (i.e., 470) whereas the severely damaged RCA and CC mixtures increased to 514 and 621.

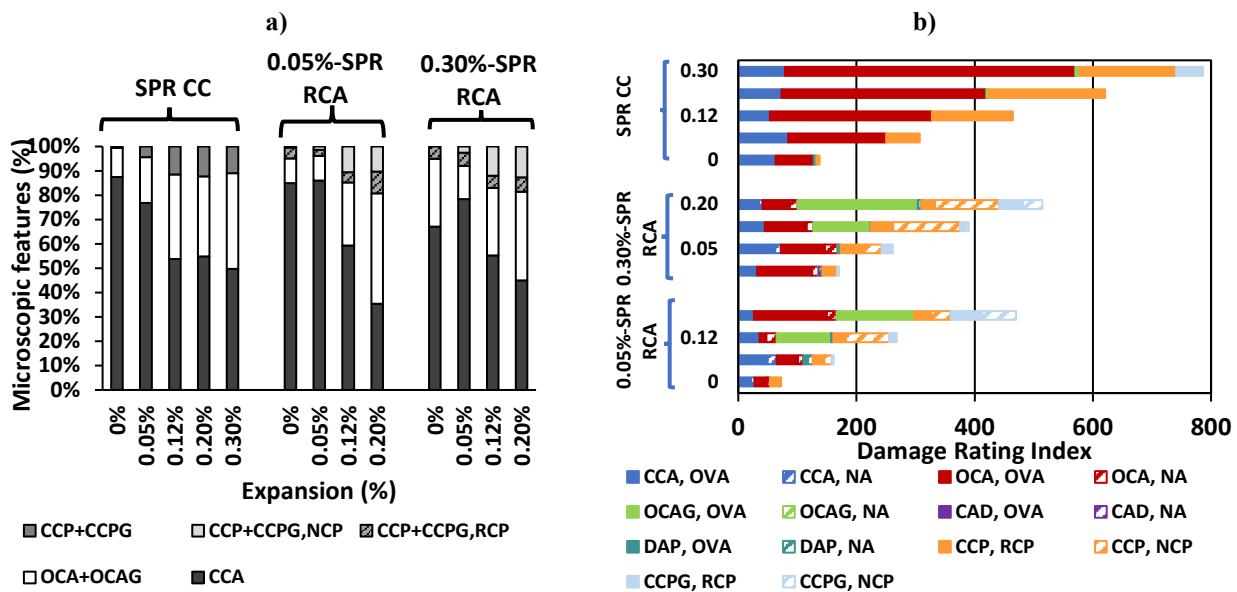


Figure 6.5: a) Percentage of distress features and b) DRI chart in CC and RCA concrete [6].

Discussion and overall assessment

The shear strength of recycled mixtures presented interesting results when compared to the CC mixture. At low expansion levels (i.e., 0.05%), CC mixtures presented cracks mainly within the aggregates [10,11,21]. This behaviour was well captured by the direct shear test (i.e., no shear strength reduction as per Figure 6.4) since no "aggregate interlock loss" is expected when cracks remain within the aggregate particles. Conversely, at moderate expansion levels (i.e., 0.12%), some of the cracks developed within the aggregates reached the cement paste (Figure 6.1), decreasing the aggregate interlock due to the splitting of the particles, which significantly reduces the shear strength of the affected material. In addition, the location of cracks (i.e., aggregate vs cement paste) and their severity (i.e., number, crack length and crack width) significantly affected the shear strength of CC [31]. On the other hand, RCA mixtures showed a lower initial shear strength when compared to CC, likely due to a) the distinct microstructure (i.e., multi-phase nature and increased number of ITZ) of RCA particles and b) the crushing/processing inducing micro-cracks, which might have compromised the aggregate interlock capacity of RCA concrete as previously observed in the literature [22,32,33]. Conversely, to the CC mixtures where the shear strength remained constant from 0% to 0.05% of expansion, the recycled mixtures showed a 19% and 20% shear strength loss. This difference in the shear strength reduction in recycled mixtures compared to CC is likely due to the previous ASR damage, resulting in the secondary damage having a short initiation period leading towards cracks extending to the cement paste in recycled mixtures before such cracks are observed in CC (Figure 6.5b). Moreover, the influence of the previous ASR damage was captured by the direct shear test where recycled mixtures made of slightly deteriorated RCA concrete displayed a greater initial shear strength when compared to RCA made of severely deteriorated particles. The DRI numbers obtained for the slightly and severely damaged recycled mixtures prior to being subjected to secondary ASR damage (i.e., 73 and 171, respectively) support the trend observed through the shear strength. Yet, a DRI number of 138 was reported for the CC, while a higher shear strength was observed at 0% of the expansion. Therefore, the number of cracks does not necessarily govern the shear strength. Moreover, the open cracks in the aggregates are significantly lower in number for the slightly damaged RCA, yet, similar numbers are observed for the severely damaged mixture and the CC. At 0.05% of expansion, although the shear strength in CC remains constant, the number of open cracks in the aggregate increases significantly while a smaller increase is observed in both recycled mixtures, highlighting the influence of the nature of the RCA presenting previous damage. Furthermore, the width of cracks may have played an essential role in the direct shear strength of recycled mixtures. Recycled mixtures at low expansion levels presented significantly wider cracks than CC (i.e., 0.15 mm and 0.10 mm, respectively) [7].

An interesting behaviour is observed at 0.20% of expansion for the slightly damaged recycled mixture observed through both the shear strength and the DRI number. The shear strength thus presents a higher loss for the slightly damaged mixture while the DRI number increases significantly with the number of open cracks in the aggregate being similar to that of the severely damaged mixture, further highlighting the difference between the

RCA particles subjected to different levels of previous damage. In addition, at high expansions (i.e., 0.20%), cracks were widest in the slightly damaged RCA concrete reaching 0.25 mm, compared to 0.20 mm for severely damaged RCA concrete and CC as previously reported [7]. The sudden loss of direct shear strength observed in the recycled concrete made of slightly damaged RCA at an expansion level of 0.20% may be linked to wider observed cracks. Nevertheless, the reactive potential of the RCA particles was captured by both tools used in this study. It is worth noting that it is generally agreed that the shear strength of concrete not only depends on the location and width of cracks, but the crack directionality could also play an important role in the shear strength of concrete specimens [34,35]. Thus the impact of crack directionality on the shear strength of RCA concrete is a recommended topic for future work.

Conclusions

This study aimed to appraise the direct shear strength reduction of concrete containing ASR reactive RCA while understanding its behaviour through microscopic analysis. The results were compared with a companion CC, and the key findings of this study are presented below:

- The results gathered in this research indicate that the severity of past deterioration in RCA affects the shear strength of recycled concrete; it is worth noting that the location and type of these distress features are of great significance toward the shear strength of recycled concrete.
- Although severely damaged RCA displays a higher level of damage through the DRI number for all three secondary expansion levels selected in this study, slightly damaged RCA presented a significantly higher loss of direct shear strength and a significant increase in the DRI number at 0.20% of the expansion.
- The direct shear strength setup used in this study was able to capture the increase in ASR damage in CC and the recycled mixtures. The influence of the primary damage in the RCA particles was also highlighted through both the shear strength and DRI numbers, which emphasizes the necessity to distinguish the type of RCA used in new concrete mixtures.
- Overall, the direct shear strength of RCA concrete depends on the original concrete properties and the secondary induced deterioration taking place in the RCA concrete. This was observed by Trottier et al. [7] when developing a qualitative model of crack generation and propagation of RCA. Further investigation of the mechanical properties is required to understand the effects of initial and secondary damage on RCA concrete.
- The overall crack width of the system plays an essential role in assessing the direct shear strength of ASR-affected specimens. This was clearly observed in this work, especially at high expansion levels.

References

- [1] International Energy Agency. Cement technology roadmap plots path to cutting CO₂ emissions 24% by 2050 - News - IEA. IEA; 2018. Available from: <https://www.iea.org/news/cement-technology-roadmap-plots-path-to-cutting-co2-emissions-24-by-2050>.
- [2] Abbas, A., Fathifazl, G., Isgor, O.B., Razaqpur, A.G., Fournier, B., & Foo, S. (2009). Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Cement and Concrete Composites*, 31(8), 555-563. <https://doi.org/10.1016/j.cemconcomp.2009.02.012>.
- [3] Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., & Foo, S. (2009). New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*, 21(10), 601-611. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2009\)21:10\(601\)](https://doi.org/10.1061/(ASCE)0899-1561(2009)21:10(601)).
- [4] Hayles M, Sanchez LFM, Noël M. Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. *Construction and Building Materials*. 2018;169:724–732. Available from: <https://doi.org/10.1016/j.conbuildmat.2018.02.127>
- [5] Ahimoghadam F, Sanchez LFM, de Souza DJ, Andrade GP, Noël M, Demers A. Influence of the Recycled Concrete Aggregate Features on the Behavior of Eco-Efficient Mixtures. *Journal of Materials in Civil Engineering*. 2020;32:04020252. Available from: [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003323](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003323).
- [6] Trottier, C., Zahedi, A., Ziapour, R., Sanchez, L., Locati, F. (2021). Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR). *Construction and Building Materials*, 269, 121250. <https://doi.org/10.1016/j.conbuildmat.2020.121250>.
- [7] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. *Cement and Concrete Research*, 144, 106426. <https://doi.org/10.1016/j.cemconres.2021.106426>.
- [8] Zhu, Y., Zahedi, A., Sanchez, L. F. M., Fournier, B., & Beauchemin, S. (2021). Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. *Cement and Concrete Research*, 142, 106350. <https://doi.org/10.1016/j.cemconres.2020.106350>.
- [9] Sims, I., & Poole, A. (Eds.). (2017). *Alkali-Aggregate Reaction in Concrete: A World Review* (1st ed.). CRC Press. <https://doi.org/10.1201/9781315708959>.
- [10] Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74-92. <https://doi.org/10.1016/j.cemconres.2014.08.002>.

- [11] Sanchez, L.F.M., Drimalas, T., Fournier, B., Mitchell, D., & Bastien, J. (2018). Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms. *Cement and Concrete Research*, 107, 284-303. <https://doi.org/10.1016/j.cemconres.2018.02.017>.
- [12] Santos, M. B., de Brito, J., Santos Silva, A., & Hawreen, A. (2020). Effect of the source concrete with ASR degradation on the mechanical and physical properties of coarse recycled aggregate. *Cement and Concrete Composites*, 111, 103621. <https://doi.org/10.1016/j.cemconcomp.2020.103621>.
- [13] Peng, Z., Shi, C., Shi, Z., Lu, B., Wan, S., Zhang, Z., Chang, J., Zhang, T. (2020). Alkali-aggregate reaction in recycled aggregate concrete. *Journal of Cleaner Production*, 255. <https://doi.org/10.1016/j.jclepro.2020.120238>.
- [14] Shehata, M. H., Christidis, C., Mikhael, W., Rogers, C., & Lachemi, M. (2010). Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction. *Cement and Concrete Research*, 40(4), 575-582. <https://doi.org/10.1016/j.cemconres.2009.08.008>.
- [15] Ideker, J. H., Adams, M. P., Tanner, J., Jones, A. (2013). Durability Assessment of Recycled Concrete Aggregates for Use in New Concrete: Phase I - Revised. TREC Final Reports. <https://doi.org/10.15760/trec.15>.
- [16] Johnson, R., & Shehata, M. H. (2016). The efficacy of accelerated test methods to evaluate Alkali Silica Reactivity of Recycled Concrete Aggregates. *Construction and Building Materials*, 112, 518-528. <https://doi.org/10.1016/j.conbuildmat.2016.02.155>.
- [17] Mukhopadhyay, A. K., Geiger, B. J., & Button, J. (2010). Use of Alkali-Silica Reaction-Affected Recycled Concrete Aggregate in Hot-Mix Asphalt. *Transportation Research Record*, 2179(1), 1-9. <https://doi.org/10.3141/2179-01>.
- [18] Li, X., & Gress, D. L. (2006). Mitigating Alkali-Silica Reaction in Concrete Containing Recycled Concrete Aggregate. *Transportation Research Record*, 1979(1), 30-35. <https://doi.org/10.1177/0361198106197900105>.
- [19] Grattan-Bellew, P. E. (1995). Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station. *ACI Materials Journal*, 92(2). <https://doi.org/10.14359/9763>.
- [20] Villeneuve, V., Fournier, B., Duchesne, J. (2012). Determination of the damage in concrete affected by ASR-the damage rating index (DRI). In 14th International Conference on Alkali-Aggregate Reaction (ICAAR). Austin, Texas (USA). <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-VilleneuveV-1.pdf>.
- [21] Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., Duchesne, J. (2016). Use of Damage Rating Index to Quantify Alkali-Silica Reaction Damage in Concrete: Fine versus Coarse Aggregate. *ACI Materials Journal*, 113(4). <https://doi.org/10.14359/51688983>.
- [22] Haskett, M., Oehlers, D.J., Mohamed Ali, M.S., Sharma, S.K. (2011). Evaluating the shear-friction resistance across sliding planes in concrete. *Engineering Structures*, 33, 1357-1364. <https://doi.org/10.1016/j.engstruct.2011.01.013>.

- [23] Canadian Portland Cement Association (1985). Concrete design handbook.
- [24] Baar, M., Hasso, E.B.D., & Liu, K. (1985). Shear strength of FRC materials. *Composites*, 16(4), 326-334. [https://doi.org/10.1016/0010-4361\(85\)90285-X](https://doi.org/10.1016/0010-4361(85)90285-X).
- [25] Gao, H., Wang, Z., Yang, C., & Zhou, A. (1979). An investigation on the brittle fracture of KI-KII composite mode cracks. *Acta Metall. Sin.*, 15(3), 380-391.
- [26] Barr, B., Hasso, E.B.D. (1986). Development of a compact cylindrical shear test specimen, *Journal of Materials Science Letters*, 5(12), 1305-1308. <https://doi.org/10.1007/BF01729401>.
- [27] De Souza, D. J., Sanchez, L. F. M., & De Grazia, M. T. (2019). Evaluation of a direct shear test setup to quantify AAR-induced expansion and damage in concrete. *Construction and Building Materials*, 229, 116806. <https://doi.org/10.1016/j.conbuildmat.2019.116806>.
- [28] ASTM International. (2021). ASTM C1293 - 20a Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction. <https://www.astm.org/Standards/C1293>
- [29] Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A. G., Fournier, B., & Foo, S. (2008). Proposed method for determining the residual mortar content of recycled concrete aggregates. *Journal of ASTM International*, 5, 1-12. <https://doi.org/10.1520/JAI101087>.
- [30] McCarthy, M. J., Csetenyi, L. J., Halliday, J. E., & Dhir, R. K. (2015). Evaluating the effect of recycled aggregate on damaging AAR in concrete. *Magazine of Concrete Research*, 67(14), 598-610. <https://doi.org/10.1680/MACR.14.00260>.
- [31] Ziapourrazlighi, R., Trottier, C., & Sanchez, L. (2022). Assessment of AAR-induced expansion and damage through the direct shear test. 16th International Conference on Alkali-Aggregate Reaction in Concrete (ICAAAR).
- [32] K.N. Rahal, A.L. Al-Khaleefi (2015). Shear-friction behavior of recycled and natural aggregate concrete-an experimental investigation. *ACI Structural Journal*, 112, 725-734. <https://doi.org/10.14359/51687748>.
- [33] Hayles, M. (2018). Investigation Into the Mechanical Properties and Structural Behaviour of Recycled Concrete Members (Master's thesis). University of Ottawa. <http://hdl.handle.net/10393/37801>.
- [34] Tanaka, Y., Kishi, R., & Maekawa, K. (2005). Experimental study on shear strength enhancement mechanism of RC members with artificial cracks. *Journal of the Japan Society of Civil Engineers, Ser. A1 (Structural Engineering & Earthquake Engineering)*, 61(2), 109-122. https://doi.org/10.2208/JSCEJ.2005.802_109.
- [35] Pimanmas, A., & Maekawa, K. (2001). Shear failure of RC members subjected to pre-cracks and combined axial tension and shear. *Materials, Concrete Structures, and Pavements*, 53, 159-174. https://www.jstage.jst.go.jp/article/jscej1984/2001/690/2001_690_159/pdf/-char/ja.

7. Mechanical appraisal of ASR-affected recycled concrete made of a reactive coarse RCA displaying distinct deterioration degrees

Abstract

Recycling concrete is an efficient method to reduce the carbon footprint of concrete production. However, there are challenges when dealing with Recycled Concrete Aggregate (RCA); among those, the presence of pre-existing damage, such as Alkali-silica reaction (ASR) in RCA, could significantly impact their quality. ASR, one of the leading concrete deterioration mechanisms, is an ongoing mechanism that has been found to continue in recycled concrete. Therefore, the reactivity of RCA has caused reservations about its use in new construction. This work aims to understand the effects of initial and *secondary* ASR-induced damage on the mechanical properties of RCA concrete. Thus, concrete specimens incorporating a coarse RCA displaying two distinct ASR initial expansion levels (i.e., slight-0.05% and severe-0.30%) induced by the reactive Springhill coarse aggregate (i.e., as Original Virgin Aggregate -OVA in the RCA) were manufactured and stored in conditions enabling further *secondary* ASR development. Upon reaching the targeted *secondary* expansion, the loss in compressive strength was determined, and the stiffness damage test (SDT) was used to assess the *secondary* damage; the latter proved to be a reliable tool to appraise damage caused by ASR in affected conventional concrete (CC). The results showed that the extent of initial damage affects the mechanical properties of RCA concrete. Finally, the mechanical response gathered from the various specimens of this work has been validated through a microscopic assessment.

Keywords: Alkali-Silica Reaction (ASR), Recycled Concrete Aggregates (RCA), damage, mechanical assessment, Stiffness Damage Test (SDT).

Introduction

Concrete's mechanical properties, economic benefits and availability of ingredients make it the most commonly used material for construction [1]. The sharp increase in population has led to the development of urban centers and, consequently, massive growth of the construction industry in the last decades. However, Portland cement (PC) production and construction waste generation have had a negative impact on the environment [1]. Therefore, recycling such material can help to reduce waste by reusing existing concrete material and transforming it into the so-called recycled concrete aggregates (RCA) [2]. Numerous studies have been conducted in the last decades to evaluate the distinct properties of recycled concrete [3–10]. Many of these studies have found that using RCA in concrete mixtures could negatively impact the mechanical properties (i.e., compressive and tensile strength as well as modulus of elasticity). Generally, the multi-phase nature of RCA materials, especially the presence of residual mortar (RM), is often reported as the cause of the aforementioned

negative impact and enhances the variability within the material [11,12]. Accordingly, as per Figure 7.1, RCA consists of a) Original Virgin Aggregate (OVA) and b) RM, along with the original interfacial transition zone (ITZ) between both components, where the amount and quality of the latter play an essential role in mixture proportioning along with the physical and mechanical properties of RCA concrete [9,11–14].



Figure 7.1: A model showing A) coarse virgin aggregate and B) coarse RCA (RM and OVA).

In recent years, several mix-design techniques have been developed to incorporate the residual mortar content (RMC) and the nature of RCA [9,10,12,15]. As such, recent studies showed that desirable fresh and hardened state [9,16] properties of RCA concrete could be achieved through the use of the equivalent volume (EV) method. In this technique, the total volume of aggregates (coarse and fine) and cement paste volume is the same as a companion conventional concrete (CC) [9]. Another concern regarding RCA is the presence of past deterioration, such as ASR [17–19]. ASR is one of the major degradation mechanisms affecting concrete's microstructure and mechanical properties; with ongoing reaction, the ASR-induced deterioration has been reported to continue in recycled concrete [17,18,20]. The reactivity potential of RCA is affected by many factors, such as aggregate crushing, washing, storage, and severity of initial expansion [4,21–25]. Although several authors [18,21,24,26–29] have assessed the various factors affecting the *secondary* ASR expansion and its kinetics, limited data is available on the effects of initial and *secondary* ASR-induced damage on the mechanical properties of recycled concrete.

In order to appraise the cause and extent of damage (diagnosis) and potential for further deterioration (prognosis) of ASR-affected concrete, a number of tools and techniques have been proposed in the past decades [30]. Among those, the Stiffness Damage Test (SDT), a mechanical and cyclic test procedure, was shown to be able to assess the ASR-induced damage in CC [31–36], while their use is extremely limited for RCA concrete [27,37]. Therefore, this work aimed to better understand the impact of initial and *secondary* ASR damage on the mechanical degradation of RCA concrete through the use of the aforementioned tools. In this regard, coarse recycled concrete aggregates (CRCA) with two distinct levels of damage (i.e., slight-0.05% and severe-0.30%) were manufactured under controlled laboratory conditions. Then, those RCA aggregates were used to produce recycled concrete specimens through the use of the EV mix-design technique [9] and stored in the conditions enabling *secondary* ASR development (i.e., 100% RH and 38°C). Once the targeted expansion levels were achieved, the mechanical properties of the specimens were appraised through the use of SDT and the loss in compressive strength.

Background

Alkali-silica reaction (ASR) in conventional concrete

Alkali-Silica Reaction (ASR) is a chemical reaction between unstable mineral phases from the aggregates and alkali hydroxides from the cement paste [18,38]. ASR produces a secondary product that expands upon the water uptake from the surrounding environment, causing internal swelling and cracks [28]. After a thorough investigation of concrete specimens incorporating various reactive aggregate particles, Sanchez et al. [34] proposed a qualitative ASR-induced crack development (Figure 7.2), where they initiate within the reactive aggregates at a low expansion level (i.e., 0.05%). As the reaction progresses, more cracks are generated, and the previously generated cracks are expanded into the cement paste at moderate expansion levels (i.e., 0.12%). As ASR continues to develop further (i.e., 0.20%), the previously generated cracks are lengthened and further propagate into the cement paste. Finally, at very high expansion levels (i.e., 0.30%), the previously mentioned cracks start linking together and generate a network of cracks [34]. Such induced cracking could significantly reduce the mechanical properties of ASR-affected concrete [27,30,31,39]. According to several authors [27,31,33,39–42], the modulus of elasticity and tensile strength could be significantly affected by ASR at low/moderate (i.e., 0.05%-0.12%) expansion. As such, 20%-50% and 40%-65% reduction of modulus of elasticity and tensile strength were observed in concrete specimens experiencing the above deterioration levels, respectively [27,31,33,39–42]. Conversely, the compressive strength of ASR-affected concrete is mainly affected at high and very high expansion levels (i.e., 0.20% and 0.30%) [31,41,43]. As such, while a compressive strength reduction of 0%-20% was observed at the beginning of ASR development (i.e., around 0.12% of expansion) [31], Esposito et al. [44] reported a compressive strength reduction of approximately 50% at very high expansion level. On the other hand, De Souza et al. [33] observed a shear strength reduction of 15-30% and 20-40% at moderate (i.e., 0.12%) and high expansion levels (i.e., 0.20%), respectively. The above information attests to the significance of ASR-induced cracking on various mechanical properties of conventional concrete. However, due to the unique microstructures of RCA, understanding the mechanical degradation of ASR-affected RCA material could be a completely different scenario compared to CC and require more research.

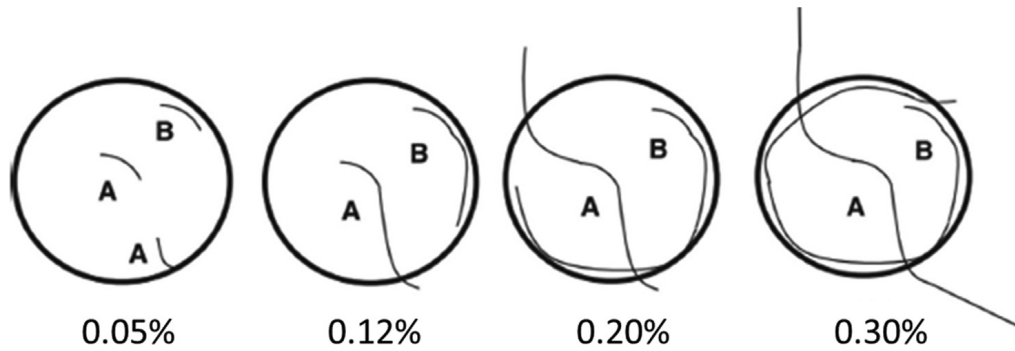


Figure 7.2: A qualitative crack propagation model in ASR-affected conventional concrete [34].

Recycled concrete aggregate (RCA) and ASR

Although recycling concrete could be a practical way to reduce construction waste, there are still many challenges when using such material [10]. To address these concerns, which are primarily derived from the microstructure of RCA and its unique physical (i.e., absorption, density) and chemical (i.e., contamination, reactivity) properties, researchers have proposed several techniques such as pre-treatment of RCA in acid, using new mix design methods and physical removal of RM [45]. Accordingly, previous studies demonstrated that if one replaces the RCA with the conventional aggregate particles in the mixture, such concrete could not achieve the desired mechanical properties. As such, Ismail and Ramli [45] observed a 20% reduction in the compressive strength of the concrete specimens incorporating 60% replacement of coarse aggregate with its RCA when compared to concrete incorporating 15% coarse RCA. Similarly, Çakır [46] observed a 24% reduction in compressive strength for mixtures with 100% RCA replacement when compared to CC mixtures. The above observations could be attributed to the microstructural properties of RCA (Figure 7.1); therefore, considering such a unique microstructure of RCA in the advanced mix design techniques could help RCA mixtures effectively achieve the desirable fresh state and mechanical properties. In this regard, initially, Fathifazl et al. [12] proposed a mix design technique, namely the equivalent mortar volume method (EMV), that required quantifying the amount of RM attached to the OVA by treating RCA as a multi-phase material (Figure 7.1). This method considers the RM of the RCA as a portion of the total mortar in the new concrete; hence, the new concrete's total mortar is equal to the summation of RM from RCA and freshly added mortar (Figure 7.3). Although Fathifazl et al. [12] achieved desirable mechanical properties (i.e., compressive strength, modulus of elasticity) for RCA concrete through the use of the EMV method, the fresh state properties of the mixtures could be further improved [9,12]. Moreover, the EMV limits the use of RCA and increases the amount of Portland cement (PC) used, which offsets its economic and environmental benefits.

Later, in order to improve the previously mentioned downfall of the EMV method, Ahimoghdam et al. [9] proposed a mix design technique that results in the same volume of aggregates and paste compared to CC mixtures. Thus, unlike EMV, EV mixtures demonstrate better fresh state behaviour and cement efficiency (PC

contents $\approx 300 \text{ kg/m}^3$). This method also significantly increases the amount of fine aggregates while decreasing the amount of coarse particles in the system, as per Figure 7.3. Considering the above-mentioned benefits, the EV mix design technique was used in this work to ensure that the total volume of reactive aggregates is comparable with the companion mixture (i.e., conventional ASR-affected concrete).

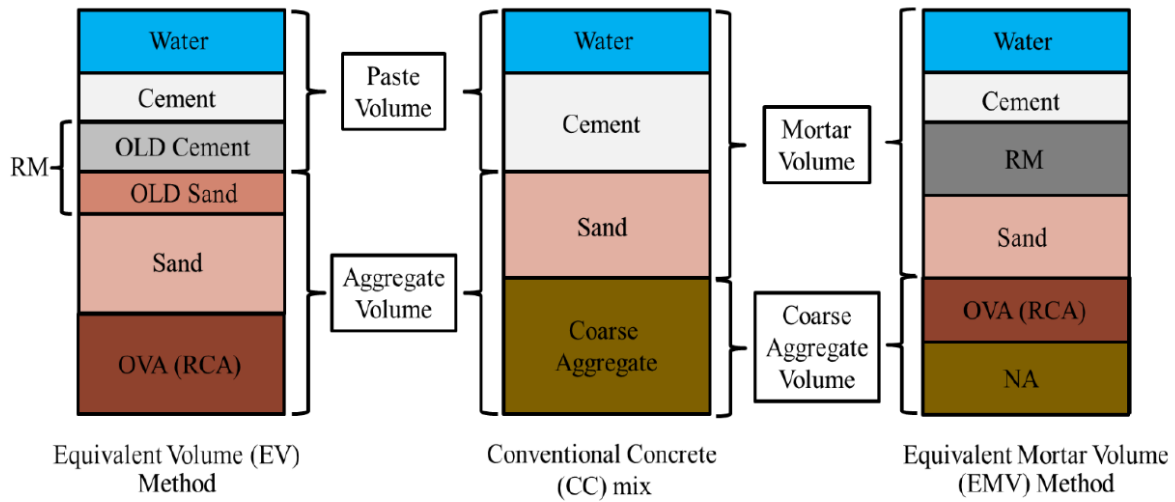


Figure 7.3: Comparison between volumetric differences of various mix design methods [47].

Another concern about using RCA in concrete is the presence of previous deterioration mechanisms such as ASR. Considering that a large number of critical concrete infrastructures in Canada and around the world are affected by ASR, thus recycling those affected concrete elements could result in a potentially reactive RCA [48]. Although many studies focused on the potential reactivity of recycled concrete and its extent, inconsistencies exist with regard to kinetics and the extent of ASR-induced damage in RCA [17,24,28,50]. Such discrepancy could be attributed to the remaining silica and alkalis of RCA; they are the necessary conditions to initiate and sustain ASR in concrete [51]. The initial expansion may not have completely depleted the reactants; thus, they could cause *secondary* damage in recycled concrete [18]. In this regard, the effects of initial expansion levels on the kinetics and microscopic features of recycled concrete were previously studied by Trottier et al. [24]. According to the authors [24], the most significant difference in terms of *secondary* induced damage (i.e., generation and propagation) of recycled mixtures is the number of cracks produced as a function of the expansion level reached, as well as the mechanism of damage development. Such differences in the *secondary* ASR-induced damage could significantly impact RCA concrete's mechanical and durability-related properties. After a thorough investigation of the available literature, to the author's best knowledge, there is only a hand full of data available on the mechanical degradation of ASR-affected RCA concrete. As such, Zhu et al. [27] worked on the mechanical degradation of RCA mixtures by directly replacing natural aggregates with recycled aggregate particles displaying various initial damage levels. According to the authors [27], the modulus of elasticity of RCA mixtures is only affected by the extent of the *secondary* damage. Although the above

information is beneficial, there is still a need for further study on the mechanical degradation of RCA concrete affected by the various initial ASR-induced damage levels presenting distinct *secondary* expansion using the new mix design techniques (e.g., the EV method [9]).

Mechanical Tools for assessing ASR-induced damage

Compressive and tensile strength tests

Compressive and tensile tests are two of the most commonly used tests for assessing concrete mechanical properties [27,31,40]. The most commonly used test procedures for assessing the tensile strength of ASR-affected specimens are the direct tensile strength, the splitting tensile strength, and the gas pressure tension test [40]. Due to the challenges associated with the direct tensile test procedure (i.e., costly, highly sensitive to load eccentricity, stress concentration at the support locations), which may result in premature failure of the specimen, limited data are available on applications of this test to assess the impact of ASR on affected concrete [40,52]. On the other hand, due to its simplicity, the splitting tensile test is the most common procedure to assess the tensile strength of concrete; the latter is an indirect measurement of the tensile strength. However, this test method can result in an inaccurate representation of ASR-induced damage due to the preselection of the failure plane. Conversely, the gas pressure tension test measures concrete's "true" tensile strength. However, it is unable to measure the impact of ASR-induced damage at expansion levels higher than 0.12% [40,53].

The compressive strength test is another technique to assess the impact of ASR-induced damage in concrete. Sanchez et al. [31] found that the impact of ASR-induced expansion on the compressive strength of specimens with low and moderate levels of expansion is negligible, and a noticeable compressive strength reduction is only observed at high and very high expansion levels. Therefore, the compressive strength test is not a reliable tool to appraise the extent of deterioration in concrete elements affected by ASR. Contrary to the aforementioned tests, the stiffness damage test (SDT) has proven to be a reliable technique for assessing the condition of ASR-affected concrete [27,31].

Stiffness Damage Test (SDT)

SDT is a mechanical and cyclic test procedure designed to assess damage in concrete specimens. SDT was first established by Walsh (1965) for evaluating rock specimens [54], being later adapted for concrete by Crouch (1987) [55]. Later, Chrisp et al. [56] and then Smaoui et al. [57–59] adopted this technique to assess the degree of ASR-induced damage on concrete specimens after performing the SDT using the fixed loads of 5.5 MPa and 10 MPa, respectively at the loading rate of 0.10 MPa/s. Finally, after an in-depth analysis of concrete with various reactive aggregates (sand and coarse) and compressive strength (i.e., 25, 35, and 45 MPa), Sanchez et al. [32] optimized the SDT procedure for appraising the condition of ASR-affected concrete specimens where they should be undergoing a 40% of the compressive strength instead of a fixed load. Furthermore, the authors [32] suggested using indices as outcomes of the test procedure, namely stiffness damage index (SDI) and plastic

deformation index (PDI), representing the ratio of dissipated energy/plastic deformation and the total energy/deformation implemented in the system (i.e., $SI / (SI+SII)$ and $DI / (DI+DII)$) over the five cycles, respectively (Figure 7.4). Moreover, the modulus of elasticity, as an average secant modulus of elasticity value of the 2nd and 3rd cycles of stiffness damage testing, would also be another output parameter for determining the extent of damage in the affected concrete. Very few works have been conducted to date on the effect of ASR-induced mechanical degradation on RCA concrete. As such, Zhu et al. [27] used SDT to assess the damage caused by past (i.e., low, moderate and high) and *secondary* (i.e., only moderate) expansion on RCA mixtures using the direct replacement of recycled concrete derived from construction demolition waste (CDW). Accordingly, the authors [27] suggested that the SDT is a reliable tool for assessing the *secondary* damage regardless of the RCA's past expansion experience. Although the SDT has been shown to be quite suitable to appraise ASR-induced deterioration in RCA concrete, the effect of various *secondary* damage on the mechanical degradation of RCA mixtures using new mix design and SDT outcomes remains mostly unknown.

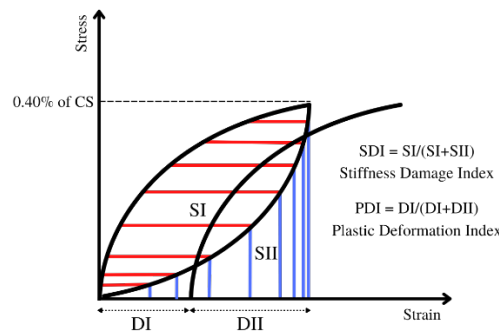


Figure 7.4: Calculation of SDI and PDI adopted from [32].

Scope of work

As previously mentioned, although limited data are available on the effects of *secondary* ASR-induced expansion on the mechanical properties of RCA concrete [21,22,24,28,60], the effects of distinct initial ASR expansion on the mechanical degradation of RCA concrete are not fully understood. Therefore, this work aims to quantitatively understand the impact of the extent of initial damage on the mechanical properties reduction of RCA mixtures as a function of their *secondary* induced expansion. The mixtures were proportioned using a new mix design technique (i.e., EV method [9]), incorporating a reactive RCA made of a reactive coarse aggregate; at distinct distress levels, mechanical testing protocols (i.e., SDT, modulus of elasticity and compressive strength) were performed on the recycled concrete specimens. Finally, comparisons on the extent of mechanical degradation (i.e., physical integrity and mechanical properties reductions) of recycled concrete presenting various “initial” damage are performed.

Materials and methods

RCA fabrication procedure

To achieve a controlled sample of reactive RCA, a highly reactive coarse aggregate from NB, Canada (Springhill - Greywacke) and a local non-reactive natural sand were selected for this work to fabricate 35 MPa concrete specimens (100 by 200 mm cylinders). The properties of aggregates used in this study are presented in Table 7.1. All CC specimens were mix-proportioned using the Concrete Prism Test (CPT) mix-design, as per ASTM C1293 [61]. A conventional industry-grade Portland cement (CSA type GU, ASTM type 1) containing a high alkali content (0.98% $\text{Na}_2\text{O}_{\text{eq}}$) was used in the mixture. Reagent grade NaOH was used to accelerate ASR development to raise the total alkali content to 1.25% $\text{Na}_2\text{O}_{\text{eq}}$ by cement mass in the mixture. The specimens were manufactured using a pan rotary mixer and moulded into cylindrical moulds; after 24 hours, all specimens were de-moulded. In order to measure the longitudinal expansion of the specimens, they were drilled, and stainless-steel gauge studs (5 mm in diameter by 15 mm length) were glued at both flat ends of the samples using a fast-setting cement. The samples were left at room temperature for 24 hours before the initial reading. Later, all specimens were stored at 38°C and 100% relative humidity (RH) using 22-litre plastic containers lined with an absorbent cloth. All cylinders were regularly monitored over time and were removed upon reaching 0.05% of expansion (slightly damaged), representing a “returned concrete” where cracks are present within the reactive OVA particle, and 0.30% of expansion (severely damaged) represents a “construction demolition waste (CDW)” where cracks are present within the reactive OVA particle and have extended into the residual cement paste (RCP). It is worth noting that all concrete specimens were cooled down to 21°C for 16 ± 4 hrs before periodic expansion measurements. Once the test specimens reached the above expansion levels, they were wrapped in plastic film and stored at 12°C to stop further ASR development until all other specimens reached the given expansion levels. The specimens were then crushed to produce reactive RCA. Later, RCAs were sieved in sizes ranging from 4.75 mm to 19 mm and then tested for RM content following the procedure proposed by Abbas et al. [62]. The test procedure involved soaking the weighed sample of RCA in a 26% by weight solution of sodium sulphate. Later, the soaked sample was subjected to five cycles of freeze and thaw (i.e., 16 h at -17° C in a freezer and 8 h at 80° C in the oven) to dissolve the attached RM in solution, and the mass loss was accounted for in percentage of RM. After conducting the above procedure, the RM content of 46% and 51.5% were obtained for slightly and severely damaged RCA, respectively.

Table 7.1: Aggregate types used in this study.

Aggregate	Location	Rock Type	Specific gravity	Absorption (%)
Reactive coarse aggregate (SP)	Fredericton, New Brunswick (Canada)	Greywacke	2.71	0.70
Non-reactive fine (Ottawa sand – OS)	Ottawa, Ontario (Canada)	Derived from granite	2.60	0.82

RCA Concrete mix design

A total of 110 recycled concrete specimens were produced using the two reactive RCAs (i.e., slightly damaged-0.05% RCA and severely damaged-0.30% RCA) in this study. Moreover, in order to be able to compare the data obtained from the reactive RCA samples with those gathered from the control specimens containing reactive aggregates, the RCAs mentioned above were proportioned using the EV method while keeping the total cement content of the system equal to 420 kg/m^3 . It is worth noting that to distinguish the RM from the new cement paste, the GU cement used for CC mixtures was replaced by white cement with $\text{Na}_2\text{O}_{\text{eq}}$ of 0.31 in RCA concrete. To accelerate ASR development, reagent grade NaOH was used to raise the total alkali content in the mixture containing reactive aggregates to 1.25% $\text{Na}_2\text{O}_{\text{eq}}$ by cement mass; the mix proportions are presented in Table 7.2. The reactive RCA concrete samples were de-moulded after 24 hours and moist cured for another 24 hours. The ASR development and expansion measurements procedure in all RCA samples is similar to the conventional specimens. Four levels of expansion were selected for further analysis (i.e., 0.05%, 0.12%, 0.20% and 0.30%), and once the test specimens reached the above expansion levels, due to testing capacity issues, they were wrapped in plastic film and stored at 12°C to stop ASR further development until mechanical tests were conducted on the samples.

Table 7.2: Conventional concrete and RCA concrete mix proportioning.

Ingredients	Springhill CC	Slightly damaged Springhill RCA-concrete (0.05% RCA)	Severely damaged Springhill RCA-concrete (0.30% RCA)
Gray cement (kg/m^3)	420	-	-
White cement (kg/m^3)	-	340	331
Ottawa sand (kg/m^3)	823	774	791
Coarse aggregate (kg/m^3)	934	1040	1048
Water (kg/m^3)	189	153	149
RMC average (%)	-	46	51.5

Testing Procedures

Compressive Strength

The compressive strength test was conducted with two main objectives in this work. First, the test was carried out on a set of specimens to obtain the 28-day strength of all mixtures. Due to the presence of reactive aggregates and the risk of ASR-induced damage impacting the compressive strength results, the procedure proposed in ASTM C 39 [63] could not be followed. Hence the specimens were wrapped in plastic and placed in an environmental chamber at 12°C for 47 days as per Sanchez et al. [64]; the above method has been shown to be an efficient way to stop ASR development in the laboratory [64]. The obtained “equivalent” 28 days ultimate strength was later used to identify the maximum load of the SDT (i.e., 40% of f'_c). The second objective of the

compressive strength test was to assess the impact of ASR-induced damage at each given expansion level (i.e., 0.05%, 0.12%, 0.20% and 0.30%) on the ultimate strength of RCA specimens. Therefore, three specimens per expansion level per family were initially removed from storage and moist cured for 48 hours. Later, both ends of the specimens were grinded off until a flat smooth surface was achieved and finally tested to obtain the compressive strength of the mixtures.

Stiffness Damage Test (SDT)

Three specimens per expansion level and per family (i.e., CC, 0.05% RCA and 0.30% RCA) were removed from the 12°C storage, and its steel studs were removed entirely. Both ends of the specimens were grinded off using a profile grinder until a flat smooth surface was achieved. Later, to reduce the variability of the results, the specimens were moist-cured for 48 hours at room temperature prior to testing. The specimens were then placed in the SDT cage in accordance with the testing procedure proposed by Sanchez et al. [31]; specimens were subjected to 5 cycles of loading and unloading at the controlled loading rate of 0.10 MPa/s up to 40% of the ultimate strength of the sound/undamaged concrete.

Results

ASR kinetics and development

Figure 7.5 illustrates the average ASR-induced expansion as a function of time for CC and both recycled mixtures made of slightly damaged and severely damaged RCA (i.e., SPR CC, 0.05% RCA and 0.30% RCA, respectively). A standard deviation of 0.01%-0.04%, 0.02%-0.04% and 0.02%-0.03% was obtained for the CC, slightly damaged and severely damaged RCA, respectively. While the expansion measurements were carried out for 150 and 261 days for the CC and both recycled mixtures, respectively, the severely damaged RCA showed no significant further expansion past 188 days, yet a few specimens were able to achieve 0.30% of the secondary expansion.

Analyzing the plots, a similar trend is observed at the beginning from 0-0.03% of expansion (i.e., 29 days), after which both recycled mixtures increase in expansion up to 0.09% and 0.06% at 51 days for the severe and slightly damaged RCA, respectively, while the CC attains only 0.05% at 52 days. After approximately 63 days, the CC swells faster than recycled mixtures; the severely and slightly damaged recycled mixtures and the CC reached an expansion level of 0.12% at 79, 94 and 75 days, respectively. Moreover, an expansion of 0.20% was obtained after 128, 157, and 94 days for the severely and slightly damaged recycled mixtures as well as the CC, respectively. The severely damaged specimens reached an average expansion of 0.28% at 261 days, while it took 203 days for slightly damaged RCA and 150 days for CC to reach an expansion level of 0.30%. It is worth noting that while only a few specimens reached the expansion level of 0.30% for severely damaged RCA, and

most specimens did not expand after an expansion level of 0.28%, the slightly damaged RCA specimens continued expanding to 0.40% at 261 days as per Figure 7.5.

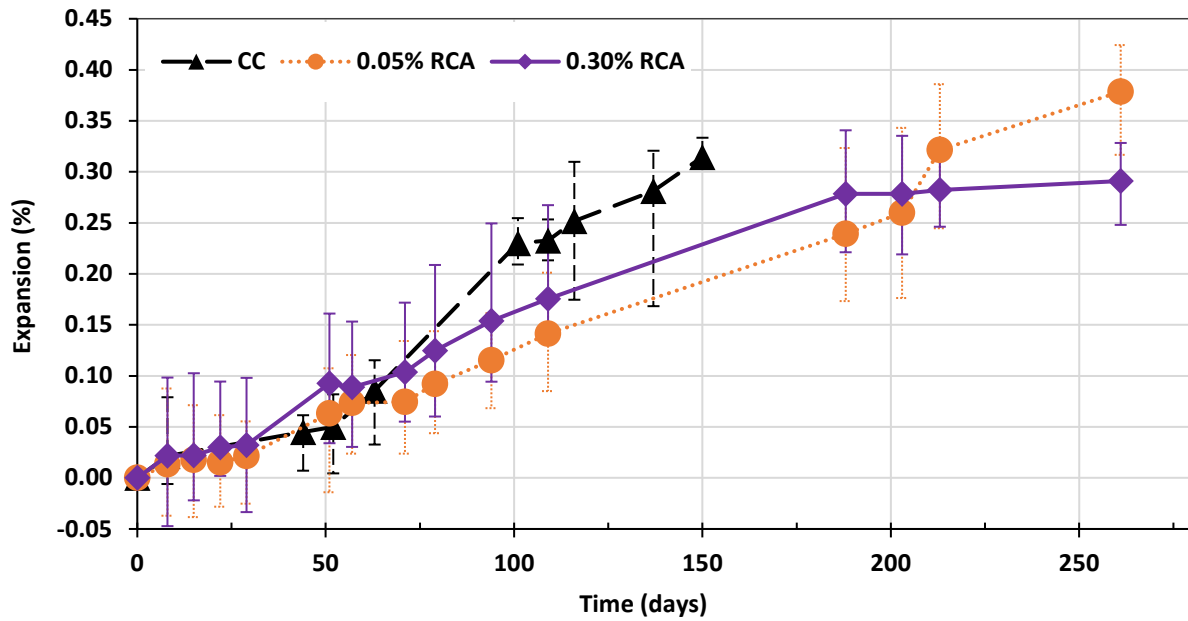


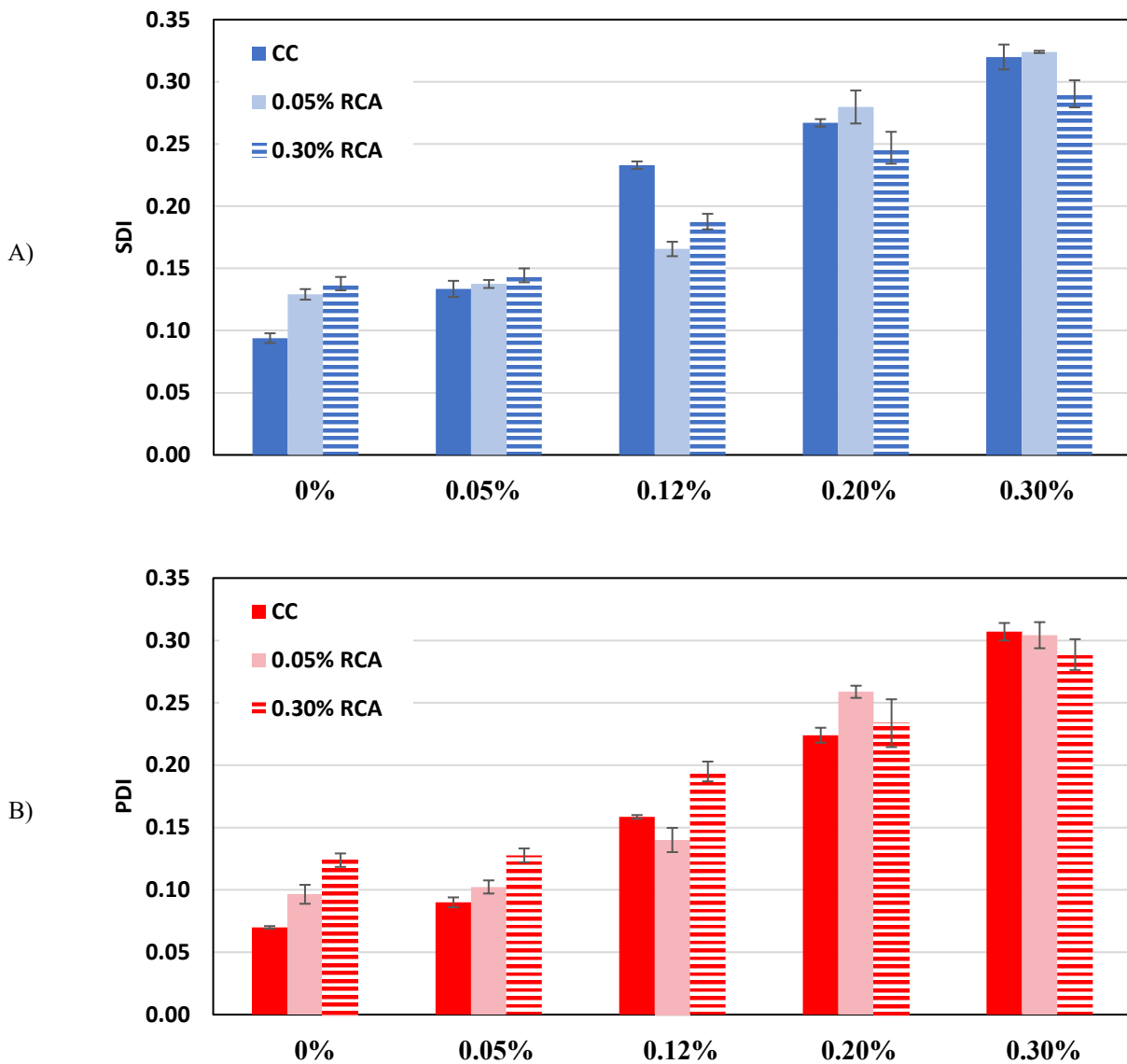
Figure 7.5: Expansion as a function of time for CC and RCA concrete mixtures partially adapted from [24].

Stiffness Damage Test (SDT)

The results in this section are the average values gathered from three concrete specimens from each of the mixtures of this work at each expansion level. Analyzing the results, one sees that the higher the ASR-induced expansion, the higher SDI, PDI and the lower modulus of elasticity (ME) for all concrete mixtures. As per Figure 7.6A and B, at 0.05% of expansion, the severely damaged RCA showed SDI and PDI values of 0.14 and 0.13, which is slightly higher than the slightly damaged RCA at 0.14 and 0.10, respectively. In comparison, the CC specimens had the lowest SDI and PDI values of 0.13 and 0.09 at the same expansion level. At moderate expansion level (i.e., 0.12%), more distinctive variation between the mixtures is observed with SDI values of 0.19, 0.17 and 0.23 for the severely and slightly damaged RCA as well as the CC, respectively. However, in the case of PDI, the severely damaged RCA presented the highest PDI (0.19), followed by CC (0.16) and slightly damaged RCA (0.14). At high and very high levels of expansion, the severely damaged RCA generally presents the lowest values of SDI and PDI (i.e., 0.25 and 0.23 for high and 0.29 and 0.29 for very high expansion levels, respectively), while the slightly damaged RCA presents the highest (i.e., 0.28 and 0.26 for high and 0.32 and 0.30 for very high expansion levels, respectively). Overall, the CC had a linear growth in SDI and PDI, reaching values of 0.27 and 0.22 for high and 0.32 and 0.31 for very high expansion levels, respectively.

Similarly, Figures 7.6C and D present the modulus of elasticity and modulus of elasticity reduction of RCA mixtures and conventional concrete specimens for all expansion levels, respectively. Before the beginning of the reaction for CC and the secondary reaction of RCA mixtures, the severely damaged RCA presented the

lowest ME of 24 GPa, followed by the slightly damaged RCA at 27 GPa, while CC had the highest ME at 31 GPa. Then a reduction trend is observed for all three mixtures (CC, 0.05% RCA and 0.30% RCA). As such, at the 0.05% of expansion, the severely damaged RCA's ME was reduced to 18 GPa (i.e., representing a ME loss of 25%), while slightly damaged RCA and CC specimens had ME of 24 GPa and 26 GPa (i.e., showing the ME loss of 12% and 17%), respectively. At moderate expansion level (0.12%), severely damaged RCA presented the lowest ME at 15 GPa, followed by the CC and the slightly damaged RCA with ME of 20 GPa and 24 GPa (i.e., demonstrating 37%, 36%, 13% of ME loss), respectively. Moreover, at high and very high expansion levels, the ME continuously dropped to values of 14 GPa (44% of ME reduction) and 13 GPa (47% of ME loss) for severely damaged RCA, respectively. Similarly, the slightly damaged RCA and CC achieved ME of 15 GPa and 16 GPa for high (i.e., representing an ME reduction of 46% and 48%) and 13 GPa and 14 GPa for very high expansion levels (i.e., having an ME reduction of 54% and 56%), respectively.



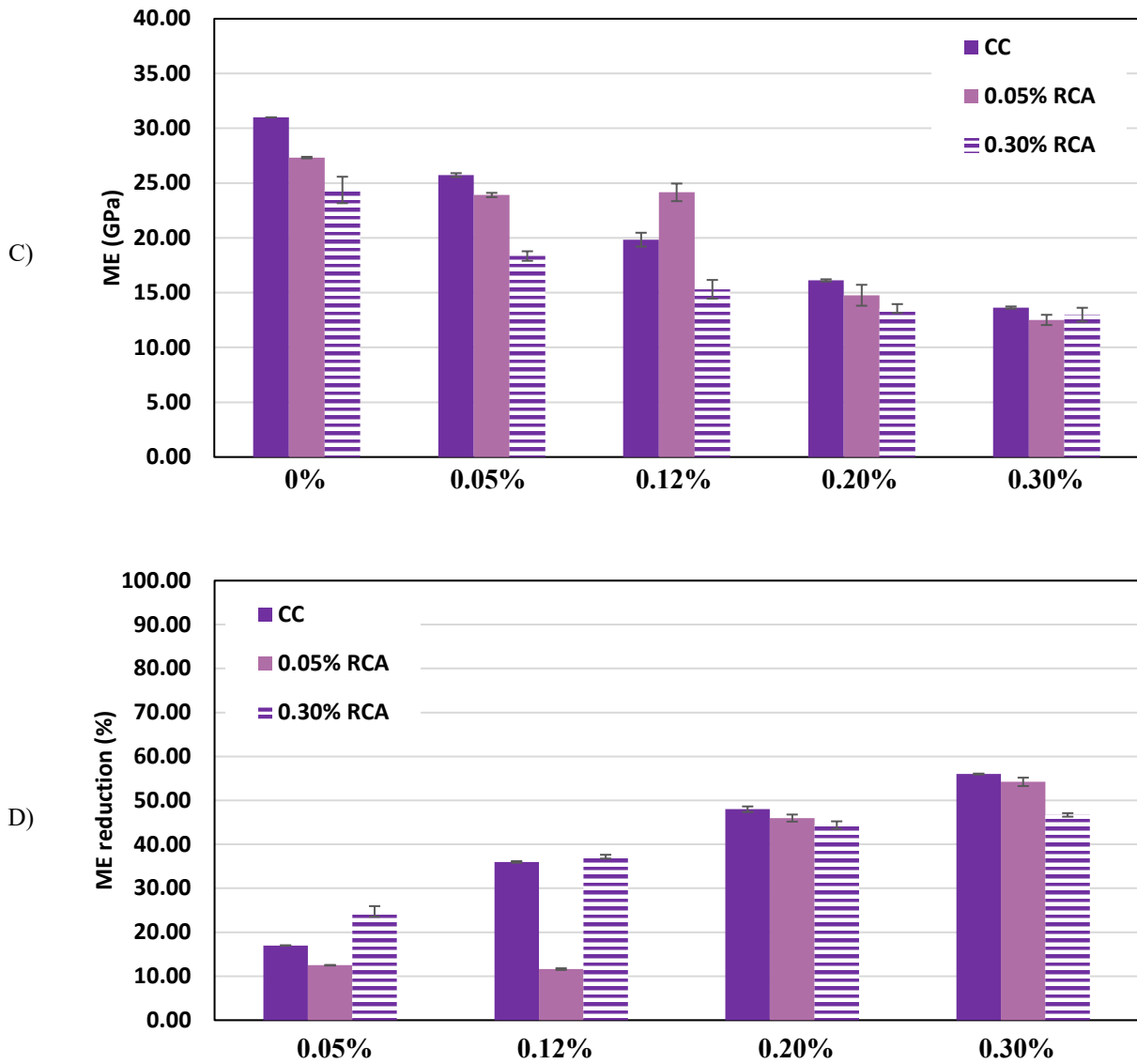


Figure 7.6: The results of A) stiffness damage index (SDI), B) plastic deformation index (PDI), C) Modulus of elasticity and D) modulus of elasticity loss (%) for slightly and severely damaged recycled aggregates (0.05% RCA, and 0.30% RCA) and conventional concrete.

Compressive Strength (CS)

This section presents the compressive strength results of all CC and RCA concrete of this work. It is worth noting that the gathered compressive strength results for CC were determined on a separate set of specimens with the same maturity.

Figure 7.7 illustrates the compressive strength (CS) and CS reduction of RCA mixtures vs. conventional concrete incorporating similar aggregates for various expansion levels. All three concrete mixtures achieved a similar compressive strength at an expansion level of 0% (sound concrete), 35 MPa, 37 MPa and 35 MPa for severely damaged RCA, slightly damaged RCA and CC, respectively. At expansion levels of 0.05%,

compressive strength of 33 MPa, 35 MPa and 33 MPa, while at 0.12% of expansion, compressive strength of 32 MPa, 33 MPa and 32 MPa were obtained from severely and slightly damaged RCA and CC specimens, respectively; thus, no significant reduction in compressive strength was observed ($< 10\%$) up to moderate expansion. At a high expansion level (0.20%), compressive strength of 31 MPa, 31 MPa and 28 MPa represents the CS reduction of 13%, 15% and 19% for severely damaged RCA, slightly damaged RCA and CC, respectively. At a very high expansion level, the compressive strength of 30 MPa, 31 MPa and 25 MPa (i.e., showing the CS reduction of 15%, 17%, and 29%) were gathered from severely and slightly damaged RCA and CC specimens, respectively.

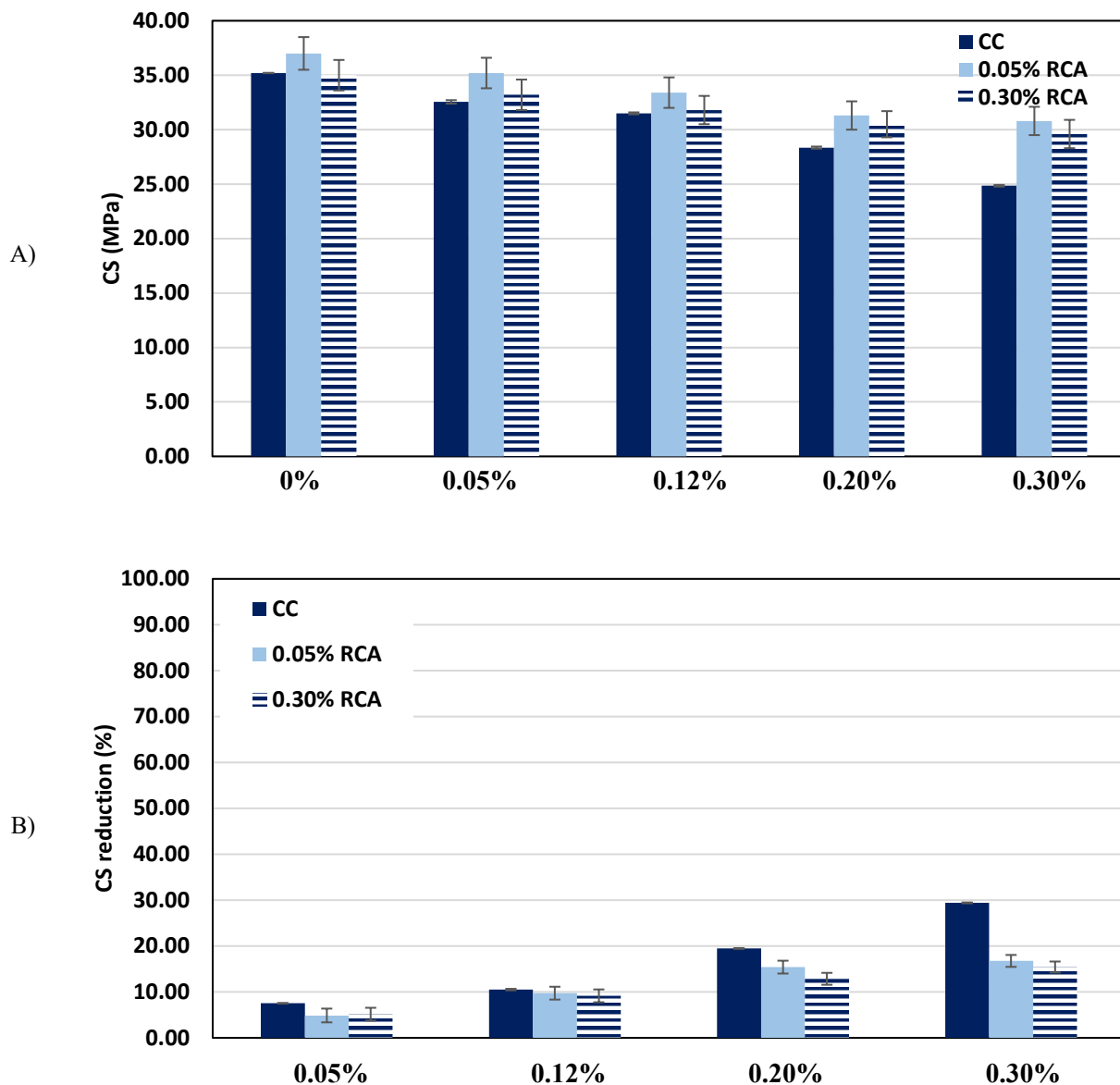


Figure 7.7: A) Compressive strength (MPa) and B) compressive strength loss (%) for slightly and severely damaged recycled aggregates (0.05% RSPR and 0.30% RSPR) and conventional concrete Vs. Expansion level.

Discussion

The analysis in this section is divided into three main topics. Initially, a discussion on the kinetics and potential of *secondary* expansion of mixtures is presented. Secondly, the effects of initial and *secondary* ASR-induced damage on the mechanical properties of distinct RCA mixtures are discussed in detail; the latter's mechanical properties are compared with the companion CC. Moreover, the statistical validity and significance of the mechanical results were investigated through analysis of variance (ANOVA) and a *t*-test. Lastly, the data gathered in this study is validated through the use of a microscopic assessment.

Development of secondary expansion

As previously mentioned, the potential and kinetics of *secondary* expansion in RCA mixtures are significantly affected by the availability of reactants (i.e., silica from the aggregates and alkalis from the cement paste) in the concrete matrix [18,24,25]. Analyzing Figure 7.5, one notices that although all three concrete mixtures present a similar trend, the induction period (time to initiate the reaction) and the obtained final expansion vary between mixtures. As such, the induction period of both RCA mixtures is slightly shorter when compared to CC, which can be explained by the presence of pre-existing cracks which may facilitate moisture ingress and access to alkalis in the system [28]. Later, after 63 days, this situation changes, and the reaction kinetics of CC increases and overcomes both RCA mixtures. Accordingly, both RCA mixtures' *secondary* expansion displayed a slower rate past 0.12% of the expansion compared to CC; such observation could be linked to a shortage of reactants, particularly the amount of silica from the OVA and alkalis in the immediate vicinity of OVA. This could be attributed to the following factors: a) part of available uncrystallized silica in OVA has already been used during the *initial* expansion that both RCAs of this study have experienced (i.e., 0.05% and 0.30%), and b) the high quantity of RM in the RCA (i.e., 46% and 51.5% for slightly and severely damaged RCA, respectively- as per Table 7.2) could be acting as a barrier and preventing the reactant silica from the OVA to reach the new alkalis present in the new mortar; such a barrier effect was also suggested by Trottier et al. [28]. Otherwise, ASR-induced expansion kinetics for both RCA mixtures had a similar trend from moderate to high expansion levels (0.12% - 0.20%). Yet, after reaching 0.20% of expansion, the severely damaged RCA presented a prolonged ASR development, and only a few specimens developed further expansion past 0.28%, while the slightly damaged RCA continued to expand, reaching an expansion of 0.40% at 261 days. This could be, on the one hand, due to the almost complete depletion of reactant silica in the severely damaged RCA's OVA. On the other hand, in the case of severely damaged RCA, previously generated cracks reached new mortar (a new source of alkali) faster. Hence, the ASR-induced development was kicked off faster and reached the plateau earlier, yet since at the beginning of the *secondary* reaction, the slightly damaged RCA consumed the remaining alkalis from the RM, the new mortar remained intact and could reserve the required alkali for further ASR development. Overall, comparing the results of ASR-induced expansion gathered in this work could attest that the level of the

initial expansion of affected concrete could affect the ASR kinetics and the ultimate *secondary* expansion of RCA's mixtures, as previously observed by Zhu et al. [27].

Understanding the difference between the mechanical properties of various recycled mixtures and conventional concrete

Slightly damaged RCA

Reviewing the results obtained through the SDT, one notices that at the beginning of the *secondary* expansion (i.e., 0.05%), the slightly damaged RCA achieved almost identical SDI and PDI compared to conventional concrete. Such observation might be attributed to A) the insignificant damage to the OVA in recycled concrete during the initial expansion; B) the presence of undamaged RM in slightly damaged RCA where, at the early stages of ASR expansion, the damage is concentrated inside the aggregate particles as shown in Figure 7.2; and, C) the removal of some of the already generated ASR-induced cracks of RCA during the crushing process as previously observed by [24]. Similarly, comparing the modulus of elasticity and compressive strength of slightly damaged RCA and conventional concrete, one realizes that their actual value at the low expansion level is almost similar (ME of 27 GPa and 31 GPa as well as CS of 37 MPa and 35 MPa, respectively).

As the expansion reaches 0.12%, no significant increase in the SDI, PDI, ME and CS reduction of RCA concrete is observed; changing SDI from 0.14 to 0.17, PDI from 0.10 to 0.14, ME reduction from 11% to 12% and CS reduction from 5% to 9%, whereas the story has changed for CC mixtures where its SDI, PDI and ME reduction demonstrated considerable differences; changing SDI from 0.13 to 0.23, PDI from 0.09 to 0.16 and ME reduction from 17% to 36%. These observations could be linked to the location of the cracks in slightly damaged RCA, where the ASR-induced cracks are mainly confined within the RCA aggregate and rarely expand into the new mortar at low and moderate *secondary* expansion. Otherwise, at high *secondary* expansion (0.20%), a sudden loss of properties in slightly damaged RCA is observed, where SDI and PDI reach 0.28 and 0.26, respectively, overtaking the SDI and PDI of CC (i.e., 0.27 and 0.22, respectively). Likewise, slightly damaged RCA displayed a 15% and 46% reduction of compressive strength and modulus of elasticity at 0.20% of *secondary* expansion, respectively. This sudden loss of mechanical properties could be linked to the significant increase in the open cracks within the aggregates as well as further propagation of ASR-induced cracks into the new cement paste and access to new alkalis resulting in the generation of a cracking network. Trottier et al. [26] explained this phenomenon, as shown in Figure 7.8. Furthermore, a significant mechanical property loss in slightly damaged RCA is observed at a very high expansion level (0.30%), similar to CC. Overall, the slightly damaged RCA had similar performance when compared to CC with two significant differences: 1) the crack propagation behaviour at various expansion levels has affected the mechanical property loss where at the beginning of the reaction, a better performance up to moderate expansion levels yet a sudden loss of mechanical

properties at high and very high expansion levels was observed; 2) significantly better performance in compression.

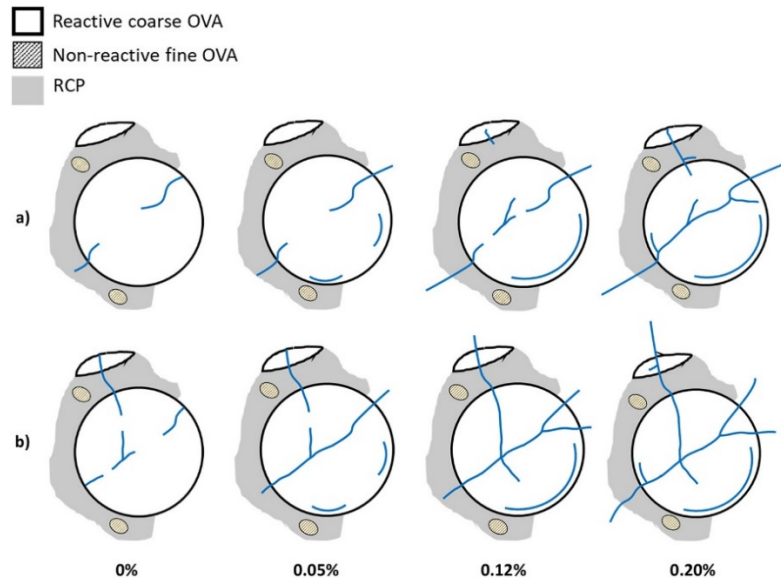


Figure 7.8: A qualitative model of crack propagation of RCA concrete induced by reactive coarse aggregate made from a) slightly damaged original concrete and b) severely damaged original concrete [28].

Severely damaged RCA

After discussing the differences in various mechanical properties of CC and slightly damaged RCA, the current section aims to describe and compare the mechanical response of slightly and severely damaged RCA. Comparing the SDI and PDI of undamaged concrete specimens incorporating both RCA mixtures, one sees that the severely damaged RCA showed a slightly higher amount when compared to slightly damaged RCA (i.e., SDI of 0.14 vs 0.13 and PDI of 0.12 vs 0.10, respectively). These observations could be due to the presence of a higher number of cracks in the severely damaged RCA specimens before the *secondary* expansion kicked off compared to the slightly damaged RCA, as displayed in Figure 7.8 [24,28]. Accordingly, although the modulus of elasticity and compressive strength of severely damaged RCA concrete have slightly inferior performance when compared to those gathered from the specimens incorporating the slightly damaged RCA, it was anticipated that such difference was significantly higher. This could be linked to the removal of some of the initial cracks during the crushing process of severely damaged RCA, along with the presence of 51.5% RM in this mixture, which considerably reduces the impact of initial ASR-induced cracks in the latter. With the progress of ASR-induced secondary expansion (i.e., 0.12%), a more significant reduction in SDI, PDI and ME reduction of severely damaged RCA is observed when compared to slightly damaged RCA (i.e., SDI of 0.19 vs 0.17, PDI of 0.19 vs 0.14 and ME reduction of 37% vs 12%, respectively) which is likely due to the presence of a more advanced cracking network within the severely damaged RCA, as shown in Figure 7.8 [28]. However, with the continuation of the reaction (i.e., 0.20% of *secondary* expansion), the severely damaged RCA concrete

demonstrated lower mechanical property loss when compared to those samples manufactured with slightly damaged RCA (i.e., SDI of 0.25 vs 0.28, PDI of 0.23 vs 0.26 and ME reduction of 44% vs 46%, respectively); such observation can be attributed to the fact that the reaction sites in the severely damaged RCA mixture are almost at their maximum potential for further expansion while the slightly damaged RCA is continuing to develop. This could be due to the fact that the impact of *secondary* ASR-induced damage surpasses the influence of initial damage and is the governing factor for mechanical property loss. As per Figure 7.8b, the 0.20% expansion is where the cracks in severely damaged RCA concrete are no longer concentrated within the RCA itself, and cracks from the OVA are linked with the RM and NM, consequently affecting the entirety of the concrete. On the other hand, although the mechanical property of severely damaged RCA concrete is reduced in the very high *secondary* expansion (i.e., 0.30%), such reduction in properties is still less than that of slightly damaged RCA (i.e., SDI of 0.29 vs 0.32, PDI of 0.29 vs 0.30 and ME reduction of 46% vs 54%, respectively).

Overall appraisal

This section aims to compare the results of mechanical degradation of ASR on conventional concrete obtained by Sanchez et al. [31] (i.e., SDI, compressive and stiffness loss) with those gathered in this work through various mechanical test procedures (i.e., stiffness damage test and compressive strength) on various RCA mixtures (Table 7.3). The authors [31] proposed a chart of values having a data envelope with a confidence level of 95% after assessing the mechanical degradation of ASR-affected CC in order to categorize the extent of the damage in specimens deteriorated by ASR. Analyzing the results, one observes that most of the results obtained in this work (i.e., SDI/PDI, ME and compressive strength loss) are within the ranges observed by Sanchez et al. [31] for CC specimens with a slightly higher loss of stiffness due to the presence of cracks within the OVA due to the initial expansion and slightly better performance in compressive strength as expected from the EV mix design technique [9]. Moreover, it was anticipated that the severely damaged RCA would demonstrate significantly higher mechanical degradation when compared to the slightly damaged RCA. Although at the beginning of ASR-induced *secondary* expansion (around 0.12%), the slightly damaged RCA presented better mechanical properties, after 0.20% of *secondary* expansion, the story has completely changed, and slightly damaged RCA demonstrated higher mechanical degradation compared to the severely damaged RCA. As previously stated, such observation could be due to the fact that while the previously generated cracks at severely damaged RCA reached new cement paste faster, which caused the ASR development to reach a plateau earlier, at the beginning of the *secondary* reaction, those previously generated cracks in the slightly damaged RCA, reached RM and consume the remaining alkali from there and after a while propagated into the new cement paste which reserved the required alkali for further ASR development.

Table 7.3: Overall assessment of ASR-induced damage on mechanical properties.

Classification of ASR damage degree	Reference expansion level (%) [31]	Assessment of ASR								
		Conventional Concrete [31]			0.05% RCA			0.30% RCA		
		ME loss (%)	CS loss (%)	SDI	ME loss (%)	CS loss (%)	SDI	ME loss (%)	CS loss (%)	SDI
Negligible	0.00–0.03	-	-	0.06–0.16	-	-	0.13	-	-	0.14
Marginal	0.04 ± 0.01	5–37	10–15	0.11–0.25	13	5	0.14	25	5	0.14
Moderate	0.11 ± 0.01	20–50	0–20	0.15–0.31	12	10	0.17	37	9	0.19
High	0.20 ± 0.01	35–60	13–25	0.19–0.32	46	15	0.28	44	13	0.25
Very high	0.30 ± 0.01	40–67	20–35	0.22–0.36	54	17	0.32	47	15	0.29

The statistical validity of the mechanical results

This section investigates the statistical validity of the results gathered through the various testing procedures presented in this study (i.e., SDT and compressive strength). Thus, a two-way ANOVA was initially performed on those results obtained from conventional, slightly and severely damaged RCA concrete as a function of ASR development. As per Table 7.4 and Table 7.5, the SDT outcomes (i.e., SDI and PDI), as well as the results of ME loss of all concrete mixtures, are statistically significant with a confidence level of 95%, where all “F values” and “P values” are higher/lower than the “ F_{critic} ” and 0.05, respectively. Conversely, since some of the “F values” and “P values” of the compressive strength results gathered from various mixtures of this study are lower/ higher than “ F_{critic} ” and 0.05, respectively, thus they were not statistically significant. Thereafter, a complementary “t-test” was conducted to confirm the significance of compressive strength results obtained at each damage level (i.e., 0.05%, 0.12%, 0.20% and 0.30%) by comparing to the data obtained from the undamaged specimens (Table 7.6). Evaluating the results, one notices that only the compressive strength gathered from the slightly damaged RCA mixture is considered significant at 0.05% of secondary expansion, while those results obtained from CC and severely damaged RCA are considered significant at 0.20% and 0.30% of expansion, respectively. The results of this study demonstrate the reliability of the SDT to appraise ASR-induced *secondary* in RCA concrete, while the compressive strength is only efficient after a certain deterioration level.

Table 7.4: Two-variable ANOVA on the SDT outcomes (i.e., SDI and PDI) of all concrete specimens of this study.

ANOVA analysis				SDI						PDI					
Concrete type	Strength (MPa)	Load (%)	Expansion (%)	SDI_F	SDI_Fcrit.	F>Fcrit.	SDI_P	α	P< α	PDI_F	PDI_Fcrit.	F>Fcrit.	PDI_P	α	P< α
Conventional concrete	35	40	0.05-0.30	72.245	4.066	✓	0.0000039	0.050	✓	134.200	4.066	✓	0.0000004	0.050	✓
0.05% RCA	35	40	0.05-0.30	302.526	4.066	✓	0.0000000	0.050	✓	299.918	4.066	✓	0.0000000	0.050	✓
0.30% RCA	35	40	0.05-0.30	94.478	4.066	✓	0.0000014	0.050	✓	59.947	4.066	✓	0.0000080	0.050	✓

Table 7.5: Two-variable ANOVA on the mechanical properties results (i.e., ME and CS) of all concrete specimens of this study.

ANOVA analysis				E						CS					
Concrete type	Strength (MPa)	Load (%)	Expansion (%)	E_F	E_Fcrit.	F>Fcrit.	E_P	α	P< α	CS_F	CS_Fcrit.	F>Fcrit.	CS_P	α	P< α
Conventional concrete	35	40	0.05-0.30	153.304	4.066	✓	0.0000002	0.05	✓	3.9389579	4.066181	x	0.0537198	0.050	x
0.05% RCA	35	40	0.05-0.30	162.593	4.066	✓	0.0000002	0.05	✓	4.7336538	4.066181	✓	0.0349761	0.050	✓
0.30% RCA	35	40	0.05-0.30	31.480	4.066	✓	0.0000886	0.05	✓	2.5518135	4.066181	x	0.1287189	0.050	x

Table 7.6: t-Test analysis on the gathered results from the compressive strength of all concrete specimens of this study.

<i>t</i> - Test analysis - compressive strength loss					
Concrete type	Compressive strength (MPa)	Expansion	CS_P value	α	P < α
CC	35	0.05%	0.174	0.05	x
		0.12%	0.062	0.05	x
		0.20%	0.025	0.05	✓
		0.30%	0.004	0.05	✓
0.05% RCA	35	0.05%	0.049	0.05	✓
		0.12%	0.048	0.05	✓
		0.20%	0.002	0.05	✓
		0.30%	0.003	0.05	✓
0.30% RCA	35	0.05%	0.238	0.05	x
		0.12%	0.115	0.05	x
		0.20%	0.062	0.05	x
		0.30%	0.045	0.05	✓

Microscopic validation of the SDT results for assessing damage in RCA concrete

A) B)

Petrographic features	Weighting factors
Closed cracks in aggregates (CCA)	0.25
Opened cracks in aggregates (OCA)	2
Opened crack with reaction product in aggregate (OCAG)	2
Coarse aggregate de-bonded (CAD)	3
Disaggregate/corroded aggregate particle (DAP)	2
Cracks in cement paste (CCP)	3
Cracks with reaction product in cement paste (CCPG)	3

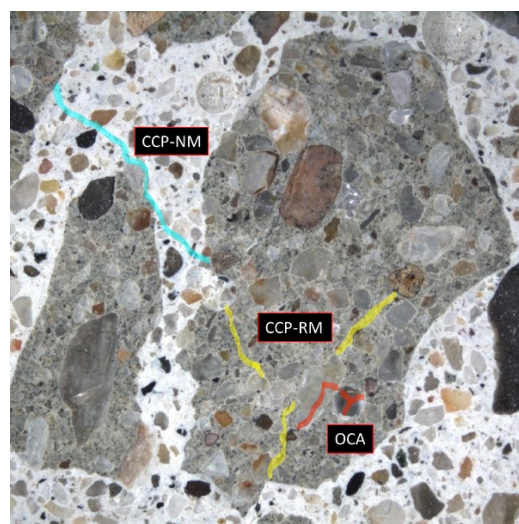


Figure 7.9: A) List of DRI distress features and their corresponding weighting factors and B) a 1cm² grid of RCA concrete where some of the distress features listed in A can be seen.

Figure 7.10 illustrates the distinct DRI numbers obtained from all specimens evaluated in this research. Trottier et al. found that [24,28] the DRI value of CC cannot be directly used to compare the level of expansion or damage with RCA concrete. Analyzing the results, one sees that at 0%, 0.05%, and 0.12% of *secondary* expansion, similar to the SDT results, the DRI number of severely damaged RCA concrete is slightly higher than the slightly damaged RCA. As such, DRI numbers 170 and 73 (expansion level of 0 %), 261 and 161 (expansion level of 0.05 %), and 390 and 268 (expansion level of 0.12 %) were obtained for the severely and slightly damaged RCA. Conversely, an inverted correlation between DRI and SDT outcomes of distinct RCA mixtures was observed at high (0.20%) and very high (0.30%) levels of expansion. Therefore, while the SDI value gathered from slightly damaged RCA is higher than severely damaged RCA at the above-mentioned expansions (e.g., 0.25 vs. 0.28 at 0.20% of expansion and 0.29 vs. 0.32 at 0.30% of expansion, respectively), the DRI number of the latter is higher than the former; severely and slightly damaged RCA displayed a DRI number of 514 and 470 at 0.20% and 1170 and 970 at 0.30% expansion.

Such inverted correlation could be explained by the observation made by Trottier et al. [24,28] through the use of the so-called extended DRI. It was found that the cracks were significantly longer in the severely damaged RCA at low and moderate and similar at high expansion levels. On the other hand, the width of the cracks was similar at low and moderate, and wider cracks was observed for slightly damaged RCA at high expansion levels. However, conventional DRI does not account for the width and length of the cracks in each DRI grid (e.g., there is no difference between cracks with a width of 0.5 mm and 1 mm in one grid, and they are treated similarly in conventional DRI). Moreover, since SDI and PDI indicate the extent of internal cracking in the overall concrete material, thus the width of the cracks plays an essential role in the outcomes of SDT. As such, the use of extended DRI can help with understanding the correlation between the mechanical and microstructure of the system.

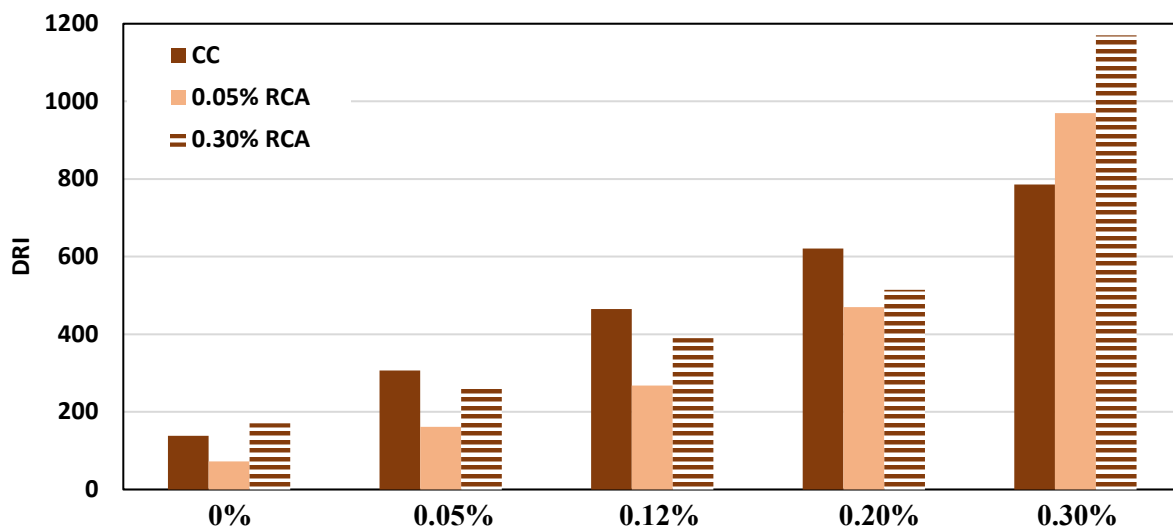


Figure 7.10: Microscopic features of mixtures assessed with the help of DRI, adapted from [24,28].

Conclusion

The main objective of this study was to assess the effects of the initial ASR-induced expansion (i.e., 0.05% representing “returned concrete” where cracks are present within the reactive OVA particle and 0.30% representing a “construction demolition waste” where cracks are present within the reactive OVA particle and have extended into the residual cement past) on the mechanical properties of RCA concrete incorporating a distinct coarse reactive aggregate (Springhill) through the use of Stiffness Damage Test (SDT) and compressive strength. The main conclusions of this work are presented hereafter:

- The ASR-induced expansion was considerably lower for both RCA mixtures when compared to the conventional concrete. Such phenomenon can be due to the following reasons: 1) consumption of source of silica in OVA during the *initial* damage that both RCAs of this work have experienced, and 2) the presence of the high amount of RM in RCA could act as a barrier for reactant silica from the OVA to reach the new alkalis in the new mortar.
- Comparing the expansion levels reached by the various RCA mixtures, one could see that the greater the initial damage, the slower the expansion rate and the lower the expansion level as a function of time. This might be due to the higher depletion of reactant silica in the severely damaged RCA when compared to the slightly damaged RCA.
- Comparing the mechanical degradation of slightly damaged RCA and conventional concrete, one realizes that they experienced almost identical mechanical property loss throughout the various ASR-induced expansion. However, comparing the mechanical results of slightly and severely damaged RCA, it is evident that the extent of initial damage significantly affects the mechanical degradation of distinct RCA mixtures, where the higher initial deterioration results in lower *secondary* mechanical properties loss. These observations could be because the influence of secondary ASR-induced damage surpasses the influence of initial damage in RCA mixtures and will govern the mechanical property loss.
- After evaluating the mechanical properties of various conventional concrete and RCA mixtures, a mechanical degradation chart of values having a data envelope with a confidence level of 95% was proposed. Moreover, statistical analysis (ANOVA- two-way analysis of variance) demonstrated that the SDT is a reliable diagnostic tool for evaluating the *secondary* ASR-induced mechanical degradation (i.e., physical integrity and stiffness reductions) in distinct RCA mixtures.
- Finally, the so-called “extended DRI” helped explain the results obtained at various *secondary* expansions. Such observation confirms that to better understand the behaviour of RCA mixtures, more thorough work focusing on the correlation of the microscopic damage features and mechanical degradation of RCA concrete is needed.

References

- [1] United States Environmental Protection Agency (EPA). (2012) Proceedings of the Water Environment Federation. 726–737. <https://doi.org/10.2175/193864705783867675>.
- [2] Makul, N. (2020). Cost-benefit analysis of the production of ready-mixed high-performance concrete made with recycled concrete aggregate: A case study in Thailand, *Heliyon*, 6, e04135. <https://doi.org/10.1016/J.HELIYON.2020.E04135>.
- [3] Paine, K.A., Dhir, R.K. (2010). Recycled aggregates in concrete: A performance-related approach. *Magazine of Concrete Research*. 62 519–530. <https://doi.org/10.1680/mac.2010.62.7.519>.
- [4] Ideker, J. H., Adams, M. P., Tanner, J., Jones, A. (2013). Durability Assessment of Recycled Concrete Aggregates for use in New Concrete: Phase I - Revised. TREC Final Reports. <https://doi.org/10.15760/trec.15>.
- [5] Fathifazl, G., & Razaqpur, G. (2013). Creep rheological models for recycled aggregate concrete. *ACI Materials Journal*, 110, 115-125. <https://doi.org/10.14359/51685526>.
- [6] Knaack, A.M. and Kurama, Y.C. (2013). Design of concrete mixtures with recycled concrete aggregates. *ACI Materials Journal*, 110, 483-493. <https://doi.org/10.14359/51685899>.
- [7] Xiao, J., Li, J., Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research*, 35, 1187–1194. <https://doi.org/10.1016/j.cemconres.2004.09.020>.
- [8] Limbachiya, M.C., Leelawat, T., Dhir, R.K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and Structures/Materiaux et Constructions*, 33, 574–580. <https://doi.org/10.1007/bf02480538>.
- [9] Ahimoghadam, F., Sanchez, L.F.M., de Souza, D.J., Andrade, G.P., Noël, M., Demers, A. (2020). Influence of the Recycled Concrete Aggregate Features on the Behavior of Eco-Efficient Mixtures. *Journal of Materials in Civil Engineering*, 32, 04020252. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003323](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003323).
- [10] Hayles, M., Sanchez, L.F.M., Noël, M. (2018). Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. *Construction and Building Materials*, 169, 724–732. <https://doi.org/10.1016/j.conbuildmat.2018.02.127>.
- [11] Razaqpur, A.G., Fathifazl, G., Isgor, B., Abbas, A., Fournier, B., Foo, S. (2010). How to produce high quality concrete mixes with recycled concrete aggregate. 2nd International Conference on Waste Engineering Management, ICWEM 2010, 73, 11–35.
- [12] Fathifazl, G., Abbas, A., Razaqpur, A.G., Isgor, O.B., Fournier, B., & Foo, S. (2009). New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*, 21(10), 601–611. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2009\)21:10\(601\)](https://doi.org/10.1061/(ASCE)0899-1561(2009)21:10(601)).

- [13] Fathifazl, G., Razaqpur, A.G., Isgor, O.B., Abbas, A., Fournier, B., & Foo, S. (2011). Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate. *Cement and Concrete Composites*, 33(9), 1026–1037. <https://doi.org/10.1016/j.cemconcomp.2011.08.004>.
- [14] Abbas, A., Fathifazl, G., Isgor, O.B., Razaqpur, A.G., Fournier, B., & Foo, S. (2009). Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Cement and Concrete Composites*, 31(8), 555–563. <https://doi.org/10.1016/j.cemconcomp.2009.02.012>.
- [15] de Freitas Macedo, H. Concrete Made with Fine Recycled Concrete Aggregate (FRCA): A Feasibility Study. Master's thesis, University of Ottawa (2019). Available from: <http://hdl.handle.net/10393/39619>.
- [16] de Grazia, M., Trottier, C., Dantas, S.R.A., Nagaraju, Y., Ziapour, R., Macedo, H.F., & Sanchez, L.F.M. (2022). Influence of Recycled Concrete Aggregate Type on Rheological Behaviour of Mixtures Proportioned Using the Equivalent Volume Method. *Recent Progress in Materials*, 4, 1–1. <https://doi.org/10.21926/RPM.2203017>.
- [17] Li, X., & Gress, D. L. (2006). Mitigating Alkali–Silica Reaction in Concrete Containing Recycled Concrete Aggregate. *Transportation Research Record: Journal of the Transportation Research Board*, 1979, 30–35. <https://doi.org/10.1177/0361198106197900105>.
- [18] Santos, M.B., de Brito, J., & Silva, A.S. (2020). A review on alkali-silica reaction evolution in recycled aggregate concrete. *Materials*, 13(11), 2625. <https://doi.org/10.3390/ma13112625>.
- [19] M.H.M.H. Shehata, C. Christidis, W. Mikhael, C. Rogers, M. Lachemi, Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction, *Cem Concr Res.* 40 (2010) 575–582. <https://doi.org/10.1016/j.cemconres.2009.08.008>.
- [20] Adams, M.P., Jones, A., Beauchemin, S., Johnson, R., Fournier, B., Shehata, M., Tanner, J.E., Ideker, J.H., Applicability of the Accelerated Mortar Bar Test for Alkali-Silica Reactivity of Recycled Concrete Aggregates, *Advanced Civil Engineering Materials*, 2 (2013) 20120030. <https://doi.org/10.1520/acem20120030>.
- [21] Shehata, M.H., Christidis, C., Mikhael, W., Rogers, C., Lachemi, M., Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction, *Cement and Concrete Research*, 40 (2010) 575–582. <https://doi.org/10.1016/j.cemconres.2009.08.008>.
- [22] Mukhopadhyay, A.K., Geiger, B.J., Button, J., Use of alkali-silica reaction-affected recycled concrete aggregate in hot-mix asphalt, *Transportation Research Record*, 2179 (2010) 1–9. <https://doi.org/10.3141/2179-01>.
- [23] Johnson, R., Shehata, M.H., The efficacy of accelerated test methods to evaluate Alkali Silica Reactivity of Recycled Concrete Aggregates, *Construction and Building Materials*, 112 (2016) 518–528. <https://doi.org/10.1016/j.conbuildmat.2016.02.155>.
- [24] Trottier, C., Zahedi, A., Ziapour, R., Sanchez, L., Locati, F., Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR), *Construction and Building Materials*, 269 (2021) 121250. <https://doi.org/10.1016/j.conbuildmat.2020.121250>.

- [25] Stark, D. (1996). The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity. Research and Development Bulletin RD114. Portland Cement Association. https://www.cement.org/docs/default-source/fc_concrete_technology/durability/rd114-the-use-of-recycled-concrete-aggregate-from-concrete-exhibiting-alkali-silica-reactivity.pdf?sfvrsn=4&sfvrsn=4
- [26] Shehata, M.H., Mikhaeel, W., Lachemi, M., Rogers, C. (2011). Mitigating the expansion in concrete containing reclaimed aggregate produced from demolished concrete affected by alkali-silica reaction. Proceedings, Annual Conference - Canadian Society for Civil Engineering, pp. 1229–1237.
- [27] Zhu, Y., Zahedi, A., Sanchez, L.F.M., Fournier, B., Beauchemin, S. (2021). Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. Cement and Concrete Research, 142, 106350. <https://doi.org/10.1016/j.cemconres.2020.106350>.
- [28] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. Cement and Concrete Research, 144, 106426. <https://doi.org/10.1016/j.cemconres.2021.106426>.
- [29] Tanner, J., Fiore, B. (2015). Risk of Alkali-Silica Reaction When Using Recycled Concrete Aggregate in New Concrete: [Project Brief]. MPC 15-302. Available: <https://rosap.nrl.bts.gov/view/dot/39917>.
- [30] Zahedi, A., Trottier, C., Sanchez, L., Noël, M. (2022). Evaluation of the induced mechanical deterioration of alkali-silica reaction affected concrete under distinct confinement conditions through the Stiffness Damage Test. Cement and Concrete Composites, 126, 104343. <https://doi.org/10.1016/j.cemconcomp.2021.104343>.
- [31] Sanchez, L.F.M., Fournier, B., Jolin, M., Mitchell, D., Bastien, J. (2017). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. Cement and Concrete Research, 93, 17-31. <https://doi.org/10.1016/j.cemconres.2016.12.001>.
- [32] Sanchez, L.F.M., Fournier, B., Jolin, M., Bastien, J., Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. Construction and Building Materials, 125, 1178-1188. <https://doi.org/10.1016/j.conbuildmat.2016.08.101>.
- [33] de Souza, D.J., Sanchez, L.F.M., de Grazia, M.T. (2019). Evaluation of a direct shear test setup to quantify AAR-induced expansion and damage in concrete. Construction and Building Materials, 229. <https://doi.org/10.1016/j.conbuildmat.2019.116806>.
- [34] Sanchez, L.F.M., Fournier, B., Jolin, M., Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). Cement and Concrete Research, 67, 74-92. <https://doi.org/10.1016/j.cemconres.2014.08.002>.

- [35] Sanchez, L.F.M., Fournier, B., Jolin, M., Bedoya, M.A.B., Bastien, J., Duchesne, J. (2016). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*, 113, 395-407. <https://doi.org/10.14359/51688983>.
- [36] Villeneuve, V., Fournier, B., Duchesne, J. (2012). Determination of the damage in concrete affected by ASR-the damage rating index (DRI). In 14th International Conference on Alkali-Aggregate Reaction (ICAAR). Austin, Texas (USA). <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-VilleneuveV-1.pdf>.
- [37] Trottier, C., de Grazia, M.T., Macedo, H.F., Sanchez, L.F.M., de Andrade, G.P., de Souza, D.J., Naboka, O., Fathifazl, G., Nkinamubanzi, P.C., Demers, A. (2022). Freezing and Thawing Resistance of Fine Recycled Concrete Aggregate (FRCA) Mixtures Designed with Distinct Techniques. *Materials*, 15, 1342. <https://doi.org/10.3390/MA15041342>.
- [38] Dunant, C.F., Scrivener, K.L. (2010). Micro-mechanical modelling of alkali-silica-reaction-induced degradation using the AMIE framework. *Cement and Concrete Research*, 40, 517-525. <https://doi.org/10.1016/j.cemconres.2009.07.024>.
- [39] Sanchez, L.F.M., Fournier, B., Jolin, M. (2012). Critical Parameters of the Stiffness Damage Test for Assessing Concrete Damage Due to Alkali-Silica Reaction (ASR). In *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction*.
- [40] Smaoui, N., Bissonnette, B., Bérubé, M.A., Fournier, B., Durand, B. (2006). Mechanical properties of ASR-affected concrete containing fine or coarse reactive aggregates. *Journal of ASTM International*, 3. <https://doi.org/10.1520/JAI12010>.
- [41] Sanchez, L.F.M., Drimalas, T., Fournier, B., Mitchell, D., Bastien, J. (2018). Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms. *Cement and Concrete Research*, 107, 284-303. <https://doi.org/10.1016/j.cemconres.2018.02.017>.
- [42] Giaccio, G., Zerbino, R., Ponce, J.M., Batic, O.R. (2008). Mechanical behavior of concretes damaged by alkali-silica reaction. *Cement and Concrete Research*, 38, 993-1004. <https://doi.org/10.1016/j.c>
- [43] Mohammadi, A., Ghiasvand, E., & Nili, M. (2020). Relation between mechanical properties of concrete and alkali-silica reaction (ASR); a review. *Construction and Building Materials*, 258. <https://doi.org/10.1016/J.CONBUILDMAT.2020.119567>.
- [44] Esposito, R., Anaç, C., Hendriks, M. A. N., & Çopuroğlu, O. (2016). Influence of the Alkali-Silica Reaction on the Mechanical Degradation of Concrete. *Journal of Materials in Civil Engineering*, 28. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001486](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001486).
- [45] Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44, 464-476. <https://doi.org/10.1016/j.conbuildmat.2013.03.014>.

- [46] Çakir, O. (2014). Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives. *Construction and Building Materials*, 68, 17–25. <https://doi.org/10.1016/j.conbuildmat.2014.06.032>.
- [47] Ahimoghdam, F. (2018). Effect of Recycled Concrete Aggregate Properties on the Behaviour of New Concrete (Master's thesis). University of Ottawa. <https://ruor.uottawa.ca/handle/10393/37588>.
- [48] European Committee for Standardization. (2004). EN 12620:2002/AC:2004 Aggregates for concrete. Retrieved from <https://standards.iteh.ai/catalog/standards/cen/e392fb77-8df5-4d0c-ba2b-2f487dda1037/en-12620-2002-ac-2004>.
- [49] Sims, I., & Poole, A. B. (2017). Alkali-aggregate reaction in concrete: A world review. Taylor and Francis. <https://doi.org/10.1201/9781315708959>.
- [50] Peng, Z., Shi, C., Shi, Z., Lu, B., Wan, S., Zhang, Z., Chang, J., Zhang, T. (2020). Alkali-aggregate reaction in recycled aggregate concrete. *Journal of Cleaner Production*, 255. <https://doi.org/10.1016/j.jclepro.2020.120238>.
- [51] Fournier, B., Bérubé, M. A. (2000). Alkali-aggregate reaction in concrete: A review of basic concepts and engineering implications. *Canadian Journal of Civil Engineering*, 27, 167–191. <https://doi.org/10.1139/199-072>.
- [52] Abrishambaf, A., Barros, J. A. O., Cunha, V. M. C. F. (2015). Tensile stress–crack width law for steel fibre reinforced self-compacting concrete obtained from indirect (splitting) tensile tests. *Cement and Concrete Composites*, 57, 153–165. <https://doi.org/10.1016/j.cemconcomp.2014.12.010>.
- [53] Resan, S. F., Chassib, S. M., Zemam, S. K., Madhi, M. J. (2020). New approach of concrete tensile strength test. *Case Studies in Construction Materials*, 12, e00347. <https://doi.org/10.1016/j.cscm.2020.e00347>.
- [54] Walsh, J. B. (1965). The effect of cracks on the uniaxial elastic compression of rocks. *Journal of Geophysical Research*, 70, 399–411. <https://doi.org/10.1029/jz070i002p00399>.
- [55] Crouch, R. S. (1987). Specification for the Determination of Stiffness Damage Parameters From the Low Cyclic Uniaxial Compression of Plain Concrete Cores, Revision A. Mott Hay & Anderson, Special Services Division, Internal Technical Note.
- [56] Chrisp, T. M., Waldron, P., Wood, J. G. M. (1993). Development of a non-destructive test to quantify damage in deteriorated concrete. *Magazine of Concrete Research*, 45, 247–256. <https://doi.org/10.1680/mac.1993.45.165.247>.
- [57] Smaoui, N., Bérubé, M. A., Fournier, B., Bissonnette, B., Durand, B. (2004). Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part I: Experimental study. *Canadian Journal of Civil Engineering*, 31, 826–845. <https://doi.org/10.1139/L04-051>.
- [58] Smaoui, N., Fournier, B., Bérubé, M.A., Bissonnette, B., Durand, B. (2004). Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part II: Application to nonreinforced

concrete specimens exposed outside. NRC Research Press Ottawa, Canada. <https://doi.org/10.1139/L04-074>.

- [59] Bérubé, M.A., Smaoui, N., Fournier, B., Bissonnette, B., Durand, B. (2005). Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part III: Application to existing structures. Canadian Journal of Civil Engineering, 32, 463–479. <https://doi.org/10.1139/L04-104>.
- [60] Mukhopadhyay, A.K. (2013). An effective approach to utilize recycled aggregates (RAs) from alkali-silica reaction (ASR) affected Portland cement concrete. Woodhead Publishing Limited. <https://doi.org/10.1533/9780857096906.4.555>.
- [61] ASTM International. (2021). ASTM C1293 - 20a Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction. <https://www.astm.org/Standards/C1293>.
- [62] Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A. G., Fournier, B., & Foo, S. (2008). Proposed method for determining the residual mortar content of recycled concrete aggregates. Journal of ASTM International, 5, 1-12. <https://doi.org/10.1520/JAI101087>.
- [63] ASTM International. (2014). ASTM C39/C39M-14 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. https://www.astm.org/c0039_c0039m-14.html.
- [64] Sanchez, L.F.M., Fournier, B., Jolin, M., Bastien, J. (2015). Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses. Construction and Building Materials, 77, 20–32. <https://doi.org/10.1016/J.CONBUILDMAT.2014.11.071>.
- [65] Grattan-Bellew, P. E. (1995). Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station. ACI Materials Journal, 92(2). <https://doi.org/10.14359/9763>.

8. Overall assessment of alkali-silica reaction affected concrete made of reactive coarse and fine aggregates

Abstract

Recycling construction demolished waste (CDW) and returned concrete (RC) is an effective way to reduce concrete production's environmental impact. However, the presence of past deterioration is always a concern when dealing with recycled concrete aggregate (RCA). Due to the presence of previous damage and unique physical/chemical properties, RCA is commonly treated as a poor-quality aggregate. Understanding the effects of past deterioration is vital in understanding its behaviour in concrete. Alkali-silica reaction (ASR) is one of Canada's leading deterioration mechanisms, creating large amounts of construction and demolition waste that can be transformed into RCA. However, ASR is an ongoing mechanism, and secondary ASR-induced expansions could severely affect recycled concrete mechanical properties. To understand the effect of pre-existing damage in each component (original virgin aggregate-OVA, residual mortar-RM) and secondary ASR-induced damage, RCA specimens are manufactured in the laboratory incorporating RCA displaying distinct ASR past deteriorations (i.e., slight and severe) using two types of reactive aggregates (i.e., reactive coarse and reactive sand). Four levels of secondary expansion were selected for analysis. Later the specimens were tested for compressive strength, direct shear strength and stiffness damage test (SDT). The results showed that the source and extent of initial damage impact the mechanical properties loss of recycled concrete. Additionally, the results were combined with the microscopic assessment of the specimens for each secondary expansion level. The results indicate that a combination of mechanical and microscopic tools is needed to assess damage in recycled concrete comprehensively.

Keywords: Recycled Concrete Aggregates (RCA), Alkali-Silica Reaction (ASR), Stiffness Damage Test (SDT), damage, mechanical assessment.

Introduction

Concrete is the most common construction material with a tremendous negative environmental impact. The strategies in place, such as using more sustainable energy sources in procuring raw materials and reusing the CO₂ emission of clinker production, cannot keep up with the construction industry's massive growth and battle its negative impacts. It is estimated that cement-based product demand will multiply by 2.5 from 2010 to 2050 [1]. However, these strategies are essential but cannot reduce CO₂ emissions to satisfactory levels. Thus finding efficient methods to increase the sustainability of concrete products is crucial.

Recycled concrete aggregate (RCA) has proven to be a sustainable alternative in concrete manufacturing. One alternative to reducing carbon footprint and improving concrete eco-efficiency is manufacturing aggregates from construction demolished waste (CDW) or returned concrete (RC), thus reducing construction waste and

landfills. However, manufacturing RCA from CDW or RC presents its unique challenges. Amongst others, the variation in the source of RCA and the presence of damage due to several deterioration mechanisms causes major concern. Alkali silica reaction (ASR) is one of the most common deterioration mechanisms. Due to the presence of reactive aggregates in many quarries in Canada [2], several infrastructures are affected by ASR. In severe cases, these structures must be demolished, which creates a large amount of waste and presents an opportunity to recycle the demolished concrete. However, ASR's potential for further expansion still causes concern [3–6]. With the many variabilities in the concrete structures affected by ASR (i.e., aggregate type, aggregate size, level of expansion, and future expansion), comprehensive research is required to assess these structures' potential to be recycled. Although there is some data on ASR-affected RCA [4,5,7–12], the relationship between the levels and source of the expansion (i.e., OVA vs. RM) and its effects on secondary ASR-induced expansions and mechanical properties is not yet fully understood [4,5,12]. The relationship between ASR-induced expansion and conventional concrete (CC) properties have been researched in depth [2,13–17]. Several mechanical and microscopic tools have been used to assess the cause and extent of deterioration (diagnosis) and potential for further damage (prognosis) of ASR-affected recycled concrete [4,5,12,18]. An example of a reliable mechanical test for assessing ASR-induced damage in conventional concrete is the stiffness damage test (SDT) [18–20].

Moreover, in recent years the direct shear test has been used as a diagnostic tool for assessing the degree of ASR damage in both conventional and recycled concrete [12,21]. Furthermore, microscopic tools such as the extended damage rating index technique (DRI) have been used to study the effects of initial and secondary ASR-induced damage in recycled concrete [4,5], and the findings show that the extent and source (i.e., reactive fine sand in the residual mortar - RM, and reactive coarse in the original virgin aggregate - OVA) of the reaction significantly affects the properties and location of the cracks generated during the secondary reaction which may affect the mechanical properties of the recycled concrete differently. Therefore, in this study, the effects of the source of the reaction (i.e., OVA, RM) and its extent on the mechanical properties of recycled concrete are investigated with the help of the aforementioned mechanical tools. Two families of conventional concrete incorporating two types of reactive aggregates (i.e., reactive coarse - Springhill and reactive fine—Texas sand) were manufactured in controlled laboratory conditions. Two distinct levels of initial ASR expansion were selected (i.e., slight-0.05% and severe-0.30%) for each family, and upon reaching the desired expansion level, the conventional concrete specimens were crushed to produce coarse recycled concrete aggregate (CRCA). The CRCA was then used to produce recycled concrete with the help of the equivalent mortar (EV) technique and was later stored in conditions that enabled secondary ASR development. Upon reaching the desired secondary expansion levels (i.e., 0.05%, 0.12%, 0.20%, and 0.30%), the mechanical properties of the specimens were appraised using the SDT, compressive and direct shear tests.

RCA microstructure

Unlike natural aggregates, CRCA is a two-phase material comprised of original virgin aggregate (OVA) and residual mortar (RM) [22]. The presence of RM creates additional interfacial transition zones (ITZs) (i.e., between OVA and RM, OVA and new mortar, and RM and new mortar) in concrete made with RCA, as shown in Figure 8.1. In the last decade alone, numerous studies focused on the unique properties of concrete made with RCA [23–30]. Most studies focused on recycled concrete's mechanical properties and concluded that using CRCA could negatively impact mechanical properties such as modulus of elasticity (ME), compressive strength and tensile strength [31–34]. Kwan et al. [34] linked the inferior compressive strength as the replacement percentage increases (from 0-80%) to the weak zones in RCA concrete (i.e., poor quality of RM and cracks introduced during the crushing process). In another study by Ismail and Ramli [35], specimens with an RCA replacement of 60% reported a 20% further reduction in compressive strength when compared to concrete incorporating 15% coarse RCA. Accounting for the unique microstructure of RCA during the mix design process has proven to be crucial in achieving desirable mechanical properties [22,36]. Fathifazl et al. [22] proposed a new mix design technique called the equivalent mortar volume (EMV) technique, where the total volume of the mortar in recycled concrete is equal to the total volume of mortar in a companion conventional concrete (CC). Fathifazl et al. [22] achieved desirable mechanical properties (i.e., compressive strength, ME); however, the fresh state properties of the mixtures needed further improvement. To improve the fresh state properties and reduce the cement used in the system, Ahimoghadam et al. [29] proposed the equivalent volume (EV) method where the total volume of aggregates (i.e., coarse and fine) and the total volume of paste are equal to a CC. Considering the benefits mentioned above, the EV technique was used in this study.

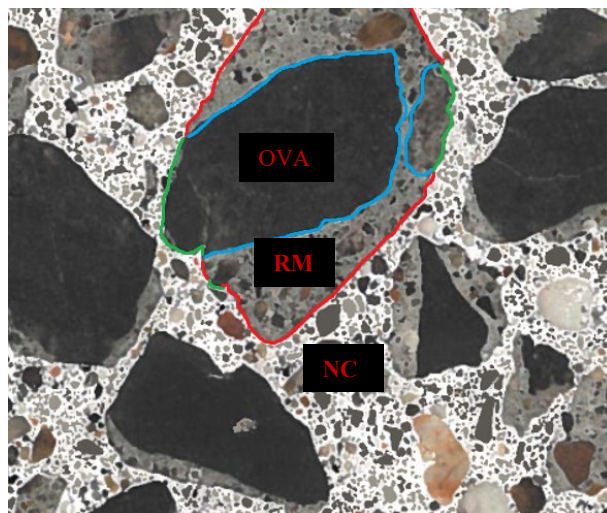


Figure 8.1: Microstructure of a coarse RCA particle highlighting the different ITZs.

ASR-induced expansion and RCA concrete

Aside from the unique physical properties of RCA (i.e., lower density, higher porosity, higher absorption), which are linked to recycled concrete's inferior performance, the presence of harmful chemicals (i.e., sulphate, reactive aggregates) could be another challenge when dealing with RCA [7]. Alkali silica reaction (ASR) is the reaction between the aggregate uncrystallized silica and the cement paste's alkalis [37]. ASR is an ongoing distress mechanism that may keep progressing in recycled concrete [7,38]. With many ASR-affected critical concrete infrastructures in Canada, understanding the impact of ongoing ASR on recycled concrete is crucial [39]. Shehata et al. [40] found that concrete made with the RCA originating from ASR reactive concrete could be as reactive as the original conventional concrete and sometimes requires higher levels of SCM to mitigate the secondary ASR expansion.

As mentioned before, ASR requires a reactant from the aggregates (Silica) and alkalis from the cement paste. As such, depending on the initial expansion level, silica may not have been completely depleted, thus, providing enough reactant for further expansions in recycled concrete [5–7,10]. However, if very high levels of expansion were achieved before demolishing the concrete, there might not be enough silica for the continuation of the reaction. Therefore, the extent of the previous reaction in parent concrete will influence the behaviour of the secondary reaction. Several studies have been conducted on the parameters affecting RCA's secondary expansion [3,6,7,40]. In general, the main factors affecting secondary expansions in RCA are [7]: reactivity of OVA and its extent in parent concrete, residual mortar content (RMC) and quality, size and density, crushing stages, RCA content, alkali content, saturation levels of the RCA, and the origin of the reaction (i.e., reactive fine vs reactive coarse).

Although the ASR-induced damage development might not be that different whether the reaction is triggered from reactive fine or a reactive coarse aggregate through a quantitative point of view, the microstructure of an ASR-affected conventional concrete where cracks are initiated inside the fine aggregates is quite different when compared to a reactive coarse (Figure 8.2) [41]. Sanchez et al. [37] proposed a multi-stage model based on the longitudinal expansion levels achieved by cylindrical specimens. In this model, the development of ASR for both cases (i.e., reactive fine vs reactive coarse) begins with a cracking formation within the reactive RCA particles at the low and moderate expansion levels, which will further extend into the mortar and generate a cracking network at high and very high levels of expansion. However, due to the unique microstructure of RCA (Figure 8.1) and the presence of additional ITZs, the crack generation and propagation could be significantly different. In this regard, Trottier et al. [4] found that not only the crack generation and propagation are different in the secondary expansion, but also the kinetics and potential could be significantly affected by the source of the secondary reaction (Figure 8.3). However, very limited data are available on the mechanical properties of ASR-affected RCA concrete.

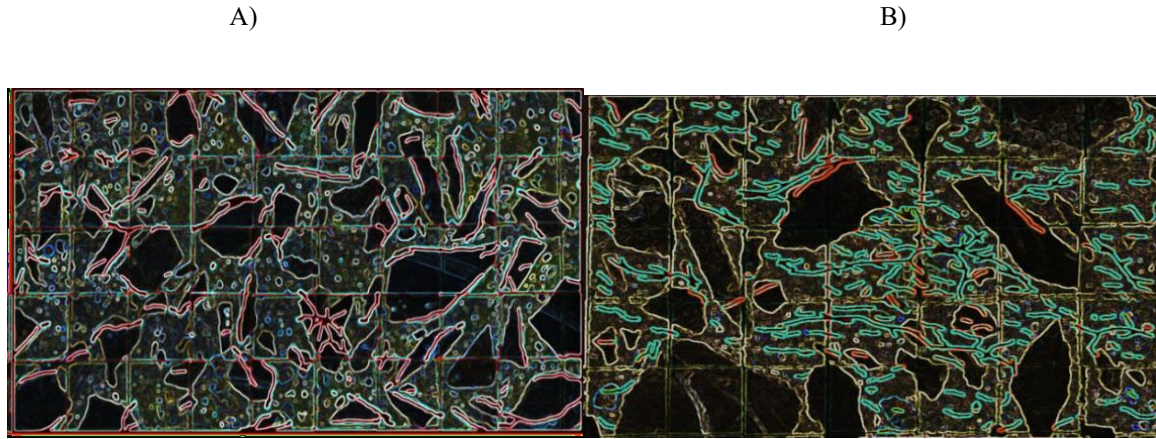


Figure 8.2: Internal cracking caused by: A) ASR coming from a reactive coarse aggregate – Spring Hill, and B) ASR coming from a reactive sand aggregate – Texas sand adopted from [42].

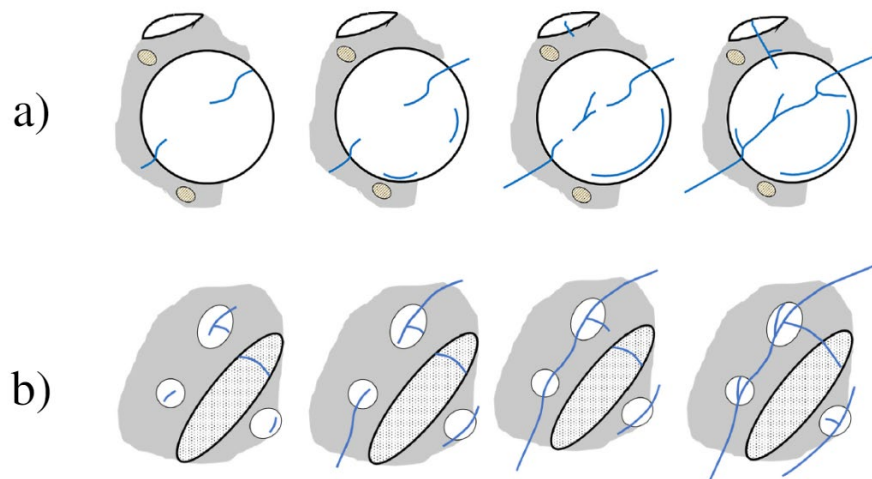


Figure 8.3: A qualitative model of crack propagation of RCA concrete induced by a) reactive coarse aggregate and b) reactive fine aggregate at four expansion levels (0.0%, 0.05%, 0.12% and 0.20%) adopted from [4].

Mechanical properties of ASR-affected recycled concrete

The mechanical properties of concrete made with RCA have always been of great interest among researchers. As such, many studies have focused on quantitatively assessing the compressive strength, tensile strength, shear strength, and ME of recycled concrete [22,27,29,31,33,43–48]. Moreover, several studies focused on the impact of ASR-induced damage on the mechanical properties of conventional concrete and found that at various levels of expansion, not all mechanical properties (i.e., compressive strength, ME, tensile strength, and shear strength) are affected in the same manner [13,21,41,49,50]. Additionally, the source of the ASR reaction (i.e., reactive

fine vs reactive coarse) could also play a role in the loss of mechanical properties at various expansion levels [13]. On this subject, Sanchez et al. [13], with the help of the stiffness damage test (SDT), direct tensile test, and damage rating index (DRI), studied twenty concrete mixtures incorporating various types of reactive aggregates. It was found that both reactive coarse and reactive sand's mechanical properties (i.e., compressive strength, tensile strength, and ME) loss generally fits within a range at each specific expansion level [13]. Other mechanical tools have been used to assess ASR-induced damage as well. De Souza et al. [21] studied the effects of AAR-induced expansion using a direct shear test setup developed by Barr and Hasso [51]. The finding shows that the shear strength of specimens reduces (up to 34%) as a function of the expansion level. The direct shear setup proved to be a reliable tool for assessing AAR-affected laboratory samples.

Although several studies [3,7,45,52,53] focused on the reactivity of RCA made with ASR-reactive construction demolition waste (CDW), there is significantly less data on the mechanical properties of recycled concrete affected by ASR where the reaction initiates within the RCA particles [11,12]. Ziapour et al. [12] found that the direct shear strength of RCA specimens is affected by the extent of the initial reaction in recycled concrete made with reactive RCA, where the reaction initiates within the OVA. Moreover, the secondary ASR expansion continues to reduce the concrete's direct shear strength [12]. Zhu et al. [11] investigated the effects of the extent of initial ASR expansion and replacement ratios on secondary ASR damage development. Zhu et al. [11] used mechanical (stiffness damage test – SDT) and microscopic tools (damage rating index – DRI) and concluded that the overall performance of the recycled mixtures depends on the past condition (extent of pre-existing damage) and the replacement ratio. However, more research is required to understand the impact of the source and extent of initial and secondary ASR development on the mechanical properties of RCA concrete.

Stiffness damage test (SDT)

The stiffness damage test (SDT) is a test procedure designed to assess damage in concrete specimens. Walsh first established SDT in 1965 for evaluating rock specimens [54], later adapted for concrete by Crouch in 1987 [55]. Chrisp et al. [56] implemented this technique by applying five compressive loading/unloading cycles using a fixed load of 5.5 MPa and a loading rate of 0.10 MPa/s to assess the degree of damage caused by ASR on concrete specimens. Smaouli et al. [57] modified the proposed technique and changed the fixed load to 10 MPa. To further optimize the procedure, Sanchez et al. [19,20] performed an in-depth analysis of the parameters affecting the SDT parameters. The authors concluded that using a fixed compressive load of 10 MPa can not capture the total impact of ASR-induced damage and proposed a new version where specimens go through five cycles of loading/unloading at 40% of the concrete strength. The total energy and energy dissipated through each cycle are measured, and output parameters such as Stiffness Damage Index (SDI) and Plastic Deformation Index (PDI) represent respectively the ratio of dissipated energy/plastic deformation and the total energy/deformation implemented in the system (i.e., $SI / (SI+SII)$ and $DI / (DI+DII)$) are used in the diagnosis of damage inflicted by ASR [19]. Furthermore, as an average secant modulus of elasticity value of the 2nd and

3rd cycles of stiffness damage testing, the modulus of elasticity would also be another SDT output parameter for determining the extent of damage in affected concrete. Figure 8.4 is an example of the output graph of SDT after the first loading and unloading cycle.

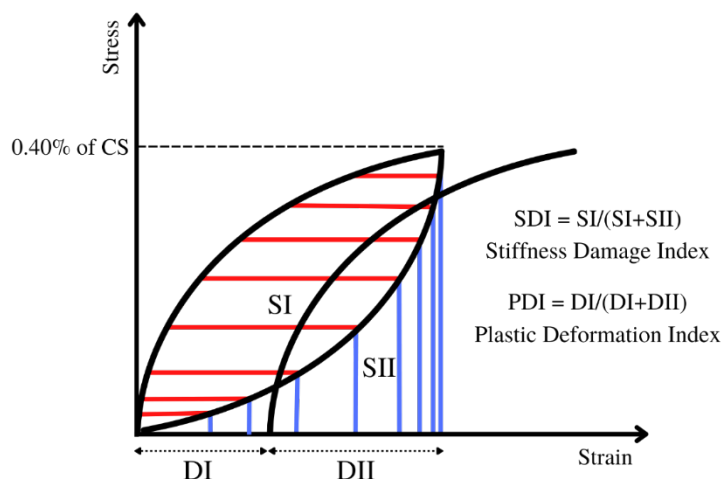


Figure 8.4: Calculation of SDI and PDI adopted from [19].

Although many studies [18–20,49] have utilized the SDT to assess the condition of ASR-affected conventional concrete (CC), very few works have assessed the impact of ASR-induced damage on the mechanical properties of RCA concrete. An experimental study by Zhu et al. [11] concluded that SDT parameters could capture the impact of secondary ASR-induced damage.

Direct shear setup test

The direct shear strength of concrete is directly correlated to its aggregate interlock property and is generally governed by compression and tension forces. The transfer of shear forces within concrete happens through the inner cracks of the system with the help of two mechanisms: a) the dowel effect and b) shear friction [58]. The Dowel effect is a mechanism related to the reinforcement used in concrete, while shear friction is concrete resistance towards crack sliding [58]. Hence, the shear resistance of concrete is often regarded as the aggregate interlock and is a critical component when designing concrete elements [59]. Several setups have been proposed in the past to assess the direct shear strength of cylindrical specimens [21,51,60,61]. Among those, Barr and Hasso [51] proposed a setup where a circumferential notch of 20-25 mm in depth is applied to ensure a shear fracture at the center of the specimen (Figure 8.5). After using the previously proposed direct shear setup to evaluate the shear strength loss of ASR-affected concrete specimens, De Souza et al. [21] suggested that the direct shear setup test is an efficient and reliable tool to assess ASR-induced deterioration level in concrete.

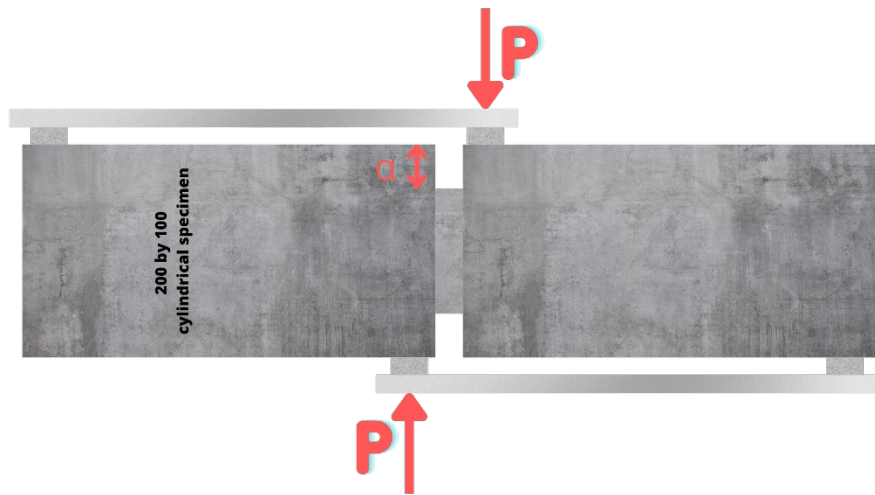


Figure 8.5. Shear setup for cylindrical concrete specimens [51].

Scope of work

The impact of ASR-induced damage on the mechanical properties of CC has been investigated in depth. However, the effect of the ASR source (i.e., coarse aggregate and fine aggregate) and the severity of the initial reaction on recycled concrete's mechanical and durability-related properties is not yet fully understood.

This work aims to understand the effect of previously existing ASR-induced deterioration in RCA and subsequent secondary ASR-induced damage on the mechanical parameters of recycled concrete made of reactive coarse (i.e., reactivity in the OVA of RCA) and fine aggregates (i.e., reactivity in the RM of RCA). Stiffness damage, compressive strength, and direct shear tests were conducted to evaluate the hardened state properties of RCA concrete affected by secondary ASR-induced expansion. The two types of RCA (i.e., reactive OVA and reactive RM) are derived from two distinct conditions: a) slightly damaged (i.e., crushed upon reaching 0.05% of expansion), representing a returned concrete (RC) where cracks are present within the reactive particles, and b) severely damaged (i.e., crushed upon reaching 0.30% of expansion) representing a "pure" demolished concrete where cracks are present within the reactive particles and have extended into the RM. Comparisons on the type and extent of damage of CC and RCA concrete at various expansion levels (i.e., 0%, 0.05%, 0.12%, 0.20%, and 0.30%) are then performed, and with the help of DRI, the impact of ASR source and previous deterioration extent are discussed in detail.

Materials and methods

Due to the variability caused by the use of CDW in making recycled concrete and the minimal control over the original concretes properties, a reactive coarse aggregate (Springhill) and a reactive fine sand (Texas sand) were

selected for this research. The Springhill coarse aggregate (SH) was combined with non-reactive sand sourced locally in Ottawa to produce a set of specimens. Moreover, the Texas reactive sand was combined with a non-reactive Limestone coarse aggregate to produce another set of specimens. As per ASTM C1293 [62], all concrete specimens had a cement content of 420 Kg/m³ using an ASTM type 1 Portland cement (PC) and a water-to-cement ratio of 0.45. To accelerate alkali-silica reaction (ASR) development, the total alkali content in the mixture was raised to 1.25% Na₂O_{eq} by cement mass. A pan rotary mixer was used, and specimens were moulded into plastic cylindrical moulds. The specimens were de-moulded after 24 hours. To measure the longitudinal expansion of the specimens, stainless steel gauge studs (5mm in diameter by 15 mm deep) were drilled and glued in at both flat ends of the samples with the help of a fast-setting cement. Prior to the first reading, the specimens were left at room temperature for 24 hours. A 22-litre plastic container lined with an absorbent cloth was used to store the specimens in 38°C and 100% relative humidity (RH) environmental chambers. The longitudinal expansion of the specimens was measured weekly until the desired expansion levels (i.e., 0.05% - representing RC, and 0.30% - representing CDW) were achieved. It is worth noting that prior to the periodic expansion measurements, the containers were cooled down by placing them outside the chambers at room temperature (23°C) for 16 ± 4 hours. Upon reaching the desired expansion levels, the specimens were wrapped in plastic sealers and placed in a separate environmental chamber at 12°C to stop ASR's further development. Once all specimens reached the desired expansion levels, they were crushed using a jaw crusher to produce RCA. Once all the specimens were crushed, the aggregates were sieved, and the RM content of the aggregates was tested following the procedure proposed by Abbas et al. [63]. In order to calculate the RM content, the oven dried RCA aggregates were weighed and then placed in a 26% by weight sodium sulphate solution. Later the soaked aggregates were placed in a controlled freezer (i.e., 17°C) for 16 hours and then placed in an oven (i.e., 80°C) for 8 hours. This cycle was repeated five times to remove the RM. The RCA aggregates were then weighted, and the percentage of RM was calculated [64].

Using the four types of recycled aggregates, 0.05% recycled Springhill aggregate (0.05% RSH), 0.30% RSH, 0.05% recycled Texas aggregate (0.05% RTX), and 0.30% RTX, 250 recycled concrete specimens were produced.

The equivalent volume method (EV) was used to ensure that the total volume of aggregates in the recycled concrete is equivalent to a companion CC; the mix proportions are presented in Table 8.2. Four levels of expansion representing damage degrees were selected for further analysis: 0.05% (low); 0.12% (moderate); 0.20% (high), and 0.30% (very high). Once the test specimens reached the above expansion levels, they were wrapped in plastic film and stored at 12°C to stop ASR further development until mechanical tests were conducted on the samples.

Table 8.1 Aggregates used in this study and their properties.

Aggregate	Location	Rock Type	Specific gravity	Absorption (%)
Reactive coarse (Springhill-SH)	Fredericton, New Brunswick (Canada)	Greywacke	2.71	0.70
Non-reactive coarse (Limestone)	Ottawa, Ontario (Canada)	Limestone	2.78	0.42
Reactive fine (Texas sand)	El Paso, Texas (USA)	Polymictic sand (granite mixed volcanic, quartzite, chert, quartz)	2.60	0.89
Non-reactive fine (Ottawa sand)	Ottawa, Ontario (Canada)	Derived from granite	2.60	0.82

Table 8.2 Mix proportioning of the specimens.

Ingredients	Springhill CC	Texas CC	Slightly damaged Springhill RCA-concrete (0.05% RSH)	Severely damaged Springhill RCA-concrete (0.30% RSH)	Slightly damaged Texas RCA-concrete (0.05% RTX)	Severely damaged Texas RCA-concrete (0.30% RTX)
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 average (%)			46	51.5	44.5	45

Experimental testing procedure

Compressive Strength

The compressive strength test was carried out with two objectives. The main objective was to see the impact of ASR-induced expansion on the compressive strength of ASR-affected recycled concrete and how the source of the reaction affects the compressive strength. Due to the impact of ASR-induced damage on compressive

strength and the time required for ASR development, the ASTM C 39 [64] was not followed. Instead, upon reaching the desired expansion levels (i.e., 0.05%, 0.12%, 0.20%, and 0.30%), the specimens were wrapped in plastic and stored at 12° C, which has proven to prevent further ASR development. Later the specimens were tested following the procedure proposed by Sanchez et al. [20]. Three specimens were tested per expansion level, and in order to have similar maturity, companion samples were manufactured and stored at similar conditions (38°C and 100% RH).

The second objective of the compressive strength test was to obtain the equivalent 28 days compressive strength to be later used as the ultimate load for the stiffness damage test (SDT)

Direct Shear Test

Similar to the previous mechanical testing, three specimens per concrete mixture (i.e., CC, 0.05% RCA and 0.30% RCA) and the desired expansion levels of this study (i.e., 0%, 0.05%, 0.12%, 0.20% and 0.30%) were prepared for the direct shear test. In this regard, initially, a circumferential 22±1 mm deep [51] and 5 mm wide (i.e., the width of the diamond blade on the masonry saw) notch at the center of the specimens was cut to ensure a shear failure at the notch (Figure 8.5). The specimens were then tested in accordance with the setup and procedure proposed by Barr and Hasso [51] (Figure 8.5). The investigation by the authors [51] showed that the notch depths of 20mm and 25mm would result in a coefficient of variation of less than 10%. After further investigation of the notch depth and loading rate, a loading rate of 100 N/s and a notch depth of 22±1mm were selected for this study to minimize the variability of the results. Using the obtained failure load, the following equation was then used to calculate the direct shear strength:

$$\tau = \frac{4 \times P}{(\phi_{cylinder} - 2a)^2 \times \pi} \quad \text{Equation 8.1}$$

Where P denotes the failure load (N), $\phi_{cylinder}$ denotes the cylinder diameter (mm), and a denotes the depth of the notch (mm).

Stiffness Damage Test (SDT)

The SDT was performed following the procedure proposed by Sanchez et al. [19]. After obtaining the equivalent 28 days compressive strength, three specimens per concrete type per expansion level were removed from the environmental chamber, and the studs used for expansion measurements were removed. Later, both ends of the specimens were flattened using a profile grinder. Prior to testing, specimens were stored in a bucket filled with a film of water for at least 48 hours; this has proven to reduce the variability of the results. The specimens were later placed in the SDT cage, and five cycles of loading and unloading at a fixed loading rate of 0.10 MPa/s and up to 40% of the ultimate strength of the sound/undamaged concrete were applied.

Results

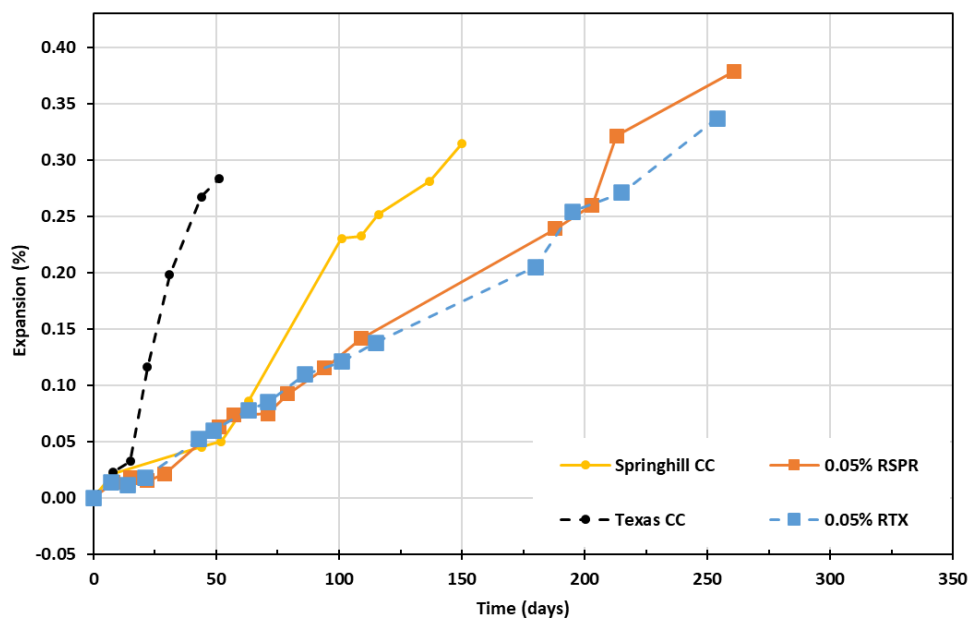
ASR development

Figures 8.6A and 6B show the ASR-induced expansion development of all concrete specimens (i.e., CC and recycled concrete). The CC specimens were measured regularly for 51 and 150 days for Texas sand and Springhill coarse, respectively, until the expansion level of 0.30% was achieved for both mixtures. The recycled concrete mixtures took 213 and 254 for 0.05% RSH and 0.05% RTX and 188 and 239 for 0.30% RSH and 0.30% RTX, respectively.

Figure 8.6 A shows that although all specimens reached the desired expansion level of 0.30%, the CC mixtures had significantly quicker ASR development throughout the experiment. Moreover, both recycled mixtures follow a similar trend from the start of the reaction up to an expansion level of 0.15%. Later, the 0.05% RSH shows a slightly higher expansion level, reaching an expansion of 0.38% after 261 days. Meanwhile, the 0.05% RTX reaches an expansion level of 0.33% after 254 days.

The ASR kinetics of 0.30% RSH and 0.30% RTX are presented in Figure 8.6B. Although the severely damaged RCA mixtures required less time to achieve an expansion level of 0.12% when compared to slightly damaged RCA mixtures, similar to the slightly damaged recycled concrete mixtures, the severely damaged recycled concrete presents a slower ASR development than CC. After 200 days, the severely damaged RCA specimens showed no signs of further expansion and were unable to achieve the average secondary expansion level of 0.30%. It is worth noting that the measurements were carried out for 300 days to ensure that a total of 10 specimens were available for further testing.

A)



B)

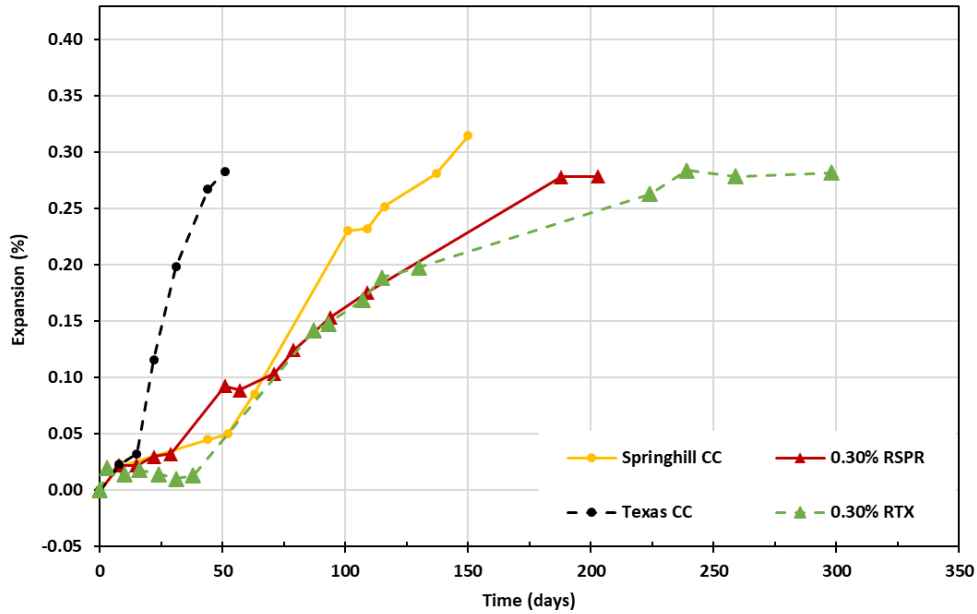


Figure 8.6: ASR expansion development for A) conventional vs slightly damaged RCA and B) conventional vs severely damaged RCA. For comparison reasons, the CC mixtures are added to both graphs.

Direct shear strength

The direct shear strength and its loss at distinct expansion levels of the CC and recycled concrete mixtures are presented in Figures 7 and 8, respectively. Before the start of the ASR reaction (0% of expansion- sound concrete), CC achieved a higher shear strength (i.e., 8.82 MPa-SH and 8.15 MPa-TX) while slightly damaged RCA mixtures had shear strength of 7.24 MPa and 7.13 MPa for 0.05% RSH and 0.05% RTX, respectively. Analyzing Figure 8.7, it is evident that the direct shear strength of all mixtures generally lessens as a function of induced expansion and development, with the exception of CC specimens whose shear strength has increased after a high expansion level (i.e., from 5.82 MPa to 7.40 MPa).

As such, at 0.05% of expansion, the shear strength of 8.8 MPa and 6.6 MPa, which represent the shear loss of 0% and 20%, were obtained for SH and TX CC specimens, respectively. Likewise, the shear strength of 5.82 MPa and 6.86 MPa was achieved, representing the shear strength loss of 0.25% and 0.34% for 0.05% and 0.05% RTX, respectively. The severely damaged recycled concrete presented the lowest shear strength with values of 5.41 MPa and 5.49 MPa for 0.30% RSH and 0.30% RTX. As the expansion progressed further (0.12%), all specimens demonstrated a lower shear strength. The SH and TX specimens achieved a shear strength of 7.13 and 6.60 MPa, while a slightly damaged recycled concrete presented values of 5.44 and 4.88 MPa for 0.05% RSH and 0.05% RTX. Similar to the previous expansion levels, the severely damaged recycled concrete presented the lowest shear strength with values of 4.79 and 4.66 MPa. Moreover, at an expansion level of 0.20%, the shear strength of all specimens continued to reduce to values of 5.82 and 6.48 MPa for RSH and RTX. It

must be pointed out that at this expansion level, the slightly damaged recycled specimens showed lower shear strength when compared to severely damaged recycled concrete with values of 4.02, 3.13, 4.40, and 4.09 MPa for 0.05% RSH, 0.05% RTX, 0.30% RSH and 0.30% RTX, respectively. Similar trends were observed at a very high expansion level (0.30%) with one exception for SH specimens which achieved a higher shear strength of 7.40 MPa compared to the shear strength achieved at an expansion level of 0.20% (i.e., 5.82 MPa).

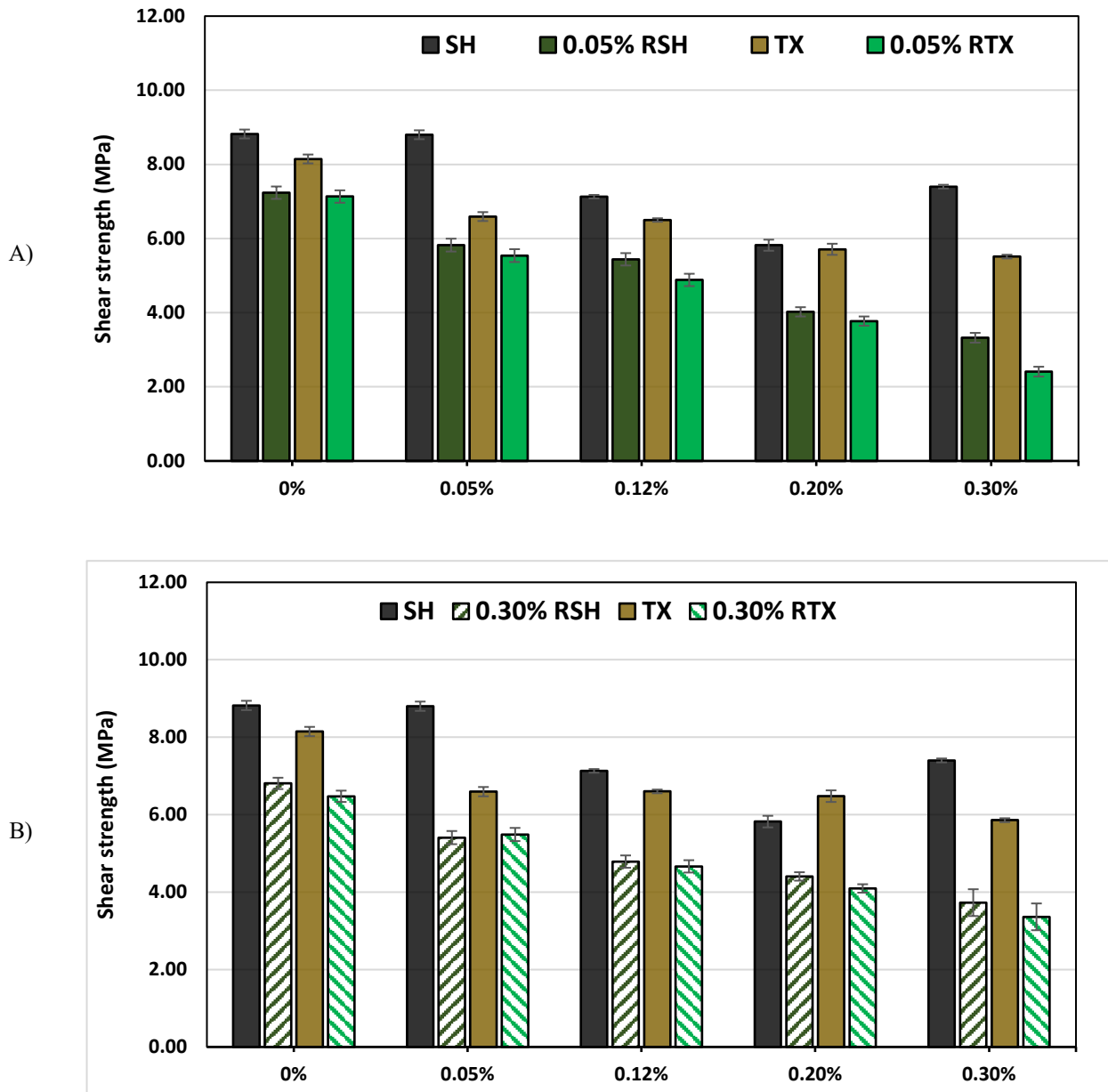


Figure 8.7: Direct shear strength (MPa) A) Slightly damaged recycled concrete, and B) Severely damaged recycled concrete. For comparison reasons, the CC mixtures are added to both graphs.

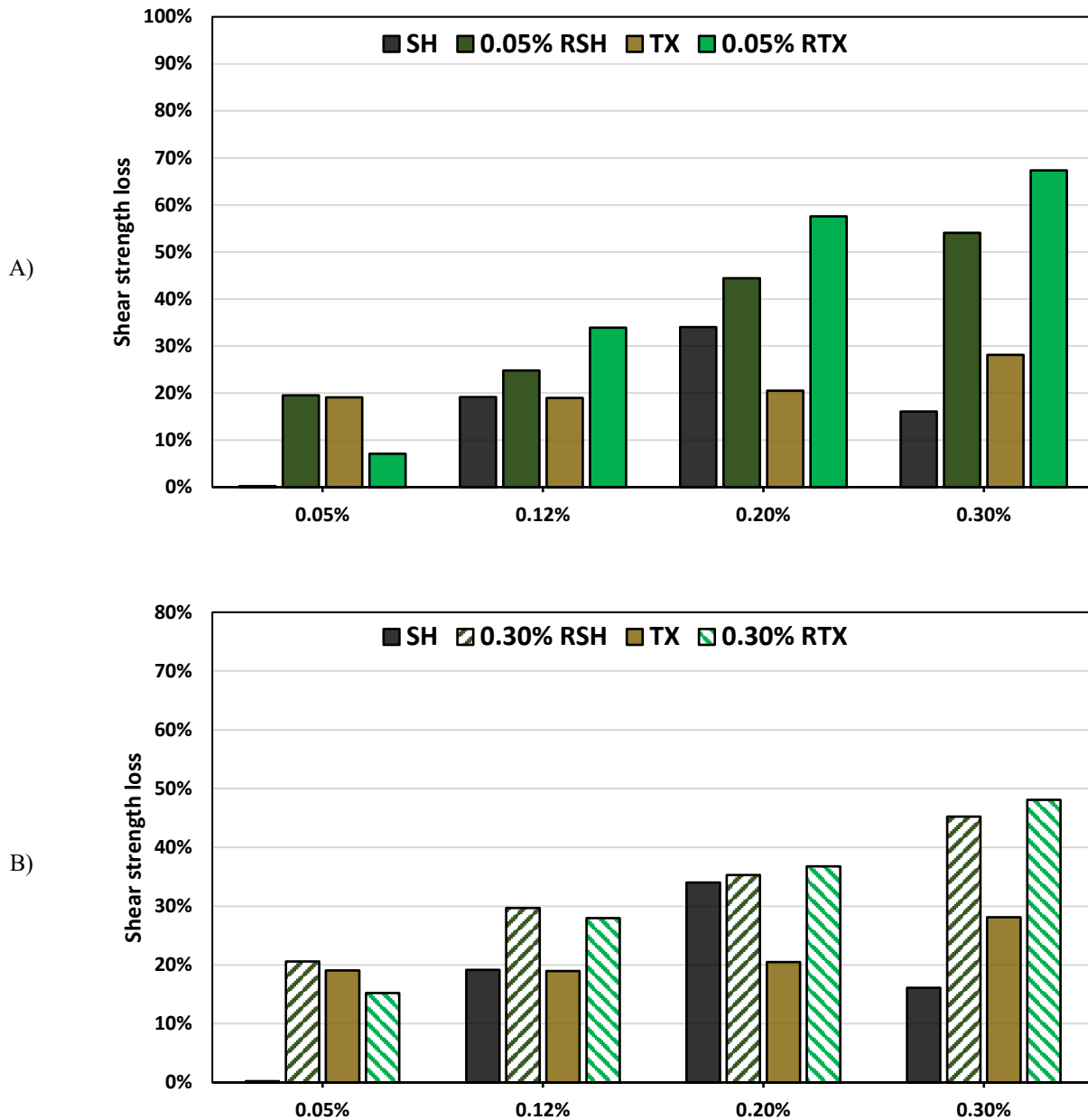
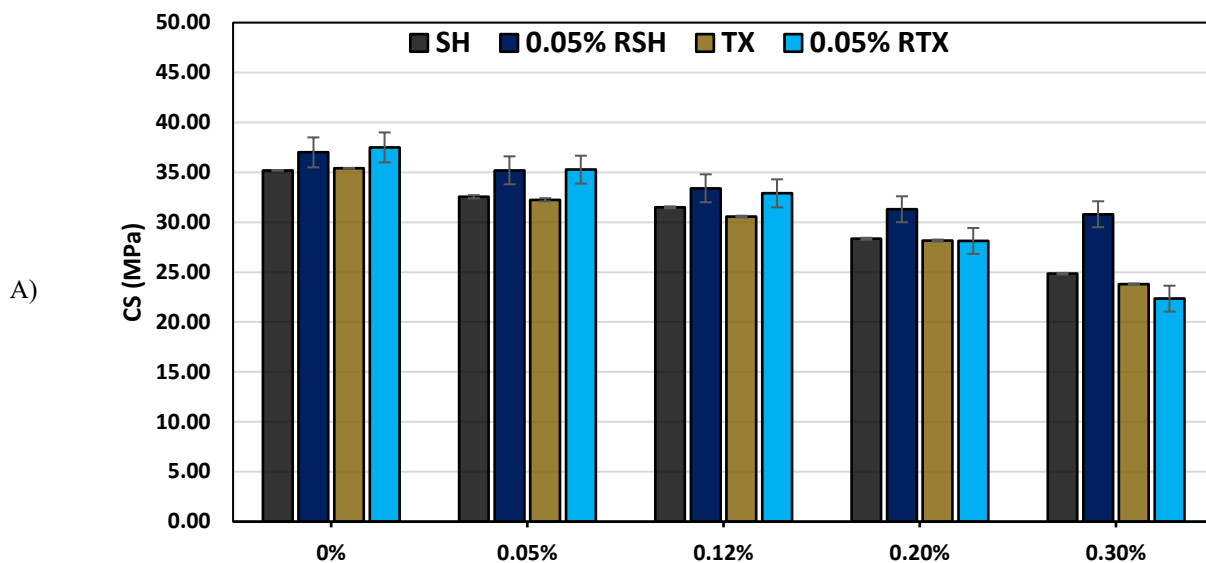


Figure 8.8: Direct shear loss (%) for A) slightly damaged recycled concrete and B) severely damaged recycled concrete. For comparison reasons, the CC mixtures are added to both graphs.

Compressive strength (CS)

This section presents the compressive strength results of all CC and RCA concrete of this work. It is worth noting that the gathered compressive strength results for CC were determined on a separate set of specimens with the same maturity.

Figures 8.9 A and B illustrate the compressive strength (CS) for slightly damaged recycled, severely damaged recycled and CC specimens. The CS reduction of RCA mixtures and conventional concrete incorporating similar aggregates are presented in Figures 8.10 A and B. All concrete mixtures achieved a similar compressive strength at the expansion level of 0% (sound concrete), with slightly damaged recycled specimens presenting a slightly higher CS. With the start of the ASR reaction, the CC specimens presented a CS of 32.5 MPa and 35.3 MPa for SH and TX, respectively. The slightly damaged recycled specimens presented the highest compressive strength at this expansion level (i.e., 35.2 MPa for 0.05% RSH and 35.3 MPa for 0.05% RTX). Similar to the slightly damaged recycled specimens, the severely damaged recycled concrete presented a higher CS compared to CC, with values of 33.2 MPa and 32.1 MPa. At the expansion level of 0.12%, CS of 31.5, 30.6, 33.4 and 32.9 MPa were obtained for CC (i.e., SH and TX) and slightly damaged recycled concrete (i.e., 0.05% RSH and 0.05% RTX), respectively. At an expansion level of 0.20%, the recycled SH presents significantly higher CS with 31.3 MPa for 0.05% RSH and 30.5 MPa for 0.30 RSH. The lowest CS of all specimens is observed at an expansion level of 0.30%, where the slightly damaged specimens presented a CS of 30.8 and 22.3 MPa for 0.05% RSH and 0.05% RTX, respectively.



B)

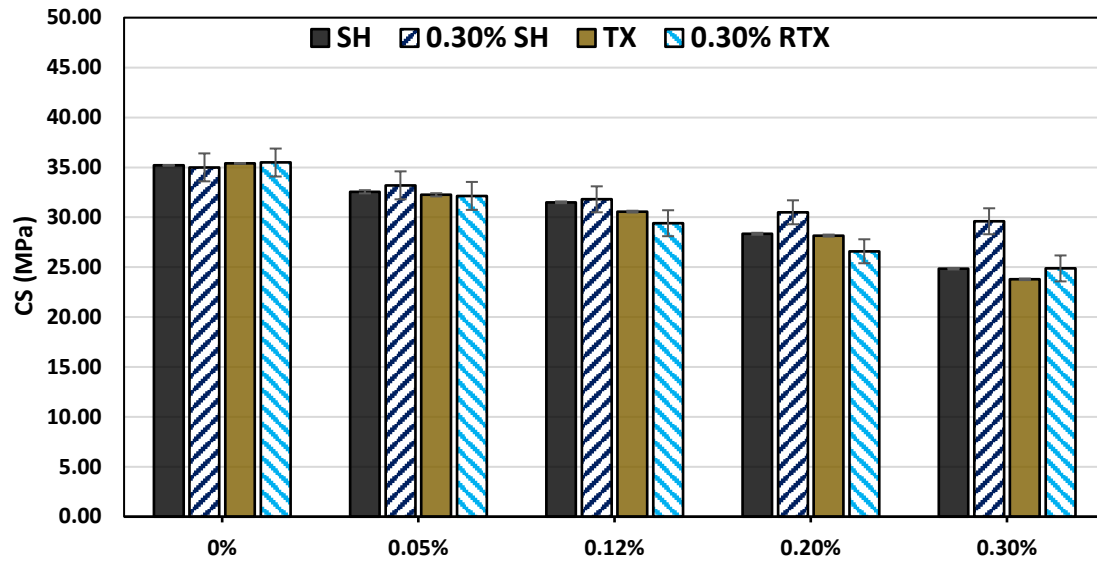
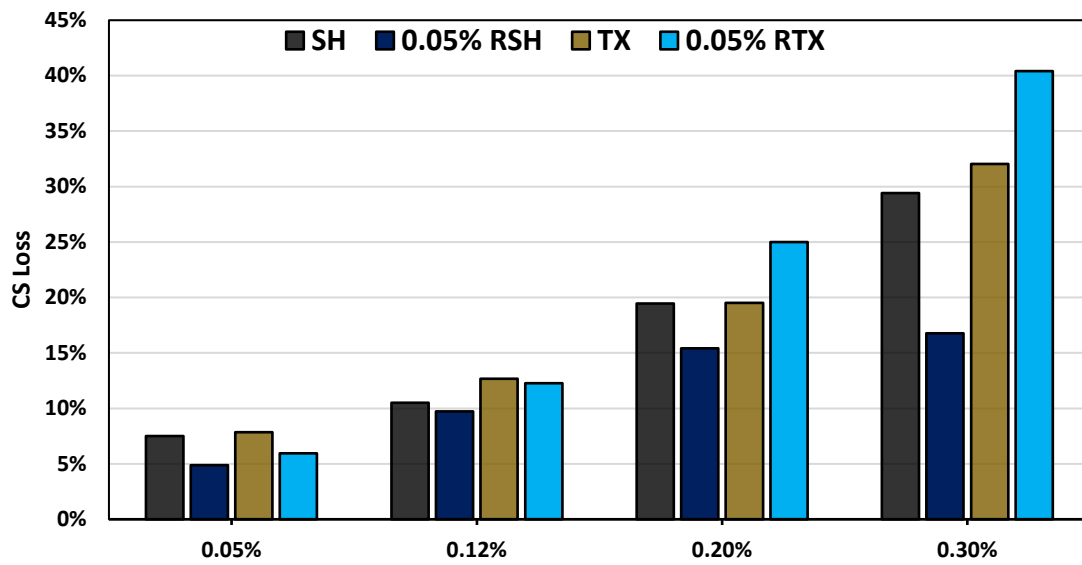


Figure 8.9: Compressive strength (MPa) for A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)

A)



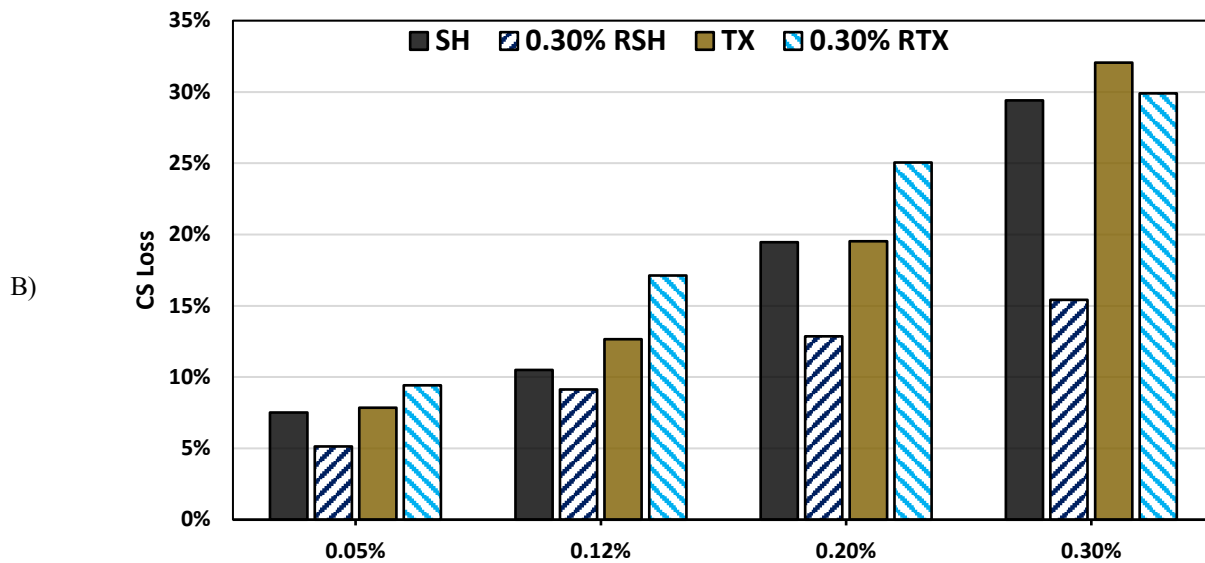


Figure 8.10: Compressive strength loss (%) for A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)

Stiffness damage test (SDT)

Figures 8.11 and 8.12 show the indices (i.e., SDI and PDI) obtained from the SDT following the procedure proposed by Sanchez et al. [19,20]. Before the start of the reaction in CC and the secondary reaction in recycled concrete, the RSH specimens presented the highest SDI (i.e., 0.13 for 0.05% RSH and 0.14 for 0.30% RSH). The CC specimens presented an SDI of 0.09, and the severely damaged recycled concrete specimens had an SDI of 0.10 and 0.13 for 0.05% RTX and 0.30% RTX, respectively. At an expansion level of 0.05%, a similar SDI was observed for all specimens.

SDI and modulus of elasticity loss for four different families of RCA. For low and moderate expansion levels, the SDI parameter is the same in all four recycled concrete types. The effect of overall pre-existing damage is not dependent on where the distress mechanism is within the RCA (OVA or RM). However, at high and severe expansion levels, specimens with reactive aggregates inside the RM suddenly increase the SDI parameter. This could be explained by the new crack development inside the new mortar at these expansion levels. The modulus of elasticity loss is higher for recycled concrete incorporating reactive coarse aggregates in most cases, with the exception of high and severe expansion levels for 0.30RTX. In severely damaged RCA where the source of expansion is the RM (0.30 RTX), the initial expansion has already damaged the OVA resulting in a higher loss of elastic modulus even at low expansion levels (i.e. highest SDI of 0.16 for TX specimens and lowest SDI of 0.13 for 0.05% SPH). Later, at a moderate expansion level (i.e., 0.12%), the CC specimens presented a significantly higher SDI with values of 0.23 for both SPH and TX. At an expansion level of 0.20%, the recycled specimens presented a spike in their SDI value (i.e., 0.28, 0.29, 0.25, 0.29 for 0.05 RSH, 0.05% RTX, 0.30%

RSH and 0.30% RSH, respectively). At the very high level of expansion, the CC followed the trend observed throughout the experiment achieving an SDI of 0.32 for SPH and 0.34 for TX. The significant jump observed in a high level of expansion (i.e., 0.20%) continues with a resulting SDI of 0.32 for 0.05% RSPH and 0.36 for 0.05% RTX. The severely damaged recycled concrete presented the lowest SDI with values of 0.29 and 0.33 for 0.30% RSH and 0.30% RTX, respectively.

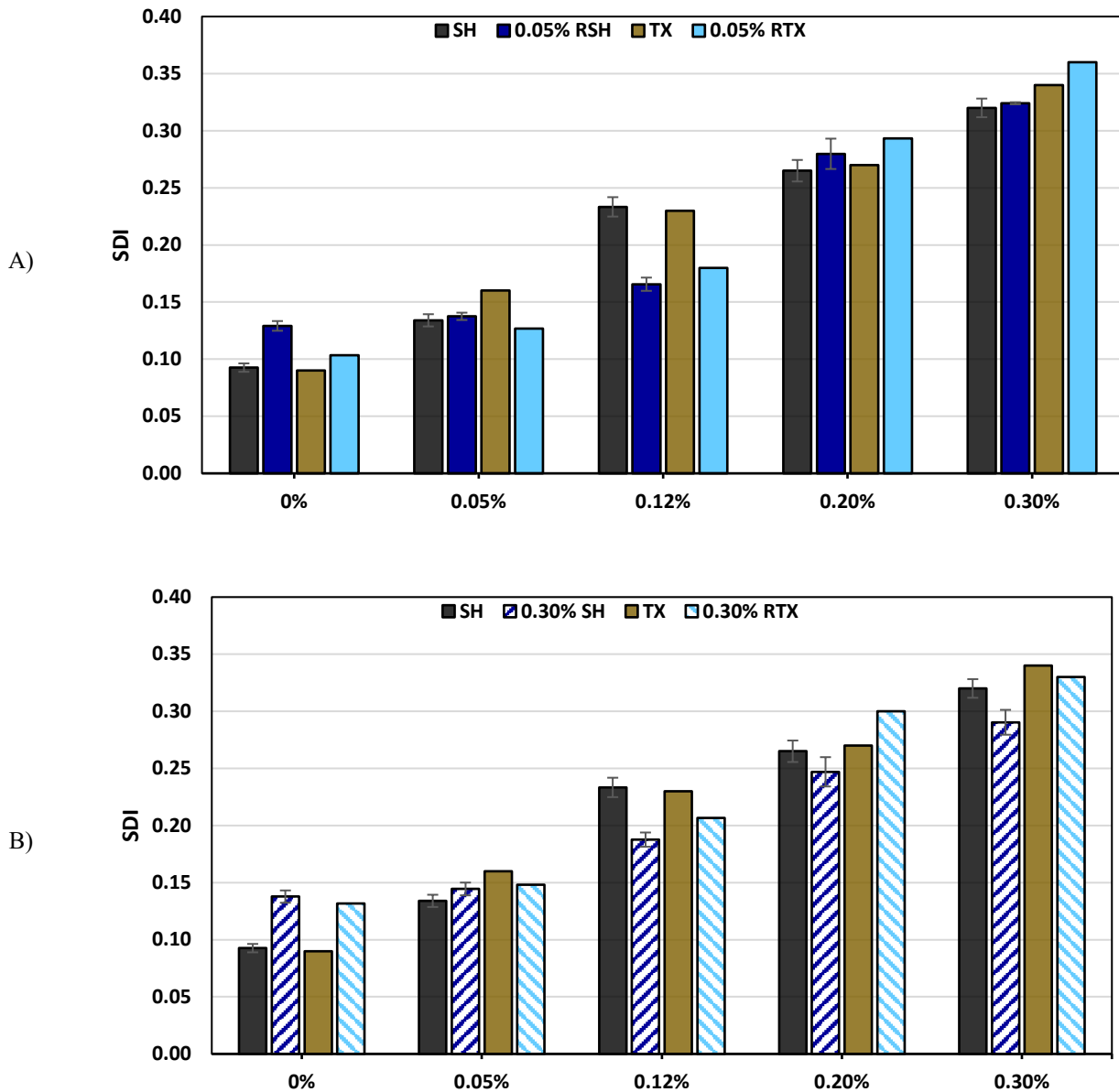
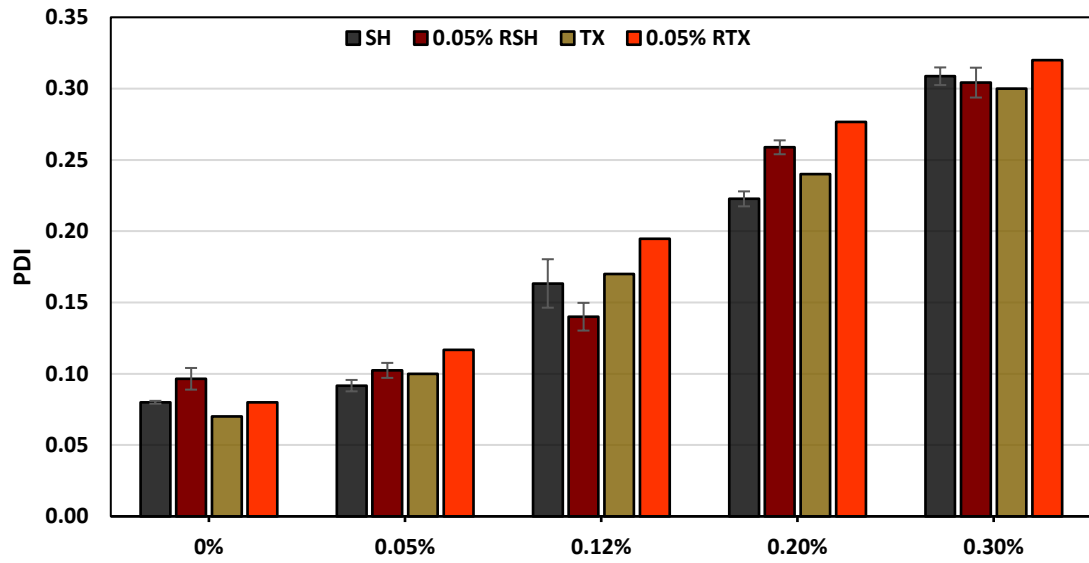


Figure 8.11: SDI parameter obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)

A)



B)

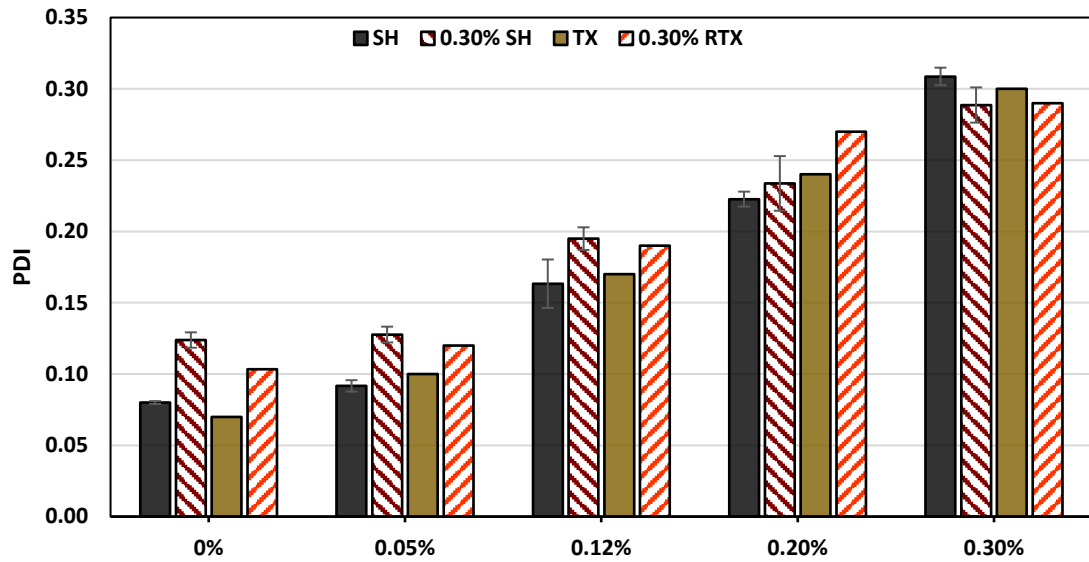


Figure 8.12: PDI parameter obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)

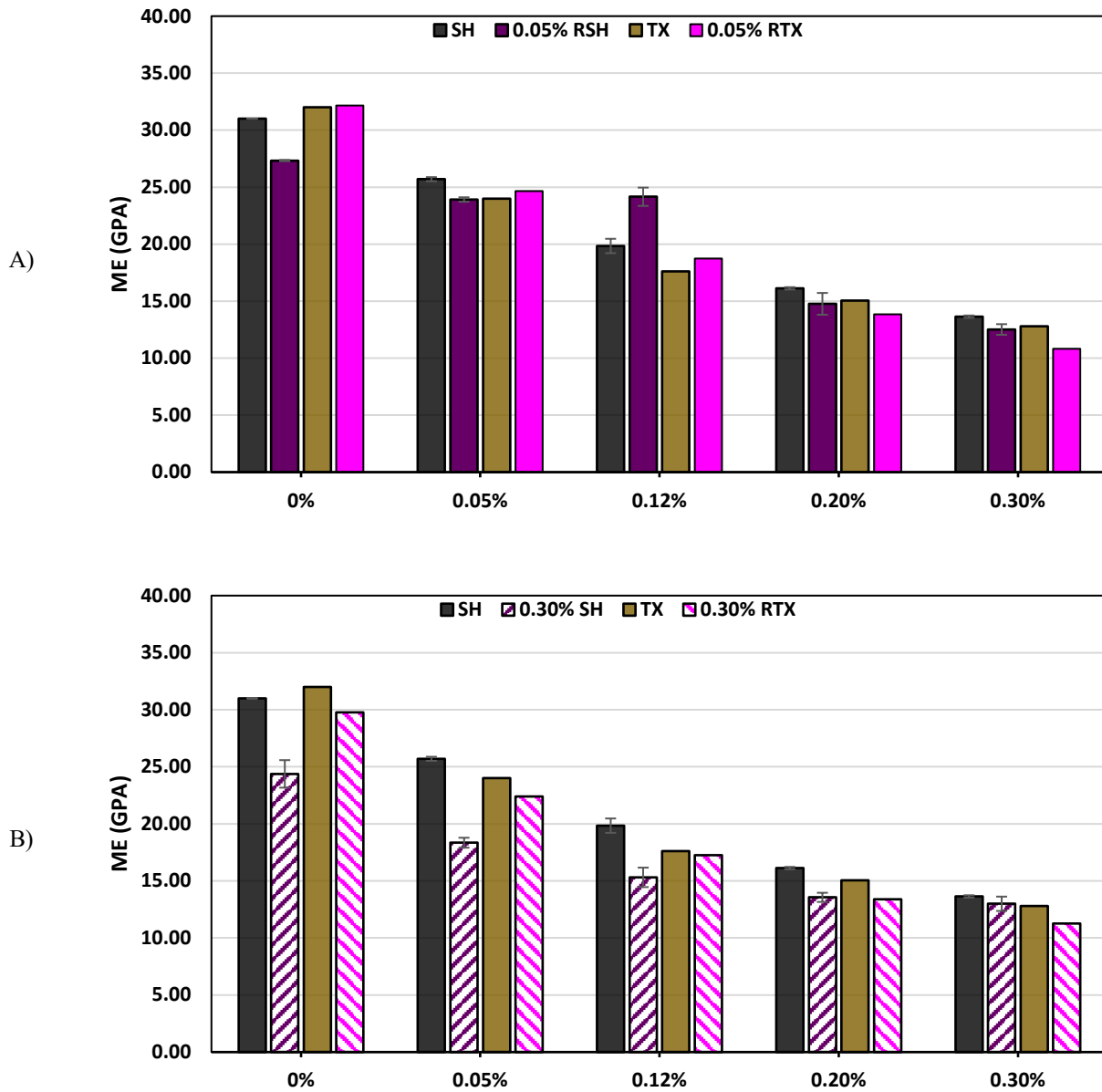


Figure 8.13: ME obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)

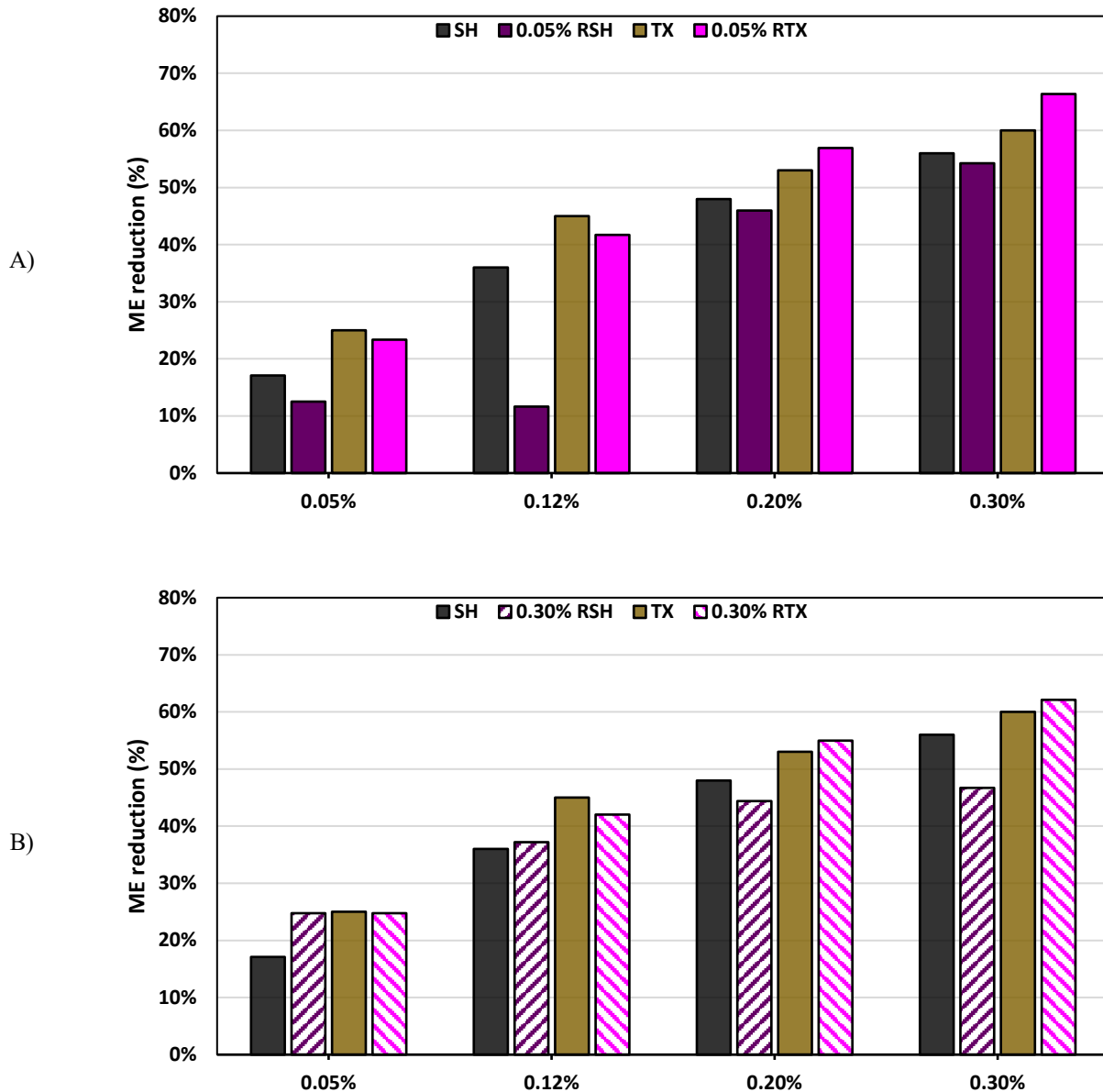


Figure 8.14: ME loss obtained from the SDT A) slightly damaged recycled aggregates (0.05% RSH and 0.05% RTX) and B) severely damaged recycled aggregates (0.30% RSH and 0.30% RTX)

Discussion

A brief introduction is given to the microscopic analysis carried out previously [4] on recycled aggregate concrete, and the data obtained are briefly explained. Later, the impact of the origin of the reaction (i.e., ASR in RM and ASR in OVA) and its severity is discussed in detail at each secondary expansion level with the help of microscopic and mechanical data obtained. Furthermore, the validity of the data is investigated through analysis of variance (ANOVA) and a *t*-test. Finally, the overall mechanical performance loss of recycled concrete due to secondary ASR reaction is discussed.

With the aim of understanding the results obtained from mechanical testing, an extended version of the damage rating index was carried out on all families of concrete presented in this work. DRI is a semi-quantitative assessment tool first developed by Grattan-Bellew et al. [65] in 1992. In this microscopic procedure, distinct distress features are counted in 1 X 1 cm grids drawn on the polished surface of the concrete by using a stereomicroscope at 15-16x magnification [37]. Later, these distress features are multiplied by weighting factors proposed by Villeneuve & Fournier [66], which aim is to balance their relative importance towards the corresponding distress mechanism (e.g., ASR), and ultimately the final DRI number is thus calculated, and the higher the damage degree represented by a higher DRI number [13]. Ideally, a surface of at least 200 cm² should be used; however, the final DRI value is normalized to a 100 cm² area for comparative purposes [66]. The reliability and effectiveness of DRI in assessing the condition of ASR-affected conventional concrete [13,37,41,66,67], as well as RCA concrete specimens [4,5,11], has previously been demonstrated. The mechanical behaviour of the concrete was therefore correlated with the microscopic observations in the separate set of specimens. Upon reaching the selected expansion levels of this study (i.e., 0.05%, 0.12%, 0.20% and 0.30%), they were cut in half longitudinally using a diamond-bladed masonry saw followed by subsequent mechanical polishing with grits of 30, 60, 140, 280, 600, 1200 and 3000. When the surface of the polished section was deemed suitable for microscopic analysis, grids of 1 cm² were drawn on the surface of each sample, and the damage features were then evaluated, as per Villeneuve and Fournier [66].

Multi-level assessment

The impact of the origin of the reaction (i.e., RM and OVA) is investigated with the help of the microscopic results previously mentioned. Families of concrete based on their level of initial reaction are compared with one another as well as CC to investigate the impact of the location and severity of the initial reaction.

Expansion level of 0.0%

The slightly damaged recycled concrete presented an initial expansion of 0.05%, which, as explained by Sanchez et al. [37], the cracks are generally present within the reactive aggregate as shown in Figure 8.15, which in this case are the SH coarse (i.e., OVA) and the TX sand (i.e., within the RM). Due to the insignificant progress during the initial expansion, more silica is available for secondary reaction. It seems that the location of the reactive aggregate has had a noticeable impact on the secondary reaction as well as the mechanical properties.

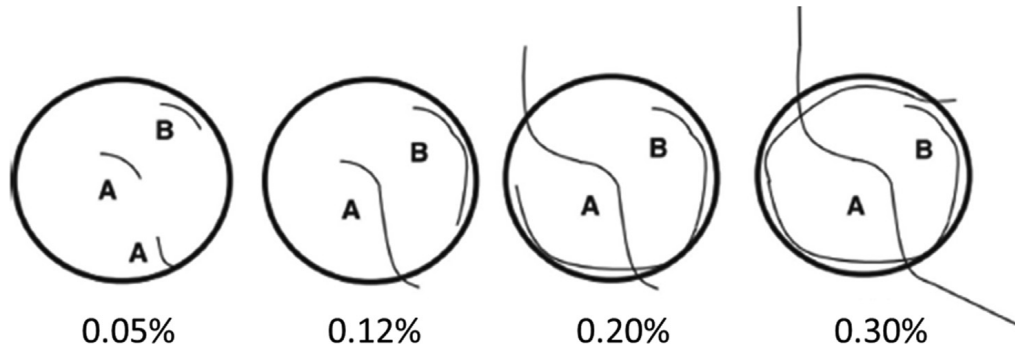


Figure 8.15: A qualitative crack propagation model in ASR-affected conventional concrete [37].

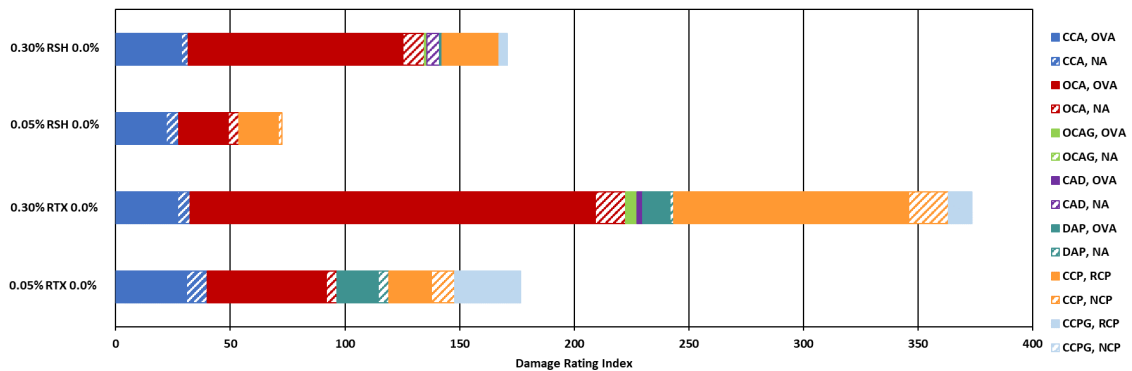


Figure 8.16: The extended DRI of all recycled specimens at an expansion level of 0.0%.

At this expansion level, the CC specimens presented higher direct shear strength with values of 8.82 and 8.15 MPa for SH and TX, respectively. Looking at the microscopic analysis before the start of the reaction, similar crack widths and lengths were reported [4] at this expansion level for both slightly damaged recycled specimens. Moreover, the DRI number of 0.05% RTX was slightly higher than 0.05% RSH (i.e., 177 and 73). However, the reported DRI is not significantly higher than CC Texas (i.e., DRI of 125) specimens at an expansion level of 0%. Overall, based on the results obtained from microscopic assessments, it is safe to assume that the initial expansion shows no significant damage at this level. As expected from the microscopic analysis, the shear strengths of the slightly damaged recycled specimens are 7.24 MPa and 7.13 MPa for 0.05% RSH and 0.05% RTX, respectively. Since the initial shear strength of the RCA specimens was lower than their companion CC (i.e., 0.18% for 0.05% RSH and 0.12% for 0.05% RTX), it is safe to assume that the crack generation due to the ASR development is not the only mechanism affecting shear strength and presence of additional ITZs could also play an important role.

The severely damaged recycled aggregate mixtures presented a more significant loss prior to the start of the reaction, with 0.30% RSH and 0.30% RTX achieving shear strengths of 6.81 and 6.47 MPa, respectively. The impact of initial damage can be clearly seen by looking at the DRI number of these specimens, with 0.30% RTX achieving a DRI number of 373. However, it is not unlikely to have a majority of the cracks generated during the initial reaction will be removed throughout the crushing process. As such, the direct impact of the initial reaction is mitigated to some degree.

The compressive strength of the recycled specimens at this level did not suffer any loss due to the initial expansion, and all specimens achieved the designed compressive strength. The recycled specimens achieved a slightly higher compressive strength (i.e., 37 MPa for both slightly damaged RCA and 0.30% RSH); similar observations were made for undamaged RCA concrete when mix proportioned with the EV mixing technique [29].

Unlike the compressive strength test, a slight difference was observed between the SDI values obtained for slightly damaged RCA and severely damaged RCA specimens. The 0.05% RSH had an SDI value of 0.13, which is higher than that of the 0.05% RTX (i.e., 0.10). The difference between the values obtained is more significant for PDI.

Expansion level of 0.05%

At the beginning of the secondary reaction, most of the cracks are within the reactive RCA particle, with a few cracks in the NM; this phenomenon is more visible for 0.05% RTX and 0.30% RTX. The severely damaged recycled specimens presented more cracks in both the RM and the NM. This section discusses the impact of a secondary expansion of 0.05% on the mechanical properties of ASR-affected RCA specimens.

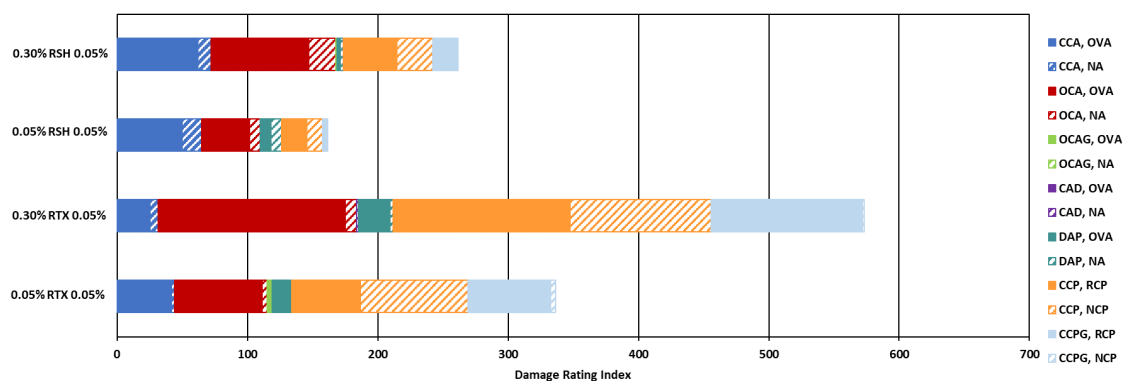


Figure 8.17: The extended DRI of all recycled specimens at an expansion level of 0.05%.

The reactive Texas sand CC specimens generally present a lower direct shear strength when compared to Springhill CC. De Souza et al. [21] found that more significant shear strength loss was observed even at low

expansion levels due to the cracks being more "spread out" in the case of reactive sand. Moreover, it was found that the failure plane tends to go through the reactive aggregates (i.e., reactive sand and reactive coarse) rather than the non-reactive aggregates. Similar to the CC specimens, the 0.05% RTX specimens show lower shear strength at all expansion levels compared to 0.05% RSH. At the expansion level of 0.05%, no significant changes were observed in the crack length and width, and a higher DRI number was achieved for 0.05% RTX, as well as more cracks in the aggregates, new and old cement pastes. Hence, the 0.05% RTX reported a lower shear strength compared to the 0.05% RSH, SH, and TX, with shear strengths of 5.82 and 8.80, and 6.59 MPa, respectively. Looking at Figure 8.8A, although the SH specimens did not show any reduction, all other specimens had a shear loss of roughly 20%. It is worth mentioning that although the microscopic analysis does not show a very high level of damage (DRI of 161 for 0.05% RSH and 337 for 0.05% RTX), the shear strength achieved at this level for 0.05% RTX and 0.05% RSH is similar to the shear strength of the companion CC specimens at an expansion level of 0.20%. The 0.30% RTX presented significantly more open cracks in the OVA as well as cracks in the RM. Similarly, the 0.30% RSH presents more open cracks in the OVA as well as cracks in the RM.

Similar to the expansion level of 0.0%, the compressive strength test was unable to capture the impact of initial and secondary ASR expansion. Similar observations were made by Sanchez et al. [13] for various reactive aggregates in CC, where a loss of 10% was observed in most cases.

Moreover, the ME of 0.05% RSH was lower than the companion CC (i.e., SH), while the 0.05% RTX achieved a ME of 32.16 GPa, similar to that of the TX CC. Mindess et al. [68] suggested that in conventional concrete, the most important governing factor for ME is the ME of coarse aggregates. As such, the impact of cracks within the reactive aggregates for both cases of 0.05% RSH and 0.30% RSH can clearly be seen in the ME of these specimens.

Expansion level of 0.12%

At this expansion level, for both recycled mixtures made with reactive coarse aggregates, the cracks lengthen in the OVA and new cement paste, while the widest cracks are still within the OVA. A cracking pattern seems to be forming by linking the cracks between two OVA particles. An extension of cracks from RM into the new cement paste is also observed. Similarly, 0.05% RTX and 0.30% RTX showed a widening of cracks, while some linking of reactive sand particles was observed. The case is more severe for 0.30% RTX, where cracks propagate through coarse non-reactive aggregates as well as the new cement paste [4]. Moreover, the 0.30% RTX has a significantly higher DRI number as well as open cracks in the reactive particles.

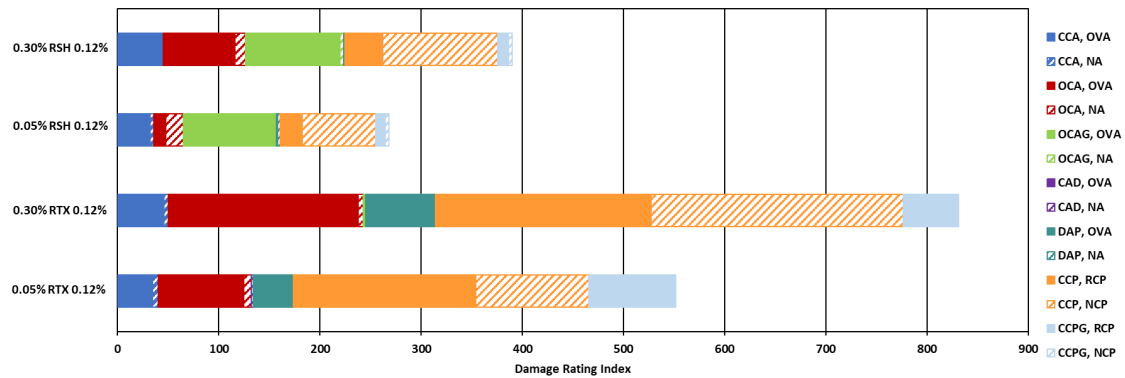


Figure 8.18: The extended DRI of all recycled specimens at an expansion level of 0.12%.

Similar trends were observed, with 0.30% RTX and 0.30% RSH still having the lowest shear strength. At this expansion level, a significant increase in the number of cracks in the RM and NM is observed for both slightly damaged recycled specimens. Due to the crack location and properties changes, a more significant loss of shear is observed (i.e., 25% to 30%) for all recycled mixtures. The impact is not as visible when looking at the SDI, with all recycled mixtures achieving lower SDI compared to their companion CC. As expected, the severely damaged recycled mixtures achieved a higher SDI than slightly damaged RCA mixtures. At this expansion level, the CC specimens have already expanded into the cement paste, as shown in Figure 8.15, while the slightly damaged recycled specimens and 0.30% RSH show significantly fewer cracks in the new cement, as shown in Figure 8.18. A more significant loss of compressive strength is observed at this expansion level, especially for 0.30% RTX. Overall recycled specimens made with reactive sand (TX) presented a higher CS loss, which may be due to the higher number of cracks in RM and NM. Based on the study by Sanchez et al. [13], a CS loss of 17% for 0.30% RTX is significant for this expansion level.

Expansion level of 0.20%

With the continuation of the expansion, the majority of the cracks continued widening and expanding into the cement paste. By comparing Figures 8.17 and 8.18, a significant increase in open cracks in aggregates and cracks in the cement paste (i.e., RM and NM) is observed. The recycled concrete made with severely damaged TX sand presented a significant increase in cracks in the cement paste with gel in the new cement paste and a very high number of cracks in the RM. Although the DRI number is higher for both cases of severely damaged recycled concrete compared to slightly damaged recycled concrete, the maximum crack width is higher in both 0.05% RSH and 0.05% RTX. The maximum crack length is similar for RSH specimens and slightly higher for 0.30% RTX compared to 0.05% RTX. It is worth noting that the maximum crack length of the slightly damaged recycled concrete is higher than the CC. Moreover, the slightly damaged specimens presented a more significant increase in their DRI number.

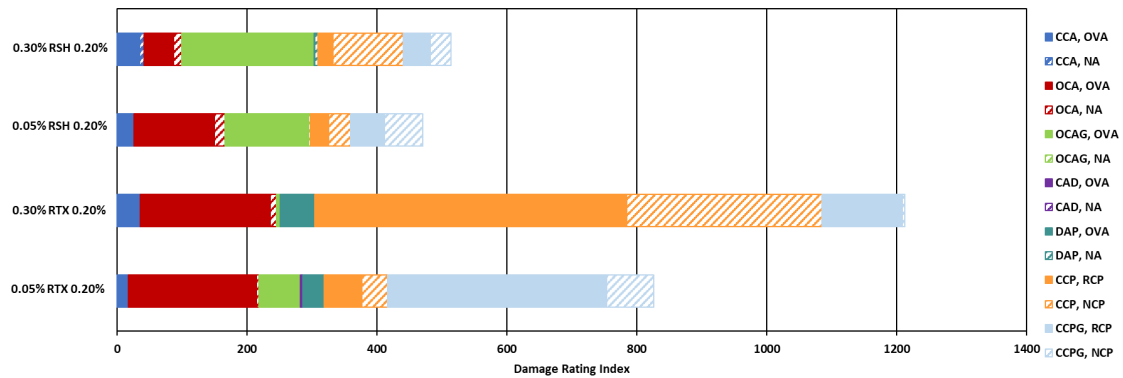


Figure 8.19: The extended DRI of all recycled specimens at an expansion level of 0.20%.

Although the severely damaged recycled concrete presented a higher DRI number, the slightly damaged specimens achieved a lower shear strength. This could be explained by the properties of the cracks at this expansion level. The difference in the DRI number between the RSH specimens is significantly less compared to the RTX mixtures. It seems that the extension of cracks into the cement paste (i.e., new and old) has significantly impacted the direct shear strength (i.e. loss of 35% to 47%). Similarly, the SDI and PDI of recycled specimens present a significant increase at this expansion level. The RTX specimens presented the highest SDI values among all the mixtures, as expected from the DRI. However, the difference between the SDI of RTX specimens is not that significant. As expected, the impact of secondary damage on the CS of the mixture is more visible at this expansion level, with RTX specimens having a CS loss of 25%. By investigating the CC specimen's behaviour in the CS test, one realizes that no significant loss was observed until cracks expanded into the cement paste.

Interestingly the CS loss of RSH specimens was lower than that of the companion CC, while the RTX mixtures showed a higher loss of CS. While RTX specimens had a higher number of cracks in the cement paste (CCP+CCPG) compared to CC TX, the RSH mixtures presented a lower number of cracks in the cement paste compared to CC SH. The impact of the sudden increase in the number of open cracks in the OVA for RSH specimens is visible by looking at the ME data gathered. In the case of slightly damaged recycled mixtures made with coarse reactive RCA (RSH), the number of open cracks in the coarse aggregate (i.e. OCA-OVA and OCAG-OVA) shows an increase of 150%. As such, the 0.05% RSH shows a ME loss of 46% compared to 0.12% at the previous expansion level, which was expected based on the extended DRI graph.

Expansion level of 0.30%

With the continuation of the reaction, a very significant increase in the number of cracks in the new cement paste is observed. Perhaps the most significant impact due to secondary ASR expansion is observed in the slightly damaged recycled specimens, where very few cracks were observed in the new cement paste at previous expansion levels. Moreover, the slightly damaged specimens presented the lengthiest cracks among mixtures

where cracks generated inside the OVA expanded through the residual cement paste and new cement paste into another OVA or new aggregate. A very well-established cracking network is observed for all recycled mixtures.

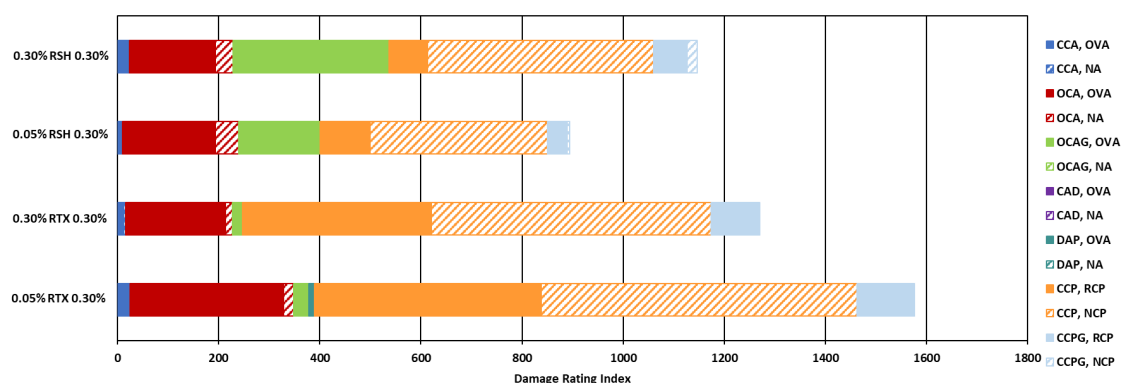


Figure 8.20: The extended DRI of all recycled specimens at an expansion level of 0.30%.

With the generation of more cracks in the new cement paste, a very significant loss of shear strength was observed for 0.05% RSH and 0.05% RTX with values of 54% and 66%, respectively. However, the changes were not as significant for severely damaged specimens. All recycled specimens presented a higher shear strength loss than their companion CC. Due to the cracking network generated inside and around all RCAs, the aggregate interlock properties of concrete are lost, resulting in shear strengths of 2.4 MPa to 3.7 MPa, which is significantly lower than CC. The SDI and PDI also report a significant increase for both slightly damaged recycled specimens ranging from 0.28 to 0.37 and 0.28 to 0.30, respectively. Further loss of CS is observed primarily for recycled concrete made with reactive sand (TX). The 0.05% RTX specimens showed a 40% loss of compressive strength, which is higher than the range that Sanchez et al. [13] suggested for CC. The ME of the RTX specimens continued their linear loss, showing a loss of 60% to 66%, which, as mentioned above, is due to the extension of cracks into the new coarse aggregates of the system.

Overall appraisal

The findings obtained in this research were combined with microscopic analysis previously conducted at [4] on the same mixtures and later compared with results obtained for CC [13]. Overall at the early stages of the expansion, the microscopic and mechanical properties fall within the ranges proposed by Sanchez et al. [13]. However, in some cases (i.e., high and very high levels of expansion), the recycled specimens presented significantly higher values of DRI as well as direct shear and compressive strength loss. Moreover, the severely damaged mixtures did not obtain the worst mechanical properties at all expansion levels, and it seems at high and very high expansion levels, the slightly damaged recycled mixtures "caught up" and resulted in inferior mechanical properties. Overall, the RTX specimens presented a more advanced cracking network with significantly higher DRI numbers at all expansion levels, but the severity of the impact of such a cracking

network on all mechanical properties was not the same, and in some cases, the RTX specimens performed better than the recycled concrete made with coarse reactive aggregate. The presence of RM had more impact on stopping the reactive coarse aggregate's access to fresh alkalis in the new cement at the early stages of the reaction, and once the cracks prolonged into the new cement paste, a rapid change was observed both in terms of mechanical property loss and increase in DRI number. On the contrary, the presence of a small cracking network within the reactive particles for severely damaged recycled mixtures facilitated access to fresh alkalis when compared to CC and caused a more severe mechanical property loss at the early stages of the reaction (i.e., 0.05% and 0.12%).

The statistical validity of the mechanical results

This section of the study examines the statistical validity of the mechanical properties (i.e., direct shear strength, SDT parameters, and compressive strength) of both conventional concrete (CC) specimens and recycled concrete mixtures using ANOVA analysis. The results in Tables 8.3 and 8.4 show that the outcomes of the SDT (i.e., SDI and PDI) and the results of the material loss for all concrete mixtures are statistically significant at a confidence level of 95%, as the "F values" and "P values" are all higher or lower than the "Fcritic" and 0.05, respectively.

Table 8.3: Two-variable ANOVA on the SDT outcomes (i.e., SDI, PDI and ME) of all concrete specimens of this study.

ANOVA analysis				SDI						PDI						E					
Concrete type	Strength (MPa)	Load (%)	Expansion (%)	SDI_F	SDI_Fcrit.	F>Fcrit.	SDI_P	α	P< α	PDI_F	PDI_Fcrit.	F>Fcrit.	PDI_P	α	P< α	E_F	E_Fcrit.	F>Fcrit.	E_P	α	P< α
SH	35	40	0.00-0.30	45.46	3.48	✓	0.0000022	0.05	✓	210.13	3.48	✓	0.0000000	0.05	✓	210.13	3.48	✓	0.0000000	0.05	✓
0.05% RSH	35	40	0.00-0.30	340.87	3.48	✓	0.0000000	0.05	✓	300.12	3.48	✓	0.0000000	0.05	✓	231.56	3.48	✓	0.0000000	0.05	✓
0.30% RSH	35	40	0.00-0.30	115.21	3.48	✓	0.0000000	0.05	✓	77.49	3.48	✓	0.0000002	0.05	✓	74.23	3.48	✓	0.0000002	0.05	✓
TX	35	40	0.0-0.30	54.952346	3.47805	✓	9.02135E-07	0.05	✓	71.36125	3.47805	✓	2.59E-07	0.05	✓	29.209969	3.47805	✓	1.71E-05	0.05	✓
0.05% RTX	35	40	0.0-0.30	60.788889	3.47805	✓	5.58E-07	0.05	✓	135.48785	3.47805	✓	1.15E-08	0.05	✓	87.539026	3.47805	✓	9.67E-08	0.05	✓
0.30% RTX	35	40	0.0-0.30	48.116087	3.47805	✓	1.69E-06	0.05	✓	146.77273	3.47805	✓	7.8E-09	0.05	✓	70.41769	3.47805	✓	2.76E-07	0.05	✓

Table 8.4: Two-variable ANOVA on the mechanical properties results (i.e., direct shear strength and CS) of all concrete specimens of this study.

ANOVA analysis				Shear strength						CS					
Concrete type	Strength (MPa)	Load (%)	Expansion (%)	Shear_F	Shear_Fcrit.	F>Fcrit.	Shear_P	α	P< α	CS_F	CS_Fcrit.	F>Fcrit.	CS_P	α	P< α
SH	35	40	0.00-0.30	44.08	3.48	✓	0.0000026	0.05	✓	5.70	3.48	✓	0.0117690	0.05	✓
0.05% RSH	35	40	0.00-0.30	199.79	3.48	✓	0.0000000	0.05	✓	14.61	3.48	✓	0.0003509	0.05	✓
0.30% RSH	35	40	0.00-0.30	65.77	3.48	✓	0.0000004	0.05	✓	13.14	3.48	✓	0.0005433	0.05	✓
TX	35	40	0.0-0.30	7.88	3.48	✓	0.0038888	0.05	✓	38.66	3.48	✓	0.0000047	0.05	✓
0.05% RTX	35	40	0.0-0.30	68.58	3.48	✓	0.0000003	0.05	✓	38.74	3.48	✓	0.0000047	0.05	✓
0.30% RTX	35	40	0.0-0.30	21.25	3.48	✓	0.0000708	0.05	✓	15.93	3.48	✓	0.0002446	0.05	✓

Conclusions

This study investigated the impact of the source of the secondary reaction in recycled concrete aggregates (i.e., reactive sand within the RM or reactive OVA) and the impact of the secondary reaction on the mechanical properties of RCA concrete. The mechanical properties were evaluated using the Stiffness Damage Test (SDT), compressive strength, and direct shear test. The main conclusions of this research are presented below:

- Based on the results of this study, it appears that the location and severity of initial ASR-induced expansion have a significant impact on the mechanical properties of recycled concrete made with reactive aggregates. The location of the initial expansion can influence the distribution and extension of damage within the various parts of the recycled concrete, while the severity of the initial expansion can affect the overall integrity of the aggregates as well as the availability of silica and alkalis for a secondary reaction.
- It is important to assess the severity of initial expansion and their source in order to ensure the durability and long-term performance of recycled concrete made with reactive recycled concrete aggregates.
- The Stiffness Damage Test (SDT) was found to be a reliable method for assessing ASR-induced secondary expansion in recycled concrete, while the compressive strength was only efficient after a certain level of deterioration. Moreover, the direct shear test proved to be a reliable tool for assessing the impact of secondary ASR damage but failed to distinguish between the reactive OVA and reactive RM recycled concretes.
- The presence of residual mortar in the recycled concrete mixtures appeared to have a greater impact on stopping the reactive coarse aggregate's access to fresh alkalis in the new cement at the early stages of the reaction, and once the cracks extended into the new cement paste, a rapid change was observed in terms of mechanical property loss and increase in Damage Rating Index (DRI).
- The presence of a small cracking network within the reactive particles for severely damaged recycled mixtures apparently facilitated access to fresh alkalis compared to conventional concrete and caused a more severe mechanical property loss at the early stages of the reaction.

References

- [1] International Energy Agency. Cement technology roadmap plots path to cutting CO₂ emissions 24% by 2050 - News - IEA. IEA; 2018. Available from: <https://www.iea.org/news/cement-technology-roadmap-plots-path-to-cutting-co2-emissions-24-by-2050>.
- [2] Sims, I., & Poole, A. (Eds.). (2017). Alkali-Aggregate Reaction in Concrete: A World Review (1st ed.). CRC Press. <https://doi.org/10.1201/9781315708959>.
- [3] Stark, D. (1996). The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity. Research and Development Bulletin RD114. Portland Cement Association. https://www.cement.org/docs/default-source/fc_concrete_technology/durability/rd114-the-use-of-recycled-concrete-aggregate-from-concrete-exhibiting-alkali-silica-reactivity.pdf?sfvrsn=4&sfvrsn=4.
- [4] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. Cement and Concrete Research, 144, 106426. <https://doi.org/10.1016/j.cemconres.2021.106426>.
- [5] Trottier, C., Zahedi, A., Ziapour, R., Sanchez, L., Locati, F. (2021). Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR). Construction and Building Materials, 269, 121250. <https://doi.org/10.1016/j.conbuildmat.2020.121250>.
- [6] Shehata, M. H., Christidis, C., Mikhael, W., Rogers, C., & Lachemi, M. (2010). Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction. Cement and Concrete Research, 40(4), 575-582. <https://doi.org/10.1016/j.cemconres.2009.08.008>.
- [7] Barreto Santos, M., De Brito, J., & Santos Silva, A. (2020). A Review on Alkali-Silica Reaction Evolution in Recycled Aggregate Concrete. Materials, 13(11), 2625. <https://doi.org/10.3390/ma13112625>.
- [8] Li, X., & Gress, D. L. (2006). Mitigating Alkali-Silica Reaction in Concrete Containing Recycled Concrete Aggregate. Transportation Research Record, 1979(1), 30-35. <https://doi.org/10.1177/0361198106197900105>.
- [9] Mukhopadhyay, A. K., Geiger, B. J., & Button, J. (2010). Use of Alkali-Silica Reaction-Affected Recycled Concrete Aggregate in Hot-Mix Asphalt. Transportation Research Record, 2179(1), 1-9. <https://doi.org/10.3141/2179-01>.
- [10] Piersanti, M., Shehata, M., Senior, S., & MacDonald, C. A. (2015). Expansion of concrete containing recycled concrete aggregate suffering different levels of Alkali-Silica reaction. In Proceedings of the Annual Conference - Canadian Society for Civil Engineering (pp. 109-116).

- [11] Zhu, Y., Zahedi, A., Sanchez, L. F. M., Fournier, B., & Beauchemin, S. (2021). Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. *Cement and Concrete Research*, 142, 106350. <https://doi.org/10.1016/j.cemconres.2020.106350>.
- [12] Ziapour, R., Trottier, C., Zahedi, A., Sanchez, L.F.M. (2022). Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete. *Materiales de Construcción*, 72, e280. <https://doi.org/10.3989/MC.2022.17621>.
- [13] Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17-31. <https://doi.org/10.1016/j.cemconres.2016.12.001>.
- [14] Dunant, C. F., & Scrivener, K. L. (2012). Effects of aggregate size on alkali-silica-reaction induced expansion. *Cement and Concrete Research*, 42(6), 745-751. <https://doi.org/10.1016/j.cemconres.2012.02.012>.
- [15] Fournier, B., & Bérubé, M. A. (2000). Alkali-aggregate reaction in concrete: A review of basic concepts and engineering implications. *Canadian Journal of Civil Engineering*, 27(2), 167-191. <https://doi.org/10.1139/199-072>.
- [16] Sinno, N., Piersanti, M., & Shehata, M. H. (2021). Assessing residual expansion of alkali-silica reaction-affected structures. *ACI Materials Journal*, 118(2). <https://doi.org/10.14359/51729330>.
- [17] Esposito, R., Anaç, C., Hendriks, M. A. N., & Çopuroğlu, O. (2016). Influence of the alkali-silica reaction on the mechanical degradation of concrete. *Journal of Materials in Civil Engineering*, 28(6), 04016007. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001486](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001486).
- [18] Zahedi, A., Trottier, C., Sanchez, L., & Noël, M. (2022). Evaluation of the induced mechanical deterioration of alkali-silica reaction affected concrete under distinct confinement conditions through the Stiffness Damage Test. *Cement and Concrete Composites*, 126, 104343. <https://doi.org/10.1016/j.cemconcomp.2021.104343>.
- [19] Sanchez, L.F.M., Fournier, B., Jolin, M., Bastien, J., & Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. *Construction and Building Materials*, 125, 1178-1188. <https://doi.org/10.1016/j.conbuildmat.2016.08.101>.
- [20] Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2015). Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters

- and variability of the test responses. *Construction and Building Materials*, 77, 20-32. <https://doi.org/10.1016/j.conbuildmat.2014.11.071>.
- [21] De Souza, D. J., Sanchez, L. F. M., & De Grazia, M. T. (2019). Evaluation of a direct shear test setup to quantify AAR-induced expansion and damage in concrete. *Construction and Building Materials*, 229, 116806. <https://doi.org/10.1016/j.conbuildmat.2019.116806>.
- [22] Fathifazl G, Abbas A, Razaqpur AG, Isgor OB, Fournier B, Foo S. New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*. 2009;21:601–611. Available from: [https://doi.org/10.1061/\(asce\)0899-1561\(2009\)21:10\(601\)](https://doi.org/10.1061/(asce)0899-1561(2009)21:10(601)).
- [23] Paine, K. A., & Dhir, R. K. (2010). Recycled aggregates in concrete: a performance-related approach. *Magazine of Concrete Research*, 62(7), 519-530. <https://doi.org/10.1680/mac.2010.62.7.519>.
- [24] Ideker, J. H., Adams, M. P., Tanner, J., Jones, A. (2013). Durability Assessment of Recycled Concrete Aggregates for use in New Concrete: Phase I - Revised. TREC Final Reports. <https://doi.org/10.15760/trec.15>.
- [25] Fathifazl, G., & Razaqpur, A. G. (2013). Creep rheological models for recycled aggregate concrete. *ACI Materials Journal*, 110(2). <https://doi.org/10.14359/51685526>.
- [26] Knaack, A.M., Kurama, Y.C. Design of Concrete Mixtures with Recycled Concrete Aggregates. *ACI Materials Journal* 110 (5) (2013). <https://doi.org/10.14359/51685899>.
- [27] Xiao, J., Li, J., & Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research*, 35(6), 1187-1194. <https://doi.org/10.1016/j.cemconres.2004.09.020>.
- [28] Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and Structures*, 33(9), 574-580. <https://doi.org/10.1007/BF02480538>.
- [29] Ahimoghadam, F., Sanchez, L. F. M., De Souza, D. J., Andrade, G. P., Noël, M., & Demers, A. (2020). Influence of the recycled concrete aggregate features on the behavior of eco-efficient mixtures. *Journal of Materials in Civil Engineering*, 32(9), 04020252. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003323](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003323).
- [30] Hayles, M., Sanchez, L. F. M., & Noël, M. (2018). Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. *Construction and Building Materials*, 169, 724-732. <https://doi.org/10.1016/j.conbuildmat.2018.02.127>.
- [31] Hansen, T. C. (1986). Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945–1985. *Materials and Structures*, 19(3), 201-246. <https://doi.org/10.1007/BF02472036>.

- [32] Silva, R. V., de Brito, J., & Dhir, R. K. (2016). Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. *Journal of Cleaner Production*, 112, 2171-2186. <https://doi.org/10.1016/j.jclepro.2015.10.064>.
- [33] McNeil, K., & Kang, T. H.-K. (2013). Recycled concrete aggregates: A review. *International Journal of Concrete Structures and Materials*, 7(1), 61-69.
- [34] Kwan, W. H., Ramli, M., Kam, K. J., & Sulieman, M. Z. (2012). Influence of the amount of recycled coarse aggregate in concrete design and durability properties. *Construction and Building Materials*, 26(1), 565-573. <https://doi.org/10.1016/j.conbuildmat.2011.06.059>.
- [35] Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44, 464-476. <https://doi.org/10.1016/j.conbuildmat.2013.03.014>.
- [36] Fathifazl, G., Razaqpur, A. G., Isgor, O. B., Abbas, A., Fournier, B., & Foo, S. (2011). Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate. *Cement and Concrete Composites*, 33(10), 1026-1037. <https://doi.org/10.1016/j.cemconcomp.2011.08.004>.
- [37] Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74-92. <https://doi.org/10.1016/j.cemconres.2014.08.002>.
- [38] Barreto Santos, M., de Brito, J., Santos Silva, A., & Hawreen, A. (2020). Effect of the source concrete with ASR degradation on the mechanical and physical properties of coarse recycled aggregate. *Cement and Concrete Composites*, 111, 103621. <https://doi.org/10.1016/j.cemconcomp.2020.103621>.
- [39] CEN. (2004). EN 12620:2002/AC:2004 - Aggregates for concrete. Retrieved from <https://standards.iteh.ai/catalog/standards/cen/e392fb77-8df5-4d0c-ba2b-2f487dda1037/en-12620-2002-ac-2004>.
- [40] Lauritzen, E.K. (1993). Recycling of concrete in aggressive environment. In *Demolition and Reuse of Concrete and Masonry* (1st ed.). CRC Press. <https://doi.org/10.1201/9781482271270-44>.
- [41] Sanchez, L. F. M., Drimalas, T., Fournier, B., Mitchell, D., & Bastien, J. (2018). Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms. *Cement and Concrete Research*, 107, 284-303. <https://doi.org/10.1016/j.cemconres.2018.02.017>.
- [42] Zahedi, A., Trottier, C., Sanchez, L. F. M., & Noël, M. (2022). Condition assessment of alkali-silica reaction affected concrete under various confinement conditions incorporating fine and coarse reactive aggregates. *Cement and Concrete Research*, 153, 106694. <https://doi.org/10.1016/j.cemconres.2021.106694>.

- [43] Richardson, A. E. (2013). Strength and durability of concrete using recycled aggregates (RAs). In F. Pacheco-Torgal, V. W. Y. Tam, J. A. Labrincha, Y. Ding, & J. de Brito (Eds.), *Handbook of Recycled Concrete and Demolition Waste* (pp. 330-348). Woodhead Publishing. <https://doi.org/10.1533/9780857096906.2.330>.
- [44] Mandal, S. K., Chakraborty, S., & Gupta, A. (2002). Some studies on durability of recycled aggregate concrete. *The Indian Concrete Journal*, 76, 385-388.
- [45] Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T.-C., Zhang, H., & Wang, Y. (2018). Durability of recycled aggregate concrete – A review. *Cement and Concrete Composites*, 89, 251-259. <https://doi.org/10.1016/j.cemconcomp.2018.03.008>.
- [46] Rahal, K. N., & Alrefaei, Y. T. (2017). Shear strength of longitudinally reinforced recycled aggregate concrete beams. *Engineering Structures*, 145, 273-282. <https://doi.org/10.1016/j.engstruct.2017.05.028>.
- [47] Safiuddin, M., Alengaram, U. J., Rahman, M. M., Salam, M. A., & Jumaat, M. Z. (2013). Use of recycled concrete aggregate in concrete: a review. *Journal of Civil Engineering and Management*, 19(6), 796-810. <https://doi.org/10.3846/13923730.2013.799093>.
- [48] Andal, J., Shehata, M., & Zacarias, P. (2016). Properties of concrete containing recycled concrete aggregate of preserved quality. *Construction and Building Materials*, 125, 842-855. <https://doi.org/10.1016/j.conbuildmat.2016.08.110>.
- [49] Sanchez, L.F.M., Fournier, B., Jolin, M. (2012). Critical Parameters of the Stiffness Damage Test for Assessing Concrete Damage Due to Alkali-Silica Reaction (ASR). In: *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction*.
- [50] Smaoui, N., Bissonnette, B., Bérubé, M. A., Fournier, B., & Durand, B. (2006). Mechanical properties of ASR-affected concrete containing fine or coarse reactive aggregates. *Journal of ASTM International*, 3. <https://doi.org/10.1520/JAI12010>.
- [51] Barr, B., & Hasso, E. B. D. (1986). Development of a compact cylindrical shear test specimen. *Journal of Materials Science Letters*, 5(12), 1305-1308. <https://doi.org/10.1007/BF01729401>.
- [52] Adams, M. P., Gray, B., Ideker, J. H., Tanner, J. E., Jones, A., Fournier, B., Beauchemin, S., Shehata, M., & Johnson, R. (2012). Applicability of standard alkali-silica reactivity testing methods for recycled concrete aggregate. In *Proceedings of the 14th International Conference on Alkali Aggregate Reaction (ICAAR)*, Austin, TX, USA. <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-AdamsMP-1.pdf>
- [53] Beauchemin, S., Fournier, B., & Duchesne, J. (2018). Evaluation of the concrete prisms test method for assessing the potential alkali-aggregate reactivity of recycled concrete aggregates. *Cement and Concrete Research*, 104, 25-36. <https://doi.org/10.1016/j.cemconres.2017.10.008>.

- [54] Walsh, J. B. (1965). The effect of cracks on the uniaxial elastic compression of rocks. *Journal of Geophysical Research* (1896-1977), 70(2), 399-411. <https://doi.org/10.1029/JZ070i002p00399>.
- [55] Crouch, R. S. (1987). Specification for the determination of stiffness damage parameters from the low cyclic uniaxial compression of plain concrete cores. Revision A, Mott, Hay & Anderson, Special services division, internal technical note.
- [56] Chrisp, T. M., Waldron, P., & Wood, J. G. M. (1993). Development of a non-destructive test to quantify damage in deteriorated concrete. *Magazine of Concrete Research*, 45(165), 247-256. <https://doi.org/10.1680/mac.1993.45.165.247>.
- [57] Smaoui, N., Bérubé, M. A., Fournier, B., Bissonnette, B., Durand, B. (2004). Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part I: Experimental study. *Canadian Journal of Civil Engineering*, 31(5), 826-845. <https://doi.org/10.1139/104-051>.
- [58] Haskett, M., Oehlers, D.J., Mohamed Ali, M.S., Sharma, S.K. (2011). Evaluating the shear-friction resistance across sliding planes in concrete. *Engineering Structures*, 33, 1357-1364. <https://doi.org/10.1016/j.engstruct.2011.01.013>.
- [59] Canadian Portland Cement Association (1985). *Concrete design handbook*.
- [60] Baar, M., Hasso, E.B.D., & Liu, K. (1985). Shear strength of FRC materials. *Composites*, 16(4), 326-334. [https://doi.org/10.1016/0010-4361\(85\)90285-X](https://doi.org/10.1016/0010-4361(85)90285-X).
- [61] Gao, H., Wang, Z., Yang, C., & Zhou, A. (1979). An investigation on the brittle fracture of KI-KII composite mode cracks. *Acta Metall. Sin.*, 15(3), 380-391.
- [62] ASTM International. (2021). ASTM C1293 - 20a Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction. <https://www.astm.org/Standards/C1293>.
- [63] Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A. G., Fournier, B., & Foo, S. (2008). Proposed method for determining the residual mortar content of recycled concrete aggregates. *Journal of ASTM International*, 5, 1-12. <https://doi.org/10.1520/JAI101087>.
- [64] ASTM International. (2014). ASTM C39/C39M-14 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. https://www.astm.org/c0039_c0039m-14.html.
- [65] Grattan-Bellew, P. E. (1995). Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station. *ACI Materials Journal*, 92(2). <https://doi.org/10.14359/9763>.
- [66] Villeneuve, V., Fournier, B., Duchesne, J. (2012). Determination of the damage in concrete affected by ASR-the damage rating index (DRI). In 14th International Conference on Alkali-Aggregate Reaction (ICAAR). Austin, Texas (USA). <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-VilleneuveV-1.pdf>.

- [67] Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., Duchesne, J. (2016). Use of Damage Rating Index to Quantify Alkali-Silica Reaction Damage in Concrete: Fine versus Coarse Aggregate. *ACI Materials Journal*, 113(4). <https://doi.org/10.14359/51688983>.
- [68] Mindess, S., Young, J. F., & Darwin, D. (2003). *Concrete*(2nd ed.). Prentice Hall.

9. Chloride diffusivity of recycled concrete made of ASR-affected fine and coarse aggregates

Abstract

The recycling of Construction and Demolition Waste (CDW) and Returned Concrete (RC) is an effective way to reduce the environmental impact of concrete production. However, the presence of previous damage in Recycled Concrete Aggregate (RCA) can be a cause for concern. Damage caused by deterioration mechanisms such as Alkali-Silica Reaction (ASR) can affect the microstructure and, thus, the mechanical properties of recycled concrete. Furthermore, previous ASR deterioration may also impact the kinetics of secondary damage caused by the presence of coupled mechanisms, such as Freeze-Thaw (F&T) and/or steel corrosion triggered by carbonation or chloride penetration. However, this impact is currently mostly unknown. This work aims to investigate the effect of ASR-induced deterioration on the chloride diffusivity of RCA concrete. Laboratory-made specimens were produced using RCA with different levels of ASR damage (i.e., slight and severe). The specimens were stored in a NaCl exposure solution with a concentration of 165 ± 1 g NaCl per L of solution for six weeks, and the chloride concentration was measured at various depths using an inductively coupled plasma (ICP) mass spectrometry of ground powder samples. The results were compared to those obtained from conventional concrete specimens, and conclusions were drawn.

Keywords: Chloride diffusivity, Corrosion, Alkali-Silica Reaction (ASR), Recycled Concrete Aggregates (RCA), Damage

Introduction

Recycled concrete

Concrete is a widely used construction material, but its production and use have negative environmental impacts. The production of concrete releases greenhouse gases, including carbon dioxide and methane, which contribute to climate change. In addition, cement production, a key component of concrete, is a significant source of air pollution, including particulate matter and nitrogen oxides.

Recycled concrete aggregate (RCA) is an alternative to using virgin materials in concrete production. RCA is made from concrete that has been demolished or removed from its original location, and it can be used as a

substitute for natural aggregate in new concrete. Using RCA can reduce the environmental impacts of concrete production, including greenhouse gas emissions and air pollution. However, RCA has challenges, including potential contamination from other materials and the need to ensure that it meets strength and durability requirements.

One potential issue with using recycled concrete aggregate (RCA) in concrete is the potential for alkali-silica reactivity (ASR). ASR is a chemical reaction between the alkalis in cement and the reactive silica in aggregates, resulting in the concrete's expansion and cracking, which can lead to reduced strength and durability-related properties and may cause structural problems over time. ASR can be particularly problematic in concrete made with RCA, as the history and composition of the RCA may be unknown.

To address the potential for ASR in concrete made with RCA, it is crucial to carefully evaluate the RCA for reactivity and select a suitable cement to use in the mix. ASR in recycled concrete can impact the concrete's chloride ingress and subsequent corrosion. ASR can cause the expansion and cracking of the concrete, which can create channels for water and chloride ions to enter the concrete. Once inside the concrete, these ions can cause corrosion of the steel reinforcement, leading to reduced strength and durability of the concrete structure. Another mechanism when dealing with chloride ingress in ASR-affected concrete is the presence of ASR gel, which can positively impact chloride ingress.

Corrosion initiation and chloride diffusivity

Chloride-induced reinforcement corrosion on the concrete structure is a significant issue in Canada. Billions of dollars are spent annually on the upkeep, maintenance, and repair of reinforced concrete (RC) structures that have been deteriorated by corrosion [1]. The resistance to chloride diffusivity is a crucial parameter affecting the durability of concrete structures.

Chloride attack is identified as the leading cause of steel rebar corrosion. Chloride-attack can be categorized into two main groups (i.e., internal and external). The main source of external chloride attacks in Canada is de-icing salt. The US Environmental Protection Agency [2] estimates that over 500 million dollars are spent annually to repair and replace highways and bridges damaged by de-icing salt. Internal chloride attack is caused by the presence of contaminated components, such as seawater, in the concrete mix. Due to the high alkali content of mortar, which produces a passive layer on steel rebars, concrete is generally protected against corrosion. However, chloride ions can act as corrosive agents, breaking this protective layer and initiating corrosion. The amount of chloride required for the initiation of corrosion is referred to as the critical chloride threshold. Figure 9.1 shows the different stages involved in steel corrosion in reinforced concrete.

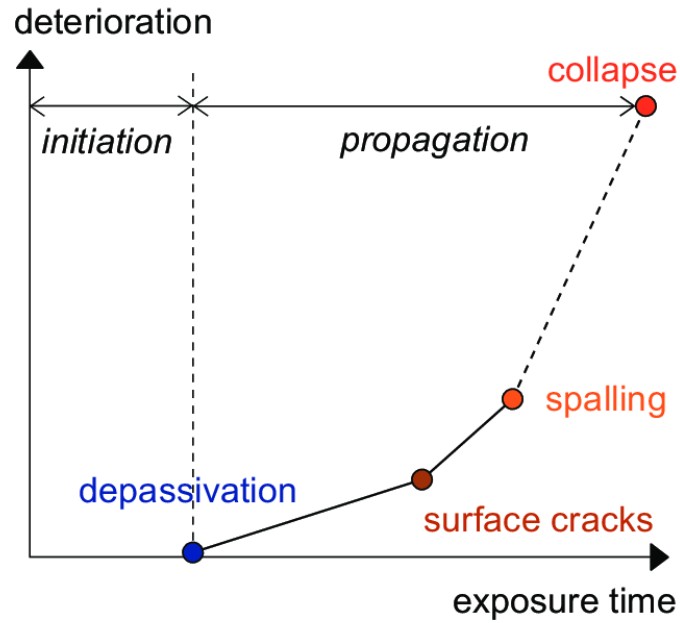


Figure 9.1: Two-stage mechanism of corrosion over time [3].

Chloride diffusion

Chloride diffusion is defined as the transfer of chloride driven by the difference in chloride concentration in various zones [4]. Along with other mechanisms, diffusion is often referred to as the primary chloride transport mechanism under most exposure conditions [5]. The theory behind diffusion is mainly based on the mathematical model proposed by Adolph Eugen Fick. Fick's diffusion theory assumes that the transport of chloride ions through a unit area of a section of the concrete per unit of time (the flux F) is proportional to the concentration gradient of the chloride ions measured normally to the section (Equation 9.1). Fick's first general law of diffusion is shown in Figure 9.2.

$$F = -D \times \frac{\partial C}{\partial x}$$

Equation 9.1

where D is called the chloride diffusion coefficient, D is not a constant but depends on many parameters like the time for which diffusion has taken place, the location in the concrete, the composition of the concrete, etc.

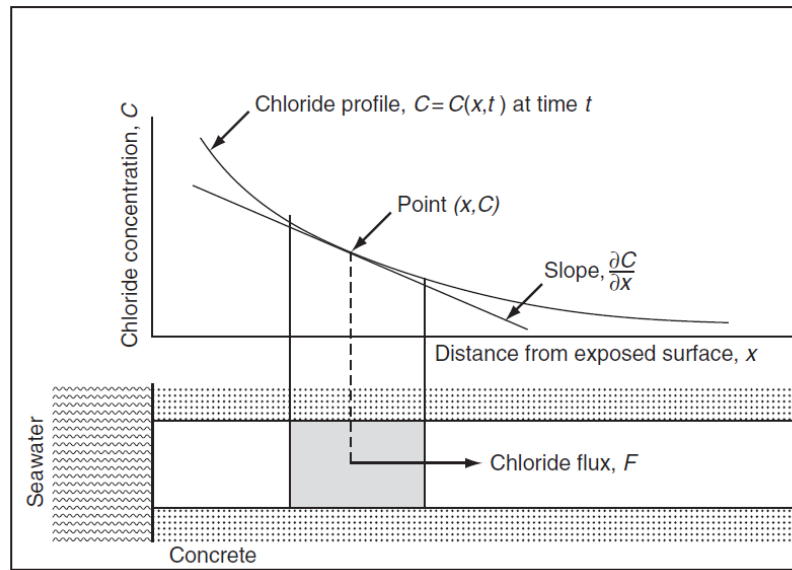


Figure 9.2: Flick's first general law of diffusion [4].

Effects of microcracking on chloride diffusion

Microcracks are present in concrete due to several causes, such as bleeding, shrinkage, thermal gradients, freeze-thaw, and alkali-aggregate reaction. Microcracks can act as flow channels and provide easy access to harmful chemicals and ions such as chloride [6]. The importance of microcracks has been highlighted recently [7]. The concrete cover's ability to protect could be significantly affected by microcracking. Lim et al. [6] studied the effects of microcracking on the chloride permeability of loaded specimens. Due to microcracks' ability to open and close under loading and unloading conditions, Lim et al. [6] concluded that microcracks' influence on concrete transportation parameters could not be measured solely based on the crack length, and the specific crack area is a more sensitive parameter as shown in Figure 9.3.

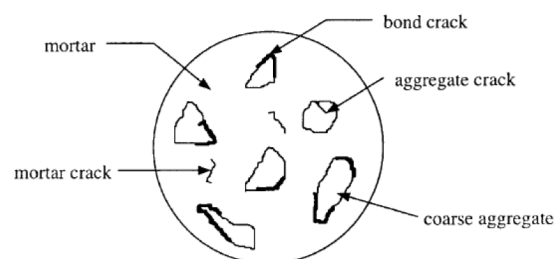


Figure 9.3: Various types of microcracking in concrete [6].

In another study by Samaha & Hover [8] on the influence of microcracking on the mass transport properties, it was found that the proportion of aggregate in the concrete mix has a significant effect on Rapid Chloride Penetration Test (RCPT) results, and Internal microcracking damage caused by oven drying shrinkage has a greater effect on chloride transport than the damage caused by short term loading of concrete that is air-dried cured. Aside from cracks due to various loading types, deterioration mechanisms (i.e., F&T, ASR, and internal sulphate attack) could be another source of cracking in concrete.

Chung et al.[9] found that the specimen's chloride ion diffusivity is significantly increased after being subjected to F&T cycles. This could be explained by the increase in potential flow channels caused by FT expansive cracking. ASR is another cracking mechanism affecting aggregates and cement paste. Trejo et al. [10] studied the effects of ASR-induced microcracks on corrosion. A fine reactive aggregate was used to generate ASR cracking. Trejo et al. [10] concluded that the time to corrosion initiation was not affected by ASR. The ASR gel had a significantly lower chloride value compared to hardened cement paste. In a similar study by Mazarei et al. [11], ASR affects corrosion initiation time in two ways: a) increasing the chloride diffusion coefficient and b) reducing the critical chloride threshold (C_T). Mazarei et al. [11] concluded that the ASR gel reduces the concrete's overall chloride diffusion coefficient by filling the cracks and the ITZ.

The effects of Interfacial Transition Zone (ITZ) on chloride diffusivity

Due to the high porosity of the ITZ caused by the wall effect, the presence of ITZ can provide channels that facilitate the transport of chlorides. The chloride diffusion coefficient of concrete can be significantly affected by the ITZ content. Delagrave et al. [12] reported that increasing the sand volume fraction in the mortar results in more connectivity of ITZs, facilitating the transport of chlorides into the mortar. The effective diffusion coefficient's main factor could be the Interfacial Transition Zone (ITZ) content [13,14]. In general, the ITZs diffusivity coefficient is reported to be 1.6 to 16.2 times greater than the bulk cement paste [12,14,15]. The presence of various types of ITZs due to the two-phase microstructure of the RCA could create new channels for chloride diffusion.

Scope of work

Chloride diffusivity parameters are governed by many factors (i.e., aggregate volume, ITZ content, hardened cement diffusivity, etc.). As such, due to the unique microstructure of RCA, the corrosion initiation period could be significantly different in recycled concrete when compared to conventional concrete. In RCA, the presence of new ITZ (i.e., ITZ between new mortar and old mortar, ITZ between new mortar and OVA, and ITZ between old mortar and OVA) can significantly affect chloride diffusivity of recycled concrete along with the presence

of previous damage (e.g., ASR-induced cracks or cracks generated during the crushing process). This work investigates the behaviour of recycled concrete previously affected by ASR and bearing deterioration at distinct locations (i.e., OVA and RM) with two levels of initial damage (i.e., slightly damaged and severely damaged) when exposed to a chloride-rich environment. It has been found that the presence of reactive fine aggregates in conventional concrete can result in worse performance compared to specimens where the reaction starts within the coarse aggregate [1]. However, in the case of recycled concrete, it seems that although more pathways for chloride ingress are generated within the sample, with the development of the secondary expansion, the generation of gel which fills these pathways has had an opposing impact on the ingress of chloride.

Materials and methods

Manufacturing of ASR reactive specimens

Two types of ASR reactive conventional concrete specimens were made using reactive coarse aggregates (i.e., Springhill coarse - SH) and reactive sand (i.e., Texas sand - TX) to produce a total of 40 specimens. Two levels of initial expansion were selected (i.e., 0.05% - low and 0.30% - very high). Upon reaching the desired levels of initial expansions, two specimens per family per expansion level were taken out for further analysis, and the rest of the specimens were crushed using a jaw crusher to produce four types of RCA (i.e., recycled slightly damaged Springhill – 0.05% RSH, recycled severely damaged Springhill – 0.30% RSH, slightly damaged Texas – 0.05% RTX, and severely damaged Texas – 0.30% RTX). The RCAs were proportioned using the EV method while keeping the total cement content of the system equal to 420 kg/m³. The mixture's total alkali content was raised to 1.25% Na₂O_{eq} by cement mass by adding reagent grade NaOH. The specimens were de-moulded after 24 hours, and two stainless steel studs were installed at both flat ends. Initial readings were performed on the specimens after 24 hours. The specimens were then placed in controlled chambers at 38°C and 100% relative humidity (RH). All the test cylinders were regularly monitored over time. Also, the containers were cooled down to 23°C for 16 ± 4 h prior to periodic expansion measurements. Two levels of secondary expansion representing damage degrees were selected for further analysis: 0.05% (low) and 0.30% (very high). Once the test specimens reached the above expansion levels, they were wrapped in plastic film and stored at 12°C to stop ASR further development until all the specimens were ready.

Sample preparation

Waterproof sealant

The specimens were taken out of the chamber once the desired expansion levels were reached. The stainless-steel studs were then removed. A water-based high-performance clear hydro-stop sealer was then applied to all the surfaces of the specimens. Later, the specimens were then placed in a 60°C chamber for two hours to dry off the coating. To completely seal the samples, this process was repeated two times. Once all the surfaces of the specimens were covered with the clear coat, a plastic-coat spray was used until a thick layer of coating was visible on the specimens. The specimens were then dried for 24 hours at room temperature. The specimens were weighed and placed in a water bath for 72 hours to ensure that specimens were entirely waterproof. The flat top surface of the specimens was grinded off using the profile grinder. The specimens were then ready to be placed inside the exposure solution.

Exposure conditions

As per ASTM C1556-11a [5], the specimens were immersed in a saturated calcium hydroxide water bath at 23 ± 2 °C in a tightly closed container until the mass of the specimens did not change by more than 0.1% in 24 hours. After removing the specimens from the calcium hydroxide bath, the specimens were completely rinsed using tap water and then immediately placed inside the exposure solution. Using 22-litre airtight buckets, the specimens described in Table 5.1 were immersed for six weeks at a temperature of 23 ± 2 °C in a NaCl exposure solution (165 g NaCl per 1 L of solution). The specimens were placed in a chamber with 50% relative humidity at 23 ± 2 °C for 24 hours. The specimens were then removed and stored in watertight polyethylene bags in a freezer maintained at -15 ± 5 °C until the time of grinding.

Powder extraction

The powder was extracted in 8 distinct depths (i.e., 0-1, 1-3, 3-5, 5-7, 7-10, 10-13, 13-16, 16-20, 20-25 mm) as per ASTM 1556 using a profile grinder. The profile grinder and all the other equipment used in the process were thoroughly cleaned at each interval. A minimum of 5 gr of concrete powder passing sieve number 20 was extracted at each depth interval.

Inductively coupled plasma mass spectrometry

Inductively coupled plasma mass spectrometry (ICP-MS) is a type of analytical technique used to determine the elemental composition of a sample. It works by introducing a sample into a high-temperature plasma, which ionizes the sample and creates a cloud of charged particles. These ions are then separated based on their mass-

to-charge ratio using a mass spectrometer and detected by a detector. The resulting data is used to identify and quantify the elements present in the sample. ICP-MS is a highly sensitive technique and is able to detect trace levels of elements in the sample [16,17]. The results gathered from the ICP-MS were later used to obtain the apparent chloride diffusion coefficient by means of a non-linear regression analysis following the procedure mentioned in ASTM C1556 [18].

Results

Chloride concentration profile

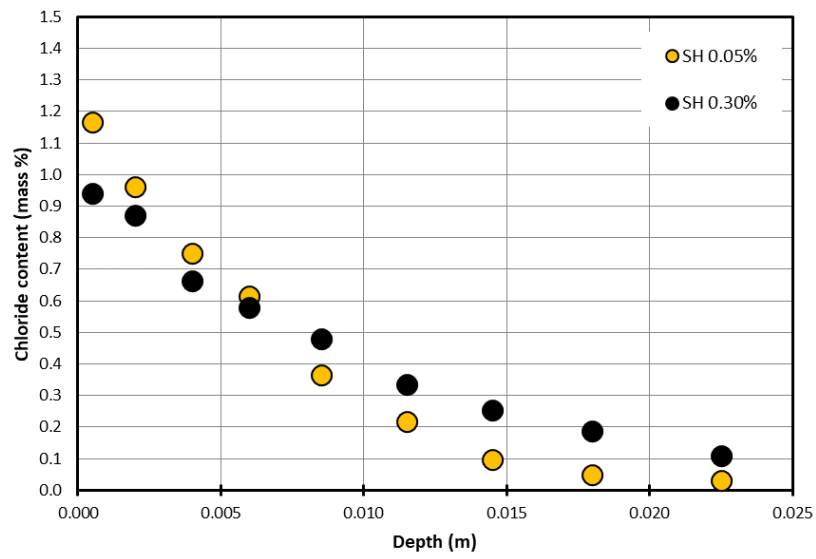
Figure 9.4 presents the chloride content (percentage of mass) at various depths of the specimens for A) conventional concrete made of Springhill aggregates with two levels of expansion (i.e., 0.05% and 0.30%) and B) conventional concrete made of Texas sand with two levels of initial expansion (i.e., 0.05% and 0.30%).

Based on Figure 9.4 A, the chloride content for the two specimens, SH-0.05% and SH-0.30%, was measured at various depths. At a depth of 0.5 mm, the chloride content for the SH-0.05% specimen was 1.165%, while the chloride content for the SH-0.30% specimen was 0.940%. As the depth increased to 2 mm, the chloride content for the SH-0.05% specimen decreased to 0.961% and further decreased to 0.752% at a depth of 4 mm. On the other hand, the chloride content for the SH-0.30% specimen decreased to 0.870% at a depth of 2 mm and further decreased to 0.665% at a depth of 4 mm. At depths up to 8 mm, it appears that the chloride content is higher in the SH-0.05% specimen, while after 8 mm, the chloride content is higher in the SH-0.30% specimen.

The chloride content for the two specimens, TX-0.05% and TX-0.30%, was measured at various depths (Figure 9.4 B). At a depth of 0.5 mm, the chloride content for the TX-0.05% specimen was 0.870%, while the chloride content for the TX-0.30% specimen was 0.770%. As the depth increased to 2 mm, the chloride content for the TX-0.30% specimen increased to 0.648%, and at a depth of 4 mm, it increased to 0.603%. The chloride content for the TX-0.30% specimen was continuously higher than that for the TX-0.05% specimen, with one exception at a depth of 18 mm.

Looking at the results, one sees that specimens made of Springhill and Texas presenting lower ASR-induced deterioration (i.e., 0.05%) displayed higher chloride content at locations closer to the specimens' surface (i.e., from 0 to 4 mm). Otherwise, this "surface effect" changed as a function of the specimen's depth, where specimens presenting greater damage (i.e., 0.30%) overcome the chloride values from specimens displaying lower ASR damage. Similar behaviour was observed for concrete specimens made of Texas sand; however, a narrower scattering between specimens from distinct deterioration levels was observed.

A)



B)

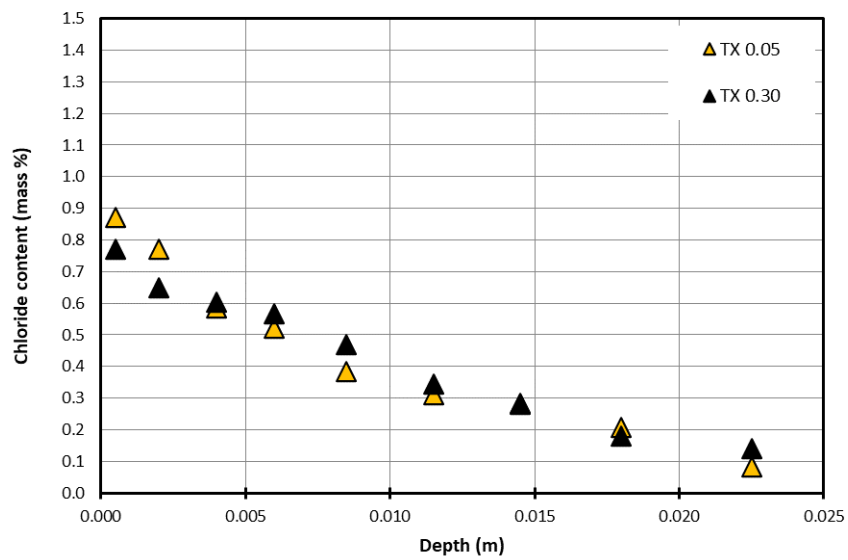
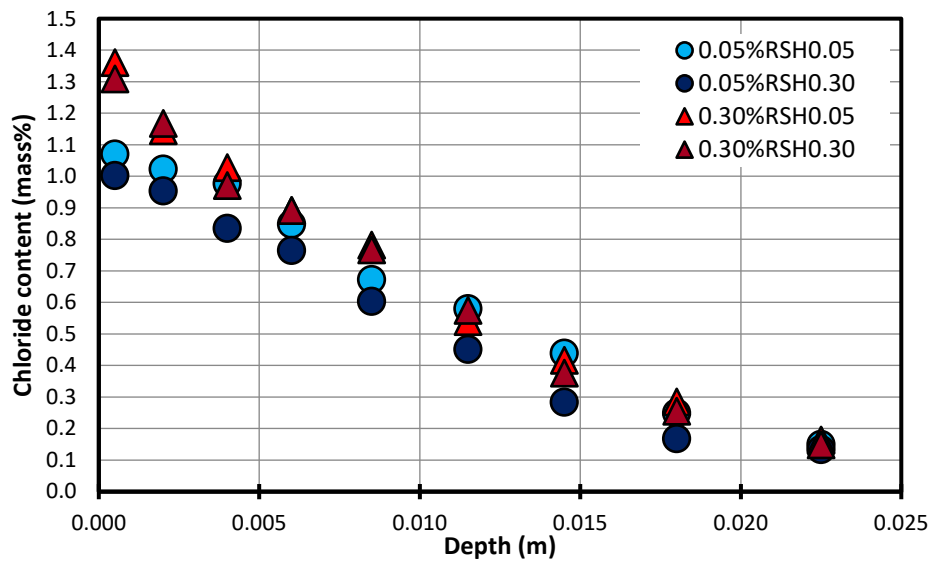


Figure 9.4: Chloride concentration profile for A) Reactive SH coarse specimens and B) Reactive Texas sand specimens.

Similarly, Figure 9.5 shows the chloride concentration profile for recycled concrete specimens for the two levels of secondary expansion (i.e., 0.05% and 0.30%). The figures are divided based on the location of the ASR reaction A) for coarse reactive aggregate-OVA and B) for reactive sand aggregates-RM.

A)



B)

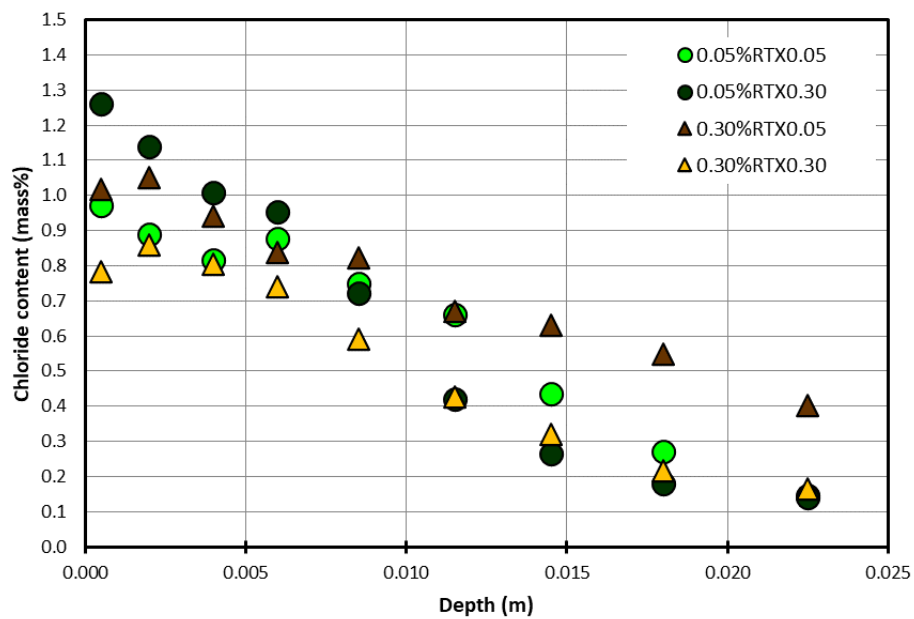


Figure 9.5: Chloride concentration profile for A) Recycled concrete made with reactive coarse aggregates and B) Recycled concrete made with reactive sand.

Evaluating the plots, one verifies that at a depth of 0.5 mm, the chloride content ranges from 1.002 % to 1.361% among the four specimens. The 0.05%-RSH-0.05% specimen displays the second lowest chloride content at this depth, while the 0.30%-RSH-0.30% specimen presents the highest chloride content. At a depth of 2 mm, the chloride content ranges from 0.953 % to 1.168%. The 0.05%-RSH-0.30% presents the highest chloride content at this depth, while the other three specimens display relatively similar values. At a depth of 4 mm, the

chloride content varies between 0.835% and 1.028%. The 0.05%-RSH-0.05% specimen presents the second lowest chloride content at this depth, while the other three have relatively similar values. Overall, the variations observed in the chloride content among the different specimens happen in locations close to the surface; yet these variations become less pronounced at deeper depths. The 0.30%-RSH-0.30% specimen generally presented the highest chloride content at the most depths, while the 0.05%-RSH-0.05% specimen displayed the second lowest chloride content at each depth. The other two specimens presented relatively similar chloride content values at each depth.

In the case of recycled concrete made of reactive Texas sand (Figure 9.5B), the chloride content at a depth of 0.5 mm varies significantly among the four specimens, with values ranging from 0.972% to 1.309%. The specimen made of slightly damaged Texas sand with a secondary expansion of 0.05%, labelled 0.05%-RTX-0.05%, exhibits the lowest chloride content at this depth. In contrast, the specimen made of severely damaged Texas sand with a secondary expansion of 0.30%, labelled 0.30%-RTX-0.30%, displays the highest chloride content at 0.5 mm. At a depth of 2 mm, the chloride content ranges from 0.89% to 1.168%. The specimen made of slightly damaged Texas sand with a secondary expansion of 0.30%, labelled 0.05%-RTX-0.30%, exhibits the highest chloride content among the four specimens at this depth. Meanwhile, the other three specimens show relatively similar levels of chloride content. Across all depths, the specimens made of severely damaged Texas sand labelled 0.30%-RTX0.05% with a secondary expansion level of 0.05% tend to have higher chloride content levels than those made of slightly damaged Texas sand, labelled 0.05%-RTX0.05%. At depths closer to the surface, such as 0.5 mm and 2 mm, the differences in chloride content among the four specimens are relatively small. However, as the depth increases, the specimens made of severely damaged Texas sand tend to have significantly higher levels of chloride content compared to the specimens made of slightly damaged Texas sand. This trend is particularly evident at depths of 4 mm and deeper, where the differences in chloride content between the two groups of specimens become more pronounced.

Chloride diffusion rate

The chloride diffusion rate was calculated using Crank's solution to Fick's second law of diffusion [19]. The apparent diffusion coefficient D_{app} was calculated using equation 9.3 with the non-linear least square regression method. The D_{app} is presented for each mixture in Table 9.1, and the correlation factor R^2 shows that the model used accurately represents the measured chloride data.

In the case of conventional concrete, the Texas sand specimens presented a higher diffusion rate with values of $2.40E-11$ and $3.71E-11$ for low and high levels of ASR-induced expansion. The specimens made of Springhill coarse aggregate also presented a higher diffusion rate at a high expansion level ($2.32E-11$ vs. $1.14E-11$).

However, this was not always the case for secondary ASR-induced expansion and both slightly damaged specimens (0.05% RSH and 0.05% RTX) and the severely damaged recycled Texas specimen; the diffusion rate was slightly less at the secondary expansion of 0.30% compared to 0.05%. The theoretical surface chloride concentration C_s in Table 9.1 ranges between 0.770% to 1.165% by weight of concrete for conventional concrete specimens and 1.072% to 1.361% for recycled specimens. Overall, less disparity was observed for the recycled concrete made of reactive coarse aggregate when compared to reactive fine.

Table 9.1 Surface chloride content C_s , apparent diffusion coefficient D_{app} , and correlation factor R^2 obtained by fitting chloride profiles for cylindrical specimens.

Mixture	C_s (%)	D_{app} (m ² /s)	R^2	Measured concentration at a depth of 2.25 cm
SH 0.05	1.165	1.14E-11	0.99	0.0298
SH 0.30	0.970	2.32E-11	0.99	0.110
TX 0.05	0.870	2.40E-11	0.96	0.152
TX 0.30	0.770	3.71E-11	0.99	0.141
0.05% RSH 0.05	1.170	3.67E-11	0.99	0.150
0.05% RSH 0.30	1.102	2.72E-11	0.99	0.134
0.30% RSH 0.05	1.361	2.93E-11	0.99	0.163
0.30% RSH 0.30	1.309	3.04E-11	0.99	0.149
0.05% RTX 0.05	1.072	4.72E-11	0.93	0.148
0.05% RTX 0.30	1.361	2.26E-11	0.98	0.141
0.30% RTX 0.05	1.118	1.21E-10	0.98	0.401
0.30% RTX 0.30	1.309	3.04E-11	0.99	0.165

Discussion

The results from the section before clearly show that the location of the ASR reaction (i.e., cement paste or coarse aggregate) impacts the chloride diffusion rate in conventional concrete. However, in the case of recycled concrete, the difference is not as evident. To fully understand the impact of ASR (i.e., initial and secondary expansion), the microstructure of both conventional and recycled concrete needs to be comprehensively studied. To do that, a semi-quantitative microscopic technique, so-called Damage Rating Index (DRI), is used, and descriptive models have been developed [20,21] for conventional and recycled concrete.

Microstructure assessment

There are several factors that can affect the chloride diffusivity in concrete, including the aggregate content, water/cement ratio, curing period, ITZ width, maximum aggregate size, and aggregate gradation [22,23]. Moreover, the permeability of the distinct concrete phases (i.e., aggregates, cement paste and ITZ) is critical in determining the chloride diffusivity [10]. The development of an ASR-induced cracking network can significantly impact concrete permeability. As such, the DRI can be used to assess the condition of concrete microstructure better.

The DRI was developed by Grattan-Bellew et al. [25] in 1992 and involved counting specific types of distress on a polished concrete surface using a stereomicroscope at a magnification of 15-16x [26]. The number of each type of distress is multiplied by a weighting factor to reflect their relative importance, and the final DRI number is calculated. The DRI has been found to be reliable and effective for assessing the condition of both conventional concrete and recycled concrete aggregate (RCA) that has been affected by alkali-silica reactivity (ASR) [20–23,27–29]. The assessment should be performed on a surface area of at least 200 cm², but the final DRI value is normalized to a 100 cm² area for comparison purposes. DRI was later used by Sanchez et al. [27] to assess the condition of several types of reactive aggregates at various expansion levels, which resulted in a qualitative model for ASR crack development in conventional concrete (Figure 9.6).

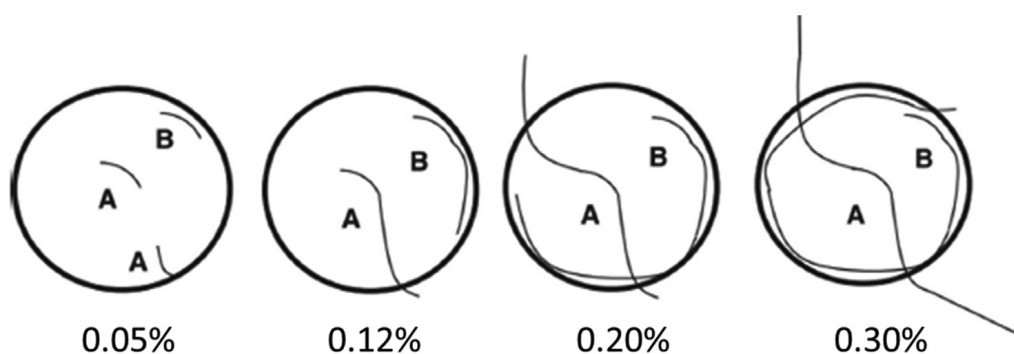


Figure 9.6: A qualitative crack propagation model in ASR-affected conventional concrete [22].

Investigating Chloride Diffusion in Conventional Concrete Specimens

The results from Figure 9.7 shows that the Texas specimens presented a higher diffusion rate than the Springhill specimens at both low and very high expansion levels. This can be explained by investigating the microstructure of conventional concrete for the two cases of ASR initiated at coarse and fine aggregates. Figure 9.8 shows that ASR-induced development in reactive fine aggregate particles results in a more *spread-out* cracking network which may result in more accessible pathways for chloride diffusion.

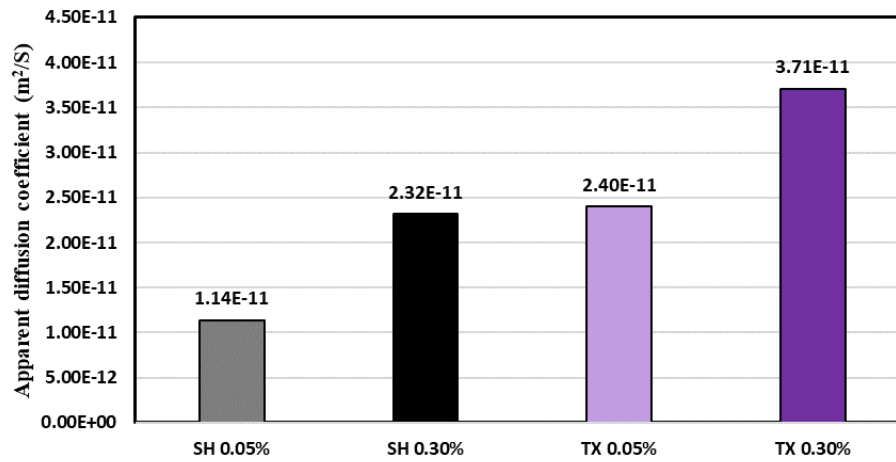


Figure 9.7: Apparent chloride diffusivity of conventional concrete specimens.

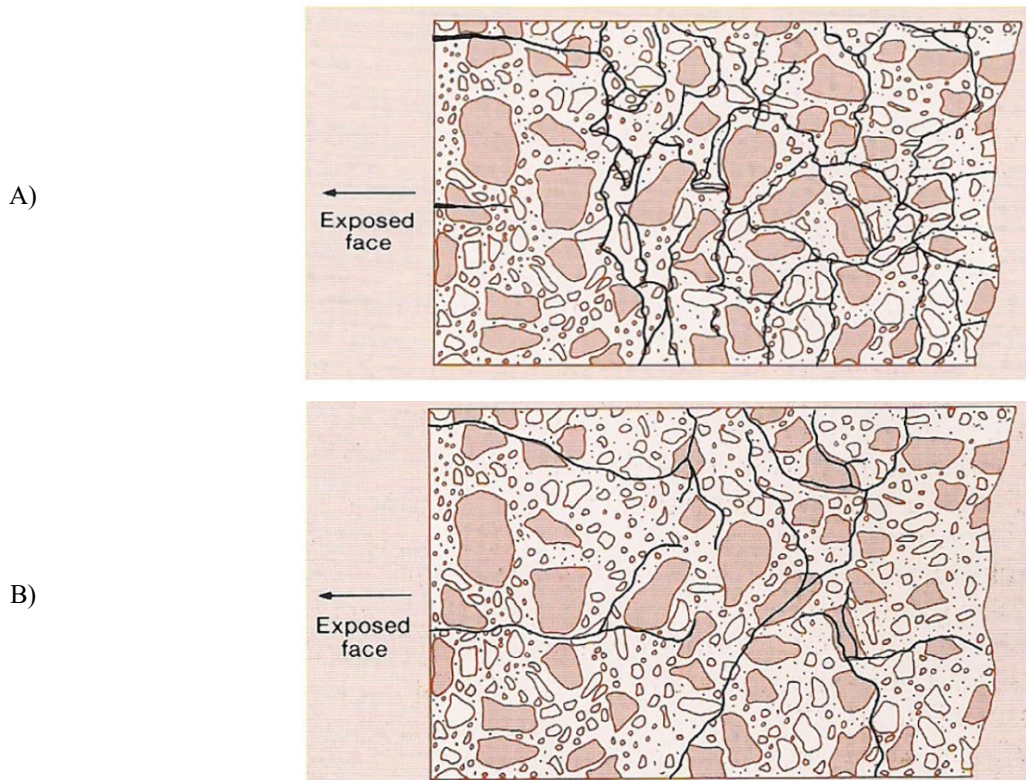


Figure 9.8: Internal cracking caused by A) ASR from reactive sand and B) ASR from reactive coarse aggregates [22].

Figure 9.9 presents the total number of cracks at each expansion level for both Springhill coarse and Texas sand specimens [20]. The Texas sand specimens presented higher cracks at both low and high expansion levels compared to Springhill CC. In the case of Springhill CC, the cracks generated at the beginning of the expansion

(i.e., 0.05%) are confined within the coarse aggregate and may not be as effective in creating pathways for chloride ingress. However, the Texas sand specimens present more cracks and a spread-out pattern. Later at the expansion level of 0.30%, the Texas sand specimens present more cracks in the cement paste (i.e., CCP – cracks in the cement paste and CCPG – cracks in the cement paste with the gel). As such, the cracking network generated by reactive Texas sand creates a suitable pathway for the ingress of chlorides. It is worth noting that the presence of gel within the cracks at high levels of expansion may act as a barrier to chloride ingress [10]. However, the difference between SH 0.30% and TX 0.30% in the number of cracks within the cement paste with gel is small (i.e., CCPG of 94 vs. 102).

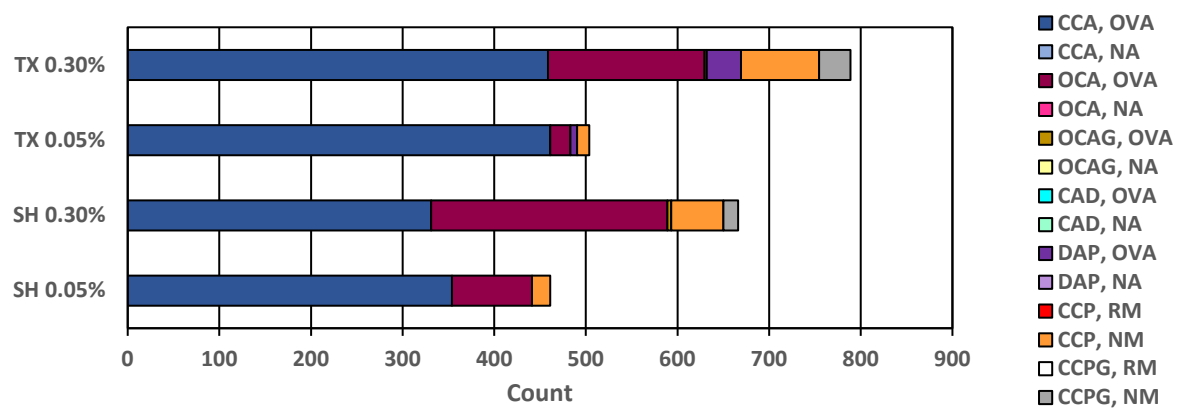


Figure 9.9: Total number of cracks for conventional concrete specimens [20].

Investigating Chloride Diffusion in Conventional Recycled Specimens

The chloride apparent diffusion coefficient of recycled concrete specimens is presented in Figure 9.10. The recycled concrete made of reactive coarse aggregate presented a similar value for all four cases, while the concrete made of reactive sand presented a significantly higher diffusion coefficient at the beginning of the secondary reaction (i.e., 0.05%).

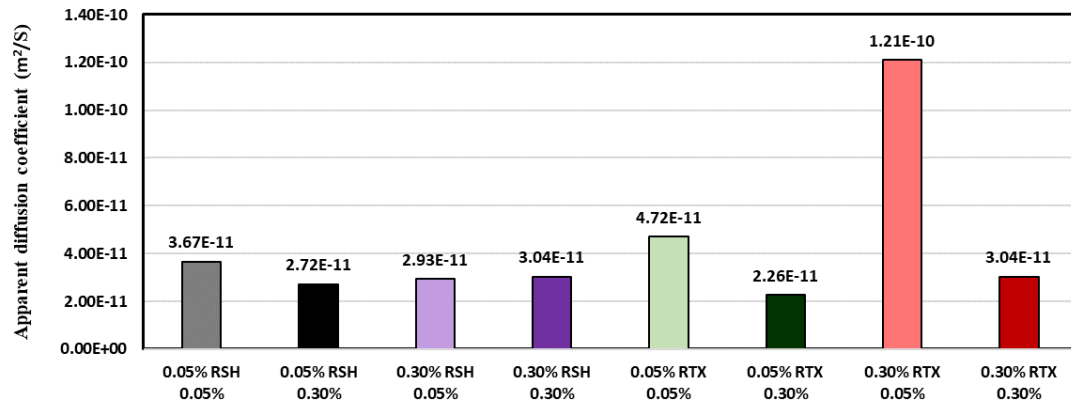
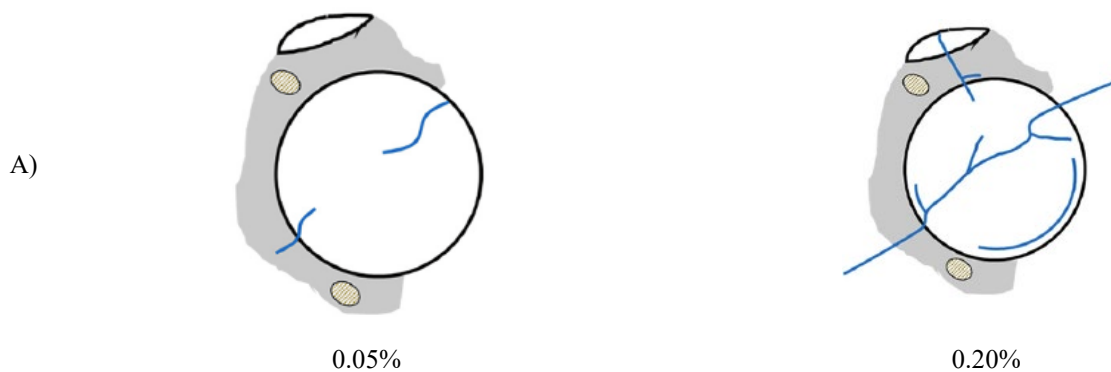


Figure 9.10: Apparent chloride diffusivity of recycled concrete specimens.

Due to the unique microstructure of RCA, the chloride mechanism seems quite different. The recycled concrete is no longer a three-phase material, and the addition of residual mortar (RM), ITZ between the RM and new mortar (NM), ITZ between the old virgin aggregate (OVA) and NM, and ITZ between the OVA and NM could significantly change the microstructure as well as the chloride diffusion rate. As such, understanding the microstructure of ASR-affected recycled concrete is crucial. Trottier et al. performed DRI [20,21] on recycled concrete specimens made of reactive fine and coarse aggregates and presented a qualitative model (Figures 9.11 and 9.12) for ASR crack propagation in recycled concrete. By comparing Figures 9.11 and 9.12, it can be seen that an existing cracking network is present within the RCA at the beginning of secondary expansion for severely damaged RCA. Later, as the expansion progresses, the cracking network developed by the secondary expansion presents more access through the reactive OVA and sand to the new cement paste in the slightly damaged RCA, while the severely damaged RCA has cracks going through the RM and OVA into the NM. Although the models presented in Figures 9.10 and 9.11 provide information about the location of cracks and the cracking network development, to understand the chloride diffusion in ASR-affected recycled concrete, more information is needed concerning the types of cracks present at each expansion level.



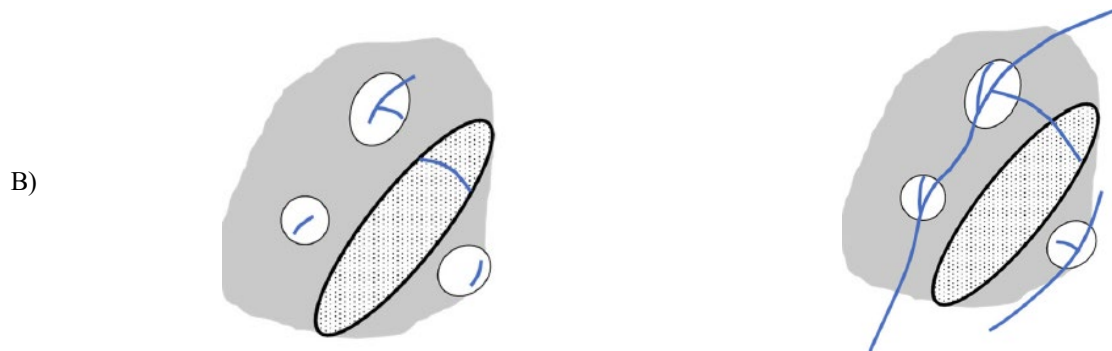


Figure 9.11: Qualitative model representing crack propagation in recycled concrete for A) slightly damaged OVA and B) slightly damaged RM at secondary expansion levels of 0.05% and 0.20% [21].

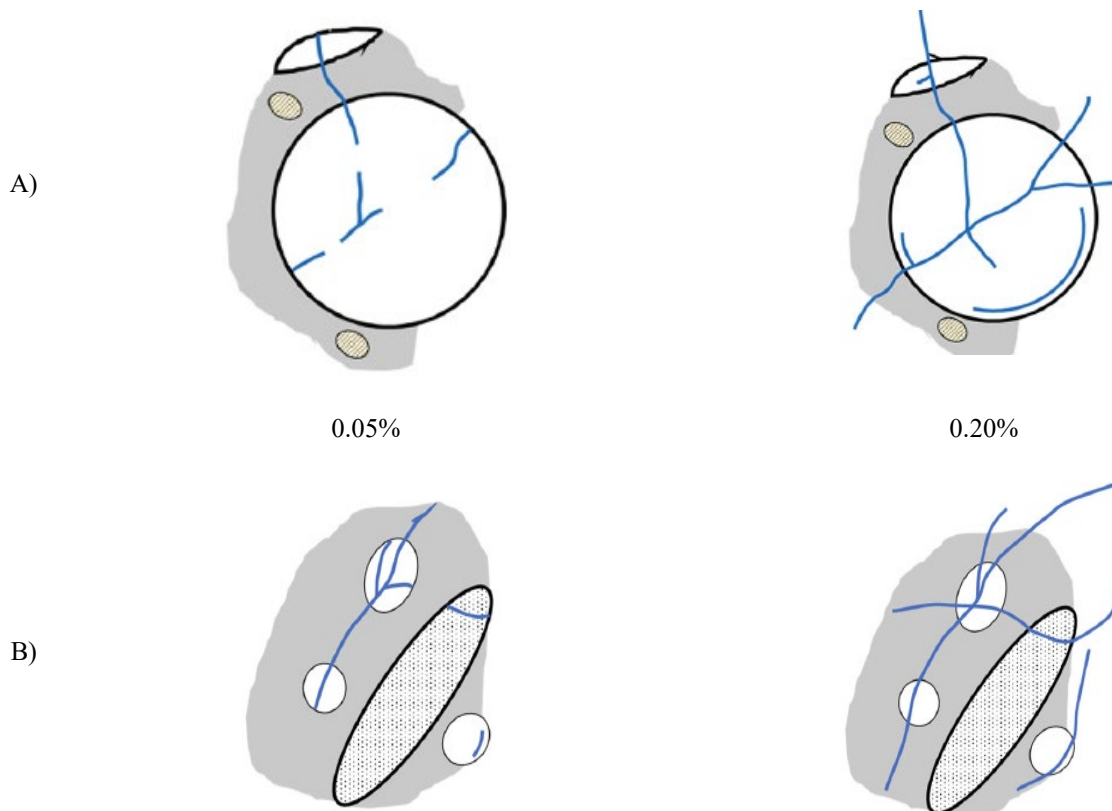


Figure 9.12: Qualitative model representing crack propagation in recycled concrete for A) severely damaged OVA and B) severely damaged RM at secondary expansion levels of 0.05% and 0.20% [21].

To investigate the impact of the location of cracks on chloride diffusivity, the total number of cracks for all four families at each secondary expansion level (i.e., 0.05% and 0.30%) are presented in Figure 9.13.

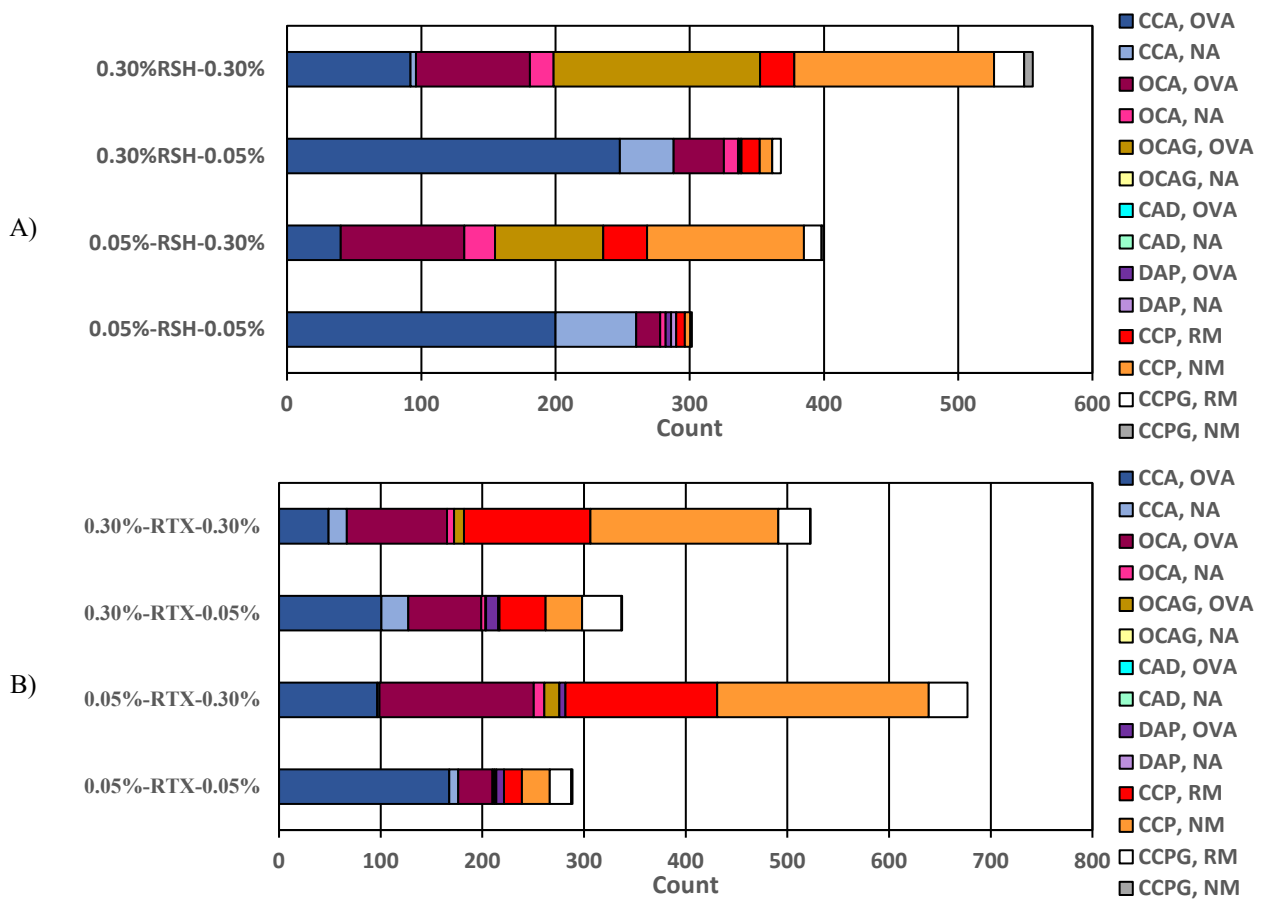


Figure 9.13: crack counts for recycled concrete specimens [21].

Analyzing the plots above, one notices that all recycled concrete mixtures present a decrease in diffusion coefficient at high expansion levels compared to their diffusion coefficient at the beginning of the secondary expansion, with only the exception of 0.30%-RSH. Trejo [10] has reported that the presence of gel in the ITZ can block the chloride transport, which could be the cause resulting in a lower diffusion rate.

At the beginning of secondary expansion (i.e., 0.05%), most cracks are confined within the OVA and have not expanded into the RM or the NM. Consequently, the ITZ between the NM and RCA, as well as the ITZs within the RCA, are a more suitable route for chloride ingress when compared to the cracks within the OVA. Moreover, although the severely damaged RSH presented a higher DRI value (Figure 9.10), more gel was observed within its RM. Later, at high levels of secondary expansion (i.e., 0.30%), more open cracks within the OVA, as well as new aggregates, are present along with new cracks in the cement paste. However, a significant increase in the number of cracks with gel is observed both surrounding the OVA and inside the RM, which may explain

the reduction in chloride diffusion in slightly damaged RSH and a minor increase in the chloride diffusion of severely damaged RSH (i.e., $2.72\text{E-}11$ and $3.04\text{E-}11$).

In the case of recycled concrete made of reactive Texas sand, the secondary reaction starts within the RM. As previously mentioned in the literature, in the case of conventional concrete, the chloride ingress happens through the cement paste and ITZ and tends to avoid the coarse aggregates. Consequently, due to the presence of highly damaged RM and easier access to the ITZ between NM and RM, it is expected that RTX specimens show a higher chloride diffusion. At the beginning of the secondary reaction (i.e., 0.05%), a total of 289 and 337 cracks were observed for 0.05% RTX and 0.30% RTX, respectively. However, the number of open cracks and cracks within the OVA are significantly higher for severely damaged RCA. The amount of gel present in both cases was considered similar.

The counter effect of the gel is more evident when comparing the recycled concrete made of reactive Texas sand, where although a very advanced cracking network is present at the high secondary expansion (i.e., 0.30%), a significant decrease in chloride diffusion parameter is observed.

Conclusions

This study investigated the impact of the source of the secondary reaction in recycled concrete aggregates (i.e., reactive sand within the RM or reactive OVA) and the impact of the secondary reaction on the chloride diffusion coefficient of RCA concrete. The chloride diffusion coefficient was calculated following the procedure in ASTM C1556. The main conclusions of this research are presented below:

- The conventional concrete specimens made with reactive fine aggregates (i.e., Texas sand) presented a higher chloride diffusion coefficient regardless of the expansion level, with Tx 0.30% having the highest chloride diffusion coefficient among the conventional specimens.
- Due to the unique microstructure of ASR-affected RCA and the presence of multiple ITZs, the chloride ingress mechanism seems to be different and needs further investigation.
- Overall, the location of reactive aggregates significantly impacts the chloride ion transport in recycled concrete. The severely damaged RCA made of Texas sand, followed by the slightly damaged RCA made of Texas sand, showed the highest chloride diffusion coefficient.
- The ASR-induced cracking network and the gel produced have a contradictory relationship when discussing the chloride diffusion coefficient, where the gel seems to be working as a barrier while the cracking network provides pathways for the chloride ingress.
- The number of open cracks with or without gel is of significant importance when discussing the chloride ingress in recycled concrete.

References

- [1] Caré, S. (2003). Influence of aggregates on chloride diffusion coefficient into mortar. *Cement and Concrete Research*, 33(7), 1021-1028. [https://doi.org/10.1016/S0008-8846\(03\)00009-7](https://doi.org/10.1016/S0008-8846(03)00009-7).
- [2] United States Environmental Protection Agency (EPA). (2012) Proceedings of the Water Environment Federation. 726–737. <https://doi.org/10.2175/193864705783867675>.
- [3] Sanchez, L., Fournier, B., Jolin, M., Bastien, J., Mitchell, D., Noel, M. (2016). The use of the damage rating index (DRI) for the condition assessment of aging distressed concrete. In 15th International Conference on Alkali-Aggregate Reaction, Sao Paulo, Brazil. <https://icaarconcrete.org/wp-content/uploads/2020/11/15ICAAR-SanchezL-2.pdf>.
- [4] Poulsen, E. (2005). Diffusion of Chloride in Concrete: Theory and Application (1st ed.). CRC Press. <https://doi.org/10.1201/9781482295108>.
- [5] Karam, A. (2014) Chloride Ingress into Submerged Concrete Under Sustained Load (Ph.D. thesis).
- [6] Lim, C.C., Gowripalan, N., & Sirivivatnanon, V. (2000). Microcracking and chloride permeability of concrete under uniaxial compression. *Cement and Concrete Composites*, 22, 353-360. [https://doi.org/10.1016/S0958-9465\(00\)00029-9](https://doi.org/10.1016/S0958-9465(00)00029-9).
- [7] Rostam, S. (1996). High performance concrete cover—why it is needed, and how to achieve it in practice. *Construction and Building Materials*, 10(5), 407-421. [https://doi.org/10.1016/0950-0618\(96\)00007-4](https://doi.org/10.1016/0950-0618(96)00007-4).
- [8] Samaha, H.R., & Hover, K.C. (1992). Influence of microcracking on the mass transport properties of concrete. *ACI Materials Journal*, 89(4). <https://doi.org/10.14359/2585>.
- [9] Chung, C.-W., Shon, C.-S., & Kim, Y.-S. (2010). Chloride ion diffusivity of fly ash and silica fume concretes exposed to freeze-thaw cycles. *Construction and Building Materials*, 24(9), 1739-1745. <https://doi.org/10.1016/j.conbuildmat.2010.02.015>.
- [10] Trejo, D., Mazarei, V., Ideker, J. H., & Isgor, O. B. (2017). Influence of Alkali-Silica Reaction Reactivity on Corrosion in Reinforced Concrete. *ACI Materials Journal*, 114(5). <https://doi.org/10.14359/51689895>.
- [11] Mazarei, V., Trejo, D., Ideker, J. H., & Isgor, O. B. (2017). Synergistic effects of ASR and fly ash on the corrosion characteristics of RC systems. *Construction and Building Materials*, 153, 647-655. <https://doi.org/10.1016/j.conbuildmat.2017.07.097>.
- [12] Delagrave, A., Bigas, J. P., Ollivier, J. P., Marchand, J., & Pigeon, M. (1997). Influence of the interfacial zone on the chloride diffusivity of mortars. *Advanced Cement Based Materials*, 5(3-4), 86-92. [https://doi.org/10.1016/S1065-7355\(96\)00008-9](https://doi.org/10.1016/S1065-7355(96)00008-9).

- [13] Climent, M.A., de Vera, G., Viqueira, E., & López-Atalaya, M.M. (2004). Generalization of the possibility of eliminating the filtration step in the determination of acid-soluble chloride content in cement and concrete by potentiometric titration. *Cement and Concrete Research*, 34(12), 2291-2295. <https://doi.org/10.1016/j.cemconres.2004.04.012>.
- [14] Caré, S., & Hervé, E. (2004). Application of a n-Phase Model to the Diffusion Coefficient of Chloride in Mortar. *Transport in Porous Media*, 56(2), 119-135. <https://doi.org/10.1023/B:TIPM.0000021730.34756.40>.
- [15] Yang, C. C. (2003). Effect of the interfacial transition zone on the transport and the elastic properties of mortar. *Magazine of Concrete Research*, 55(4), 305-312. <https://doi.org/10.1680/macr.2003.55.4.305>.
- [16] Bonta, M., Eitzenberger, A., Burtscher, S., & Limbeck, A. (2016). Quantification of chloride in concrete samples using LA-ICP-MS. *Cement and Concrete Research*, 86, 78-84. <https://doi.org/10.1016/j.cemconres.2016.05.002>.
- [17] Silva, N., Luping, T., & Rauch, S. (2013). Application of LA-ICP-MS for meso-scale chloride profiling in concrete. *Materials and Structures*, 46(8), 1369-1381. <https://doi.org/10.1617/s11527-012-9979-y>.
- [18] ASTM International. ASTM C1556-11a (2016). Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion. <https://www.astm.org/c1556-11ar16.html>.
- [19] Bentur, A., Berke, N., & Diamond, S. (1997). *Steel Corrosion in Concrete: Fundamentals and civil engineering practice* (1st ed.). CRC Press. <https://doi.org/10.1201/9781482271898>.
- [20] Trottier, C., Zahedi, A., Ziapour, R., Sanchez, L., Locati, F. (2021). Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR). *Construction and Building Materials*, 269, 121250. <https://doi.org/10.1016/j.conbuildmat.2020.121250>.
- [21] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. *Cement and Concrete Research*, 144, 106426. <https://doi.org/10.1016/j.cemconres.2021.106426>.
- [22] Sanchez, L.F.M., Drimalas, T., Fournier, B., Mitchell, D., & Bastien, J. (2018). Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms. *Cement and Concrete Research*, 107, 284-303. <https://doi.org/10.1016/j.cemconres.2018.02.017>.
- [23] Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17-31. <https://doi.org/10.1016/j.cemconres.2016.12.001>.

- [24] Zheng, J., Wong, H. S., & Buenfeld, N. R. (2009). Assessing the influence of ITZ on the steady-state chloride diffusivity of concrete using a numerical model. *Cement and Concrete Research*, 39(9), 805-813. <https://doi.org/10.1016/j.cemconres.2009.06.002>.
- [25] Grattan-Bellew, P. E. (1995). Laboratory Evaluation of Alkali-Silica Reaction in Concrete from Saunders Generating Station. *ACI Materials Journal*, 92(2). <https://doi.org/10.14359/9763>.
- [26] Villeneuve, V., Fournier, B., Duchesne, J. (2012). Determination of the damage in concrete affected by ASR-the damage rating index (DRI). In 14th International Conference on Alkali-Aggregate Reaction (ICAAR). Austin, Texas (USA). <https://icaarconcrete.org/wp-content/uploads/2022/10/14ICAAR-VilleneuveV-1.pdf>.
- [27] Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74-92. <https://doi.org/10.1016/j.cemconres.2014.08.002>.
- [28] Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., Duchesne, J. (2016). Use of Damage Rating Index to Quantify Alkali-Silica Reaction Damage in Concrete: Fine versus Coarse Aggregate. *ACI Materials Journal*, 113(4). <https://doi.org/10.14359/51688983>.
- [29] Zhu, Y., Zahedi, A., Sanchez, L. F. M., Fournier, B., & Beauchemin, S. (2021). Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. *Cement and Concrete Research*, 142, 106350. <https://doi.org/10.1016/j.cemconres.2020.106350>.

10. Future works

As previously mentioned in Chapter 2, limited data is available on recycled concrete mechanical and durability-related properties, primarily when advanced mix design techniques are used for mix proportioning. This study aims to improve the overall understanding of the impact of ASR on mechanical and durability-related properties. Further research is needed to fully understand the behaviour of recycled concrete affected by various types of deterioration mechanisms.

Based on this thesis's findings, many subjects related to the mechanical and durability-related properties of recycled concrete require more research. Here a few examples are presented:

- The ASR reaction presented a unique behaviour in the case of recycled concrete. As such, it is expected that the prevention measures in place for conventional concrete may not be suitable for stopping the secondary reaction in RCA.
- The impact of the location of secondary ASR reaction where the reaction starts within the OVA and the RM was investigated in depth in this work. However, to fully understand ASR in recycled concrete, a combination of these two reactive aggregates (i.e., reactive coarse in OVA and reactive sand in RM), as well as the introduction of new reactive sand aggregates in the new mortar, needs to be investigated.
- To achieve desirable fresh and hardened state properties, the EV mix design technique was selected for the development of recycled concrete. It would be interesting to see how various mix design techniques would impact the secondary ASR development as well as the material property loss of recycled concrete.
- In recent years several studies have focused on the improvement of RCA overall performance by pre-mixing processes such as carbonated RCA aggregate. A combination of these techniques with advanced mix design techniques and prevention methods could be another topic of interest.
- In this work, the impact of initial and secondary ASR reactions was investigated in depth. However, several other degradation mechanisms in Canada (i.e., freeze and thaw, corrosion of rebars) could be interesting due to their unique way of affecting mechanical properties and the RCA produced with concrete affected by these mechanisms.
- The chloride diffusion rate of recycled and conventional concrete affected by ASR was investigated in this work. However, this phenomenon requires further investigation due to the presence of gel and the development of the cracking network at each expansion level (i.e., the initial expansion for CC and secondary expansion for RCA). Using reactive aggregates to produce concrete with embedded rebars could be a solution to better understand the impact of ASR-induced damage on chloride diffusion.

- The combination of various deterioration mechanisms is another field that requires more research. In this regard, a combination of F&T, ASR and corrosion could be of interest, especially in Canada.
- One of the main challenges with the use of RCA is the significant variability of the material. The presence of previous damage (CDW) amplifies the variability in the RCA itself, making the use of RCA more challenging for the industry. A study focused on a procedure to assess the use of RCA in the industry, and present quality control standards could be helpful.

11. Scientific and engineering contributions

This study aims to understand the overall impact of ASR on recycled concrete's properties. While a thorough investigation was conducted on the impact of initial and secondary ASR expansion, whether the reaction starts within the OVA or the RM, and the conclusions were drawn in the previous chapters, the findings of this research can be classified as scientific or engineering contributions, as outlined below:

Scientific contributions:

- Understanding the importance of initial ASR damage severity on several mechanical properties of recycled concrete.
- Understanding the impact of reactive aggregates location (OVA or RM) on properties of recycled concrete.
- Presenting a link between the mechanical properties of recycled concrete and the findings using microscopic assessments.
- Understanding the impact of secondary ASR-induced damage on mechanical properties of recycled concrete.
- Investigating the chloride diffusion rate of various recycled concrete specimens at different stages of the reaction.

Engineering contributions:

- Demonstrating the diagnostic potential of direct shear and stiffness damage tests (SDT) in ASR-affected recycled concrete.
- Presenting a reference chart for mechanical property loss of recycled concrete specimens affected by ASR, which can serve as a diagnostic tool.
- Presenting a chart for assessing the risk of using ASR-affected recycled concrete where corrosion of rebars is of concern.

12. Conclusions of the Thesis

The objectives of this thesis were thoroughly described in Chapter 3, and each of the scientific papers included in the thesis was specifically designed to address these objectives. The main findings of the scientific papers are summarized below:

This thesis showed that the direct shear strength setup could capture ASR-induced development in both conventional and recycled concrete mixtures. The influence of initial damage in the RCA particles was also highlighted through the shear strength and DRI analyses, emphasizing the importance of distinguishing the type of RCA used in recycled mixtures. It is also noted that the overall crack width of the system plays an essential role in assessing the direct shear strength of ASR-affected specimens. Overall, the direct shear setup proved to be a reliable tool for assessing the impact of initial and secondary ASR-induced expansion. However, it is recommended that the DRI be used in combination with the direct shear test via the so-called multi-level approach.

In this thesis, it has been observed that the ASR-induced expansion rate is considerably lower for both RCA mixtures when compared to conventional concrete. This could be due to a) the consumption of the source of silica in OVA during the initial damage that both RCAs of this work have experienced and b) the presence of high amounts of residual mortar (RM) in RCA, that could act as a barrier for reactant silica from the OVA to reach the new alkalis in the new mortar.

The initial ASR location and severity significantly affect the kinetics and potential of secondary ASR-induced damage. The concrete made of 0.30% RSH displayed an ultimate expansion of 0.35%, while the 0.30RTX showed a lower ultimate secondary expansion of 0.30%. Moreover, these specimens presented a faster reaction rate at the beginning of secondary expansion but slowed down after 0.12% of expansion when compared to specimens made of slightly damaged RCA.

When comparing the mechanical degradation of slightly damaged RCA and conventional concrete, it is noted that they experienced almost identical mechanical property losses at low and moderate ASR-induced expansion. However, comparing the mechanical results of slightly and severely damaged RCA, it is evident that the extent of initial damage significantly affects the mechanical degradation of distinct RCA mixtures. At low and moderate expansion levels, severely damaged specimens had inferior mechanical properties, and at high and very high levels of expansion, the slightly damaged specimens presented the highest mechanical properties among mixtures.

The location of the initial expansion can influence the distribution and extension of damage within the various parts of the recycled concrete, while the severity of the initial expansion can affect the overall integrity of the aggregates as well as the availability of silica and alkalis for a secondary reaction. The slightly and severely

recycled Springhill specimens presented better shear and compressive strength at all secondary expansion levels and lower modulus of elasticity at the beginning of the secondary expansion when compared to slightly and severely recycled Texas specimens.

The apparent chloride diffusion coefficient variation was more significant for the recycled specimens made of Texas sand, while the RSH specimens presented a more similar chloride diffusion coefficient among the four concrete families. Overall, the specimens made of Texas sand presented a higher chloride diffusion coefficient for both recycled and conventional concrete. More studies focused on the impact of ASR gel are needed to understand how the amount and location of ASR gel can impact the chloride diffusion coefficient.

Finally, the DRI was used to validate the results obtained in this work. The so-called “extended DRI” enabled validation along with a better understanding of the results obtained at various secondary expansions.